Effects of combined resistance training and weightlifting on motor skill performance of adolescent male athletes

Andrew W. Pichardo[1], Jon L. Oliver[1,2], Craig B. Harrison[1], Peter S. Maulder[1,3], Rhodri S. Lloyd[1,2,3]

[1]Sports Performance Research Institute New Zealand, AUT University, Auckland, New Zealand

[2]Youth Physical Development Centre, School of Sport, Cardiff Metropolitan University, Cardiff, United Kingdom

[3]Centre for Sport Science and Human Performance, Waikato Institute of Technology, Hamilton, New Zealand

ABSTRACT

Resistance training and weightlifting are regarded as safe and effective training methods for youth. However, no studies have examined the effects of a year-long resistance training program using weightlifting movements on strength, speed or power. Therefore, the purpose of this study was to determine the long-term effects of combined resistance training (traditional strength training + plyometrics) with or without weightlifting movements on motor skill performance of adolescent males. Fifty-nine males aged 12-14 were matched by maturity and allocated to a combined resistance training or a combined resistance training with weightlifting group. Each group completed 28 total weeks of training over an academic year. Pre-, mid- (14 weeks of training) and post-training (28 weeks of training) tests included the Resistance Training Skills Battery quotient (RTSQ), absolute isometric mid-thigh pull peak force ($IMTP_{ABS}$) and ratio scaled isometric mid-thigh pull peak force ($IMTP_{REL}$), countermovement jump, horizontal jump and 10, 20 and 30 m sprint. Repeated measure analysis of variance revealed that there were no significant between-group responses, but all variables improved significantly within-group. Both groups made small-moderate improvements in RTSQ, $IMTP_{ABS}$ and $IMTP_{REL}$ after the first 14 training weeks (d = 0.45 to 0.86), whereas small-moderate improvements in lower body power, upper body power and speed were made after the second 14 training weeks (d = 0.30 to 0.95). Both groups made small-moderate improvements in all performance variables after 28 weeks of training. These findings highlight the importance of establishing movement competency and strength as a foundation for the subsequent development of power. Furthermore, these findings may help practitioners understand the time course of certain adaptations following a long-term periodized plan for adolescent males.

KEYWORDS: youth, long-term athletic development, strength, power, speed

WORD COUNT: 271

INTRODUCTION

Resistance training is becoming a widely accepted training method to promote successful long-term athletic development. Common forms of resistance training such as traditional strength training, plyometric training, weightlifting and a combination of these have been shown to be safe and effective when performed under proper supervision, and subsequently, are endorsed by several organizations' position statements (18-20). A recurring theme surrounding successful long-term athletic development includes proper progression of training structure, exercises and intensity taking into account technical competency and biological age (18). Evidence indicates that a longer training period (> 23 weeks) and higher exercise intensity (+80% 1 repetition maximum) are most effective in improving strength in young athletes (17) and are appropriate for boys and girls that display high levels of motor competency. Specifically, a series of studies on youth soccer players and weightlifters following a two-year traditional strength training program adhering to these guidelines showed large gains in relative and absolute squat strength (14), sprint (14) and change of direction performance (15). Despite the evidence regarding the efficacy of consistent training at the appropriate intensity, different resistance training programs have not been compared over a longer period of time.

Training adaptations in youth are generally specific to the type of training performed. For example, meta-analytical data show that power training improves jump performance more than strength training, but the latter is more effective in eliciting gains in strength (3). However, the broader goal of long-term athletic development programs is to promote the improvement of multiple physical qualities. Specifically, evidence suggests a combined approach that includes traditional strength training and plyometric training is most effective for improving various motor skill outcomes (23, 35).

Weightlifting training, which refers to highly technical, explosive multi-joint exercises such as the snatch, clean and jerk, and their derivatives (22), provides a more specialized form of resistance training. However, there is limited research that has examined how combining this mode of training with more traditional resistance training influences long-term athletic development. Research suggests that the derivatives of the full lifts can serve as a valuable teaching progression that also provides a similar training stimulus to the full movements (4, 41). One study on young weightlifters (aged 10-15 years) showed absolute and relative snatch and clean and jerk strength nearly doubled over extended training periods (28.8 ± 4.4 months), demonstrating the safety and trainability of weightlifting movements when performed under qualified supervision (4). Training with these movements has been shown to improve jump (5) and sprint (6) performance compared to traditional strength training after 8 and 12 weeks in post- and pre-peak height-velocity males, respectively. Peak height velocity refers to the maximal velocity of growth in height, and typically occurs between age 13.8-14.2 in European males (25). Due to the paucity of long-term research examining motor skill development, it is important to determine how motor skill development might be disrupted, or even improved, using different types of training during periods of maximal growth in height. Therefore, the purpose of this study was to determine the effects of different long-term training programs that combine different forms of resistance training with or without weightlifting on motor skill performance in adolescent male athletes.

METHODS

Experimental Approach to the Problem

A cluster randomized trial was used to determine the effects of a combined resistance training (CRT) or a combined approach that included weightlifting movements (CRT&WL) on motor skill performance in young males (age 12-14) over an academic year (11 months). Boys enrolled in an athlete development program at their school were matched by maturation, then divided into one of two training groups: CRT or CRT&WL training. The CRT undertook a combination of strength and plyometric training, whereas the CRT&WL group also completed strength and plyometric training but replaced some of the strength exercises with weightlifting exercises. The groups performed their training program twice weekly throughout the academic year. Once testing weeks and school holidays were accounted for, this allowed for 28 weeks of training, as shown in Figure 1. All participants were tested pre-, mid- (14 training weeks) and post-training (28 training weeks) for the following dependent variables: resistance training skills quotient (RTSQ) (24), absolute ($IMTP_{ABS}$) and relative peak force of the isometric mid-thigh pull ($IMTP_{REL}$), countermovement jump (CMJ), horizontal jump (HJ), seated medicine ball throw (SMBT), 10 m sprint, 20 m sprint and 30 m sprint.

Figure 1 near here

Subjects

Seventy-three male secondary school students (year 9 & 10) aged between 12-14 years were recruited to participate in this study. To be included in the final analyses, participants were required to complete at least 70% of the training sessions. Fourteen subjects did not meet this criterion and therefore 59 subjects were included in the analyses. The participants were recruited from their school's athlete development program and each class was matched by maturity offset (29) then assigned to a CRT (n = 28) or CRT&WL training (n = 31) group. There were no significant between-group differences at baseline for any of the performance variables ($p > 0.05$). All the year 10s (half in each training group) had participated in the program the year before and all year 9s (half of each training group) were new to the program. However, resistance training was not included in the program the previous year, so all of the participants had a resistance training age of less than one year. Subject physical characteristics are shown in Table 1. Both groups performed the training program as well as their habitual physical education curriculum, which included 2-3 hour-long sessions per week inclusive of physical activities. All participants and parents or guardians were informed about the testing procedures and provided written informed assent and consent. The study was reviewed and approved by the Institutional Research Ethics Committee.

Table 1 near here

Procedures

During each testing week, sessions took place during an hour-long secondary school lesson on 2 non-consecutive days. Session one consisted of collecting anthropometric measures, the isometric mid-thigh pull, HJ distance, CMJ height and sprint measures and session two consisted of the Resistance Training Skills Battery and SMBT. The mid- and post-testing sessions were performed during the same lesson on the same day of the week and at the same time of day as the pre-testing session. Prior to testing each session, a standardized dynamic warm-up consisting of bodyweight exercises and submaximal jumping and running was completed by all participants. After the warm-up, participants completed each test in a randomized order which was held constant for each subsequent testing session. Participants performed two trials of each test and the best trial was used for analysis.

