Effects of Plyometric and Resistance Training on Muscle Strength, Explosiveness, and Neuromuscular Function in Young Adolescent Soccer Players

Brandon J. McKinlay,[1] Phillip Wallace,[2] Raffy Dotan,[1] Devon Long,[1] Craig Tokuno,[3] David A. Gabriel,[3] and Bareket Falk[4]

[1]Applied Physiology Laboratory, Faculty of Applied Health Sciences Brock University, St Catharines, Ontario Canada; [2]Environmental Ergonomics Laboratory, Faculty of Applied Health Sciences Brock University, St Catharines, Ontario Canada; and [3]Department of Kinesiology, Faculty of Applied Health Sciences Brock University, St Catharines, Ontario Canada; and [4]Applied Physiology Laboratory, Department of Kinesiology, Center for Bone and Muscle Health, Faculty of Applied Health Sciences Brock University, St Catharines, Ontario Canada

Abstract

McKinlay, BJ, Wallace, P, Dotan, R, Long, D, Tokuno, C, Gabriel, D, and Falk, B. Effects of plyometric and resistance training on muscle strength, explosiveness, and neuromuscular function in young adolescent soccer players. *J Strength Cond Res* 32(11): 3039–3050, 2018—This study examined the effect of 8 weeks of free-weight resistance training (RT) and plyometric (PLYO) training on maximal strength, explosiveness, and jump performance compared with no added training (CON), in young male soccer players. Forty-one 11- to 13-year-old soccer players were divided into 3 groups (RT, PLYO, and CON). All participants completed isometric and dynamic ($240^\circ \cdot s^{-1}$) knee extensions before and after training. Peak torque (pT), peak rate of torque development (pRTD), electromechanical delay (EMD), rate of muscle activation (Q_{50}), m. vastus lateralis thickness (VL_T), and jump performance were examined. Peak torque, pRTD, and jump performance significantly improved in both training groups. Training resulted in significant ($p \leq 0.05$) increases in isometric pT (23.4 vs. 15.8%) and pRTD (15.0 vs. 17.6%), in RT and PLYO, respectively. During dynamic contractions, training resulted in significant increases in pT (12.4 and 10.8% in RT and PLYO, respectively), but not in pRTD. Jump performance increased in both training groups (RT = 10.0% and PLYO = 16.2%), with only PLYO significantly different from CON. Training resulted in significant increases in VL_T (RT = 6.7% and PLYO = 8.1%). There were no significant EMD changes. In conclusion, 8-week free-weight resistance and plyometric training resulted in significant improvements in muscle strength and jump performance. Training resulted in similar muscle hypertrophy in the 2 training modes, with no clear differences in muscle performance. Plyometric training was more effective in improving jump performance, whereas free-weight RT was more advantageous in improving peak torque, where the stretch reflex was not involved.

Key Words athlete, child, exercise, electromyography, force, maturity, neuromotor, sport, torque

Introduction

Free-weight (FW) resistance training (RT), as well as plyometric training, have been widely used and studied among adults, but much less so in children. Both types of training have been shown to be effective and safe and are recommended for youth by various professional associations (4,7,19,37). Both the safety aspects and functional benefits of FW resistance training and plyometric training in youth (i.e., gains in muscular strength, power, endurance, and sports performance) are well documented (7,9,20,23,26,35–37).

Little or no hypertrophy has been observed after various forms of RT in youth (21). Therefore, the training-induced enhancement in maximal strength has been attributed solely to neuromuscular adaptations, although these have been investigated to a limited extent (46,47,51). The effects of FW RT on explosive strength in youth remain unclear (16,51). Performance in tasks, such as jumping and sprinting, has been shown to improve after plyometric training among both children and adults (39). Such tasks have served as indirect measures of explosive strength (17,31). The effects of FW resistance and plyometric training on young athletes have recently been reviewed, but no clear training-mode differences were apparent in muscular strength or vertical

Address correspondence to Bareket Falk, bfalk@brocku.ca.

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jump performance (36). In addition, although neuromuscular adaptations to traditional RT have been investigated in youth (46,47,51), this has not been the case for plyometric training (26). Thus, more research is needed to elucidate the influence of neuromotor adaptations regarding muscular strength.

In adults, various forms of resistance and plyometric training have been shown to result in increased explosiveness, as measured directly by peak rate of torque development (pRTD) (12,34). These changes have been attributed to enhanced rate of muscle activation (1,24), muscle hypertrophy (27), and increased musculotendinous stiffness (14,15). In youth, training-induced neuromuscular adaptations related to explosive strength have only been studied by Waugh et al. (51), who reported a significant reduction in electromechanical delay (EMD) after 10 weeks of RT. Although shortened, EMD could indicate increased musculotendinous stiffness (MTS), which would be expected to increase pRTD, the reported pRTD changes in that study did not reach statistical significance. No studies have examined possible structural or neurophysiological mechanisms responsible for the augmented explosiveness after plyometric training in youth. In fact, the unknown nature of the neuromuscular responses to resistance and plyometric training in youth athletes has been recently highlighted as a gap in the current strength and conditioning literature (26).

Age-related increases in strength are generally attributed to increased muscle size and neuromuscular activation (45). However, prepubertal children typically respond to otherwise-effective strength training with little or no muscle hypertrophy, which, in turn, suggests that children's strength gains are largely neuromotor in nature (7,23). In addition, it has been proposed that children use their higher threshold (type II) motor units to a lesser extent than adults (18). Thus, it is reasonable to expect that children's neuromotor response pattern may be different than that observed in adults.

It is therefore the purpose of this study to compare the effects of FW resistance vs. plyometric training, in young adolescent athletes, on jump performance, dynamometer-measured muscular strength and explosiveness, neuromuscular parameters, and muscle hypertrophy. It was hypothesized that both FW resistance and plyometric training will result in improved muscular and jump performance. It was further hypothesized that changes induced by FW RT will be mediated more by morphological adaptations, whereas plyometric-induced changes would be mediated mostly by enhanced neuromuscular activation.

