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The effect of maturation on adaptations to strength training and detraining in 11–15-year-olds

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To investigate how maturity status modifies the effects of strength training and detraining on performance, we subjected 33 young men to 8 weeks of strength training twice per week followed by 8 weeks without training. Changes in performance tests were analyzed in three maturity groups based on years from/to age of predicted peak height velocity (PHV): pre-PHV (–1.7 ± 0.4 years; *n* = 10), mid-PHV (–0.2 ± 0.4 years; *n* = 11), and post-PHV (1.0 ± 0.4 years; *n* = 12). Mean training effects on one repetition maximum strength (3.6–10.0%), maximum explosive power (11–20%), jump length (6.5–7.4%), and sprint times (–2.1% to –4.7%) ranged from small to large, with generally greater changes in mid- and post-PHV groups. Changes in force–velocity relationships reflected generally greater increases in strength at faster velocities. In the detraining period, the pre-PHV group showed greatest loss of strength and power, the post-PHV group showed some loss of sprint performance, but all groups maintained or improved jump length. Strength training was thus generally less effective before the growth spurt. Maintenance programs are needed for most aspects of explosive performance following strength training before the growth spurt and for sprint speed after the growth spurt.

Knowledge of when to apply an optimal training stimulus during athlete development is essential for effective programming and improving athletic performance. Major morphological and neural changes are occurring due to growth and maturation (Malina et al., 2004). These parameters could play an important role in the ability to adapt to a specific training stimulus. Based on these premises, the theory of windows of trainability associated with natural accelerated development of a specific athletic characteristic (e.g., speed) has been articulated (Balyi & Hamilton, 2004). Several researchers (Beunen & Malina, 1988; Philippaerts et al., 2006) have suggested an adolescent performance spurt in strength and power development about 1.5 years prior to peak height velocity (PHV) and peaking approximately 0.5–1.0 years after PHV, whereas an accelerated period in sprint performance was found to occur prior to PHV (Beunen & Malina, 1988; Philippaerts et al., 2006). However, there is a lack of empirical knowledge on the effects and optimization of training during growth and maturation, resulting in conjecture and debate (Blimkie & Bar-Or, 2008; Ford et al., 2011).

Resisted training methods are commonly used to improve strength, power, and speed in young athletes (Behringer et al., 2011). A few studies (Pfeiffer & Francis, 1986; Sailors & Berg, 1987) have investigated the change in strength measures across different maturity groups after performing the same training program, but failed to determine the transference of strength gain to athletic performance or discuss any kinetic adaptations (force-velocity-power relationships). As maturation-related physiological changes (e.g., hormonal rise, central nervous system myelinization) may favor different types of adaptation depending on maturity status, the assessment of strength, power, speed, and the force–velocity (F–v) relationship might provide greater insight into the way maturity modifies the effects of strength training. These physiological changes during growth may also influence the decay in performance following cessation of strength training. The maturity-related difference in decay may guide maintenance programs and maturity-specific training periodization as well as disentangle training effect from natural athletic development. However, to the authors' knowledge, no studies have investigated the detraining effect of different maturity groups following the cessation of a strength training program.

Typically, volume and intensity parameters were described in previous studies, but very little discussion has been given to exercise selection and progression in relation to athletic performance (Behringer et al., 2011; Harries et al., 2012). Minimal attention to exercise selection may have contributed to the beneficial (Hetzler et al., 1997; Christou et al., 2006) or trivial (Faigenbaum, 1996; Faigenbaum et al., 2005) enhancement of athletic performance following strength training. Despite the unilateral and multi-planar force requirement in athletic performance, strength training design in youth mostly consisted in prescribing exercises bilateral and vertical in nature. The systematic implementation of additional unilateral and horizontal force production exercises would seem to be a more efficient approach to enhance athletic performance such as sprinting (Randell et al., 2010). Recent literature in youth has also recommended implementing exercise progression based on movement competency with a strong coaching focus (Lloyd & Oliver, 2012). Rather than using progressive overload training only, movement-based periodization could also be used as a loading parameter to stimulate strength adaptations and enhance athletic performance (Kritz et al., 2009). The strength, power, and speed adaptations of such an approach to training youth of different maturity status have not been documented to the authors' knowledge. Given the limitations previously cited, the purpose of this study was to determine the effect of a movement-based strength training program and detraining on force, velocity, and power measures as well as sprint performance in young athletes of different maturity status.

Methods

Subjects

Thirty-eight young men between 11 and 15 years of age volunteered for this study. All participants were nominated by their physical education teacher to be part of the school sports academy. Following the baseline testing, four participants dropped out of the training program (90% retention) because of lack of interest ($n = 2$), nontraining-related injury ($n = 1$), and excessive sports commitment ($n = 1$), whereas one individual was sick on post-training testing. Participant characteristics are present in Table 1. Following the detraining period, four other participants did not complete the performance testing because of sports commitment. The Human Research Ethics Committee of Auckland University of Technology approved the study, and both the participants and their parents/guardians gave their written consent/assent prior to the start of the study.