Resistance training skills battery

The Resistance Training Skills Battery provides an assessment of basic resistance training skill competency using 6 movements: the bodyweight squat, push-up, lunge, suspended row, standing overhead press, and front support with chest touches (24). Each movement was performed according to the guidelines from Lubans et al. (24) except the bodyweight squat, which was performed using a back squat assessment protocol from Myer et al. (30). This protocol included a wooden dowel across the back which aids upper back engagement and prepares athletes for back squatting with external loads, which is more specific to the aims of the intervention. Each movement was filmed from the sagittal and frontal plane with an iPad (3rd and 4th generation, Apple Inc., USA) mounted on a tripod set approximately 1 m high and 3 m from the center of the capture area. Video assessments were retrospectively played using QuickTime Player (version 10.4) and rated according to criteria from Lubans et al. (24) to determine a resistance training skills quotient (RTSQ), where a higher score is favorable to a lower score. Test-retest reliability of the Resistance Training Skills Battery has been shown to effectively rank youth's RTSQ (ICC = 0.88), while construct validity demonstrated a significant relationship between RTSQ and muscular fitness, making it a valuable screening tool for overall motor skill performance.

Isometric mid-thigh pull

The isometric mid-thigh pull was performed using two portable force plates (Pasco, California, USA) sampling at 100 Hz and variables were analyzed using custom software. A barbell was fixed in place and the distance between the bar and force plates was adjusted by raising each plate on dense, incompressible 1 cm thick rubber mats until the barbell was positioned just below the hip crease, approximately where the second-pull of a clean starts. Subjects used a self-selected mid-thigh clean position (knee angle approximately 125-135°). Feet were approximately shoulder width apart with hands just outside the legs, knees flexed, and torso upright in accordance with previous research (12). A self-selected position was used because previous research has shown that differences in knee and hip joint angles during the IMTP do not influence kinetic variables (7). Once stable in their self-selected position, participants were instructed to pull as hard and as fast as possible for approximately 3 seconds. Verbal encouragement was given to all subjects throughout the pull. $IMTP_{ABS}$ refers to the highest force obtained during the pull and was divided by body mass to obtain $IMTP_{REL}$. Each participant performed 2 maximal trials with approximately 1 minute rest and the best trial was used for analysis. Within-session and between-session reliability of peak force of the IMTP using this protocol was found to be high in youth males (within-session ICC: 0.97-0.98, CV: 4.1-4.3%; between-session ICC: 0.96, CV: 4.6%) (9).

Countermovement jump

The CMJ was performed using a linear position transducer (GymAware; Kinetic Performance Technology, Canberra, Australia) attached to a wooden dowel rod placed across the shoulders in a back-squat position. The subject was instructed to squat down to a self-selected depth and jump as high as possible. The jump height was recorded using the GymAware Lite app (version 2.10) on an iPad (3rd generation; Apple, Inc., USA). Each subject performed 2 jump with approximately 1 minute rest and the best jump was used for analysis. Previous studies have shown high reliability in CMJ height using linear position transducers (32, 33).

Horizontal jump

Subjects performed the horizontal jumps with their hands on hips to minimize the effect of arm swing (2, 45). The trial was discounted if the participant's hands moved from the hips or the feet moved upon landing and another trial was allowed. Jump distance was measured to the nearest cm from the furthest back heel using a tape measure taped to the floor. Each participant performed 2 jumps with about 1 minute rest and the best jump was used for analysis. Previous research has shown horizontal jump distance in youth to have a CV of < 10% and ICC > 0.80 in pre-, mid- and post-peak height-velocity youth (27).

Sprints

The 10 m sprint time was measured in an indoor gymnasium using a wired dual-beam infrared system (Swift Performance, Australia). Acceleration was measured over 10 m with a stationary start 50 cm behind the first timing gate. Each participant completed two trials each and the best performance was used for analysis. A 30 m sprint, with 20 m and 30 m split times, was measured outside on an artificial turf surface using a wireless dual-beam infrared system (SpeedLight; Swift Performance, Australia). Subjects used a stationary start 50 cm behind the first timing gate. Each participant performed two 30 m sprints with approximately 1 minutes rest and the best 20 m and 30 m splits were used for analysis. Participants used the same footwear for each testing session.

Seated Medicine Ball Throw

The SMBT was used to assess upper body power and was measured to the nearest cm using a tape measure placed against the wall and taped to the wooden floor of an indoor gymnasium. Subjects were instructed to sit with their legs straight and back flat against the wall and hold a 4-kg rubber medicine ball at chest level until instructed to throw. A pause at the chest was used to minimize any momentum or stretch-shortening cycle effects of using a dynamic start. When instructed, the subject threw the ball as far as possible with their back staying in contact with the wall. The distance was measured from the wall to where the middle of the ball landed. Each participant performed 2 throws with about 30 seconds rest and the best throw was used for analysis. Acceptable within- (r = 0.93-0.94) and between-session (r = 0.88) reliability has been shown for SMBT distance in youth (10).

Training Program

Training took place twice per week on nonconsecutive days for 28 weeks of training in total. Due to the four-term New Zealand academic schedule, training was divided into four training periods lasting 6-weeks, 8-weeks, 8-weeks and 6-weeks separated by two-week holidays between terms, as shown in Figure 1. Each 6- or 8-week training block was then divided into two mesocycles lasting 3 or 4 weeks, respectively. Both groups split each session between training in the weight room and a field or court, alternating which type of training was performed first. Each group completed the same 3-week introductory mesocycle using bodyweight exercises only. After the first mesocycle, both training groups completed the same field-based exercises but followed slightly different resistance training programs. The training programs were identical in sets and repetitions, but exercise selection differed between the CRT and CRT&WL groups, as shown in Figure 1. Each participant completed either 2-3 weightlifting movements or similar traditional strength training exercises depending on group, followed by 2-3 key exercises common to both groups, such as the back squat. The weightlifting movements followed a top-down approach as suggested by previous literature, starting from the mid-thigh, or power, position (4, 22). Volume increased from 1-3 sets of 5-12 repetitions in the first 6-week term, to 2-5 sets of 2-4 repetitions in the last 6-week term. Each exercise was progressed across 3 variations based on exercise complexity and external load, similar to Meylan et al.'s study using a similar cohort (26). Athletes started each term with the least complex exercise variation and progressed complexity and external load with the guidance of the practitioners. Participants also recorded the load used for each set in a training log, which helped to ensure they were progressively overloading each exercise. Feedback to ensure technical competency and motivation were given throughout the intervention. Each training session was supervised by the primary researcher who was a certified strength and conditioning specialist and held a Sport Performance Coach certification with USA Weightlifting. A physical education teacher and an exercise science graduate assistant were also present throughout the study period. A reduced test battery was completed at the end of term 1 and 3 but did not include all the tests that the pre-, mid- and post-test sessions did and therefore were not included in the analysis.

