Lloyd, Rhodri S. and Radnor, John M. and De Ste Croix, Mark B and Cronin, John B and Oliver, Jon L (2015). ***Changes in sprint and jump performance following traditional, plyometric and combined resistance training in male youth pre- and post-peak height velocity.*** **Journal of Strength and Conditioning Research. ISSN 1064-8011**

Published in Journal of Strength and Conditioning Research, and available online at:

http://dx.doi.org/10.1519/JSC.0000000000001216

We recommend you cite the published (post-print) version.

The URL for the published version is http://dx.doi.org/10.1519/JSC.0000000000001216

ABSTRACT

The purpose of this study was to compare the effectiveness of 6-week training interventions utilizing different modes of resistance (traditional strength, plyometric and combined training) on sprinting and jumping performance in boys pre- and post-peak height velocity (PHV). Eighty school-age boys were categorized into two maturity groups (pre- or post-PHV) and then randomly assigned to 1) plyometric training, 2) traditional strength training, 3) combined training, or 4) a control group. Experimental groups participated in twice-weekly training programmes for 6-weeks. Acceleration, maximal running velocity, squat jump height and reactive strength index data were collected pre- and post-intervention. All training groups made significant gains in measures of sprinting and jumping irrespective of the mode of resistance training and maturity. Plyometric training elicited the greatest gains across all performance variables in pre-PHV children, whereas combined training was the most effective in eliciting change in all performance variables for the post-PHV cohort. Statistical analysis indicated that plyometric training produced greater changes in squat jump and acceleration performance in the pre-PHV group compared to the post-PHV cohort. All other training responses between pre- and post-PHV cohorts were not significant and not clinically meaningful. The study indicates that plyometric training might be more effective in eliciting short-term gains in jumping and sprinting in boys that are pre-PHV, whereas those that are post-PHV may benefit from the additive stimulus of combined training.

Key words: strength training, plyometric training, combined training, children, adolescents

INTRODUCTION

It is well documented that developmentally appropriate, well supervised resistance training interventions are safe and effective in stimulating positive adaptations on a range of physical performance measures in children and adolescents (21, 22). Resistance training is defined as a specialized method of conditioning whereby an individual is working against a wide range of resistive loads in order to enhance health, fitness and performance (21). Researchers have shown that a myriad of resistance training modes have all been effective in eliciting beneficial training responses in neuromuscular performance in youth, including, traditional strength training (28) which involves the lifting of moderate to heavy loads with moderate inter-set recovery using free weights or resistive machines (19), weightlifting (7), plyometrics (26, 36) and combined strength and plyometric training (11, 37). However, while studies have examined the efficacy of individual forms of resistance training (e.g. plyometrics), minimal evidence exists that compares the effectiveness of different resistance training modes and their potential interaction with maturation in youth populations.

Previous meta-analyses have attempted to examine the effects of resistance training on muscular strength (3) and motor skill performance (2) in youth of different maturational status. Combined these meta-analyses showed that while adolescents were able to make greater adaptations with respect to muscular strength, the transference of resistance training gains to motor skill performance were more pronounced in children (2). Such findings may reflect the heightened neural plasticity and increased sensitivity for motor control and coordinative adaptation during childhood (34, 35), versus the enhanced hormonal profile and greater muscle mass associated with adolescence (10). However, it should be noted that neither meta-analysis showed differential responses to different resistance training modes in relation to maturation. Additionally, very few studies have specifically examined the interaction of training responses with maturation (20, 28, 31). These studies focused solely on the interaction of maturation with strength training and combined, showed varying results.

Sprinting and jumping ability are fundamental locomotive skills that form part of the athletic motor skill spectrum (23). Also, they are commonly used as indicators of neuromuscular fitness in youth (33) and within talent identification screens to discriminate between potential elite and non-elite youth athletes (12). Recently, Rumpf et al. (32) reviewed existing speed training literature to examine the effects of different training methods on sprint performance in male youth. Interestingly, the review showed that boys that were pre-peak height velocity (PHV) and circum-PHV appeared to benefit most from plyometric training, while post-PHV adolescents maximized gains in sprint speed following a combination of strength and plyometric training methods (32). While these data, and those reported by Behringer et al. (2, 3) show that maturity may play a role in the trainability of youth, an experimental study examining the interaction effects of different resistance training modes and maturation is still warranted.

Therefore, the purpose of this study was to determine the effectiveness of different resistance training modes (traditional strength training, plyometric training or combined training) on measures of neuromuscular performance (squat jump height, reactive strength index, acceleration and maximal running velocity) in boys of different maturational status. We hypothesized that boys that were pre-PHV would respond more favorably to plyometric training, whereas boys that were post-PHV would show a greater training response to traditional strength training or combined training.

METHODS

Experimental approach to the problem

A between-group, repeated measures design was used to examine the effects of different resistance training programs on measures of sprinting and jumping. Pre and post-PHV male youth were placed within one of three experimental groups (traditional strength training, plyometric training, combined training) or a control group. The experimental groups participated in their respective training programs twice-weekly for 6 weeks, while the control group completed their regular physical education lessons. The training period of 6 weeks was selected to match the typical duration of a school term, while also reflecting a recognized mesocycle duration (13). All participants were tested before and after the 6-week intervention for the following independent variables: squat jump height, reactive strength index, acceleration and maximal running velocity. Repeated measures of analyses of variance were used to test for possible changes in test scores across the 6-week intervention period, while inferential statistics were used to examine the qualitative meaning of the observed changes in the independent variables.