This study is unique in its design and scope. Previous studies have examined the effects of various strength-training regimens on muscle performance in youth (see Ref. 7,9,26,36 for reviews). However, this is the first study to examine the effects of plyometric training in youth, not only on external performance, but on neuromuscular function, as well. In addition, most previous studies have focused on field tests or on isometric testing parameters. In this study, dynamic contractions were also examined in an attempt to provide further insight into the mechanisms of training-induced enhancement in performance.

Methods

Experimental Approach to the Problem

The objective of the study was to compare the effectiveness of 8-week FW RT vs. plyometric (PLYO) training in improving maximal strength, explosiveness, and sport performance and to examine accompanying neuromuscular and morphological adaptations in midpubertal boys. Before and after training assessments of physical characteristics, maximal isometric and dynamic ($240° \cdot s^{-1}$) strength, and explosiveness, jump performance, neuromuscular, and morphological adaptations were measured.

Subjects

The experimental protocol and procedures were cleared by the Biosciences Research Ethics Board at Brock University (Institutional Ethics Board) (REB #13-305) and conformed to the latest revision of the Declaration of Helsinki. Written informed parental consent and child consent was obtained after a thorough explanation of the study's purpose, procedures, benefits, and potential risks or discomforts were provided.

The participants were 41 competitive male soccer players (11–13 years) of similar soccer-training histories (mean ± *SD* 4.2 ± 1.1 years; 6 hours$\cdot$wk^{-1}), with no previous strength-training experience in either FW RT or plyometric training, who participated in structured soccer training (2 hours, 3 times$\cdot$wk^{-1}). They were divided into 3 groups: RT (n = 14), PLYO (n = 13), and CON (n = 14), matched for age, body size, somatic maturity, and maximal isometric muscle strength (Table 1). Participants were recruited from several local soccer clubs. Pretraining data of this study's participants have been previously published (40).

Procedures

Tests and measurements were administered in 2 sessions just before (Pre) and after (Post) the training period. Session 1, performed in the laboratory, comprised familiarization to the tests and procedures, anthropometric measurements, and isometric and dynamic dynamometer testing. In session 2, jump testing of countermovement jump (CMJ) and the squat jump (SJ) was conducted at the boys' soccer-training facility on a separate day.

Training. Before the 8-week training program, all participants underwent a 2-week, modality-specific familiarization training (6 × 45-minute sessions). During this time, both training groups (RT and PLYO) practiced proper techniques using bodyweight exercises to ensure correct form/posture. It was ensured that movement patterns and landing strategies were being executed correctly and technique competency was attained. Child-appropriate equipment (e.g., 5-ft

Olympic straight bar for squats and lunges) was gradually integrated into these sessions to allow for safe progression of various forms of multijoint exercises (e.g., squat). The instructor-to-participant ratio was 1:8 in both the PLYO and RT groups.

Initial volume (sets and reps) and intensity (weight) for the RT used during familiarization (1− 2 sets of 2−5 reps, bodyweight), as well as during the 8-week training program (3 sets × 8−12 reps, <80% one repetition maximum), were in line with recommendations provided by the International Consensus Position Statement on youth RT (37). Progressions for RT were determined based on participants' ability to successfully complete 2 or more repetitions in the last set in 2 consecutive workouts for a given exercise. If the participant successfully completed these final repetitions, the load was increased until the participant fell into the desired repetition programming range (8−12 reps). Much like RT, initial volume (sets and # of foot contacts) and intensity (exercise complexity, box height) for PLYO used during familiarization (1 set, 6−10 foot contacts/exercise), as well as during the 8-week training program (3 sets × 10−12 foot contacts/exercise), were in line with previously published recommendations (3,38). Progression for PLYO was based on technique competency and amortization phase (ground contact time) during exercises. If participants were able to show quality technique during given exercises without alterations in form or prolonged amortization phase, exercise complexity was progressed (e.g., from 2-legged to 1-legged hops, or increased jump box height).

Each training session began with a standardized 15-minute dynamic warm-up, followed by the appropriate number of sets and reps (see above) of 4–5 exercises focused on the lower limb (Table 2). After the warm-up, both experimental groups completed ~30 minutes of training, 3 times per week, for 8 weeks, just before their regular soccer training for a total of 90 minutes per session. The CON group underwent 90 minutes of regular soccer training. Training protocols for both types of training modalities are described in Table 2. Specific attention and instruction were provided to ensure safety, proper exercise technique, and progression throughout the training period. All participants were continually monitored by trained staff to ensure proper form and safety in each training session. FW resistance training exercises were all performed at low velocities (2-second eccentric, 1-second pause, and 2-second concentric), whereas PLYO exercises were all performed as fast as possible. For both groups, rest intervals were 60–90 s between sets and 2–3 min between different exercises.

Measurements: Anthropometry, Maturity, and Body Composition. Height (Ht) and sitting Ht were measured using a stadiometer (Ellard Instrumentation, Ltd., Monroe, WA, USA) and recorded to the nearest 1 mm. Body fat percentage (% fat) was estimated using bioelectrical impedance analysis (BIA, InBody520; Biospace Co., Ltd., Seoul, S. Korea), which has previously been validated in children and adolescents (33). The digital scale of the InBody520 was used to measure body mass (Wt). Both values were recorded to the nearest 0.1 % fat and kg, respectively. All anthropometric measurements were performed by the same investigator to eliminate interobserver variability.

Somatic maturity (maturity offset) was estimated based on the calculated number of years from the age of peak height velocity, using Ht, sitting Ht, leg length (Ht minus sitting Ht), and Wt, and sex-specific regression equations (41).

