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THE EFFECTS OF A 12-WEEK TRAINING PROGRAM ON ISOMETRIC AND DYNAMIC FORCE-TIME CHARACTERISTICS IN PRE- AND POST-PEAK HEIGHT VELOCITY MALE ATHLETES

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ABSTRACT

Literature shows that training children and adolescents can enhance strength and power irrespective of their stage of development; however, the development of the kinetic variables that underpin strength and power performance are typically unreported in youth training studies. Twenty-four pre- and 14 post-peak height velocity (PHV) males were divided into maturity-specific experimental (EXP) and control groups (CON), with the EXP groups completing a twice-weekly, 12-week training program. Force-time characteristics during the isometric mid-thigh pull (IMTP), countermovement jump (CMJ), and squat jump (SJ) tests were quantified at both baseline and following the completion of the 12-week program. Alpha level was set at $p < 0.05$. No changes in total score for back squat assessment (BSA) were observed in any group ($p > 0.05$). Analysis of IMTP data revealed that only the post-PHV EXP group significantly increased absolute isometric peak force (PF_{abs}) and peak rate of force development within the IMTP following training. Both EXP groups displayed significant increases in isometric PF at time epochs 0-90 ms, 0-150 ms, 0-200 ms, and 0-250 ms. Data from the dynamic tests indicated that the pre-PHV EXP cohort improved concentric qualities as reflected by increased SJ height and CMJ concentric power. There were no significant changes for any variables across all tests within either CON group ($p > 0.05$). Maturity related differences in response to short-term training affects the kinetic variables associated with strength and power performance, but not movement competency in young male athletes.

Key words: strength, power, movement, competency, youth, maturity

INTRODUCTION

When examining strength and power adaptations in response to training, it is important to assess neuromuscular function across a range of test protocols that target different regions of the force-velocity curve. Force-time data has commonly been analyzed in isometric conditions, due to the ability to closely regulate optimal joint angles and body position (50), thereby minimizing the potential confounding influence of the length-tension relationship typically seen in more dynamic actions (e.g. countermovement jumps [CMJ]). Despite research supporting the use of isometric testing to assess neuromuscular function, one limitation is that it only assesses length-specific adaptations and arguably does not reflect force-producing capabilities at different joint angles and muscle lengths (13). Therefore, it is important to incorporate tests that assess dynamic movements with varying joint angles and muscle lengths alongside isometric tests (49). Consequently, force-time data is also typically assessed during a variation of a vertical jump protocol, such as the CMJ (26). Considering that relationships in force-time variables between isometric and dynamic muscle actions are weaker when lighter external loads are used during the dynamic action (36), it is evident that tests such as the isometric mid-thigh pull (IMTP), CMJ and squat jump (SJ) will test different regions of the force-velocity curve and thus different expressions of strength and power. Somewhat surprisingly, minimal evidence exists that has attempted to investigate the effects of neuromuscular training on isometric and dynamic force-time characteristics in youth, especially in a sample of varying maturity status.

Pediatric literature indicates that improving movement competency in children and adolescents can be achieved through neuromuscular training (37). Neuromuscular training is the inclusion of a wide range of training modes such as resistance training, plyometrics, balance, speed, and core strength with the goal of enhancing an athletes movement skill base (37). While pre-adolescence offers a more opportune time for developing movement competency due to the brain's neuroplasticity (37), it is important for all youth to refine and develop motor skills irrespective of their stage of development, due to the associated athletic and health related benefits (11, 24). Movement competency can be assessed through a range of fundamental movement patterns, but perhaps the most commonly assessed movement is the squat pattern (8, 17, 38). This particular movement is important due to squatting requiring numerous neuromuscular capabilities such as coordination, strength, stability, and mobility (16, 38). The back squat assessment (BSA) was developed by Myer *et al.* (38) with the goal of identifying technical deficits and rating the quality of the squatting movement pattern in young athletes using a 10-point scale. Recently, Dobbs *et al.* (8) established the BSA as a reliable tool for measuring and assessing movement competency in children and adolescents. In the same study, it was demonstrated that a four-week neuromuscular training program could improve movement competency in the BSA in both pre- and post-peak height velocity (PHV) males (8). However, further investigation is warranted to determine how neuromuscular training can affect movement competency following a longer training intervention, inclusive of sequential training mesocycles, in children and adolescents.