Subjects

Eighty young male school children (n = 40 pre-PHV and n = 40 post-PHV) from a local secondary school in the United Kingdom volunteered to participate in the study and were subsequently divided into one of three training groups (traditional strength training, plyometric training or combined strength and plyometric training) or a control group (n = 10 x pre-PHV and 10 x post-PHV per group). Participant characteristics per maturation group and training intervention are presented in *table 1*. All participants had previously engaged in physical education-based activities, however they were not involved in any formalized strength and conditioning program. The training groups completed 2 training sessions per week for 6-weeks instead of their regular physical education classes. Conversely, the control group continued with their physical education curricula. Parental informed consent and participant assent were obtained in advance of the study and ethical approval for the research was granted by the University Research Ethics Committee in accordance with the Declaration of Helsinki.

****Table 1 near here****

Testing procedures

Prior to the start of the intervention period, all participants took part in a familiarization session, which provided opportunities to practice both jumping and sprinting test protocols. Participants were allowed to complete as many practice trials as required to ensure they fully understood the protocols and could demonstrate consistent technical execution as determined by the principal investigator. For the purposes of the actual test sessions, participants completed a standardized 10-min dynamic warm-up inclusive of 3 min of sub-maximal multidirectional running and 7 min of light dynamic mobilization and activation exercises targeting the main muscle groups of the upper and lower extremities. Following the warm-up and practice attempts of the test protocols, participants completed the battery of tests in the following order: anthropometrics, squat jump test, 5-maximal rebound test, 10 m and flying 20 m sprint tests. For each test, participants completed three trials with the best of three trials being used for further analysis. Two and five minute rest periods were given between each trial and test respectively to limit the effects of fatigue on consecutive efforts.

Anthropometrics. Standing height (cm) and seated height (cm) were measured using a stadiometer (SC126, Holtan, Wales), while body mass (kg) was measured using a balance beam scale (Seca 700, seca gmbh, Germany). This data was then incorporated into a sex-specific regression equation (equation 1) to predict whether participants were either pre- or post-PHV (29).

Jump protocols. Squat jump height (cm) and reactive strength index (mm/ms) were calculated from a squat jump and 5-maximal rebound test respectively, both of which were performed on a mobile contact mat (Smartjump, Fusion Sport, Australia). Both protocols have been shown to be valid and reliable means of assessing neuromuscular performance in youth (squat jump, ICC = 0.93; reactive strength index, ICC= 0.90 (24)). The squat jump was performed starting from an initial semi-squat position (90° knee flexion as determined subjectively by the principal researcher), with participants holding the position for approximately two seconds before jumping vertically for maximum height on the command of the tester (24). Hands remained akimbo for the entire movement to eliminate any influence from arm swing and participants were instructed to maintain fully extended lower limbs throughout the flight period. Reactive strength index was determined during a 5-maximal rebound test, with participants required to perform five consecutive maximal vertical rebounds on the mobile contact mat. Participants were instructed to maximize jump height and minimize ground contact time (8). The first jump in each trial served as a countermovement jump and consequently was discounted for analysis, while the remaining four rebounds were averaged for analysis of reactive strength index (24).

Sprinting protocols. Sprint times were recorded using wireless timing gates (Smart Speed, Fusion Sport, Australia) in an indoor sports hall. Data was instantaneously collected via a handheld PDA (iPAQ, Hewlett Packard, USA). Acceleration was measured over 0-10 m with a stationary start from a line 30 cm behind the first timing gate. Maximal running velocity was measured over a 20 m distance with a flying start.

Training programs

Training took place twice per week for 6-weeks and training sessions were designed and implemented by a fully accredited strength and conditioning coach (ASCC). Training sessions were separated by at least 48 hours to enable full recovery. Within each session, a fully qualified physical education teacher was present, which enabled a staff-to-pupil ratio of 1:10. To be included in the final analyses, participants were required to complete at least 80% of the total training sessions within their respective program. Correct technical execution was stressed at all times throughout the program with relevant feedback provided on an individual basis; while intensity was never increased at the expense of technical competency. In the event of participants being unable to competently perform any given exercise, relevant exercise regressions were prescribed on an individual basis. Within all training programs, training sessions lasted no longer than 60 minutes and prescribed inter-set rest periods ranged between 1-2 minutes dependent on the relative intensity of the exercise; an approach that is commensurate with recommended guidelines for youth resistance training (21).

Throughout the intervention period the control group received games-based physical education lessons commensurate with the requirements of the UK national curriculum. The principal investigator was not present during the control group physical education classes.

Traditional strength training group. Within traditional strength training sessions, participants completed 3 sets of 10 repetitions of a barbell back squat, barbell lunge, dumbbell step up and leg press. In order to enable the prescription of individualized training intensities, 10-repetition maximum (10RM) loads were calculated for participants in the traditional strength training group prior to the start of the training period using a protocol previously identified in the literature (16). In the event of technical failure, where the coach deemed that competent technique was no longer maintained to a satisfactory standard, the set was stopped to avoid potential risk of injury to the participant. To progressively overload the training stimulus, intensity was increased each week via a 5% increment in external load for all participants on the proviso that technical competency was maintained. In the event of a particular exercise being too difficult or failing to provide enough challenge, loads were reduced or increased respectively on an individual basis.