Muscle thickness of the vastus lateralis was measured by a single investigator, using real-time B-mode ultrasound (System 5; GE Vingmed, Horten, Norway) with 5-MHz linear-array probe, obtaining transverse images of the vastus lateralis at rest. The scanning head of the probe was oriented

Table 1. Physical characteristics of participants in the FW RT, plyometric training and control groups.*†

	FW RT		Plyometric training		Control	
	Pre	Post	Pre	Post	Pre	Post
Age (y)‡	12.5 ± 0.7		12.6 ± 0.7		12.5 ± 0.3	
Height (cm)‡	155.1 ± 7.7	156.3 ± 8.1	157.8 ± 7.9	159.2 ± 7.8	152.1 ± 8.5	153.0 ± 8.5
Mass (kg)‡	44.6 ± 7.6	46.1 ± 8.1	47.2 ± 10.2	49.2 ± 10.9	41.3 ± 6.4	42.0 ± 6.2
Body fat (%)	14.1 ± 4.9	15.0 ± 4.7	12.9 ± 6.3	12.8 ± 5.8	12.3 ± 5.4	11.4 ± 5.6
BMI ($kg \cdot m^{-2}$)	18.5 ± 2.2	18.8 ± 2.1	18.8 ± 1.6	19.3 ± 1.6	17.8 ± 1.5	17.9 ± 1.5
Maturity offset (y)‡	−1.47 ± 0.60	–	−1.14 ± 0.66	–	−1.57 ± 0.34	–
VL_T (mm)‡	19.9 ± 2.4	21.2 ± 3.8§	20.1 ± 1.2	21.6 ± 3.6§	20.3 ± 1.9	20.4 ± 1.7

*BMI = body mass index ($kg \cdot m^{-2}$); FW RT = free-weight resistance training; VL_T = vastus lateralis thickness.
†Values are mean and *SD*.
‡Significant increase from preintervention to postintervention (significant time effect, $p < 0.01$).
§Significantly greater increase from pretraining to posttraining compared with the control group. VL_T increased only in the resistance and plyometric training groups (significant group-by-time interaction, $p < 0.04$).

TABLE 2. Training program.*

	Sets × repetitions per set							
Exercise	Week 1	Week 2	Week 3	Week 4	Week 5	Week 6	Week 7	Week 8
FW RT								
Squats	3 × 12	3 × 12†	3 × 12	3 × 12†	3 × 12	3 × 12†	3 × 12	3 × 12†
Lunges	3 × 12	3 × 12						
Step-ups	3 × 12	3 × 12†	3 × 12†	3 × 12	3 × 12†	3 × 12		
Calf raises	3 × 12	3 × 12†					3 × 12†	3 × 12
Wide stance squats			3 × 12	3 × 12†	3 × 12	3 × 12†	3 × 12	3 × 12†
Raised rear foot lunge			3 × 12	3 × 12†	3 × 12	3 × 12†	3 × 12	3 × 12†
One-legged sit-to-stand rises			3 × 12	3 × 12				
One-legged squats					3 × 12	3 × 12†	3 × 12	3 × 12†
Plyometric training								
Countermovement jumps	3 × 12	3 × 12						
Knees-to-chest jumps	3 × 12	3 × 12						
Drop jumps	3 × 12	3 × 12	3 × 12†	3 × 12	3 × 12†	3 × 12	3 × 12†	3 × 12
Consecutive long jumps	3 × 3 × 5	3 × 3 × 5						
Jump lunges			3 × 12	3 × 12	3 × 12	3 × 12	3 × 12	3 × 12
Straight-legged jumps w/toe-touch			3 × 12	3 × 12				
Side-to-side lateral hops			3 × 12	3 × 12				
High knee skips			3 × 12	3 × 12	3 × 12	3 × 12		
Hop & skip jumps					3 × 12	3 × 12		
One-legged countermovement jumps					3 × 12	3 × 12	3 × 12	3 × 12
One-legged knees-to-chest jumps							3 × 12	3 × 12
One-legged consecutive long jumps							3 × 12	3 × 12

*FW RT = free-weight resistance training.
†Increase in resistance (weight) or jump box height from previous session.

along the midtransverse axis of the muscle. All images were analyzed offline in duplicate. Muscle thickness was determined as the distance between the bone-muscle and adipose tissue–muscle interfaces. Because of the flat cross-sectional shape of the vastus lateralis, the muscle's thickness cannot be considered a diameter, so as to calculate cross-sectional area. For the same reason, however, changes in cross-sectional area can be approximated by changes in the muscle's thickness. Test-retest reliability of muscle thickness determination was $ICC_{(3,1)} = 0.98$, $n = 10$.

Muscle Strength. All isometric and dynamic strength measurements were performed on the right leg, using a Biodex System III dynamometer (Biodex, Shirley, NY, USA). The participants were seated in the dynamometer's chair and stabilized by a cross-hip, and 2 diagonal chest shoulder straps. The dynamometer's lever arm attachment pad was adjusted to the participant's leg 3 cm above the lateral malleolus and secured by a strap. The lever arm's axis of rotation was aligned with the knee's center of rotation (femur's lateral condyle). The knee was then set at a 90° starting position (full knee extension = 180°).

Once the participant was properly seated and secured, a familiarization and warm-up protocol was performed, consisting of 3 moderate- to high-velocity dynamic contractions ($180°\cdot s^{-1}$) and 3 submaximal isometric contractions, followed by 2 fast ($240°\cdot s^{-1}$) dynamic and 2 maximal isometric contractions. If a participant did not feel comfortable with the contractions, or showed inconsistency, more trials were added.

After the familiarization trials, participants performed the testing protocol, which consisted of 5- , 3-second, maximal isometric knee extensions at 90°, followed by 5 maximal dynamic contractions at $240°\cdot s^{-1}$. Contractions were separated by 30-second rest intervals. The 2 sets of contractions were separated by 5-minute rest.