Research has established that well supervised, developmentally-appropriate neuromuscular training is beneficial to sport performance as well as the overall long-term athletic development of youth (12, 18-20). Neuromuscular training in youth populations has not only been proven to elicit positive responses for motor competency (8, 11), but also for strength (16, 47) and power (35, 42). Despite a plethora of research supporting the trainability of both children and adolescents (16, 20), there are fewer studies comparing the effects of training on youth of different maturity status. Existing evidence suggests that more mature athletes have a greater response to strength training than immature athletes (29), with recent meta-analytical data showing that resistance training elicited greater strength adaptations in circa- and post-PHV boys after only 4 weeks of training compared to those who were pre-PHV (3, 4, 18, 34). Studies comparing different training modalities on pre- and post-PHV athletes indicate that training responsiveness may be influenced by maturity status, with pre-PHV boys commonly shown to respond favorably to plyometric training, whereas more mature athletes require a combination of plyometric and resistance training to induce specific performance adaptations (23, 35, 42).

Another limitation with existing pediatric intervention studies is that strength and power attributes are often measured using field-based tests that solely assess performance outcomes such as sprint time (27, 41, 44, 51), vertical jump height (15, 25, 31, 44, 52) or one repetition maximum (1RM) strength (15, 16, 29, 47). While these tests can certainly indicate training effects, insights into the mechanical adaptations (e.g. force-time characteristics) that likely underpin strength and power performance typically go unreported. Some of the available data indicate that qualities such as rate of force development (RFD) is associated with explosive strength and plyometric performance (1, 14, 25), while concentric peak force is able to differentiate between weaker and stronger adolescent athletes (48). However, the manner in which these and other force-time variables are influenced by training in youths at different stages of maturation remains unclear.

Assessment of ground reaction forces during tests such as the IMTP, SJ or CMJ can provide insights into the force-time characteristics that influence explosive activities such as jump and sprint performance (1, 14, 27). Examining force-time characteristics in youth of different maturity status during commonly used strength and power tests would provide greater clarity on potential specific maturity-related adaptations that may result from exposure to neuromuscular training. Therefore, the aim of the present study was to examine the effects of a 12-week neuromuscular training intervention on movement competency and force-time characteristics in isometric and dynamic tests in youth male cricketers of different maturational status. Maturational status was determined through a validated equation (32) which predicts if males have yet to reach peak-height velocity (pre-PHV) or have already experienced peak height velocity (post-PHV). Owing to their respective stages of development, it was hypothesized that a) the pre-PHV cohort would experience greater improvements than the post-PHV group in BSA movement competency; and b) the post-PHV cohort would achieve greater improvements in force-time characteristics within the isometric and dynamic tests.

METHODS

Experimental Approach to the Problem

This study used a repeated-measures design to determine changes in force-time characteristics during an IMTP and dynamic jump tests (SJ and CMJ) following exposure to a 12-week neuromuscular training intervention in young male athletes. Participants were split into four groups; pre-PHV experimental group, pre-PHV control group, post-PHV experimental group, and post-PHV control group. All groups were tested before and after the twelve-week training intervention.

Subjects

Thirty-nine young male athletes (n = 24 pre-PHV, n = 14 post-PHV) aged 9-17 years at a sporting academy in the United Kingdom agreed to participate in the study. Participants were grouped according to maturity status and further sub-divided into an experimental (EXP) or control (CON) group (Table 1). Maturity status refers to the biological age of an individual and gives a clear indication as to the stage of development the individual is in (19-21, 32). Maturity status was determined by calculating maturity offset (32), which estimates a participants PHV. A PHV score < -1.0 yrs indicates an individual as pre-PHV and a score >1.0 yrs indicates post-PHV. The pre- and post-PHV EXP groups completed 12 weeks of twice-weekly, hour-long neuromuscular training sessions in addition to their regular sports training sessions. Conversely, the CON groups only participated in their sport-specific training with no exposure to neuromuscular training. Participants reported no injuries at baseline testing or during post-testing and were informed of the risks and benefits of taking part in the study. Prior to the 12-week training program, both EXP groups received 4-weeks of general neuromuscular training but had no experience with strength and conditioning training previous to that. Parental consent and participant assent were obtained following ethical approval from the institutional research ethics committee.