Statistical Analysis

A 2 x 3 repeated-measures analysis of variance (ANOVA) was performed on the absolute values of height, body mass and maturity offset, as well as the absolute values of 9 performance variables to determine the main effects between group (CRT vs CRT&WL) and time (pre, mid, post). Sphericity was assessed using Maulchy's Test and the Greenhouse-Geisser adjustment was applied where this was violated. A Bonferroni post hoc test was used to identify pairwise differences. Effect size calculations on absolute values were performed using Cohen's *d* both for within-group changes and to examine any effects in the CRT&WL group over and above effects of the CRT group. In the latter, effect sizes were calculated by the change in mean of the variables (post-test minus pre-test values) in the CRT&WL group minus the change in the mean in the CRT group, divided by the pooled SD of both groups. Effect sizes were interpreted according to Hopkins et al. (13) as follows: < 0.20 trivial; ≥ 0.20 and < 0.60 small; ≥ 0.60 and < 1.2 moderate; ≥ 1.20 and < 2.0 large; ≥ 2.0 and < 4.0 very large. Effect sizes and percentage change were calculated in Microsoft Excel (version 16), whereas the repeated measures ANOVA and tests of sphericity were calculated using Statistical Package for Social Sciences (SPSS Statistics, version 25). Statistical significance was set at alpha level $p \leq 0.05$ for all tests.

RESULTS

Repeated-measures ANOVA indicated there was a significant time effect for height, mass or maturity ($F_{(2,86)} \geq 64.417$, $p \leq 0.001$) but no significant interaction effects between group and time ($F_{(2,86)} \leq 1.805$, $p > 0.05$). Post hoc analysis confirmed there were no between-group differences in these variables at pre, mid or post time points (all $p > 0.05$). These findings confirm the homogeneity of participants across both groups and time points. When growth rates across the total intervention period were converted to annual growth rates, height increased by 6.4 ± 2.9 cm/year for the CRT group and 6.0 ± 2.8 cm/year for the CRT&WL group, while body mass increased by 6.2 ± 4.2 kg/year and 7.2 ± 3.4 kg/year, respectively. The average training adherence rates were 84.3 ± 0.1% for the CRT group and 85.2 ± 0.1% for the CRT&WL group.

There were significant main effects of time for all dependent variables ($F_{(2,86)} \geq 7.628$, $p \leq 0.001$), but no significant interactions between group and time ($F_{(2,86)} \leq 1.976$, $p \leq 0.001$). Post hoc analysis revealed significant within-group effects between at least two time points for all variables ($p < 0.05$) except RTSQ for the CRT group, as shown in Figures 2, 3 and 4. However, the time course of change differed between variables. RTSQ significantly improved pre to mid and pre to post in the CRT&WL group only ($p < 0.05$). The $IMTP_{ABS}$ significantly improved pre to mid and pre to post in both groups ($p < 0.001$), but only mid to post in the CRT group ($p < 0.05$), whereas $IMTP_{REL}$ significantly improved pre to mid in both groups ($p < 0.01$), but only pre to post in the CRT group ($p < 0.001$) (Figure 2). Jump and throw measures only increased significantly from mid to post and pre to post in both groups ($p < 0.05$) (Figure 3). Both groups significantly improved 10, 20 and 30 m sprint performance from mid to post and pre to post ($p < 0.01$), but only the CRT group significantly improved 20 and 30 m sprint performance from pre to mid ($p < 0.05$) (Figure 4).

Figure 2, 3 and 4 near here

The mean percentage change and within-group effect sizes for the CRT and CRT&WL groups from pre to mid, mid to post and pre to post are shown in Table 2. When comparing between-group effects from pre to mid, there were small effects for 20-meter sprint, $IMTP_{ABS}$ and $IMTP_{REL}$ in favor of the CRT group (d = 0.22-0.49), whereas there were small effects for CMJ and RTSQ in favor of the CRT&WL group (d = 0.36 and 0.26, respectively). Comparing mid to post improvements showed small between-group effects for CMJ in favor of CRT&WL (d = 0.24), but HJ improvements were in favor of the CRT group (d = 0.23). Pre to post between-group comparisons revealed a small effect in favor of the CRT group for $IMTP_{REL}$ (d = 0.41). All other between-group comparisons were trivial.

Table 2 near here

DISCUSSION

To our knowledge, this was the first study to compare the effects of a long-term periodized combined resistance training program with or without weightlifting movements on the motor skill development of adolescent boys. The findings suggest that performance gains were similar between both groups, but the pattern of change varied. Movement competency and strength improved after initial training while power and speed responded positively to the higher intensities provided in the second half of the training program. The findings also suggest that movement competency and strength are trainable through periods of the adolescent growth spurt.

It was expected that due to the complex and explosive nature of the lifts, including weightlifting exercises in a combined resistance training program would induce larger gains in movement competency, strength, power and sprint performance. However, in general, our findings showed similar gains in strength, power and speed for both training groups. The CRT group, which had a higher proportion of exercises that allowed for greater external loading, showed similar increases as the CRT&WL group for strength as measured by $IMTP_{ABS}$ and $IMTP_{REL}$. The CRT&WL group, which had a higher proportion of high velocity movements, showed similar improvements to the CRT group in jump, throw and sprint performance. These results are in contrast to a recent meta-analysis (107 studies) that suggested power training improves jump performance more than strength training, whereas strength training improves strength and speed measures more than power training (3).

Adaptations to specific training types may also be influenced by maturation status (6, 23, 31, 34). Specifically, previous studies in prepubertal children (aged 10-12 years) have found that strength, jump and sprint performance improved more after 12-weeks of weightlifting or plyometric (6) and a high velocity resistance training program (31) than age-matched controls participating in sports only. Additionally, 6 weeks of plyometric training elicited greater gains in squat jump and acceleration performance in pre-peak height velocity children (23), whereas combined (traditional strength training + plyometrics) was most effective for sprint and jump performance in post-pubertal children (23, 34). Together, the findings of these studies suggests that more mature children may require a greater neuromuscular stimulus and a variety of training methods to elicit gains in motor performance (36). Therefore, the age (13.9-14.0 years) and maturational status (maturity offset = 0.1-0.3) of subjects in the current study might explain the similar training responses between both groups, as both groups were performing combined training approaches and had participants pre-, circa- and post-PHV.

Several factors in the current study may reflect the time course of the motor skill adaptations observed. The initial gain in resistance training skills and absolute and relative strength, as well as the delayed gains in sprint, jump and throw performance, may have resulted from the long-term periodized nature of the program. The participants used moderate volume (1-3 sets, 8-12 reps) and bodyweight or light resistance to develop resistance training competency in the first half of the intervention, which provided sufficient stimulus to induce gains in strength as they were relatively untrained. Throughout the current study, more complex exercises and greater external loads were used as the participants increased their technical competency and training age. This translated into greater gains in sprint, jump and throw performance in the second half of the training program. Previous research has found similar trends with a long-term periodized program (38). Specifically, initial increases in back and front squat strength resulted in improved subsequent sprint performance (38), suggesting that strength may serve as a basis for power development. The current study showed that relatively low resistance training intensity may be adequate to stimulate moderate strength adaptations in adolescent boys with a relatively low training age. However, in order to promote long-term changes in performance and realize greater magnitudes of training-induced neuromuscular adaptation, participants will need to progressively overload and train with relatively higher resistance training intensities (17).