Testing procedures

Participants attended two testing sessions at least 48 h apart at baseline, post-training, and after detraining. The baseline session was preceded by an independent familiarization session. Anthropometric measurements were taken prior to each of the testing occasions. Standing height (cm), sitting height (cm), and mass (kg) were measured, and the athletes' maturity status determined using years from/to PHV (i.e., PHV offset; Mirwald et al., 2002) as well as the percentage of predicted adult stature (Khamis & Roche, 1994). Based on PHV offset, the participants, ranging from –2.36 to +2.05 years from/to PHV, were split into three maturity groups for analysis: pre-PHV ($n = 10$), mid-PHV ($n = 11$), and post-PHV ($n = 12$). Given the error associated with the calculation of PHV offset (±0.5 years, 95% confidence limits) (Mirwald et al., 2002), the reader must be mindful that an athlete may have been assigned to the wrong group. However, the small standard deviation (SD) in the determination of maturation in each group, the additional assessment of maturity status using percentage of predicted adult stature, and the difference in leg length, height, and body mass data between the groups (Table 1) indicated that the measurement of athletes' maturation were relatively homogeneous and accurate.

On day 1, performance testing consisted of three trials of ballistic concentric squats on a supine squat machine (FitnessWorks, Auckland, New Zealand) at five different relative loads to body mass (%BM) in a randomized order: 80%, 100%, 120%, 140%, and 160%. The mean of the three trials was used for further analysis. Participants started by undertaking a 15-min standardized warm-up using different loads. Prior to each load, participants were asked to fully extend their leg to determine the zero position, which was used to determine the end of the pushing phase. A recovery of 30 s between trials within load and 120 s between loads was given. The foot position and knee angle (70°) were standardized. The supine squat machine was designed to allow novice participants to perform maximal squats or explosive squat jumps, with the back rigidly supported, thus minimizing the risk associated with such exercises in an upright position (e.g., excessive landing forces, lumbar spine flexion, and extension).

Table 1. Baseline participant characteristics (mean ± standard deviation) of the maturity groups based on peak height velocity (PHV)

	Pre-PHV ($n = 10$)	Mid-PHV ($n = 11$)	Post-PHV ($n = 12$)
Age (year)	12.4 ± 0.7	13.6 ± 0.6	14.3 ± 0.7
PHV offset (year)	–1.7 ± 0.4	–0.2 ± 0.4	1.0 ± 0.4
Predicted adult height (%)	85.9 ± 2.9	91.8 ± 1.7	96.3 ± 1.7
Mass (kg)	41.5 ± 4.0	53.6 ± 10.0	66.0 ± 9.1
Height (cm)	152.0 ± 4.7	165.0 ± 5.8	174.0 ± 4.2
Leg length (cm)	74.3 ± 3.1	79.4 ± 4.1	82.7 ± 2.7
1-RM (kg)	85.0 ± 12.0	107.0 ± 14.0	125.0 ± 10.0
P_{max} (W)	336.0 ± 70.0	447.0 ± 97.0	570.0 ± 47.0
Horizontal jump (cm)	136.0 ± 19.0	150.0 ± 23.0	156.0 ± 19.0
10-m sprint time (s)	2.13 ± 0.10	2.04 ± 0.14	1.96 ± 0.09
30-m sprint time (s)	5.31 ± 0.29	4.95 ± 0.27	4.73 ± 0.25
F_{max} (N)	870.0 ± 130.0	1060.0 ± 140.0	1220.0 ± 120.0
V_{max} (m/s)	1.53 ± 0.24	1.67 ± 0.36	1.97 ± 0.23
F_{max}/V_{max} [N/(m/s)]	–590.0 ± 140.0	–660.0 ± 160.0	–630.0 ± 120.0

1-RM, estimated one repetition maximal based on load–velocity relationship; F_{max}, estimated maximal force from force–velocity relationship; F_{max}/V_{max}, ratio between F_{max} and V_{max}; P_{max}, maximal power estimated from power–load relationship; V_{max}, maximal velocity from force–velocity relationship.

On the second day, participants performed three trials of horizontal jumps with their arms akimbo, followed by three 30-m sprints. The mean of the three trials was used for further analysis. Jump length was measured with a measuring tape from the starting line (toes just behind it) to the back of the heel on stick landing. The 30-m sprint was conducted on a wooden indoor surface and measured with a dual-beam timing light system (Swift Performance, Wacol, Queensland, Australia) placed at 0, 10, and 30 m. Participants were asked to start in a still split stance with the preferred leg forward 30 cm behind the starting line.