Before each contraction, participants were instructed to "kick out as fast and as hard as possible" from a completely relaxed state. Verbal encouragement was given, along with visual torque-level feedback, displayed on the Biodex monitor. Torque and electromyographic (EMG) signals were recorded before and throughout each contraction. Additional repetitions were added when contractions were deemed unsuitable because of execution errors (e.g., preceding countermovement), baseline instability, or abnormalities in the torque or EMG traces, determined visually. All dynamometer measurements, measurement suitability, and verbal encouragement were performed by the same investigator, to eliminate interobserver variability.

Muscle Force Variables. Peak torque (pT) was defined as the peak torque developed during a maximal voluntary contraction. Values were recorded from the dynamometer's torque signal and are presented in absolute (N·m), and in body mass–corrected values ($N\cdot m\cdot kg^{-1}$).

Peak rate of torque development (pRTD) was defined as the highest rate at which torque developed (Δtorque/Δtime) (1) and determined as the highest peak of the first derivative of the torque trace. Values are presented in absolute terms ($N\cdot m\cdot s^{-1}$) and relative to maximal strength ($N\cdot m\cdot s^{-1}\cdot N\cdot m^{-1}$).

TABLE 3. Peak torque and rate of torque development, initial muscle activation, and electromechanical delay in the FW RT, plyometric training, and control groups before and after intervention.*†

Variables		FW RT		Plyometric training		Control	
		Pre	Post	Pre	Post	Pre	Post
pT (N·m)	Isometric ‡	141.2 ± 34.7	172.9 ± 46.2§	149.4 ± 40.8	172.1 ± 45.3§	127.7 ± 26.2	127.1 ± 25.6
	Dynamic	62.6 ± 13.2	70.1 ± 16.7§	75.2 ± 24.5	80.0 ± 18.6	61.3 ± 7.9	59.0 ± 11.3
pRTD ($N\cdot m\cdot s^{-1}$)	Isometric ‡	678 ± 243	766 ± 267§	786 ± 247	898 ± 224§	617 ± 179	624 ± 169
	Dynamic ‡	395 ± 75	435 ± 106	464 ± 143	478 ± 117	385 ± 67	396 ± 70
Q_{50} (mV·s)	Isometric	11.0 ± 6.1	12.0 ± 8.1	16.3 ± 17.8	20.5 ± 15.7	12.8 ± 7.3	12.5 ± 7.7
	Dynamic	15.8 ± 6.8	19.2 ± 13.1	21.4 ± 18.7	22.5 ± 18.3	14.9 ± 7.2	15.0 ± 9.8
EMD (ms)	Isometric	47.2 ± 9.5	47.8 ± 7.0	43.2 ± 7.6	40.7 ± 6.9	48.4 ± 9.5	49.7 ± 14.6
	Dynamic	38.2 ± 6.4	36.5 ± 7.1	37.5 ± 9.7	37.8 ± 8.7	44.3 ± 6.4	45.0 ± 9.0

*FW RT = free-weight resistance training; pT = peak torque; pRTD = peak rate of torque development; Q_{50} = area under the rectified electromyographic trace in the initial 50 ms of activity; EMD = electromechanical delay.
†Values are mean ± *SD*.
‡Significant increase from preintervention to postintervention (significant time effect, $p < 0.01$).
§Significantly greater increase from pretraining to posttraining compared with the control group.

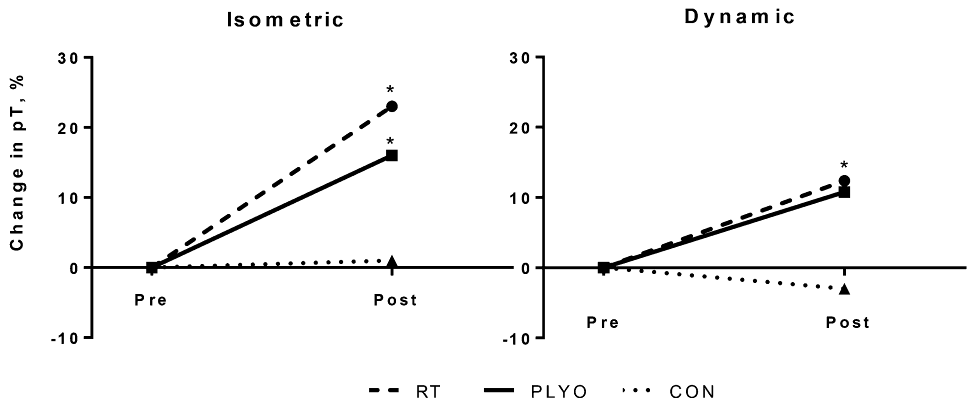

Figure 1. Percent change in isometric peak torque (pT, left) and dynamic pT (right) from preintervention to postintervention in the free-weight (FW) resistance training (RT), plyometric training (PLYO), and control (CON) groups. * = significant difference from CON ($p < 0.01$).

Selection of Best Trials. All isometric and dynamic knee extension trials were ranked by their pT and pRTD. Both variables were expressed as a percentage of the respective maximal value, obtained in any of the trials. For each trial, the product of the percentage value of pT and pRTD was calculated to provide a composite score for that trial. Trials were then assigned a ranking from 1 to 5. The 2 highest ranked trials were used for further analysis, provided both pT and pRTD were above 80% of their respective maxima.

Electrode Placement. Electromyography was recorded from the right vastus lateralis using a bipolar surface electrode (Delsys 2,1; Delsys, Inc., Boston, MA, USA). Electrode skin sites were cleaned with isopropyl alcohol and abrasive gel (Nuprep, Weaver and Co., Aurora, CO, USA) to minimize interference with signal transmission. The electrode was placed on the vastus lateralis belly, in parallel to the muscle-fiber direction, using Delsys's proprietary double-sided adhesive interface. Exact placement was determined by manual palpation and visual inspection during a resisted isometric contraction according to the SENIAM recommendations (http://seniam.org/quadricepsfemorisvastuslateralis.html). A reference/ground electrode was placed over the most prominent cervical vertebra (C-7).