Another factor that may be responsible for the time course of gains in $IMTP_{ABS}$, $IMTP_{REL}$ and jump, throw and sprint performance in the current study is a lag between the realization of strength gains into power performance (8, 40). The larger gains in movement skill and isometric mid-thigh pull strength after the first 14 weeks of training are likely a result of greater neuromuscular coordination or mobility and maximal force output, respectively. However, the rapid rate of force development required for jumping, sprinting and throwing tasks was not realized until the last 14 weeks of training, when plyometric and resistance training intensity and complexity was highest. The greater intensity of traditional strength training, weightlifting and plyometric exercises in the latter half of the intervention may have helped the transfer of strength to more dynamic activities (e.g. CMJ, horizontal jump and SMBT) due to an increase in rate of force development via an enhanced neural drive (1). Furthermore, increases in lower-limb muscular pre-activation (21), stiffness and power (37) as children mature may contribute to the larger gains in jump and sprint performance seen in the second half of the intervention. The results of this study demonstrate the importance of establishing movement competency and muscular strength before focusing on power development in youth, as well as the specificity of adaptations according to the emphasis of training.

Training age may also contribute to the aforementioned lag effect in power and sprint performance due to the type of training performed during different stages of development. For example, previous research has shown that larger strength gains occur during the first year than the second year of resistance training in adolescent male athletes (38). Furthermore, Till et al. (42) also found that a group of rugby athletes (age 16-19 years) with a resistance training age of 0 or 2 years saw greater annual gains in strength compared to a group with 1 year training experience. However, the older athletes in that study were likely all post-pubertal and therefore the results may not translate to an adolescent population. Regardless, this plateau period between initial and later strength gains may be partially explained by the emphasis of training during certain stages of development. Practitioners should ensure youth use light resistance and less complex movements when initially beginning resistance training before progressing to higher intensity and more complex movements as technical competency is established. The tests used to assess resistance training skills and strength were relatively new and simple, so the subjects responded to these novel stimuli more quickly than the more habitual complex tests involving more habitual activities such as sprinting, jumping and throwing. Therefore, they essentially have a higher training age for those tests and therefore take longer to respond to training. More importantly, however, the more complex activities do not respond as much until training intensity and complexity increase, which primarily occurred in the second half of the periodized program.

A limitation to this study is the lack of a control group, as the performance gains were not compared directly to similar aged subjects that did not complete the training. However, both groups, whose height, body mass and maturity offset did not differ significantly, were in an athletic development program and were all required to receive strength and conditioning support. Therefore, the purpose of this study was to compare responses to different resistance training programs in the sample population, with the overall dose of training kept similar between groups. The temporal responses of both groups provide support for the evidence of training effects beyond that of growth and maturation; while height and body mass improved at consistent rates between testing sessions, performance outcomes were more phasic and generally included a period of trivial change and a period of more substantial change. In periods where training effects were most evident, they are well beyond those expected for growth and maturation. For example, in the 14-week mid to post period, CMJ height improved by >10% and sprint performance by 3-6%. This compares favourably to previous research. Specifically, in athletic boys aged between 13-17 years old completing plyometric, resistance or combined training twice a week for between 12-16 weeks, sprint performance has been reported to improve by 2-6% and CMJ height by 7-9% (16, 28, 39, 44). Even when considering the entire intervention period and converting to annual rates of improvement, boys in the present study improved CMJ height by a rate of > 26% per year and sprint performance by > 9% per year. These annual rates of improvement are well beyond those reported for the CMJ (6.9% per year) and sprint performance (2.7-3.1% per year) of boys in a talent development program but who received no resistance training (43).

The present study aimed to compare the effects of a combined resistance training with or without weightlifting on the long-term athletic development of adolescent boys. Major findings revealed largely similar performance gains between both groups. Interestingly, there were clear differences in the pattern of change across variables. In the first half of the year significant improvements in movement competency and strength were observed, while in the second half of the year jump, throw and sprint performance significantly improved. While height and body mass changed at consistent rates throughout the intervention, the different temporal responses shown for the performance variables likely aligned to the periodized design of the training program. Therefore, to effectively make long-term gains in motor skill performance, both coaches and athletes should trust in a long-term training process and adopt patience when pursuing long-term goals (11, 18).

PRACTICAL APPLICATIONS

Strength and conditioning programs that include weightlifting movements can be safely and effectively integrated within an academic schedule and result in gains in performance which supersede growth and maturation changes. Despite the proposed motor control challenges of learning weightlifting techniques, practitioners should consider the findings of the current study as evidence of how weightlifting movements can be successfully embedded within the physical education curricula to promote improvements in motor skill competency and physical fitness. Arranging the educational schedule into a series of training blocks, practitioners can effectively theme the delivery of weightlifting movements throughout the academic year to progressively teach and refine technical competency and enhance muscle strength in early stages of the year, before seeking adaptations in higher velocity movements in subsequent blocks. These approaches are in-line with the central tenets of current long-term athletic development policy (18) and should only be delivered by qualified coaches with experience training youth.

REFERENCES

1. Aagaard P, Simonsen EB, Andersen JL, Magnusson P, and Dyhre-Poulsen P. Increased rate of force development and neural drive of human skeletal muscle following resistance training. *J Appl Physiol* 93: 1318-1326, 2002.
2. Ashby BM and Heegaard JH. Role of arm motion in the standing long jump. *J Biomech* 35: 1631-1637, 2003.
3. Behm DG, Young JD, Whitten JH, Reid JC, Quigley PJ, Low J, Li Y, Lima CD, Hodgson DD, Chaouachi A, Prieske O, and Granacher U. Effectiveness of traditional strength vs. power training on muscle strength, power and speed with youth: A systematic review and meta-analysis. *Front Physiol* 8: 423, 2017.
4. Byrd R, Pierce K, Reilly L, and Brady J. Young weightlifters' performance across time. *Sports Biomech* 2: 133-140, 2003.
5. Channell BT and Barfield J. Effect of olympic and traditional resistance training on vertical jump improvement in high school boys. *J Strength Cond Res* 22: 1522-1527, 2008.
6. 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.
7. Comfort P, Jones PA, McMahon JJ, and Newton R. Effect of knee and trunk angle on kinetic variables during the isometric midthigh pull: Test–retest reliability. *Int J Sports Physiol Perform* 10: 58-63, 2015.
8. Delecluse C. Influence of strength training on sprint running performance. *Sports Med* 24: 147-156, 1997.
9. Dos'Santos T, Thomas C, Comfort P, McMahon JJ, Jones PA, Oakley NP, and Young AL. Between-session reliability of isometric mid-thigh pull kinetics and maximal power clean performance in male youth soccer players. *J Strength Cond Res*, 2017.
10. 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.
11. Faigenbaum AD and Meadors L. A coach's dozen: An update on building healthy, strong, and resilient young athletes. *Strength Cond J* 39: 27-33, 2017.
12. Haff GG, Stone MH, O'bryant HS, Harman E, Dinan C, Johnson R, and Han K-H. Force-time dependent characteristics of dynamic and isometric muscle actions. *J Strength Cond Res* 11: 269-272, 1997.
13. Hopkins W, Marshall S, Batterham A, and Hanin J. Progressive statistics for studies in sports medicine and exercise science. *Medicine+ Science in Sports+ Exercise* 41: 3, 2009.
14. Keiner M, Sander A, Wirth K, Caruso O, Immesberger P, and Zawieja M. Strength performance in youth: Trainability of adolescents and children in the back and front squats. *J Strength Cond Res* 27: 357-362, 2013.
15. Keiner M, Sander A, Wirth K, and Schmidtbleicher D. Long-term strength training effects on change-of-direction sprint performance. *J Strength Cond Res* 28: 223-231, 2014.
16. Kotzamanidis C. Effect of plyometric training on running performance and vertical jumping in prepubertal boys. *J Strength Cond Res* 20: 441, 2006.
17. Lesinski M, Prieske O, and Granacher U. Effects and dose-response relationships of resistance training on physical performance in youth athletes: A systematic review and meta-analysis. *Br J Sports Med* 0: 1-17, 2016.
18. Lloyd RS, Cronin JB, Faigenbaum AD, Haff GG, Howard R, Kraemer WJ, Micheli LJ, Myer GD, and Oliver JL. National Strength and Conditioning Association position

statement on long-term athletic development. *J Strength Cond Res* 30: 1491-1509, 2016.