Data processing

To analyze the ballistic movement on the supine squat machine, a linear position transducer (Celesco, Chatsworth, California, USA) attached to the weight stack of the supine squat machine measured vertical displacement relative to the ground with an accuracy of 0.1 cm, which corresponded to the horizontal displacement of the participant during the effort. Data were collected at a sample rate of a 1000 Hz by a computer-based data acquisition and analysis program. The displacement–time data were filtered using a low-pass fourth-order Butterworth filter with a cutoff frequency of 50 Hz, to obtain position. The filtered position data were then differentiated using the finite–difference technique to determine velocity (v) and acceleration (a) data, which were each successively filtered using a low-pass fourth-order Butterworth filter with a cutoff frequency of 6 Hz (Harris et al., 2007). The force (F) produced during the thrust was determined by adding the mass of the weight stack to the force required to accelerate the system mass, which consisted of the mass of the weight stack (M_{WS}), the mass of the participant (M_P), and the mass of the sled (M_S), so $F = g.M_{WS} + a(M_{WS} + M_P + M_S)$, where g is the acceleration due to gravity and a is the acceleration generated by the movement of the participant. Following these calculations, power (P) was determined by multiplying the force by velocity at each time point ($P = F \times v$). Average force, velocity, and power were determined from the averages of the instantaneous values over the entire push-off phase until full-leg extension. The external validity of the derived measurements from a linear position transducer has been assessed using the force plate as a gold standard device (correlations of 0.81–0.96), with the only limitation of underestimating force and power output (Hori et al., 2007).

The relationship between load and mean velocity was used to predict a dynamic one repetition maximum (1-RM) at an average 1-RM velocity of 0.23 m/s (Harris et al., 2007; Jidovtseff et al., 2011). A Pearson correlation of 0.94 between the actual 1-RM (119 ± 27 kg) and predicted 1-RM (112 ± 23 kg) was found in a pilot study with 10 of the current subjects. Using average force and velocity, F–v relationships were determined by least-squares linear regressions. F–v slopes were extrapolated to obtain maximum force (F_{max}) and maximal velocity (V_{max}), which corresponded to the intercepts of the F–v slope with the force and velocity axes, respectively (Samozino et al., 2012). Because the power–load relationship is derived from the product of force and velocity, it was described by second-degree polynomial functions, maximal power output (P_{max}), and the optimal load at which P_{max} occurred determined using the power–load regression curve (Harris et al., 2007).

Training program

The training program consisted of two 45-min resistance training sessions per week for 8 weeks, with mean group adherence of 91% and a minimum individual requirement of 80% to be included in the study. It was followed by an 8-week detraining period. Prior to each session, a 15-min warm-up focusing on fundamental movements such as lunging, squatting, or good mornings as well as dynamic flexibility was conducted. The 8-week training was divided into two blocks of 4 weeks consisting of four main lifts and two core exercises. The main lifts were purposefully selected to develop both horizontal and vertical force production given the multi-planar nature of sprint performance. Also, to mimic the demands of running and sporting activities, two lifts were unilateral in each of the 4-week cycles. Exercise progression was based not only on increasing load but also on movement complexity across four different levels (bronze, silver, gold, and platinum) in order to enhance movement competency, create a diverse training stimulus, and challenge the athletes relative to their movement competency (Table 2). In the first session, all athletes started at the bronze level and self-determined their load with the coaches' help.

Table 2. Exercise progression during the two training blocks of 4 weeks

	Exercise level			
	Bronze	Silver	Gold	Platinum
Weeks 1–4				
Bulgarian split squat	Body mass	Front foot elevated	Dumbbells	Dumbbells front foot elevated
Lunge	Body mass in place	Body mass walking	Dumbbells walking	Dumbbells overhead walking
Hip thrust	Shoulder and feet on floor	Shoulder elevated	Single leg on floor	Single leg shoulder elevated
Single leg Romanian dead lift	Wall assisted	Body mass	Body mass hand reach	Dumbbells contralateral
Prone plank	Regular (60–90 s)	Alternate leg raise	Alternate leg raise hold	Alternate leg raise and abduction
Band hold	Straight hold	Rotation and hold	↑Band thickness	Partner disturbance
Weeks 5–8				
Step-up lunge	Low box	High box	Dumbbells high box	Dumbbells high box overhead
Single-leg squat	High box assisted	Low box assisted	High box unassisted	Low box unassisted
Hip thrust	Single leg floor	Single leg shoulder elevated	SL shoulder and feet elevated	Load single leg shoulder and feet elevated
Dead lift	Sandbag	↑Load	↑Load	↑Load
Carpet slide hip flexion	Knee to chest	Single leg knee to chest	Toe to hand	Single leg toe to hand
Side plank	Foot on floor	Foot elevated	Foot elevated and abduction hold	Foot elevated and abduction