Insert table 1 here

Procedures

Back-Squat Assessment

To assess the BSA, participants were instructed to perform ten continuous squat repetitions in place with a wooden dowel on their back as per previously published guidelines (38).

Participants were required to position their feet slightly wider than hip-width and instructed to descend until thighs were parallel to the ground. Each participant completed the BSA twice, with one minute between each trial. Aside from the standardized script proposed by Myer and colleagues (38), no other verbal cues or advice were given to participants before or during the testing sessions. All ten repetitions were recorded at 30 Hz using two 2D high definition cameras (Apple iPad, California, USA) positioned at a height of 0.70 m and at a distance of 5 m from the center of the capture area in both frontal and sagittal planes. Scoring of BSA performance was conducted retrospectively using a 10-point criteria, with one point given for each technical fault (38). The 10-point criteria consisted of: head position, thoracic position, trunk position, hip position, frontal knee position, tibial progression angle, foot position, descent, depth, and ascent. During the scoring process, each of the 10 criteria were analyzed and a deficit was scored if present during two or more repetitions. Movement variation between repetitions indicates inefficient motor-unit coordination and is likely due to factors such as muscle weakness, strength asymmetry and joint instability (38). Therefore, a deficit occurring twice or more highlights movement variability by the participant in the BSA (38). Deficits were tallied to provide a total score, with higher total scores indicative of poorer squat technique. The lowest total score for each participant was used for statistical analysis at both baseline and post-testing. The variables recorded for each participant were BSA total score.

Isometric mid-thigh pull

The IMTP test was performed on a custom built IMTP testing device using dual Kistler force plates sampling at a frequency of 1000 Hz (type 9287BA, Kistler Instruments AG, Winterthur, Switzerland). In line with previous research, participants were positioned with: feet hip-width apart, the bar positioned at mid-thigh, the torso upright with a neutral spine and knee and hip angles were near 140° (2, 10). The customized IMTP rig allowed for incremental bar height adjustments of 1 cm to accommodate athletes of different leg length. Once in position, all participants received the same instructions, "*pull as hard and as fast as you can in 3, 2, 1, go*" (33). All participants were given verbal encouragement while pulling and were instructed to not stop until told. Following familiarization, three maximal effort trials were recorded from each participant with a minimum of 90 seconds rest between each trial to ensure sufficient recovery. Each trial was collected for eight seconds, which included a three second countdown and the participants pulling on the bar for five seconds. During the three second countdown, participants were instructed to remain still to optimize stabilization of body weight in order to identify the initiation of the pull. All trials and data were analyzed on a customized IMTP LabView program. Force-time variables calculated from the customized software included: absolute peak force (PF_{abs}), peak force relative to body weight (kg) (PF_{rel}) , time to peak force (tPF), peak rate of force development (PRFD), time to peak rate of force development (tPRFD), and peak force at time periods of 0-50 ms (PF50), 0-90 ms (PF90), 0-150 ms (PF150), 0-200 ms (PF200), and 0-250 ms (PF250). Acceptable within- and between-session reliability has previously been reported for this IMTP protocol using youth athletes (33).

Squat jump

The SJ test was recorded on an AMTI force plate with a sampling rate of 1000 Hz (Accupower, AMTI, Boston, MA, USA). Participants were required to assume a squat position with 90° of knee flexion (40, 46) which was visually observed by the researcher. Once in the squat position, participants were instructed to remain still for three seconds, keep hands on hips, and to not perform a countermovement prior to jumping. Following familiarization, participants performed three maximal trials with 60 seconds rest between jumps. Trials were discounted and repeated if any of the following errors occurred: failure to remain still during countdown, hands removed off hips, or if a visible countermovement was detected from the force trace prior to the jump. All trials and data were analyzed using a customized SJ LabVIEW program and the SJ variables measured were: PF, jump height (JH), average RFD, peak velocity, peak power (PP), impulse, PRFD, and tPRFD. Acceptable reliability has previously been reported for the SJ protocol using youth athletes (22).