Plyometric training group. Plyometric training prescription included a combination of exercises that were geared towards developing both safe jumping and landing mechanics (e.g. drop landings, vertical jumps in place, single leg forward hop and stick) and to also stress stretch-shortening cycle activity (e.g. pogo hopping, drop jumps, multiple horizontal rebounds). Within each session, participants were exposed to multiple sets of 4 exercises to enable sufficient repetition to develop motor control programs. The plyometric training program (*table 2*) was progressed conservatively according to number of foot contacts completed within each session (week 1 foot contacts = 74 per session; week 6 foot contacts = 88 per session).

****Table 2 near here****

Combined training group. The combined training program involved exposure to two traditional strength training exercises (barbell back squat and barbell lunge) and two varied plyometric exercises each session taken from the plyometric training program (*table 3*). As per the traditional strength training group, individualized training intensities were prescribed based on baseline 10RM loads. Similarly, a 5% increment in external load was selected to progressively overload the traditional strength training exercises, while plyometric exercises were progressed according to total foot contacts per exercise, per session.

****Table 3 near here****

Statistical Analysis

Descriptive statistics (means ± *sd*) were calculated for all performance variables for both pre- and post-training intervention data. Differences in all performance variables were analyzed using separate 2 x 4 x 2 (time x training group x maturity) repeated measures ANOVA, where 'time' denotes pre- to post-training data, 'training group' represents plyometric training, traditional resistance training, combined training or control groups, and 'maturity' refers to pre- vs post-PHV. Sphericity of data was tested by Mauchly's statistic, and where violated, Greenhouse-Geiser adjustment was used. Bonferroni and Games-Howell post hoc tests were used to determine the origin of any between-group differences when equal variance was or was not assumed respectively. Effect sizes were calculated for all performance variables in each training group and assessed using the magnitude of effect sizes according to Cohen's *d* statistic. Descriptive statistics and repeated measures ANOVA analysis were computed using SPSS V.20 (SPSS Inc., Chicago, IL, USA), with statistical significance for all tests set at an alpha level of $p < 0.05$.

Inferential statistics were used to examine the meaning of differences in the training response between pre and post-PHV groups for each training modality. The smallest worthwhile effect was used to determine whether the observed changes were considered negative, trivial or positive. The smallest worthwhile effect was calculated as 0.20 of the pooled between-group standard deviation pre-training (1). A 90% confidence interval was applied to the between-group difference using an online spreadsheet (14) to calculate the probabilistic inference of each observed difference being greater than the smallest worthwhile effect, applying thresholds of 25-75% as possibly, 75-95% as likely, 95-99.5% as very likely and >99.5% as almost certainly (15). The outcome was deemed unclear when the 90% confidence interval of the mean change overlapped both positive and negative outcomes, otherwise the outcome was clear and inference reported as the category (negative, trivial or positive) where the greatest probability was observed.

RESULTS

Mean changes in sprint and jump performance, including effect sizes, are displayed in *table 4* for pre- and post-PHV groups respectively and where significant, changes in sprint and jump performance in both pre-PHV and post-PHV groups ranged from small (<0.20) to large (>0.90). Irrespective of maturation, none of the control groups made any significant changes in performance over the 6-week training period. Attendance rates for pre-PHV (plyometric training = 91%, traditional strength training = 89% and combined training = 90%) and post-PHV (plyometric training = 83%, traditional strength training = 88% and combined training = 87%) experimental groups and both control groups (>82%) were above the predetermined attendance threshold across the intervention period.

****Table 4 near here****

Significant main effects in acceleration and maximal running velocity were reported for time and maturity. For both indices of sprinting, post-PHV boys demonstrated faster performances following the training intervention period. For acceleration, significant interactions were found for time x maturity, time x training group, and time x maturity x training group. Acceleration significantly improved in all three training groups from within the pre-PHV cohort and in the resistance and combined training groups within the post-PHV cohort. Analysis of maximal running velocity data revealed a significant interaction for time x training group. Maximal running velocity significantly increased in the plyometric and combined training groups of both pre- and post-PHV cohorts.

Analysis of squat jump and reactive strength index data showed main effects for both time and maturity. For both jumping variables, post-PHV youth demonstrated greater performances following the training intervention period. Significant interactions were found for time x maturity and time x training group for both squat jump and reactive strength index. Additionally, there was a significant time x maturity x training group interaction for squat jump performance. Significant improvements in squat jump height and reactive strength index were seen in all pre-PHV training groups. In the post-PHV cohort, squat jump height increased significantly in the resistance and combined training groups, while reactive strength index improved significantly in the plyometric and combined training groups.

While within-group analysis showed that all training groups improved some aspect of neuromuscular performance in response to their specific training interventions, significance testing failed to determine any significant differences in training response between pre- and post-PHV groups. Nearly all of the differences in training responses between pre- and post-PHV cohorts were not significant and 'trivial' for traditional strength training, combined training and control groups. However, pre-PHV children who completed the plyometric training intervention showed changes in acceleration and squat jump height that were 'very likely greater' than post-PHV youth who also followed the plyometric training intervention (*Figure 1*).