Table 3. Training and detraining effects* (with 90% confidence limits) for the performance and force–velocity variables for the three maturity groups based on peak height velocity (PHV)

	Training effect (post-training minus baseline) (%)			Detraining effect (detraining minus post-training) (%)		
	Pre-PHV	Mid-PHV	Post-PHV	Pre-PHV	Mid-PHV	Post-PHV
1-RM	3.6 (–1.0, 8.5) small↑†	3.5 (–0.1, 7.2) small↑†	10.0 (6.7, 13.3) moderate↑§	–4.6 (–8.2, –0.8) small↓‡	0.0 (–4.5, 4.7) trivial‡	–0.7 (–3.8, 2.4) small↓†
P_{max}	11 (7, 16) moderate↑†	16 (8, 24) moderate↑†	20 (14, 27) large↑‡	–11 (–18, –3) moderate↓†	–3 (–11, 4) small↓†	–6 (–14, 2) moderate↓†
F_{max}	–2.1 (–7.0, 3.0) small↓†	2.5 (–3.4, 8.7) unclear	8.7 (3.6, 14.1) moderate↑†	–6.6 (–14.0, 1.0) small↓‡	–2.2 (–10.5, 6.9) small↓†	1.4 (–6.7, 4.2) small↑†
V_{max}	16 (5, 29) moderate↑†	14 (2, 28) small↑‡	11 (2, 22) small↑‡	–2 (–19, 18) unclear	4 (–13, 24) unclear	–10 (–22, 5) small↓‡
F_{max}/V_{max}	16 (3, 27) small‡	10 (–6, 24) small†	2 (–11, 14) unclear	5 (–24, 26) unclear	6 (–22, 27) unclear	–9 (–33, 11) unclear
Horizontal jump	6.5 (1.2, 12.2) small↑‡	6.8 (2.2, 11.6) small↑‡	7.4 (4.7, 10.2) moderate↑†	2.4 (–4.1, 9.4) unclear	1.9 (–2.7, 6.6) unclear	3.7 (0.6, 6.8) small↑‡
10-m sprint time	–2.6 (–4.0, –1.2) small↑§	–4.7 (–7.0, –2.3) moderate↑‡	–4.0 (–5.7, –2.3) moderate↑‡	0.1 (–1.2, 1.5) trivial‡	–1.1 (–2.2, 0.1) small↑†	0.9 (0.0, 1.7) small↓†
30-m sprint time	–2.1 (–3.5, –0.7) small↑‡	–3.6 (–5.0, –2.3) moderate↑‡	–3.0 (–4.1, –2.0) moderate↑‡	0.1 (–0.5, 0.6) trivial§	–0.4 (–1.6, 0.8) trivial‡	0.6 (–0.5, 1.7) small↓†

*Effects are shown with probabilistic inferences about the true standardized magnitude.

†Possibly.

‡Likely.

§Very likely.

↑, improvement in performance; ↓, impairment in performance; 1-RM, estimated one repetition maximal based on load–velocity relationship; F_{max}, estimated maximal force from force–velocity relationship; F_{max}/V_{max}, ratio between F_{max} and V_{max}; P_{max}, maximal power estimated from power–load relationship; V_{max}, maximal velocity from force–velocity relationship.

Within the first session, the coaches assigned each athlete to the appropriate level of movement complexity based on predefined coaching points made clear to the athletes. Following the initial session, each athlete moved across the movement complexity when the coach decided that the previous level was completed with proficiency after an increase in mechanical load for 10–12 repetitions over two to three sessions. Three sets of 10–12 repetitions to near failure were conducted for each exercise apart from sessions 1 and 9, when new exercises were being introduced (two sets). A rest of 90 s was allowed between sets. The coach to athlete ratio was ≤1:5, and no more than 10 athletes trained at the same time to emphasize education and coaching. To increase motivation, athletes kept a diary to record the number of sets and repetitions performed at each level of exercises, and the rating of perceived exertion (RPE) was recorded on a visual analog scale (range 0–10) during the 8-week training period (McGuigan et al., 2008). The session RPE indicated that training was lighter on weeks when new exercises were being introduced (weeks 1 and 5) and increased progressively from 3.7 ± 1.3 (mean ± SD) to 6.1 ± 1.5 and from 5.5 ± 1.6 to 6.6 ± 1.3 for blocks 1 and 2, respectively.