19. Lloyd RS, Faigenbaum AD, Myer GD, Stone MH, Oliver JL, Jeffreys I, and Pierce KC. UKSCA position statement: Youth resistance training. *Professional Strength and Conditioning* 26: 26-39, 2012.
20. 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.
21. Lloyd RS, Oliver JL, Hughes MG, and Williams CA. Age-related differences in the neural regulation of stretch-shortening cycle activities in male youths during maximal and sub-maximal hopping. *J Electromyogr Kinesiol* 22: 37-43, 2012.
22. Lloyd RS, Oliver JL, Meyers RW, Moody JA, and Stone MH. Long-term athletic development and its application to youth weightlifting. *Strength Cond J* 34: 55-66, 2012.
23. Lloyd RS, Radnor JM, De Ste Croix MB, Cronin JB, and Oliver JL. Changes in sprint and jump performances after traditional, plyometric, and combined resistance training in male youth pre- and post-peak height velocity. *J Strength Cond Res* 30: 1239-1247, 2016.
24. Lubans DR, Smith JJ, Harries SK, Barnett LM, and Faigenbaum AD. Development, test-retest reliability, and construct validity of the resistance training skills battery. *J Strength Cond Res* 28: 1373-1380, 2014.
25. Malina RM, Bouchard C, and Bar-Or O. *Growth, maturation, and physical activity.* Champagne, IL: Human Kinetics, 2004.
26. 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-e164, 2014.
27. Meylan CM, Cronin JB, Oliver JL, Hughes MG, and McMaster T. The reliability of jump kinematics and kinetics in children of different maturity status. *J Strength Cond Res* 26: 1015-1026, 2012.
28. Meylan CM and Malatesta D. Effects of in-season plyometric training within soccer practice on explosive actions of young players. *J Strength Cond Res* 23: 2605-2613, 2009.
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, Brent JL, Schoenfeld BJ, Hugentobler J, Lloyd RS, Vermeil A, Chu DA, Harbin J, and McGill SM. The back squat: A proposed assessment of functional deficits and technical factors that limit performance. *Strength Cond J* 36: 4-27, 2014.
31. Negra Y, Chaabene H, Hammami M, Hachana Y, and Granacher U. Effects of high-velocity resistance training on athletic performance in prepuberal male soccer athletes. *J Strength Cond Res*, 2016.
32. Nuzzo JL, Anning JH, and Scharfenberg JM. The reliability of three devices ssed for measuring vertical jump height. *J Strength Cond Res* 25: 2580-2590, 2011.
33. O'Donnell S, Tavares F, McMaster D, Chambers S, and Driller M. The validity and reliability of the GymAware linear position transducer for measuring counter-movement jump performance in female athletes. *Meas Phys Educ Exerc Sci* 22: 101-107, 2018.
34. Radnor JM, Lloyd RS, and Oliver JL. Individual response to different forms of resistance training in school-aged boys. *J Strength Cond Res* 31: 787-797, 2017.

35. Rodriguez-Rosell D, Franco-Márquez F, Pareja-Blanco F, Mora-Custodio R, Yáñez-García JM, González-Suárez JM, and González-Badillo JJ. Effects of 6 weeks resistance training combined with plyometric and speed exercises on physical performance of pre-peak-height-velocity soccer players. *Int J Sports Physiol Perform* 11: 240-246, 2016.
36. Rumpf MC, Cronin JB, Oliver JL, and Hughes MG. Effect of different training methods on running sprint times in male youth. *Pediatr Exerc Sci* 24: 170, 2012.
37. Rumpf MC, Cronin JB, Oliver JL, and Hughes MG. Vertical and leg stiffness and stretch-shortening cycle changes across maturation during maximal sprint running. *Hum Mov Sci* 32: 668-676, 2013.
38. Sander A, Keiner M, Wirth K, and Schmidtbleicher D. Influence of a 2-year strength training programme on power performance in elite youth soccer players. *Eur J Sport Sci* 13: 445-451, 2013.
39. Söhnlein Q, Müller E, and Stöggl TL. The effect of 16-week plyometric training on explosive actions in early to mid-puberty elite soccer players. *J Strength Cond Res* 28: 2105-2114, 2014.
40. Stone MH, Sanborn K, O'bryant HS, Hartman M, Stone ME, Proulx C, Ward B, and Hruby J. Maximum strength-power-performance relationships in collegiate throwers. *J Strength Cond Res* 17: 739-745, 2003.
41. Suchomel TJ, Lake JP, and Comfort P. Load Absorption Force-Time Characteristics Following the Second Pull of Weightlifting Derivatives. *J Strength Cond Res* 31: 1644-1652, 2017.
42. Till K, Darrall-Jones J, Weakley JJ, Roe GA, and Jones BL. The influence of training age on the annual development of physical qualities within academy rugby league players. *J Strength Cond Res* 31: 2110-2118, 2017.
43. Williams CA, Oliver JL, and Faulkner J. Seasonal monitoring of sprint and jump performance in a soccer youth academy. *Int J Sports Physiol Perform* 6: 264-275, 2011.
44. Wong P-l, 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.
45. Wu W-L, Wu J-H, Lin H-T, and Wang G-J. Biomechanical analysis of the standing long jump. *Biomed Eng (Singapore)* 15: 186-192, 2003.

ACKNOWLEDGEMENTS

The authors did not receive any funding or grant support for the study. The authors would like to acknowledge and thank St John's College and Wintec students for their assistance in the data collection for this study.

FIGURE LEGENDS

Figure 1. Annual plan for combined resistance training and combined resistance training & weightlifting groups. The exercises in bold represent the differences between the groups while all italicized exercises represent exercises common to both groups. In the daily plans, each row represents an exercise slot, so taller blocks indicate multiple exercises used for a given movement. UB = upper body; SL = single leg; H = horizontal; V = vertical; COD = change of direction; ** = reduced test battery that was not included in analysis.

Figure 2. A) RTSQ = resistance training skills quotient; B) $IMTP_{ABS}$ = absolute peak force of isometric mid-thigh pull; C) $IMTP_{REL}$ = ratio scaled peak force of isometric mid-thigh pull; CRT = combined resistance training; CRT&WL = combined resistance training & weightlifting; * significant within-group difference between time points for CRT group ($p < 0.05$), ** ($p < 0.01$), *** ($p \leq 0.001$); † significant within-group difference between times points for CRT&WL group ($p < 0.05$), †† ($p < 0.01$), ††† ($p \leq 0.001$); error bars represent standard deviation.