****Figure 1 near here****

DISCUSSION

From the results of this study it was observed that boys, both pre- and post-PHV, were able to make significant improvements in jumping, sprinting, or both qualities following a range of 6-week resistance-based training programs. Irrespective of maturation, none of the control groups showed any significant changes in performance across the intervention period. Plyometric training appeared to stimulate the greatest gains in pre-PHV children, with significant improvements (range of % or ES) reported for all sprinting and jumping variables. Across all pre-PHV training groups, effect sizes were greater for changes in jumping versus sprinting performance. For the post-PHV cohort, combined training appeared to be the most effective in eliciting change across all performance variables, with moderate to large effects reported in acceleration, maximal running velocity and squat jump height. Inferential statistics showed that for almost all variables, comparable performance changes between pre- and post-PHV boys were trivial following both resistance and combined training interventions. However, following plyometric training, changes in squat jump and acceleration performance were significant and very likely greater in pre-PHV children versus their post-PHV peers.

It should also be noted that in addition to the current study showing beneficial effects for all resistance training modes, performance gains were achieved without any occurrence of musculoskeletal injury. This finding provides further support to recent recommendations from international consensus statements that children should participate in a varied, technical competency driven, and age appropriate strength and conditioning program to facilitate athletic development (4, 21).

Developmentally appropriate strength training (28), weightlifting (7), plyometric training (26) and combined training (9) have all been proven effective in mediating beneficial adaptations in numerous measures of neuromuscular performance in youth. In the current study, significant main effects for time across all variables indicated that irrespective of resistance training mode, both pre- and post-PHV boys were able to make worthwhile improvements in jumping and sprinting performance. The current study also identified significant time x training group interactions for all jumping and sprinting variables, with all training programs having a significant influence on the performance changes reported following the 6-week intervention period.

Of greater interest to the youth practitioner however, was the significant time x training group x maturity interaction for both squat jump and acceleration performance. Furthermore, magnitude-based inferences confirmed that in response to the plyometric training intervention, pre-PHV children had improvements in acceleration and squat jump height that were very likely greater than post-PHV males. Almost all other between-maturity group differences were non-significant and trivial, irrespective of training intervention. Intuitively, this suggests that the pre-PHV boys responded more favorably to the plyometric training program. These findings may reflect the process of 'synergistic adaptation', which refers to the symbiotic relationship between specific adaptations of an imposed training demand with concomitant growth and maturity-related adaptations. It is acknowledged that appropriately prescribed plyometric training enhances stretch-shortening cycle function in youth (26). Stretch-shortening cycle activity is governed by efficient neural regulation (18) and research shows that pre-pubescence is a timeframe during which children experience a proliferation in neural coordination and central nervous system maturation (5, 30, 34). It could be suggested that the high neural demand of plyometric training provided a stimulus that coincided with the natural adaptive response of the pre-PHV boys resulting from growth and maturation. Combined, this synergistic relationship may have led to an amplified age-related training response and suggests that training during this developmental period should include exposure to plyometric training to complement motor skill and foundational strength development.

Squat jump and acceleration performance are indicative of slower stretch shortening cycle activity (6), while reactive strength index and maximal running velocity typically utilize faster-stretch-shortening cycle actions (25). Interestingly, the heightened training response shown by the pre-PHV group following the plyometric training intervention resulted only in very likely greater adaptations in squat jump and acceleration performance, but unlikely changes in measures of reactive strength index and maximal running velocity. This may simply be a reflection of adaptations emanating from specifics of program design and exercise selection. For example, the plyometric training program included a number of exercises that targeted effective landing mechanics and movements that recruited longer ground contact times (e.g. drop landings, single leg forward hop and stick, horizontal jumps and multiple horizontal rebounds), which may have led to a bias in adaptations of slower stretch-shortening cycle mechanics. The notion of different jump protocol strategies eliciting specific neuromuscular adaptations is supported by previous literature (17, 25).

While magnitude-based inferences indicated that the post-PHV boys failed to show an enhanced training response compared to the pre-PHV children for any of the performance variables, it is worth noting that statistical significance testing showed that the training mode that led to the largest and highest number of significant performance changes was combined training. Combined training incorporates both plyometric and traditional strength training exercises, and while speculative, it could be suggested that the stimulus of this training mode more closely reflected the internal milieu of the post-PHV participants. Performance of plyometrics and traditional strength training differs in the time available in which to produce force. Plyometrics involve rapid movement speeds and high rates-of-force development, whereas traditional strength training allows for much longer contraction times in order to attain higher peak force outputs. Developmentally, post-PHV boys will experience morphological changes that facilitate force generation (e.g. increased motor unit size and pennation angles) in addition to continued neural adaptations as a consequence of maturation (27). The synergistic relationship between the combined training and natural adaptive processes may have provided a more potent maturity-related training stimulus. Combined, the findings for both pre- and post-PHV cohorts support recent meta-analyses that showed pre-PHV boys made the greatest gains in sprinting performance following plyometric training (32), while post-PHV males benefitted most from combined training modes.

In conclusion, in order to acutely improve vertical jump and acceleration capacities, pre-PHV children appear to benefit more than post-PHV males from plyometric training that requires high rates-of-force development and high velocity movement speeds. Post-PHV males appear to make greater adaptations from combined training, which utilizes a greater range of exercises that stress different regions of the force-velocity continuum. While speculative, these specific training responses appear to be age- and maturity-related respectively, reflecting the natural adaptive processes experienced by both pre- and post-PHV males. We suggest these concomitant adaptations may reflect the process of 'synergistic adaptation'.