Statistical analysis

Uncertainty in the estimates of effects on performance was expressed as 90% confidence limits. Threshold values for assessing magnitudes of standardized effects (changes as a fraction or multiple of baseline SD) were 0.20, 0.60, 1.20, and 2.00 for small, moderate, large, and very large, respectively (Hopkins et al., 2009). These probabilities are not presented quantitatively but were used to make a qualitative probabilistic clinical inference about the effect in preference to a statistical inference based on a null hypothesis test (Hopkins et al., 2009). The effect was deemed unclear when the chance of benefit (a standardized improvement in performance of >0.20) was sufficiently high to warrant use of the intervention, but the risk of impairment was unacceptable. Such unclear effects were identified as those with an odds ratio of benefit to impairment of <66, a ratio that corresponds to an effect that is borderline possibly beneficial (25.0% chance of benefit) and borderline most unlikely detrimental (0.5% risk of harm). The effect was otherwise clear and reported as the magnitude of the observed value, with the qualitative probability that the true value was at least of this magnitude. The scale for interpreting the probabilities was as follows: 25–75%, possible; 75–95%, likely; 95–99.5%, very likely; >99.5%, most likely (Hopkins et al., 2009). Magnitudes of differences in training effects between groups were evaluated nonclinically (Hopkins et al., 2009): if the confidence interval overlapped thresholds for substantial positive and negative values, the effect was deemed unclear. The effect was otherwise clear and reported as the magnitude of the observed value with a qualitative probability, as above.

Results

The changes in body mass across all groups were trivial at 8 and 16 weeks, apart from a small increase of 3.1% (90% confidence limits 1.1, 5.2) for pre-PHV after 16 weeks. In all groups, a small change in height of between 0.6–1.1% and 0.9–1.6% was found after 8 and 16 weeks, respectively. There was a small increase in leg length in pre- (1.4%; 0.7, 2.2) and mid- (0.9%; 0.2, 1.6) relative to the post-PHV group (0.4%; –0.1, 0.9).

Relative changes and qualitative outcomes resulting from the within-group analysis are presented in Table 3 and illustrated in Fig. 1. Comparisons of the changes in the three groups are presented in Table 4. The training effect on sprint performance, 1-RM, P_{max}, and horizontal

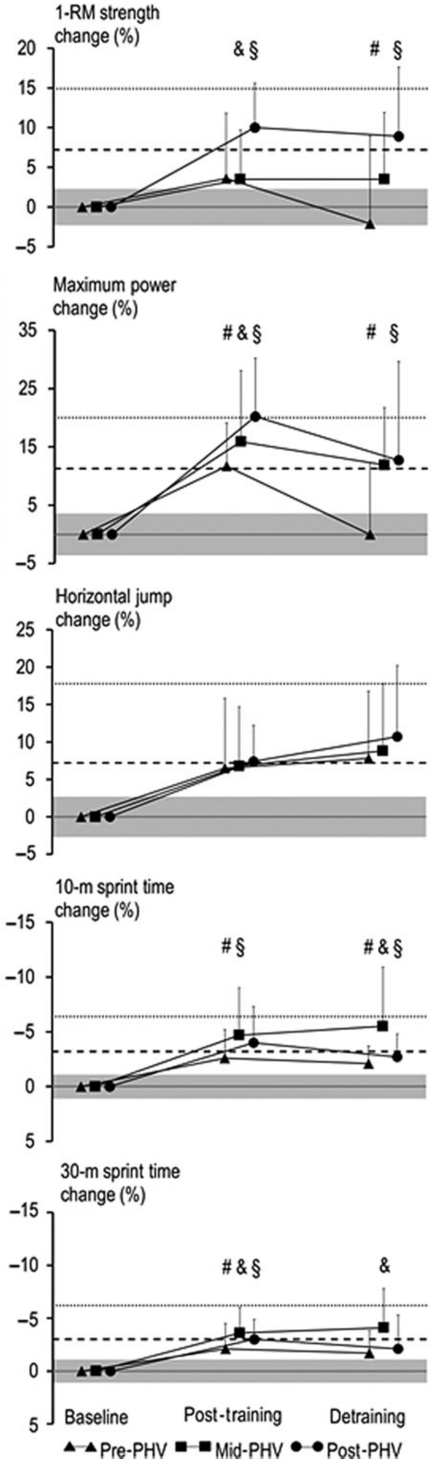

Fig. 1. Changes in performance measures from baseline in the three maturity groups based on peak height velocity (PHV). The shaded area represents trivial changes, the dash line represents the lower limit for moderate changes, and the dotted line represents the lower limit for large changes (<0.20, >0.60, and >1.20 of baseline between-subject standard deviation (SD) averaged over the three groups, respectively). Bars are SDs of changes from baseline to post-training and baseline to detraining. [#]Small differences in training effect between pre- and mid-PHV groups; [&]Small differences in training effect between mid- and post-PHV groups; [§]Small differences in training effect between pre- and post-PHV groups. 1-RM, one repetition maximum.

jump was beneficial for all groups, but mid- and post-PHV improved more than pre-PHV in sprint performance and P_{max} to a small effect, and post-PHV 1-RM improved more by a smaller effect compared with the other two groups. Kinetically, training only had a small positive effect on F_{max} for the post-PHV group but a small-to-moderate effect on V_{max} for all groups. The training program also induced a small shift in the F–v relationship toward velocity capabilities in pre- and mid-PHV, and a moderate effect of maturity on the F–v relationship shift was observed between pre- and post-PHV.