Countermovement jump

Countermovement jumps were recorded using an AMTI force plate sampling at 1000 Hz (Accupower, AMTI, Boston, MA, USA). In line with previous research, all participants were instructed to perform maximal effort jumps with hands remaining on hips throughout to limit the influence of the upper body on jump performance (1). Participants were able to descend to a self-selected depth during the eccentric portion of the jump (40). The same verbal cues were given before each trial, "*jump as high as you can in 3, 2, 1, go". Following familiarization, three maximal effort trials were recorded per participant with a minimum of 60 seconds rest between trials. During the countdown participants remained still to optimize stabilization of body weight and establish a baseline prior to the jump. All trials and data were exported from the Accupower software (Accupower 3.0, Accupower solutions, Boston, MA, USA) and analyzed using a validated custom built automated CMJ spreadsheet (6). The variables measured for CMJ analyses were; jump height, time to take off, reactive strength index modified (RSI_{mod}), PF, eccentric impulse, duration of eccentric phase, concentric impulse, duration of concentric phase, peak landing force, peak power (PP), eccentric power, and concentric power. Acceptable reliability has previously been reported for the CMJ protocol using youth athletes (30).

Training program

Baseline testing for all groups was conducted one week prior to the start of the training program. Following baseline testing, both EXP groups commenced the 12-week training intervention. All training sessions were led and supervised by a National Strength and Conditioning Association Certified Strength and Conditioning Specialist.

Insert tables 2 and 3 here

The first 4-week mesocycle was primarily a skill development phase in order to develop a larger training base and build on movement technique. The volume of sets increased following the fourth week once all participants displayed satisfactory competency in the exercises, while repetitions for multi-joint dynamic exercises gradually decreased after the fourth week due to an increase in load. Rest periods during the first training block were ~90 seconds due to the lower loads and higher repetition ranges. The focus of the second 4-week training cycle was to build strength and participants were instructed to appropriately increase resistance for each exercise providing technical competency was maintained. The multi-joint exercises ranged between 5-8 repetitions with the goal of exposing participants to an adequate strength stimulus. The goal for the final training cycle was to further develop strength and as such, the main multi-joint exercises used a prescription scheme of 5 sets of 3-5 repetitions. Rest periods during the second and third training block were 2-3 minutes between sets to ensure sufficient recovery from the strength stimulus in the multi-joint exercises. Every training session consisted of a 10-minute dynamic warm up consisting of ~7 minutes of light dynamic mobilization and activation exercises in the upper and lower extremities, followed by ~3 minutes of submaximal sprinting. Following the dynamic warm up, participants performed the structured exercise program focusing on the development of whole-body strength and power and core strength. Throughout the program, participants performed a minimum of two warm-up sets and gradually increased the load for the main strength exercises. Despite different exercise selections, the pre- and post-PHV EXP groups followed similar training regimens in terms of targeted movements. For a progressive overload stimulus, participants increased external load of each exercise if technical competency was displayed during each repetition of a set. If technique was not displayed to a satisfactory standard during a set, participants ceased the set and were instructed to decrease the load. The first training session of each week targeted primarily plyometric and high velocity movements, using body weight, medicine balls, kettlebells or dumbbells as a form of resistance. The second session was designed to target movement competency and strength development using multi-joint exercises with greater external resistance. Exercises in the second weekly training session utilized equipment such as barbells, weighted plates, heavy dumbbells, resistance bands and kettlebells. Participants were familiarized with each exercise within the program and performed at least one warm up set prior for a given exercise.

Statistical analyses

Descriptive statistics (means ± SD) were calculated for all performance variables for each group at both pre- and post-training intervention testing sessions. To determine the effectiveness of the training program, differences in all performance variables were analyzed using separate 2 x 2 x 2 (time x group x maturity) repeated measures analysis of variance (ANOVA), where “time” denotes pre- to post-training intervention, “group” refers to EXP or CON, and “maturity” represents pre- or post-PHV. Homgeneity of variances were determined using the Levene’s Test, and where violated, Greenhouse-Geisser adjustment was used. Effect sizes were calculated to interpret the magnitude of between- and within-group effects according to Cohen’s d statistic, using the following thresholds: <0.20 (trivial), 0.20-0.59 (small), 0.60-1.19 (moderate), 1.20-1.69 (large), and >1.70 (very large). All statistical analyses were computed using SPSS (V.24 Chicago, IL, USA), with statistical significance for all tests set at an alpha level of $p < 0.05$.