PRACTICAL APPLICATIONS

The novel findings of the study suggest that when seeking to induce specific acute adaptations (6-week) in vertical jump and acceleration capacities in boys that are pre-PHV, practitioners may benefit from devoting increased training time to plyometrics. Alternatively, post-PHV males may benefit more from exposure to a combination of plyometric and traditional strength training methods. Given the short-term nature of the current study, it should be stressed that the resistance training stimulus should be changed periodically in order to facilitate continued progressive neuromuscular adaptation. Thus, while a focus on plyometrics may initially provide a preferential training response for pre-PHV boys, practitioners should routinely change the primary training mode to facilitate long-term adaptation. Practitioners must ensure that youth of all ages are prescribed varied, periodized and developmentally appropriate training programs. Furthermore, rather than an independent entity, resistance training should be a component of an integrated approach to youth physical development, which targets multiple physical fitness qualities and aligns with the goals of long-term physical development strategies (22).

ACKNOWLEDGEMENTS

There are no acknowledgements.

REFERENCES

1. Batterham AM and Hopkins WG. Making meaningful inferences about magnitudes. *Int J Sports Physiol Perform* 1: 50-57, 2006.
2. Behringer M, Vom Heede A, Matthews M, and Mester J. Effects of strength training on motor performance skills in children and adolescents: a meta-analysis. *Pediatr Exerc Sci* 23: 186-206, 2011.
3. Behringer M, Vom Heede A, Yue Z, and Mester J. Effects of resistance training in children and adolescents: a meta-analysis. *Pediatrics* 126: e1199-1210, 2010.

4. Bergeron MF, Mountjoy M, Armstrong N, Chia M, Cote J, Emery CA, Faigenbaum A, Hall G, Jr., Kriemler S, Leglise M, Malina RM, Pensgaard AM, Sanchez A, Soligard T, Sundgot-Borgen J, van Mechelen W, Weissensteiner JR, and Engebretsen L. International Olympic Committee consensus statement on youth athletic development. *Br J Sports Med* 49: 843-851, 2015.
5. Borms J. The child and exercise: an overview. *J Sports Sci* 4: 3-20, 1986.
6. Bret C, Rahmani A, Dufour AB, Messonnier L, and Lacour JR. Leg strength and stiffness as ability factors in 100 m sprint running. *J Sports Med Phys Fitness* 42: 274-281, 2002.
7. Chaouachi A, Hammami R, Kaabi S, Chamari K, Drinkwater EJ, and Behm DG. Olympic weightlifting and plyometric training with children provides similar or greater performance improvements than traditional resistance training. *J Strength Cond Res* 28: 1483-1496, 2014.
8. Dalleau G, Belli A, Viale F, Lacour JR, and Bourdin M. A simple method for field measurements of leg stiffness in hopping. *Int J Sports Med* 25: 170-176, 2004.
9. Faigenbaum AD, Farrell A, Fabiano M, Radler T, Naclerio F, Ratamess NA, Kang J, and Myer GD. Effects of integrative neuromuscular training on fitness performance in children. *Pediatr Exerc Sci* 23: 573-584, 2011.
10. Faigenbaum AD, Lloyd RS, and Myer GD. Youth resistance training: past practices, new perspectives, and future directions. *Pediatr Exerc Sci* 25: 591-604, 2013.
11. Faigenbaum AD, McFarland JE, Keiper FB, Tevlin W, Ratamess NA, Kang J, and Hoffman JR. Effects of a short-term plyometric and resistance training program on fitness performance in boys age 12 to 15 years. *J Sports Sci Med* 6: 519-525, 2007.
12. Gissis I, Papadopoulos C, Kalapotharakos VI, Sotiropoulos A, Komsis G, and Manolopoulos E. Strength and speed characteristics of elite, subelite, and recreational young soccer players. *Res Sports Med* 14: 205-214, 2006.
13. Haff GG. Periodization strategies for youth development, in: *Strength and Conditioning for Young Athletes: Science and Application*. RS Lloyd, JL Oliver, eds. Oxford, United Kingdom: Routledge, 2013, pp 149-168.
14. Hopkins WG. A spreasheet for deriving a confidence interval, mechanistic inference and clinical inference from a p value. *Sportscience* 11: 16-20, 2007.
15. Hopkins WG, Marshall SW, Batterham AM, and Hanin J. Progressive statistics for studies in sports medicine and exercise science. *Med Sci Sports Exerc* 41: 3-13, 2009.
16. Ingle L, Sleap M, and Tolfrey K. The effect of a complex training and detraining programme on selected strength and power variables in early pubertal boys. *J Sports Sci* 24: 987-997, 2006.
17. Jidovtseff B, Quievre J, Harris NK, and Cronin JB. Influence of jumping strategy on kinetic and kinematic variables. *J Sports Med Phys Fitness* 54: 129-138, 2014.
18. Komi PV. Stretch-shortening cycle: a powerful model to study normal and fatigued muscle. *J Biomech* 33: 1197-1206, 2000.
19. Kraemer WJ and Ratamess NA. Fundamentals of resistance training: progression and exercise prescription. *Med Sci Sports Exerc* 36: 674-688, 2004.