A small detrimental detraining effect was found in 1-RM and sprint performances for pre- and post-PHV, as well as a small-to-moderate decay in P_{max} for all groups. The detraining period was also associated with small decrease in F_{max} in pre- and mid-PHV. There was a small increase in the decay in 1-RM and P_{max} for pre-PHV compared with the other two groups as well as in F_{max} compared with post-PHV. Reduction in sprint performance was only meaningful in post-PHV, and there was a small enhancement in 10-m sprint time for the mid-PHV group, which led to the detraining period being less harmful for 10-m sprint time in the mid-PHV compared with pre- and post-PHV. All other comparisons following the detraining period were trivial or unclear, except for a small improvement in horizontal jump performance for the post-PHV group.

Discussion

The current study demonstrated the efficiency of a new vertical and horizontal movement-based strength training approach to enhance force, velocity, power, and speed measures in young athletes of different maturity status, with generally greater changes in mid- and post-PHV groups. In the detraining period, the pre-PHV group showed greatest loss of strength and power, the post-PHV group showed some loss of sprint performance, but all groups maintained or improved jump length. These results demonstrated that athletic performance may not only be induced by a training stimulus but also natural development, which is dependent on maturity status.

The training duration or the training stimulus did not induce any meaningful change in body mass for any of the groups. Peak mass velocity has been reported to occur about half a year to a year post-PHV (Malina et al., 2004), but the program was probably of insufficient duration to elicit any measurable changes. The greater change in height for mid-PHV compared with post-PHV over 16 weeks confirmed that the participants in this group were going through their growth spurt. Similarly, the greater increase in leg length over 16 weeks for pre- and mid-PHV compared with post-PHV was in line with normal somatic growth where peak leg length growth occurs just before PHV (Mirwald et al., 2002). In summary, the anthropometric characteristics of the

Table 4. Differences between the three maturity groups (based on peak height velocity, PHV) in the training and detraining effects* (with 90% confidence limits) on performance and force–velocity variables

	Training effect (post-training minus baseline) (%)			Detraining effect (detraining minus post-training) (%)		
	Mid–Pre-PHV	Post–Mid-PHV	Post–Pre-PHV	Mid–Pre-PHV	Post–Mid-PHV	Post–Pre-PHV
1-RM	–0.1 (–5.4, 5.5) Unclear	6.2 (1.7, 11.0) small↑‡	6.1 (0.7, 12.0) small↑†	8.0 (0.1, 17.0) small↑‡	–0.7 (–5.9, 4.7) Unclear	7.2 (–0.2, 15.0) small↑†
P_{max}	4 (–4, 12) small↑†	4 (–4, 13) small↑†	8 (1, 15) small↑†	9 (–2, 21) small↑†	–3 (–13, 8) unclear	5 (–6, 18) small↑†
F_{max}	5 (–3, 13) small↑†	6 (–1, 14) small↑‡	11 (4, 19) small↑‡	5 (–6, 17) unclear	1 (–9, 11) unclear	6 (–3, 16) small†
V_{max}	–2 (–15, 13) unclear	–2 (–15, 12) unclear	–4 (–16, 9) unclear	6 (–16, 35) unclear	–13.0 (–31.0, 8.5) Unclear	–7 (–26, 16) unclear
F_{max}/V_{max}	–7 (–31, 13) unclear	–9 (–32, 11) unclear	–16 (–39, 3.0) moderate†	1 (–38, 30) unclear	–16 (–58, 15) unclear	–14 (–55, 16) unclear
Horizontal jump	0.2 (–6.0, 6.9) unclear	–0.6 (–4.2, 5.6) Unclear	0.8 (–4.7, 6.6) unclear	–0.5 (–7.8, 7.3) Unclear	1.8 (–3.4, 7.2) unclear	1.7 (–5.2, 9.1) unclear
10-m sprint	–2.1 (–4.7, 0.6) small↑†	0.7 (–2.1, 3.6) unclear	–1.4 (–3.5, 0.8) small↑†	–1.2 (–2.9, 0.5) small↑†	1.9 (0.5, 3.4) small↓‡	0.7 (–0.8, 2.3) small↓†
30-m sprint	–1.6 (–3.4, 0.3) small↑†	0.6 (–1.0, 2.3) small↓†	–1.0 (–2.6, 0.7) small↑†	–0.6 (–1.8, 0.7) trivial‡	0.6 (–1.0, 2.3) small↓†	0.4 (–0.7, 1.6) trivial‡

*Effects are shown in percentage units with 90% confidence limits and probabilistic inferences about the true standardized magnitude.