Figure 3. A) CMJ = countermovement jump; B) HJ = horizontal jump; C) SMBT = seated medicine ball throw; CRT = combined resistance training; CRT&WL = combined resistance training & weightlifting; * significant within-group difference between time points CRT group ($p < 0.05$), ** ($p < 0.01$), *** ($p \leq 0.001$); † significant within-group difference between times

points for CRT&WL group ($p < 0.05$), †† ($p < 0.01$), ††† ($p \leq 0.001$); error bars represent standard deviation.

Figure 4. A) 10-meter sprint; B) 20-meter sprint; C) 30-meter sprint; CRT = combined resistance training; CRT&WL = combined resistance training & weightlifting; * significant within-group difference between time points for CRT group ($p < 0.05$), ** ($p < 0.01$), *** ($p \leq 0.001$); † significant within-group difference between times points for CRT&WL group ($p < 0.05$), †† ($p < 0.01$), ††† ($p \leq 0.001$); error bars represent standard deviation.

Table 1. Subject physical characteristics (mean ± SD).*

	Combined Resistance Training (n = 28)			Combined Resistance Training & Weightlifting (n = 31)		
Age (years)	13.9 ± 0.6			14.0 ± 0.5		
Maturity offset (years from PHV)	0.1 ± 0.9			0.3 ± 0.6		
	Pre	Mid	Post	Pre	Mid	Post
Height (cm)	165.2 ± 10.11	167.9 ± 10.1	170.2 ± 10.1	167.6 ± 8.1	172.4 ± 7.9	173.4 ± 8.4
Body mass (kg)	56.4 ± 13.1	59.1 ± 13.4	61.4 ± 13.3	56.7 ± 10.9	60.0 ± 11.7	64.2 ± 12.1