20. Lillegard WA, Brown EW, Wilson DJ, Henderson R, and Lewis E. Efficacy of strength training in prepubescent to early postpubescent males and females: effects of gender and maturity. *Pediatr Rehabil* 1: 147-157, 1997.
21. Lloyd RS, Faigenbaum AD, Stone MH, Oliver JL, Jeffreys I, Moody JA, Brewer C, Pierce KC, McCambridge TM, Howard R, Herrington L, Hainline B, Micheli LJ, Jaques R, Kraemer WJ, McBride MG, Best TM, Chu DA, Alvar BA, and Myer GD. Position statement on youth resistance training: the 2014 International Consensus. *Br J Sports Med* 48: 498-505, 2014.
22. Lloyd RS and Oliver JL. The youth physical development model: a new approach to long-term athletic development. *Strength Cond J* 34: 61-72, 2012.
23. Lloyd RS, Oliver JL, Faigenbaum AD, Howard R, De Ste Croix MB, Williams CA, Best TM, Alvar BA, Micheli LJ, Thomas DP, Hatfield DL, Cronin JB, and Myer GD. Long-term athletic development, part 2: barriers to success and potential solutions. *J Strength Cond Res* 29: 1451-1464, 2015.
24. Lloyd RS, Oliver JL, Hughes MG, and Williams CA. Reliability and validity of field-based measures of leg stiffness and reactive strength index in youths. *J Sports Sci* 27: 1565-1573, 2009.
25. Lloyd RS, Oliver JL, Hughes MG, and Williams CA. Specificity of test selection for the appropriate assessment of different measures of stretch-shortening cycle function in children. *J Sports Med Phys Fitness* 51: 595-602, 2011.
26. Lloyd RS, Oliver JL, Hughes MG, and Williams CA. The effects of 4-weeks of plyometric training on reactive strength index and leg stiffness in male youths. *J Strength Cond Res* 26: 2812-2819, 2012.
27. Malina RMB, C.; Bar-Or, O. *Growth, Maturation and Physical Activity*. Champaign, IL: Human Kinetics, 2004.
28. Meylan CM, Cronin JB, Oliver JL, Hopkins WG, and Contreras B. The effect of maturation on adaptations to strength training and detraining in 11-15-year-olds. *Scand J Med Sci Sports* 24: e156-164, 2014.
29. Mirwald RL, Baxter-Jones AD, Bailey DA, and Beunen GP. An assessment of maturity from anthropometric measurements. *Med Sci Sports Exerc* 34: 689-694, 2002.
30. Myer GD, Kushner AM, Faigenbaum AD, Kiefer A, Kashikar-Zuck S, and Clark JF. Training the developing brain, part I: cognitive developmental considerations for training youth. *Curr Sports Med Rep* 12: 304-310, 2013.
31. Pfeiffer RDF, R.S. Effects of strength training muscle development in prepubescent, pubescent, and postpubescent males. *Phys Sportsmed* 14: 142-143, 1986.
32. Rumpf MC, Cronin JB, Pinder SD, Oliver J, and Hughes M. Effect of different training methods on running sprint times in male youth. *Pediatr Exerc Sci* 24: 170-186, 2012.
33. Runhaar J, Collard DC, Singh AS, Kemper HC, van Mechelen W, and Chinapaw M. Motor fitness in Dutch youth: differences over a 26-year period (1980-2006). *J Sci Med Sport* 13: 323-328, 2010.
34. Sowell ER, Thompson PM, Leonard CM, Welcome SE, Kan E, and Toga AW. Longitudinal mapping of cortical thickness and brain growth in normal children. *J Neurosci* 24: 8223-8231, 2004.
35. Sowell ER, Trauner DA, Gamst A, and Jernigan TL. Development of cortical and subcortical brain structures in childhood and adolescence: a structural MRI study. *Dev Med Child Neurol* 44: 4-16, 2002.

36. Thomas K, French D, and Hayes PR. The effect of two plyometric training techniques on muscular power and agility in youth soccer players. *J Strength Cond Res* 23: 332-335, 2009.
37. Wong PL, Chamari K, and Wisloff U. Effects of 12-week on-field combined strength and power training on physical performance among U-14 young soccer players. *J Strength Cond Res* 24: 644-652, 2010.

FIGURE LEGEND

Figure 1. Mean difference (90%CI) between pre and post-PHV groups in 10 m sprint time, 20 m sprint time, squat jumps height (SJ) and reactive strength index (RSI) across different training interventions. Training interventions are presented as; PLY = plyometric training, TST = traditional strength training, COM = combined training and CON = control group. The grey shaded area represents the smallest worthwhile effect. Magnitude-based inferences are represented by; U = unclear, T = trivial, VL-N = very likely negative, VL-P = very likely positive.