†Possibly.

‡Likely.

↑, increase in training/detraining effect with maturation; ↓, decrease in training/detraining effect with maturation; 1-RM, estimated one repetition maximal based on load–velocity relationship; F_{max}, estimated maximal force from force–velocity relationship; F_{max}/V_{max}, ratio between F_{max} and V_{max}; P_{max}, maximal power estimated from power–load relationship; V_{max}, maximal velocity from force–velocity relationship.

maturity groups seemed representative of the normal growth and maturation associated with human development (Malina et al., 2004).

The strength training program in the current study was beneficial in enhancing 1-RM, P_{max}, 10- and 30-m sprint time, and horizontal jump in all maturity groups. To the authors' knowledge, the current study is the first to demonstrate the ability to enhance explosive actions in different planes of motion across different maturity groups. The small-to-moderate training effect on 10-m sprint time (−2.6% to −4.7%) and 30-m sprint time (−2.1% to −3.6%) was within the effect size (ES = 0.54; Behringer et al., 2011) and percentage changes (−1.5% to −5.8%; Rumpf et al., 2012) reported in meta-analyses. Previous strength training (Kotzamanidis et al., 2005; Faigenbaum et al., 2007) failed to induce a change in sprint performance despite an increase in strength and/or power. These findings are probably explained by the principle of training specificity, as these studies used exercises only in a vertical direction, whereas it seems wise to incorporate strategies to work the hips from a horizontal vector if increased speed and acceleration are sought (Randell et al., 2010; Contreras et al., 2011). The hip thrust exercise to stimulate end-range hip extension strength, along with the other hip extension exercises to stimulate flexed-range hip extension strength such as the forward lunge or dead lift, was found to be effective and appropriate to the age of the athletes in the current study. The effectiveness of these exercises was supported by their transference to produce a small-to-moderate increase in horizontal power (horizontal jump = 6.5–7.4%), which is comparable (5.7–7.3%; Faigenbaum et al., 2002, 2005, 2007) or better (1.6–4.6%; Matavulj et al., 2001; Ingle et al., 2006) than found in previous pediatric studies. Owing to the specificity of P_{max} as an instantaneous power measure of less than 2 s, comparison to other studies is limited. If vertical jump height is considered as an indirect measure of vertical power (Markovic & Jaric, 2007), the moderate-to-large increase in P_{max} in the current study was comparable with those of meta-analysis reporting the ESs of resistance training on the vertical jump (ES = 0.99) (Behringer et al., 2011). Although the training effect in the current study can be compared with other studies, the reader must recognize that the adaptations were sample specific and other subjects may have responded differently.

Even though the strength training program was beneficial for all maturity groups, the effects of training became greater with maturity in movements where vertical strength and power are dominant (1-RM, F_{max}, P_{max}, 10-m sprint), but not in high-velocity movement through multi-planar direction (30-m sprint and horizontal jump). A previous meta-analysis (Behringer et al., 2010) also demonstrated that interpubertal and postpubertal subjects (Tanner stages 2–5) were more likely to increase strength levels after resistance training compared with prepubertal children (Tanner stage 1). Behringer et al. (2010) argued that the greater gain in strength with maturity was due to the hormonal rise during puberty. Interestingly, the magnitude of the change in strength (3.6–10.0%) was not as great as previously reported (14–32%) in studies with similar duration of training, frequency of training, and age of subjects (Faigenbaum et al., 2002, 2005). The training background could explain this discrepancy as the current subjects were part of a sport academy, whereas in the other studies (Faigenbaum et al., 2002, 2005), the subjects were considered untrained. The training response may have differed in a different subject cohort. The minimal strength gain compared with other studies could also be attributed to intensity, which may not have been optimal for strength increase (10–12 repetitions vs 1–6 repetitions). However, the 10–12 repetition range was chosen as being most suitable for youth participants with limited resistance training history. The fact that the athletes' RPE was low in the initial sessions indicated that the loading could have been higher to induce greater training adaptations, but progressive loading was chosen to reduce initial muscle soreness and injury risk. Finally, the focus on exercise progression and unilateral movement may have not allowed optimal loading the young athletes for strength gains but may have more benefit for long-term athletic development (Lloyd & Oliver, 2012).