Electromyography and Torque Data Acquisition. Electromyographic signals were Butterworth band pass filtered at 20–450 Hz, using the Bagnoli-4 bioamplifier (Delsys, Inc., Boston, MA, USA). Position and torque signals from the

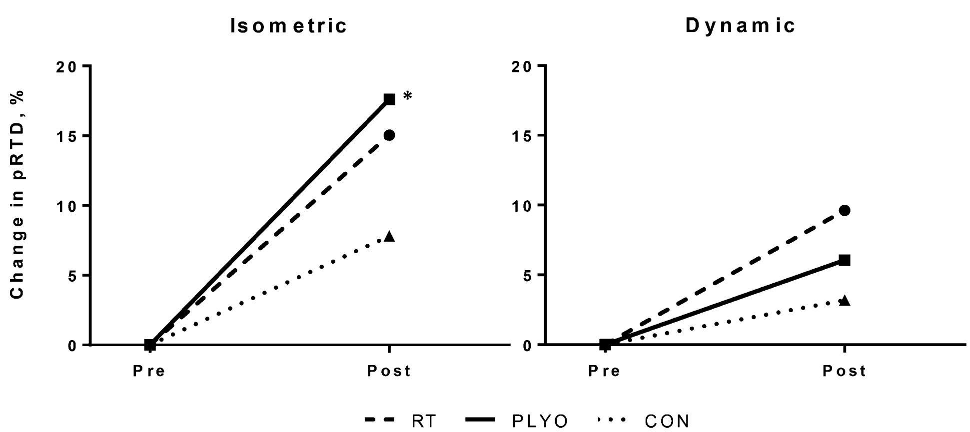

Figure 2. Percent change in isometric peak rate of torque development (pRTD, left) and dynamic pRTD (right) from preintervention to postintervention in the free-weight (FW) resistance training (RT), plyometric training (PLYO), and control (CON) groups. * = significant difference from CON ($p < 0.02$).

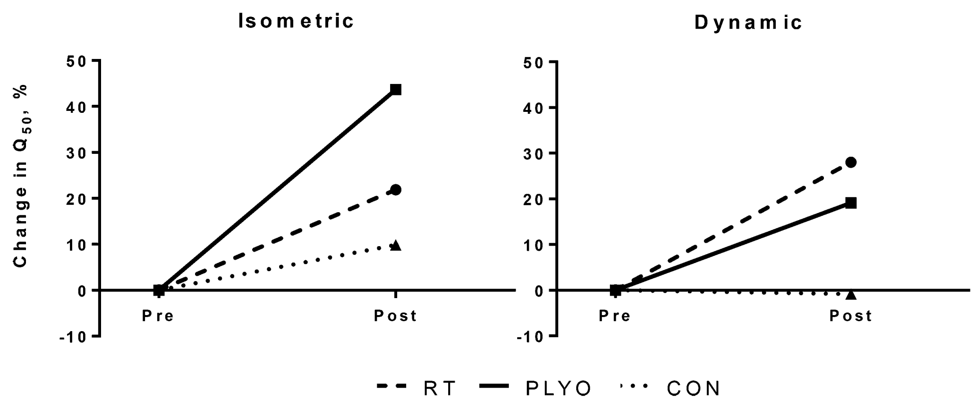

Figure 3. Percent change in the rate of muscle activation (Q_{50}) in isometric (left) and dynamic (right) contractions from preintervention to postintervention in the free-weight (FW) resistance training (RT), plyometric training (PLYO), and control (CON) groups. No significant between-group differences were detected. In pair-wise comparison, PLYO was significantly greater than CON ($p \leq 0.05$).

Biodex were sent to a 16-bit A/D converter (BNC-2110, National Instruments) and sampled at 1000 Hz using a computer-based oscillograph and data acquisition system (EMGworks; Delsys, Inc., Boston, MA, USA). Position and torque signals from the Biodex were sent to a 16-bit A/D converter (BNC-2110, National Instruments) and smoothed using a 6-Hz low pass, 2nd-order Butterworth filter. Recorded data were stored and subsequently analyzed using MATLAB (The MathWorks, Natick, MA, USA).

Electromyographic Variables. All EMG variables were analyzed from the rectified linear envelope. The onset of muscle activation was defined as the point at which the EMG signal reached and surpassed 2 *SD*s above the average amplitude of the initial 500 ms of baseline activity for at least 100 ms. The rate of muscle activation was defined as the area under the rectified linear envelope of the EMG signal of the initial 50 ms (Q_{50}); (24).

Electromechanical delay was calculated as the time difference between the onset of muscle activation and the onset of torque production (14,50). The onset of torque was determined by first calculating a baseline mean of the torque signal (750–250 ms before contraction onset). A reference torque level was then defined (10 N·m), which was above any baseline noise. The torque signal trace was then followed backward in time until it reached the first value equal to the baseline mean. The onset was visually verified.

Performance Testing. Maximal jump height was assessed for 2 jump types (CMJ and SJ), using the Optojump photoelectric system (Microgate, Bolzano, Italy). The Optojump system, which uses flight (airborne) time as a proxy of jump height, has been shown valid and reliable in measuring vertical jump height (25). Jump height was calculated as $9.81 \cdot (\text{flight time})^2/8$.