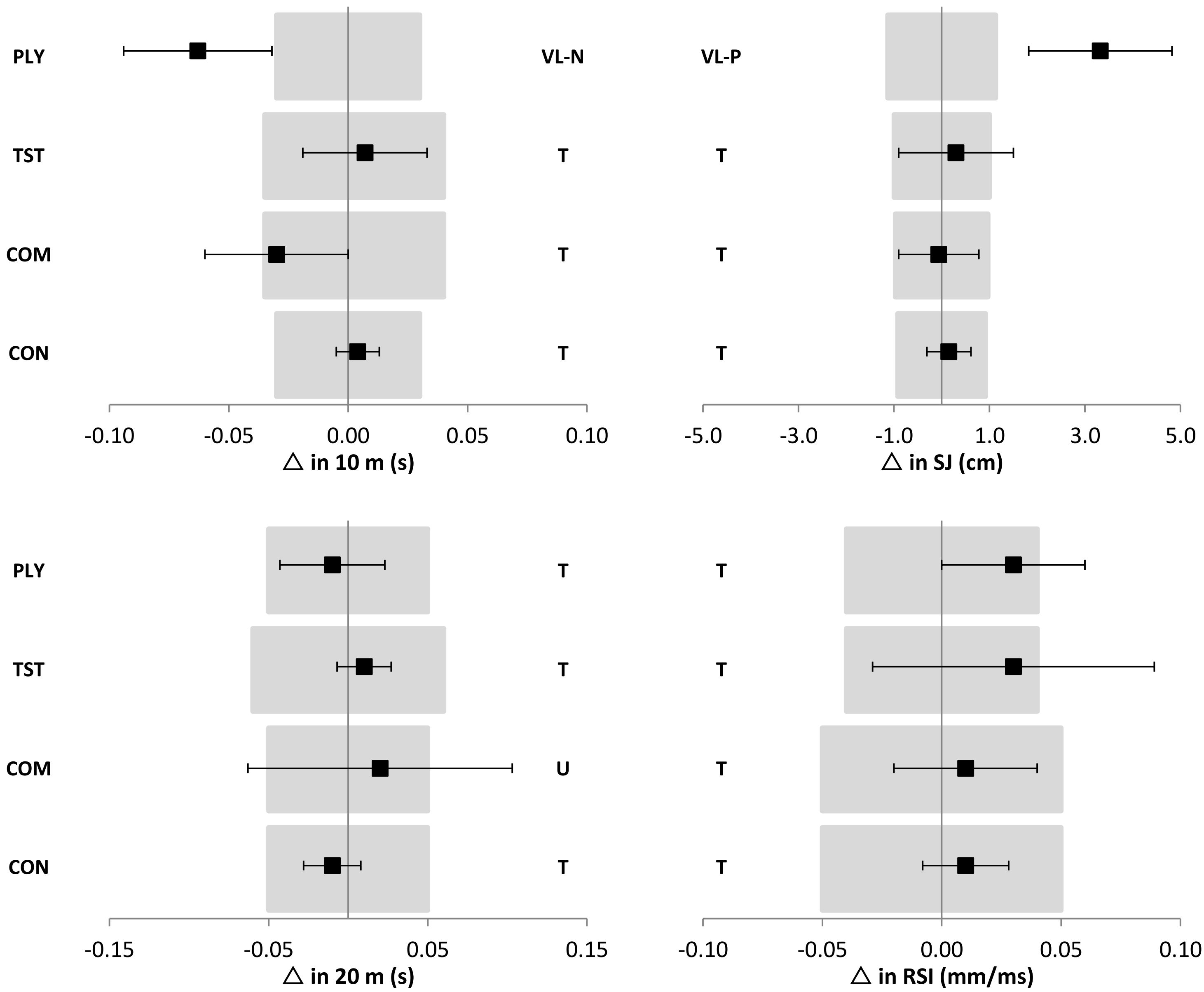

Figure 1. Mean difference (90%CI) between pre and post-PHV groups in 10 m sprint time, 20 m sprint time, squat jump height (SJ) and reactive strength index (RSI) across different training interventions. Training interventions are presented as; PLY = plyometric training, TST = traditional strength training, COM = combined training and CON = control group. The grey shaded area represents the smallest worthwhile effect. Magnitude-based inferences are represented by; U = unclear, T = trivial, VL-N = very likely negative, VL-P = very likely positive.

Table 1. Descriptive statistics for anthropometrics per group

Maturation Stage	Group	Sample size	Age	Height	Body mass	PHV
Pre-PHV	PT	10	12.7 ± 0.3	159.6 ± 8.9	56.0 ± 11.0	-1.5 ± 0.4
	TST	10	12.6 ± 0.3	156.9 ± 6.3	50.3 ± 14.4	-1.4 ± 0.6
	CT	10	12.7 ± 0.3	158.3 ± 7.6	53.5 ± 10.7	-1.5 ± 0.7
	CON	10	12.8 ± 0.2	157.0 ± 9.2	54.9 ± 10.6	-1.5 ± 0.6
Post-pubertal	PT	10	16.4 ± 0.2	179.5 ± 5.7	67.8 ± 6.1	1.3 ± 0.3
	TST	10	16.3 ± 0.3	177.5 ± 5.3	64.9 ± 5.3	1.3 ± 0.3
	CT	10	16.2 ± 0.3	178.3 ± 5.4	65.3 ± 7.2	1.3 ± 0.6
	CON	10	16.2 ± 0.3	179.0 ± 5.2	67.2 ± 8.4	1.2 ± 0.4

Note: PT = plyometric training, TST = traditional strength training, CT = combined training, CON = control group