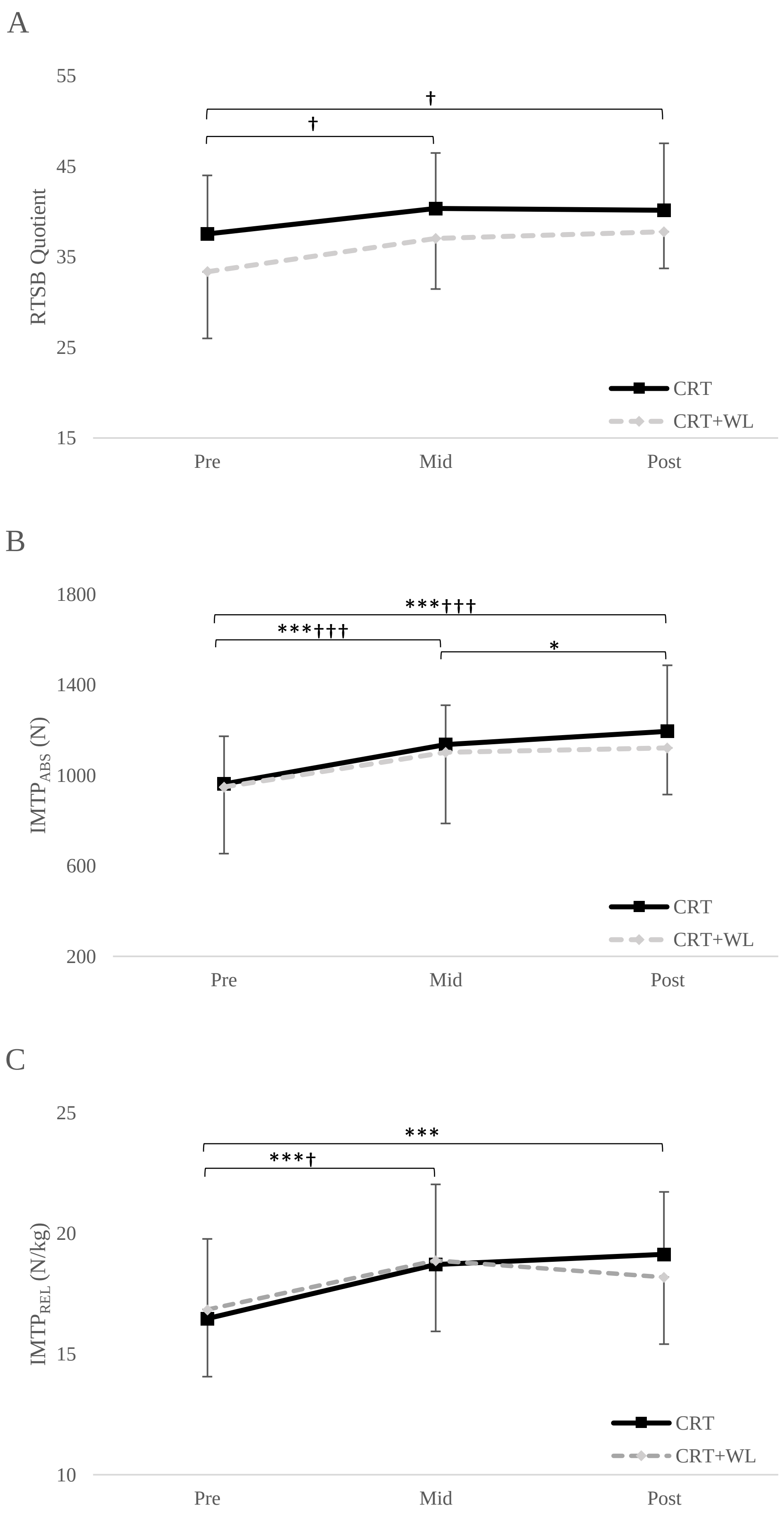
*PHV = peak height velocity

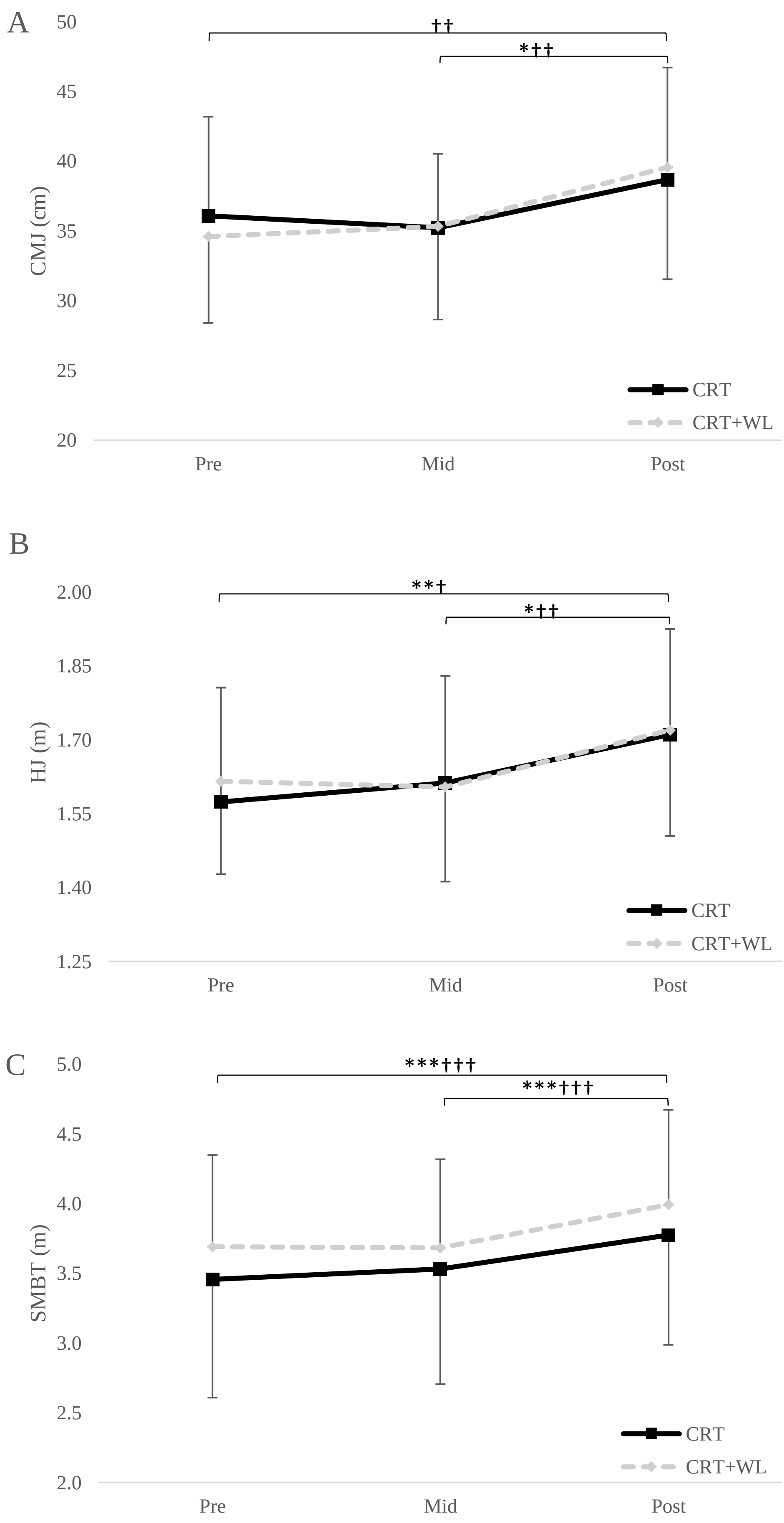
Table 2. Individual percentage change (mean ± SD) and within-group effect sizes for motor skill performance assessments.*

	Combined Resistance Training						Combined Resistance Training & Weightlifting					
	% change			Within-group effect size			% change			Within-group effect size		
	Pre-mid	Mid-post	Pre-post	Pre-mid	Mid-post	Pre-post	Pre-mid	Mid-post	Pre-post	Pre-mid	Mid-post	Pre-post
RTSQ	9.08 ± 17.08	0.40 ± 17.17	8.22 ± 17.36	0.45	-0.03	0.38	15.28 ± 27.263	3.91 ± 16.43	18.97 ± 31.55	0.56	0.15	0.74
IMTP$_{ABS}$	19.69 ± 18.25	7.09 ± 11.85	27.95 ± 22.95	0.53	0.18	0.78	18.65 ± 19.22	2.10 ± 8.43	20.66 ± 18.71	0.71	0.10	0.80
IMTP$_{REL}$	14.99 ± 18.69	2.85 ± 10.14	17.96 ± 21.06	0.86	0.16	1.07	13.65 ± 18.45	-3.11 ± 9.57	9.57 ± 16.71	0.67	-0.23	0.47
CMJ	-0.26 ± 16.44	10.52 ± 16.93	9.14 ± 19.64	-0.14	0.55	0.36	3.69 ±16.94	13.98 ± 20.29	17.05 ± 23.41	0.12	0.65	0.80
HJ	3.44 ± 13.85	6.86 ± 11.27	9.57 ± 11.73	0.17	0.47	0.62	-0.41 ± 8.40	7.63 ± 9.71	6.98 ± 10.95	-0.06	0.58	0.53
SMBT	2.47 ± 7.32	7.70 ± 7.53	10.14 ± 8.62	0.09	0.30	0.38	0.07 ± 5.82	8.61 ± 6.30	8.62 ± 7.89	-0.01	0.47	0.45
10 m sprint	0.87 ± 3.89	-4.58 ± 3.08	-6.07 ± 10.96	0.15	-0.95	-0.75	0.42 ± 2.24	-5.19 ± 2.86	-4.79 ± 3.36	0.07	-0.91	-0.83
20 m sprint	-2.18 ± 2.59	-3.18 ± 2.97	-5.30 ± 3.64	-0.41	-0.70	-0.98	-1.23 ± 1.80	-2.78 ± 2.49	-3.98 ± 2.87	-0.20	-0.46	-0.64
30 m sprint	-2.70 ± 3.02	-3.54 ± 3.13	-6.17 ± 3.77	-0.44	-0.71	-0.99	-1.54 ± 2.48	-3.59 ± 2.79	-5.08 ± 3.44	-0.23	-0.54	-0.71

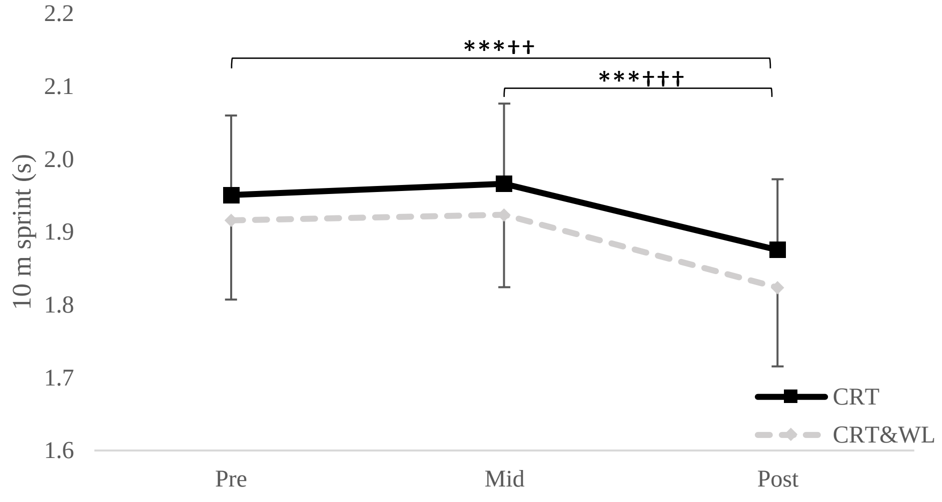
*RTSQ = resistance training skills quotient; IMTP$_{ABS}$ = absolute peak force of isometric mid-thigh pull; IMTP$_{REL}$ = ratio scaled peak force of isometric mid-thigh pull; CMJ = countermovement jump height; HJ = horizontal jump; SMBT = seated medicine ball throw.