Participants were familiarized with all jumps before testing. For all jumps, participants were instructed to "jump as high as you possibly can, as if you are trying to touch the ceiling." In addition, participants were instructed not to "tuck" or "bend" their knees during the flight phase. All participants performed each jump

Table 4. Jump performance in the FW resistance, plyometric, and control training groups, before and after intervention.*†

	FW RT		Plyometric training		Control	
	Pre	Post	Pre	Post	Pre	Post
CMJ (cm)	30.7 ± 3.6	29.3 ± 4.5	31.1 ± 5.0	31.5 ± 3.9	30.2 ± 4.6	30.3 ± 4.4
SJ (cm)‡	23.6 ± 4.4	25.9 ± 5.0	24.7 ± 3.6	28.7 ± 4.5§	27.2 ± 5.5	27.9 ± 5.2

*FW RT = free-weight resistance training; CMJ = countermovement jump; SJ = squat jump.
†Values are mean ± *SD*.
‡Significant increase from preintervention to postintervention (significant time effect, $p < 0.01$).
§Significantly greater increase from pretraining to posttraining compared with the control group.

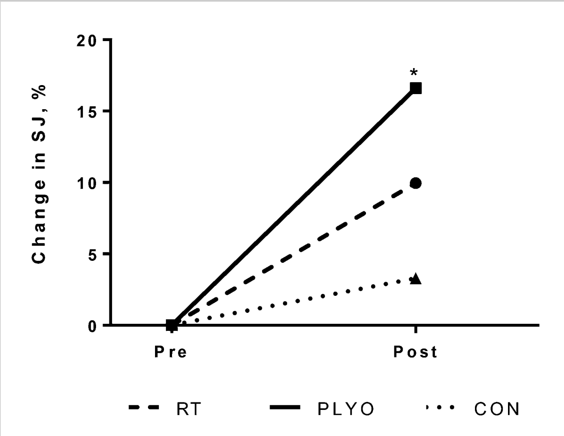

Figure 4. Percent change in maximal squat jump (SJ) height from preintervention to postintervention in the free-weight (FW) resistance training (RT), plyometric training (PLYO), and control (CON) groups. * = significant difference from CON ($p < 0.01$).

3 times at maximal effort, with 1-minute rest intervals. The maximal height achieved was used for further analysis.

The CMJ was performed from an upright erect position with arms in a rested state. When ready, the participant made a downward movement to ~90° bent knee position and immediately jumped vertically as high as possible (13). Arm swing was permitted. Squat jump was performed from a ~90° squat position with hands placed on hips. When ready, the participant jumped vertically, as high as possible (13). No countermovement or arm swing was permitted during the jump.

Statistical Analyses

All statistical analyses were performed using SPSS v.22 (SPSS, Inc., Chicago, IL, USA). The data for all groups are presented as mean ± 1 *SD*. An average value of the best two contractions for each contraction type and participant was used for analysis. Group differences in muscle performance and neuromuscular function at baseline (pre-training) were assessed using a 1-way analysis of variance (ANOVA). The effect of the intervention was determined using a 2-way ANOVA for repeated-measures with one within-subject main effect (time) and one between-subject main effect (group). When a significant group-by-time interaction was observed, univariate gain scores were calculated, and a pairwise comparison, using the Bonferroni correction, was used to determine the between-group differences. Covariates were used when appropriate, as indicated below. The acceptable level of significance was set at $p \leq 0.05$.

Results

There were no training-related injuries throughout the study period. No group differences in age, Ht, Wt, BMI, %fat, VL_T, or maturity offset were observed before the intervention (Table 2). There were similar increases in Ht, Wt, BMI, and maturity offset in all groups after the intervention period. There were no changes in adiposity. There was a significant group-by-time interaction ($p = 0.03$) for the changes in muscle thickness, reflecting a significant increase in thickness in both, the RT and PLYO training groups ($p \leq 0.05$), but not in the CON group.

Before the intervention, there were no group differences in isometric and dynamic pT, pRTD, EMD, and Q_{50}, as well as in the 2 jump performances ($p > 0.05$). Isometric pT increased significantly in both RT and PLYO groups but not in CON (group-by-time interaction, $p = 0.001$). Pairwise comparisons revealed a significantly greater increase in isometric pT in both training groups compared with CON (Table 3). When VL_T changes were used as a covariate, pairwise differences remained significant. A similar pattern was observed in dynamic pT (group-by-time interaction, $p = 0.04$), reflecting dynamic pT increases in the training groups, but not in CON. Pairwise comparisons revealed a significantly greater increase in dynamic pT in RT compared with CON. When the VL_T change was used as a covariate, a similar pattern was observed but group-by-time interaction did not reach significance ($p = 0.07$). The percent changes in isometric and dynamic pT are illustrated in Figure 1. Expressed as percent changes, isometric pT improved significantly more in the RT and PLYO groups compared with CON, whereas dynamic pT improved significantly in RT (but not PLYO) compared with CON.

Isometric pRTD increased significantly in both training groups (group-by-time interaction, $p < 0.01$). Pairwise comparisons revealed a significantly greater increase in isometric pRTD in both RT and PLYO compared with CON (Table 3). When the change in pT was used as a covariate, the pairwise comparison was no longer statistically significant ($p = 0.1$). Analysis of the dynamic pRTD revealed a significant time effect ($p = 0.02$), reflecting an overall increase in pRTD in absolute values. No significant group-by-time interaction was observed. The percent changes in isometric and dynamic pRTD are illustrated in Figure 2. Expressed as percent changes, isometric pRTD improved significantly in both RT and PLYO. However, pairwise comparisons revealed that only PLYO increased significantly more than CON. Change in dynamic pRTD was not significantly different between groups.

No significant preintervention to postintervention changes were observed in EMD or Q_{50} in any of the groups under both, isometric and dynamic conditions (Table 3). Q_{50} increased in both the RT (22 ± 55%) and PLYO (44 ± 39%) groups, but these changes did not reach statistical significance (Figure 3).

Squat jump performance significantly increased postintervention in both training groups (group-by-time interaction, $p = 0.002$), but not in CON. However, only the increase in PLYO was significantly greater than that in CON (Table 4, Figure 4). The group-by-time interaction in CMJ was significant ($p = 0.04$). Although no significant pairwise differences were observed, note that CMJ increased by 2.2 ± 8.7% in PLYO, whereas it decreased by 4.8 ± 6.5% in RT.