Table 2. Overview of the plyometric training program

Week	Exercise	Sets	Repetitions	Total Foot Contacts
1	Drop landings	3	6	74
	Vertical jumps in place	3	6	
	Horizontal jumps	3	6	
	SL forward hop and stick	2	10	
2	Drop landings	3	6	76
	SL forward hop and stick	2	10	
	Split squat drop lands	3	6	
	SL lateral hop and stick	2	10	
3	Box jumps	3	6	78
	Pogo hopping	3	8	
	Multiple horizontal bilateral rebounds	4	3	
	“Ankling” drill	3	8	
4	Power skipping	3	10	80
	Unilateral pogo hops	2	10	
	Multiple horizontal rebounds	5	3	
	Multiple horizontal rebounds over hurdles	5	3	
5	Unilateral pogo hops	2	10	83
	Alternate leg bounding	3	8	
	Multiple bounding	3	8	
	Multiple horizontal rebounds over hurdles	5	3	
6	Drop jumps	4	4	88
	Alternate unilateral horizontal jumps	3	8	
	Power skipping	3	8	
	Alternate leg bounding	3	8	

Table 3. Overview of the combined training program

Week	Exercise	Sets	Repetitions
1	Drop lands	3	6
	Back squat	3	10
	Broad jump	3	6
	Barbell lunge	3	10
2	Back squat	3	10
	SL forward hop and stick	2	10
	Split squat drop lands	3	6
	Barbell lunge	3	10
3	Back squat	3	10
	Pogo hopping	3	8
	Barbell lunge	3	10
	Multiple bilateral bounds	4	4
4	Back squat	3	10
	Alternate leg bounds	3	10
	Barbell lunge	3	10
	Multiple bilateral bounds + hurdles	5	3
5	Back squat	3	10
	Alternate leg bounds	3	8
	Barbell lunge	3	10
	Unilateral pogo hopping	2	10
6	Drop jumps	4	4
	Back squat	3	10
	Power skipping + hurdles	3	8
	Barbell lunge	3	10

Table 4. Changes in running speed and jump performance for pre-PHV subjects post-6-week training intervention (mean ± *sd*)

Variable/Maturity Group	Condition	PT	TST	CT	CON
10 m acceleration (s)	Pre	2.3 ± 0.2	2.3 ± 0.2	2.2 ± 0.2	2.2 ± 0.2
Pre-PHV	Post	2.2 ± 0.2[b]	2.2 ± 0.2[a]	2.1 ± 0.2[b]	2.2 ± 0.2
	Effect size (Cohen's *d*)	0.38	0.11	0.32	0.00
10 m acceleration (s)	Pre	1.9 ± 0.1	1.9 ± 0.1	1.9 ± 0.1	1.9 ± 0.1
Post-PHV	Post	1.9 ± 0.1	1.8 ± 0.1[b]	1.8 ± 0.1[b]	1.9 ± 0.1
	Effect size (Cohen's *d*)	0.06	0.36	0.62	0.04
20 m speed (s)	Pre	3.4 ± 0.2	3.4 ± 0.3	3.4 ± 0.3	3.3 ± 0.3
Pre-PHV	Post	3.3 ± 0.2[b]	3.4 ± 0.3	3.3 ± 0.3[b]	3.3 ± 0.3
	Effect size (Cohen's *d*)	0.45	0.04	0.31	0.02
20 m speed (s)	Pre	2.7 ± 0.3	2.8 ± 0.2	2.8 ± 0.2	2.7 ± 0.3
Post-PHV	Post	2.6 ± 0.3[b]	2.7 ± 0.2	2.6 ± 0.2[a]	2.7 ± 0.3
	Effect size (Cohen's *d*)	0.34	0.08	0.50	0.02
SJ (cm)	Pre	24.6 ± 4.9	22.3 ± 4.9	24.1 ± 4.3	23.4 ± 4.6
Pre-PHV	Post	28.3 ± 4.6[b]	24.8 ± 4.6[b]	28.2 ± 4.6[b]	23.5 ± 4.2
	Effect size (Cohen's *d*)	0.77	0.52	0.96	0.03
SJ (cm)	Pre	32.3 ± 6.4	32.4 ± 5.0	33.2 ± 5.4	34.2 ± 4.6
Post-PHV	Post	32.7 ± 6.3	34.6 ± 5.1[b]	37.4 ± 5.5[b]	34.2 ± 4.6
	Effect size (Cohen's *d*)	0.07	0.45	0.79	0.00
RSI (mm/ms)	Pre	1.0 ± 0.2	0.9 ± 0.2	1.0 ± 0.3	1.0 ± 0.2
Pre-PHV	Post	1.1 ± 0.2[b]	1.0 ± 0.2[b]	1.0 ± 0.3[b]	1.0 ± 0.2
	Effect size (Cohen's *d*)	0.53	0.16	0.19	0.04
RSI (mm/ms)	Pre	1.4 ± 0.2	1.4 ± 0.2	1.4 ± 0.2	1.4 ± 0.3
Post-PHV	Post	1.5 ± 0.2[b]	1.4 ± 0.2	1.4 ± 0.2[b]	1.4 ± 0.3
	Effect size (Cohen's *d*)	0.27	0.05	0.28	0.01

[a]significantly different from pre-test ($p < 0.05$); [b]significantly different from pre-test ($p < 0.01$)

PT = plyometric training group; TST = traditional strength training group; CT = combined training group; CON = control group; SJ = squat jump; RSI = reactive strength index