A fundamental relationship exists between strength and power, which dictates that an individual cannot possess a high level of power without first being relatively strong. This assertion is supported by the robust relationship that exists between maximal strength and maximal power production (Cormie et al., 2011). The moderate increase in 1-RM for post-PHV associated with a large increase in P_{max} would support this relationship. Yet, there was still a moderate training effect on P_{max} for pre- and mid-PHV despite a possibly small increase only in maximal strength. As P_{max} is the product of force and velocity and is limited by the F–v relationship, an increase in velocity capability can explain changes in power output as does an increase in force (Cormie et al., 2011). From the analysis of the F–v relationship, it was concluded that maturity groups had different kinetic adaptations to the strength training intervention. Although the post-PHV group increased their F_{max} and V_{max}, the training program resulted in greater increases in V_{max} for the pre- and mid-PHV, as observed in differences in the F–v slope shift between pre- and post-PHV. Kinetic adaptations in the current study could have been partially independent of the training methods and related to the natural development of force, velocity, and power during growth and maturation. Several researchers (Beunen & Malina, 1988; Philippaerts et al., 2006) have demonstrated an adolescent performance spurt in strength and power development to start around 1.5 years prior to PHV and to peak approximately 0.5–1.0 years after PHV. In previous studies (Martin et al., 2003, 2004), change in optimal velocity was found to be responsible for the natural increase in P_{max} with age prior to puberty, whereas the increase of P_{max} in pubertal and postpubertal boys was accompanied by an increase in optimal force. In this sense, previous models of youth training have recommended training methods that stimulate intermuscular coordination, movement efficiency, and movement velocity prior to puberty (Mero, 1998) rather than strength training to improve power (Mero, 1998; Rumpf et al., 2012).

Overall, the decay in performance was greater in high-force variables (1-RM, F_{max}, P_{max}) than in high-velocity variables (V_{max}, sprinting). A recent review on the topic (Bosquet et al., 2013) also demonstrated that the effect of training cessation on maximal strength and power was quite similar during the first weeks. However, there appeared to be dissociation after 16 weeks of inactivity as maximal strength continued to decrease while maximal power remained leveled. An increase in the expression of fast muscle myosin heavy-chain isoforms following 3 months detraining period has been associated with an increase in velocity capability, which may have compensated for the loss in maximal force to maintain maximal power (Andersen et al., 2005). These adaptations could partly explain the initial decrease in maximal strength and power and maintenance in velocity capabilities in the current study. The pre-PHV boys underwent a greater detraining effect than the mid- and post-PHV groups in force-dependent variable (1-RM, F_{max}, P_{max}) apart from F_{max} between pre- and mid-PHV. The accelerated period in strength and power development during puberty (Beunen & Malina, 1988; Philippaerts et al., 2006) may play a confounding role in adaptation and reduce the decay in strength during mid- and post-PHV (trivial to possibly small, respectively) in comparison with pre-PHV (possibly small) and adults (small to moderate; Bosquet et al., 2013; McMaster et al., 2013) after the same period of training cessation. A previous review on strength maintenance in youth also supported a return to strength baseline in prepubescent after an 8-week detraining period (Blimkie & Bar-Or, 2008). The small decay in sprint performance for the post-PHV group could be associated with the small decrease in V_{max} and an inability to maintain force at fast velocity following a detraining period. The maintenance of V_{max} and sprint performance in pre- and mid-PHV but inability to maintain F_{max} would suggest that a greater natural development of velocity capability could be observed during this period compared with force characteristics (Martin et al., 2003, 2004), on the contrary to post-PHV. These adaptations could be related to the increase in fascicle length during somatic growth and faster maturation of the central nervous system prior to puberty (Malina et al., 2004).

The detraining phase enables to disseminate the possible contribution of natural development not only to maintain athletic performance after the cessation of training but also during the training phase. However, the lack of control group represented a limitation to the current study to disentangle with absolute clarity the contribution of natural development in performance enhancement following the training program. Based on the decay in performance following cessation of training, natural development could play a role in accelerated training adaptations in strength and power measures in mid- and post-PHV, and velocity and sprint performance in pre- and mid-PHV but further research is this area should be conducted before conclusion can be made.

Perspectives

The strength training program was beneficial in improving vertical strength, vertical and horizontal power, 10-m sprint time, and 30-m sprint time across different maturity groups, but the magnitude of training and detraining as well as the kinetic adaptations were maturity dependent. The maturity-specific force, velocity, and power adaptations to training and detraining have important implications for the development of these neuromuscular characteristics during growth and maturation. Strength training was more beneficial at enhancing maximal strength, maximal power, and sprinting in mid- and post-PHV groups than in the pre-PHV group. Some form of training other than (or additional to) strength training, such as activities providing a velocity stimulus, may be valuable for athletes pre-PHV (Mero, 1998), considering their lower response to strength training in the current study and greater natural velocity development in comparison with athletes who have entered PHV (Martin et al., 2003, 2004). Regardless, practitioners should include bilateral and unilateral vertical and horizontal force production exercises to optimally enhance all aspects of explosive athletic performance (Randell et al., 2010; Contreras et al., 2011). Future research should attempt to compare the effects of velocity-dominant and force-dominant training in maturing athletes while accounting for the natural development in the measure of interest.

Key words: pediatrics, resistance training, decay, human development.

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