There were moderate-to-strong correlations between the change in pT and the change in pRTD in both isometric and dynamic contractions ($r = 0.47$ and 0.69; $p < 0.003$ and 0.0001, respectively). There was a weak correlation between the change in pRTD in the isometric contraction and the change in SJ height ($r = 0.27$; $p = 0.1$). The changes in pT and pRTD during isometric contractions were moderately correlated with the corresponding VL_T changes ($r = 0.38$ and 0.41; $p < 0.02$ and 0.01, respectively). No such correlations were observed in dynamic contractions. There were no significant correlations between the changes in pRTD and the change in EMD or Q_{50}.

Discussion

This study demonstrates that both FW resistance and plyometric training of young adolescent soccer players result in improved muscular performance compared with no added training. More specifically, FW resistance and plyometric training resulted in enhanced pT and pRTD. However, compared with no added training, only plyometric training elicited enhanced jump performance. No clear effects of training were observed on neuromuscular characteristics (EMD, Q_{50}) during isometric or dynamic contractions.

As previously shown (36), both RT and PLYO increased both isometric pT (23.4 and 15.8%, respectively, $p < 0.001$) and dynamic pT (12.4 and 10.8%, respectively, $p < 0.01$ for RT only), compared with the CON (0.001 and −3.8%) (Figure 1). These findings agree with previous studies on isometric strength in youth (10,11,16,47,51) and extend them to also include dynamic strength. They are also in agreement with a recent meta-analysis on the effects of strength and power training in youth (9) and extend it to include the effects of plyometric training on lower body strength measures in adolescent athletes.

Muscle size has not been shown to be significantly affected by strength training in prepubertal children (23,32,46,47). The observed hypertrophy in this study may be explained by the fact that our participants were predominantly pubertal (Table 1). To our knowledge, this is the first study to report muscle hypertrophy after FW resistance or plyometric training in early adolescence.

Although all pT increases were positively associated with muscle hypertrophy ($r = 0.38–0.40$), isometric pT improvements were 2–3 times larger than the increase in VL_T and nearly 50% larger in RT than in PLYO (23.4 vs. 15.8%, respectively). Expectedly then, the isometric pT increase remained significant when the change in VL_T was introduced as a covariate, whereas the corresponding change in dynamic pT approached significance ($p = 0.07$). This suggests that factors in addition to hypertrophy are contributing to training-induced strength improvements in young adolescents. Such factors may include increased muscle activation, decreased agonist-antagonist co-contraction, and greater intermuscular coordination. However, these factors were not evaluated in this study.

The plyometric training effect on pRTD has not been previously examined in pediatric populations. After FW RT of 9-year-old children, Waugh et al. (51) observed an increase in pRTD, which did not reach statistical significance, possibly due to small sample size ($n = 10$/group). In this study, isometric pRTD improved in both RT and PLYO (15.0 and 17.6%, respectively) (Figure 2).

Absolute dynamic pRTD increased 9.6 and 6.1% in RT and PLYO, respectively, with no significant difference between the 2 groups (Table 3 and Figure 2). Chaouachi et al. (16) recently reported that traditional RT in 10- to 12-year-old boys improved dynamic power (presumably reflecting pRTD), more than plyometric training, in slow contractions ($60°\cdot s^{-1}$). Plyometric training, however, resulted in greater dynamic power improvement in fast contractions ($300°\cdot s^{-1}$). The apparent incongruity in the pattern of improvement in dynamic pRTD between that study and ours study may, at least in part, be due to differences in study durations. Although this study examined FW resistance and plyometric training over the course of 8 weeks, Chaouachi et al. (16) training program lasted for 12 weeks. The additional 4 weeks of training (8 extra training sessions) may have allowed for greater strength or power adaptations, eliciting a greater divergence between the various training programs, thus better highlighting the specific adaptations to a given training modality.

A review by Behm and Sale (8) on training specificity highlighted that training at a particular speed produces the greatest adaptations at similar testing velocities. Although it was expected that the plyometric training group would possess superior explosiveness under the dynamic (fast contraction) testing condition, their improvements were no different than those of FW RT, contradicting what one would typically observe in response to a high-velocity style of training in adults. Although our study's results suggest a lack of specificity of dynamometer testing in relation to training, PLYO's performance in the SJ improved by 16.2%, while RT's performance in SJ improved by 10%, indicating a jumping-specific advantage inherent to plyometric training. Furthermore, when changes in SJ performance were examined in relation to those in isometric or dynamic pT and pRTD, no significant correlations were observed. This is an indication that dynamometer-measured pT and pRTD do not appropriately reflect the important factors determining jumping performance and, therefore, may not be useful in monitoring jumping-oriented training programs. Dynamometer testing is initiated from a static, unloaded state, typically examining one joint, which is not the case in jumping. Future research should involve testing modalities specific to the training and performance modes. In the case of jumping, force plates, rather than standard dynamometry to assess explosiveness as well as jump height ability, would be a more suitable testing modality.

In adults, a positive relationship between pT and pRTD has been shown (5). Similarly, training-induced changes in pT are often associated with changes in pRTD (e.g., $r = 0.69$; (6)). In this study, we observed moderate positive correlations between pT and pRTD changes (r = 0.47–0.69). Indeed, when using the change in pT as a covariate, the effect of training on isometric pRTD was no longer significant, suggesting that pT was the predominant factor in isometric pRTD changes. This is similar to what has typically been observed in adults (6,28).

Peak rate of torque development has previously been shown to be positively affected by musculotendinous stiffness (MTS; e.g., Ref. 14). Although not examined in this study, MTS is also known to inversely affect EMD (44). Waugh et al. (51) reported that in previously untrained children, a 10-week plantar-flexor-focused RT program significantly shortened EMD but did not significantly enhance pRTD. Because EMD in the present study was not significantly affected by training mode in any contraction type (Table 3), it may indicate no significant change in MTS. Possibly, being well-trained before intervention, our young athletes may have already incurred much of the potential for training-induced MTS increase before the study. Thus, our observed pRTD changes were more likely due to direct training effects.