Academic Term	Term 1						Term 2					Term 3					Term 4		
Academic Week	3	4, 5, 6	7, 8, 9	10	11		12, 13, 14, 15	16, 17, 18, 19	20	21		22, 23, 24, 25	26, 27, 28, 29	30	31		32, 33, 34	35, 36, 37	38
Mesocycle		1	2				3	4				5	6				7	8	
Microcycle		1, 2, 3	4, 5, 6				7, 8, 9, 10	11, 12, 13, 14				15, 16, 17, 18	19, 20, 21, 22				23, 24, 25	26, 27, 28	
Volume		1-3 sets, 8-20 reps					1-3 sets, 8-12 reps					1-4 sets, 2-6 reps					1-4 sets, 2-5 reps		
Day 1 - Weight Room	Pre-intervention test battery	*Squat*	**Clean derivatives (power position) OR Total body pull + V plyo + Squat**	Reduced test battery**	OFF WEEK	Term break	**Clean derivatives (above knee) OR Conventional deadlift + V plyo**	**Clean derivatives (above knee) OR Conventional deadlift + V plyo**	Mid-intervention test battery	OFF WEEK	Term break	**Clean derivatives (below knee) OR Conventional deadlift + V plyo**		Reduced test battery**	OFF WEEK	Term break	**Clean derivatives (floor) OR Conventional deadlift + V plyo**		Post-intervention test battery
		Lunge																	
		UB H Push						*Squat*				*Squat*					*Squat*		
		UB H Pull	*Squat*				*Squat*	*UB H Push*				*UB H Push*					*UB H push*		
		Brace	*UB H Push*				*UB H Push*	*UB H Pull*				*UB H Pull*							
		Rotate	*UB H Pull*				*UB H Pull*												
Day 1 - Field / Court		*Load Absorption*	*V Jump*				*Reactive V Jump*					*Reactive V Jump*					*Depth V Jump*		
		SL Load Absorption	*SL V Jump*				*Reactive SL V Jump*					*Reactive SL V Jump*					*SL Depth V Jump*		
		Submax Jump & Stick	*SL Hop & Stick*				*Rapid Jumps*					*Rapid Jumps*					*Rapid Hops*		
		Linear Speed	*Linear Speed*				*Linear Speed*					*Linear Speed*					*Linear Speed*		
Day 2 - Weight Room		*Hinge*	**Snatch derivatives (power position) OR Total body pull + H plyo + Squat**				**Snatch derivatives (above knee) OR Sumo deadlift + H plyo**	**Snatch derivatives (above knee) OR Sumo deadlift + H plyo**				**Snatch derivatives (below knee) OR Sumo deadlift + H plyo**					**Snatch derivatives (floor) OR Sumo deadlift + H plyo**		
		SL Hinge																	
		UB V Push						*Hinge*				*Hinge*					*UB V Push*		
		UB V Pull	*Hinge*				*Hinge*	*UB V Push*				*UB V Push*					*UB V Pull*		
		Rotate	*UB V Push*				*UB V Push*	*UB V Pull*				*UB V Pull*							
		Brace	*UB V Pull*				*UB V Pull*												
Day 2 - Field / Court		*Load Absorption*	*H Jump*				*Reactive H Jump*					*Reactive H Jump*					*Depth H Jump*		
		Horizontal Plyos	*SL H Jump*				*Reactive SL H Jump*					*Reactive SL H Jump*					*SL Depth H Jump*		
		Lateral Hop & Stick	*Lateral SL Hop & Stick*				*Lateral Jump*					*Lateral Jump*					*Lateral Hop*		
		COD	*COD*				*Agility*					*Agility*					*Agility*		

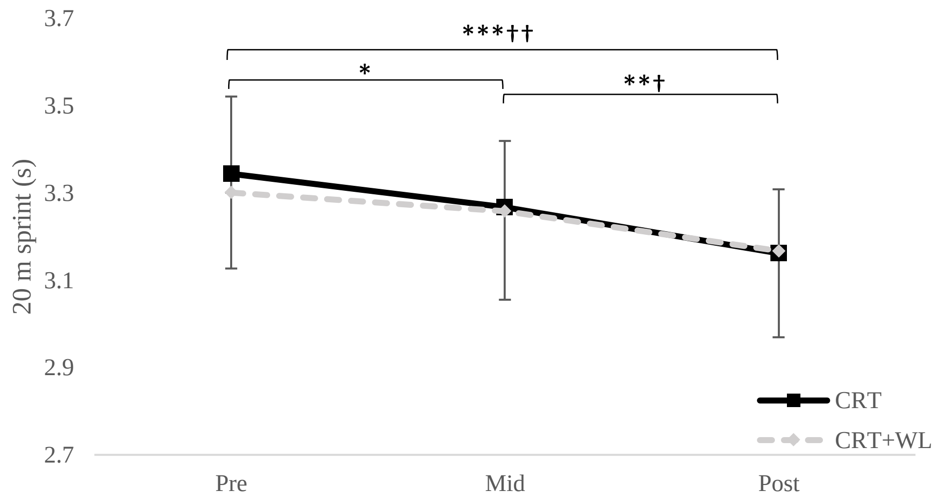

A
55
45
35
25
15
RTSB Quotient
†
†
CRT
CRT+WL
Pre
Mid
Post
B
1800
1400
1000
600
200
IMTP_ABS (N)
***†††
***†††
*
CRT
CRT+WL
Pre
Mid
Post
C
25
20
15
10
IMTP_REL (N/kg)
***
***†
CRT
CRT+WL
Pre
Mid
Post


A
50
45
40
35
30
25
20
CMJ (cm)
††
*††
CRT
CRT+WL
Pre
Mid
Post
B
2.00
1.85
1.70
1.55
1.40
1.25
HJ (m)
**†
*††
CRT
CRT+WL
Pre
Mid
Post
C
5.0
4.5
4.0
3.5
3.0
2.5
2.0
SMBT (m)
***†††
***†††
CRT
CRT+WL
Pre
Mid
Post

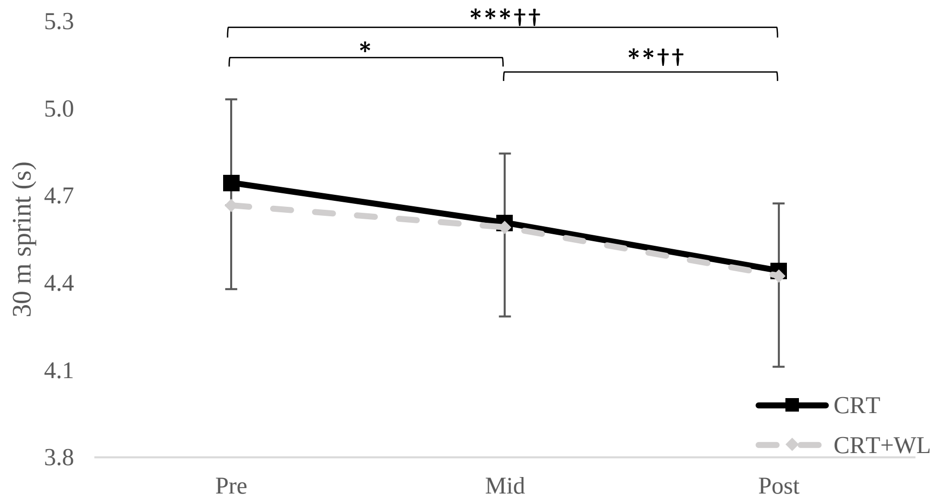
A


***††
***†††
10 m sprint (s)
2.2
2.1
2.0
1.9
1.8
1.7
1.6
CRT
CRT&WL
Pre
Mid
Post

B


***††
*
**†
20 m sprint (s)
3.7
3.5
3.3
3.1
2.9
2.7
CRT
CRT+WL
Pre
Mid
Post

C


***††
*
**††
30 m sprint (s)
5.3
5.0
4.7
4.4
4.1
3.8
CRT
CRT+WL
Pre
Mid
Post