Peak rate of torque development is directly affected by the rate of muscle activation (2,49), presumably reflected by the rate of EMG increase (Q_{50}). Interestingly, the increase in isometric Q_{50} from pretraining to posttraining seems to be greatest in the PLYO group (44%) (Figure 3), as opposed to RT (21%) and CON (9.8%), although the group-by-time interaction did not reach statistical significance (p = 0.2). Thus, it is possible that PLYO's increased pRTD was facilitated by an enhanced rate of muscle activation.

The training-response pattern of jump performance in the two jump types and the RT–PLYO differential response deserves scrutiny. A priori, all jumps could be expected to improve with enhanced pT or pRTD. However, after training, SJ performance improved much more in PLYO than in RT (16.2 vs. 10.0%), whereas CMJ performance deteriorated in RT ($-4.8 \pm 6.5\%$, $p = 0.02$). Squat jump is the simplest of the 2 jump types in terms of skill and coordination and where knee extensor strength and explosiveness are most directly applied. Countermovement jump, however, particularly when arm movement is allowed, is more complex, requiring arm-leg coordination, which tends to be less developed in young adolescents compared with adults or older adolescents (30). Indeed, Moran et al. (42) recently demonstrated plyometric training to be effective in increasing jump performance in older (14–16 year-olds), but not in younger (11–13 years) hockey players. Moreover, the lack of improvement in CMJ after FW RT suggests that enhanced strength per se may not improve jumping performance when velocity of training exercises is controlled (e.g., longer time under tension and low-velocity movements) avoiding the addition of elastic energy and stretch-shorting cycle components. This may explain the observed improvement in SJ but not in CMJ.

Plyometric contractions can be considerably more forceful than maximal isometric contractions, due to the addition of musculotendinous elastic energy, as well as to the myotatic stretch reflex enhancement of motor unit recruitment beyond that attainable volitionally (43). Consequently, it is tempting to consider whether plyometric training can enhance voluntary recruitment of motor units, previously recruited only by the plyometric stretch reflex. This is specifically of interest in children, in whom it has been proposed that recruitment of higher threshold (type II) motor units is lower than in adults (18). Although this study was not designed to answer this question, our findings seem to provide worthwhile insight. In accordance with the size principle (29), any additionally recruited motor units would largely consist of fast-twitch, type II motor units. This in turn means that maximal volitional contractions after plyometric training could be expected to be not only more forceful, but also more explosive than after FW RT. This, however, was not the case. Although the difference did not reach statistical significance, PLYO demonstrated lesser, rather than greater improvements compared with RT in both pT and pRTD in the dynamic ($240° \cdot s^{-1}$) contractions. This would suggest that no additional volitional motor unit recruitment was effected by plyometric training. PLYO's greater improvements in SJ performance and apparent greater increase in isometric Q_{50} suggest that other neural adaptations may have occurred such as enhanced motor unit synchronization and intramuscular as well as intermuscular coordination rather than any increase in motor unit recruitment.

One limitation of our study is the assumption that the 8-week training duration was the appropriate duration to detect significant neuromuscular adaptations. In adults, Tillin et al., for example Ref. 48, demonstrated significant neuromuscular adaptations in recreationally active young men after only 4 weeks of training. Because neuromuscular adaptation is thought to precede muscular hypertrophy, it is possible that the present study missed the window of peak neuromuscular enhancement. Future studies examining training-induced neuromuscular adaptation in youth may benefit from also collecting data at earlier time points as shown by previous adult studies (48).

Our sample size was similar to or even greater in most other training studies in youth (17,31,42,46,47,51). However, in view of children's greater response variability (22), particularly in neuromotor variables measured in the present study, either a longer intervention or larger sample size may be necessary to demonstrate some of the expected training-specific adaptations. Furthermore, considering the homogeneity of our sample, our findings should not be generalized to similarly aged girls, nor to populations with different training background. Nevertheless, this study demonstrates that both FW resistance and plyometric training can effectively improve muscle strength in young adolescent male athletes, although plyometric training seems more effective in improving jump performance. These improvements are partly accounted for by muscle hypertrophy, but the expected complementing increases in muscle activation require further clarification. Future research should examine neuromuscular function during jump-specific tasks.

Practical Applications

Both FW resistance training and plyometric training improve muscular performance in young adolescent soccer players, beyond soccer-only training. However, peak torque gains, even at high contractile velocities, seem to be more effectively attained through FW resistance rather than by plyometric training. However, jumping benefits more from plyometric than from FW RT, likely due to its association with the stretch reflex. Presumably, plyometric training can be similarly effective in improving contractile explosiveness in other activities, such as sprinting, where contractions are immediately preceded by musculotendinous stretching and the stretch reflex.

Standard FW RT seems superior to plyometric training at increasing general static or dynamic strength, as measured by an isokinetic dynamometer. This is likely also true for other forms of slow, nonexplosive types of RT. Improved general static or dynamic strength may be important for various sports and other activities where jumping is not a central objective, as well as a means of enhancing the strength base for jumping or sprinting. However, simple strength gains may not, by themselves, lead to improved jumping or sprinting unless supplemented by explosive training involving the stretch reflex. Plyometric training, when applicable, seems to be the method of choice for that purpose.

The findings of this study highlight the fact that standard laboratory/dynamometer strength tests provide poor predictive measures of jumping ability. This is due to the static, unloaded nature of their contraction onsets, the absence of musculotendinous prestretching, and the consequent lack of stretch reflex. It is encouraged then, that when attempting to accurately predict jump height ability, testing modalities used should reflect jumping-relevant forces and rates of their development.

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