RESULTS

At baseline, there were no anthropometric differences between the EXP and CON groups for both pre- and post-PHV cohorts (Table 1). The mean attendance rates across all training sessions for the pre-PHV EXP and post-PHV EXP groups were 77.1% and 75.7% respectively.

Back-Squat Assessment

There were no statistically significant interactions revealed in between- or within- groups factors ($p > 0.05$). At baseline there was a moderate difference between the pre-PHV EXP and CON groups ($g = 1.18$) and a small difference between the post-PHV EXP and CON groups ($g = 0.54$) for BSA total score. At post-testing there was a moderate difference for both the pre-PHV EXP ($g = 1.19$) and post-PHV EXP ($g = 0.92$) groups compared to the CON groups.

Isometric mid-thigh pull

Mean changes in IMTP kinetic variables, including effect sizes, are displayed in Table 4. Data showed main effects for time, maturity and training for the following variables: PF_{abs}, PRFD, PF90, PF200, PF250 ($p < 0.05$). For PF_{abs}, PF200 and PF250, there were significant interactions in time x training, and time x group x maturity (all $p < 0.05$). The interactions are due to both CON groups showing no change in IMTP performance, while both EXP groups improved in nearly all force-time variables. At post testing, there were moderate significant differences between the pre-PHV EXP and CON groups for tPF and PRFD ($p < 0.05$). There was also a moderate significant difference between the post-PHV EXP and CON groups for PF_{abs} at baseline and a very large difference at post-testing ($p < 0.05$). Changes in PF_{abs} and PF_{rel} in the pre-PHV EXP group were small and non-significant; whereas PF_{abs} ($p < 0.05$, $d = 0.79$) had a moderate significant increase and PF_{rel} was non-significant in the post-PHV EXP group. The post-PHV EXP group had a very large significant within-group change in PRFD ($p < 0.05$, $d = 2.60$) and a moderate change in tPF ($p < 0.05$, $d = 1.00$). Both EXP groups showed moderate significant increases in PF90, PF150, PF200, and PF250 (Figures 1).

Insert table 4 here

Insert figures 1 and 2 here

Squat jump

Analysis revealed a three-way interaction for time x group x maturity ($p < 0.05$) for JH. The pre-PHV EXP group were the only cohort to significantly increase JH from baseline (13.32 cm ± 2.65 cm) to post-testing (14.44 cm ± 2.28 cm) ($p < 0.05$, $d = 0.42$). The post-PHV EXP group had a lower JH at post-testing (18.87cm ± 5.18 cm) than at baseline (19.71 cm ± 4.27 cm) and there was no change in JH for either CON group. There were no significant within-group changes for PF, average RFD, peak velocity, PP, impulse, PRFD, and tPRFD for any group ($p > 0.05$) and all effect sizes were trivial or small. There were large and moderate between-group differences between the pre-PHV EXP and CON groups for average RFD ($d = 1.47$), impulse ($d = 0.84$), and PRFD ($d = 0.69$), and tPRFD ($d = 0.73$) at pre-testing ($p < 0.05$). At post-testing there were also large and moderate differences between the pre-PHV EXP and CON groups for JH ($d = 0.72$), average RFD ($d = 1.08$), impulse ($d = 1.29$), and tPRFD ($d = 0.86$) ($p < 0.05$). For the post-PHV groups, the post-PHV CON group had a moderately greater between-group difference at baseline for PRFD ($d = 0.77$) and at post-testing for peak velocity ($d = 0.82$) than the post-PHV EXP group ($p < 0.05$). All other between-group effect sizes between both EXP and CON groups were calculated as trivial or small.

Countermovement jump

Mean changes and effect sizes in CMJ kinetic variables, are displayed in Table 5. Neither CON group displayed significant within-group increases for any of the CMJ kinetic variables. Analysis revealed significant main effects for time and maturity for JH and PP. For JH, significant interactions were found for time x group and time x maturity. There was a small significant increase for JH in the pre-PHV EXP ($p < 0.05$, $d = 0.32$) and a moderate significant increase for the post-PHV EXP ($p < 0.05$, $d = 0.73$) groups, with no change in either CON group. Analysis of other kinetic variables within the CMJ revealed time x group interactions for RSI_{mod}, PF, and PP. There was a small increase for RSI_{mod} for the pre-EXP ($p < 0.05$, $d = 0.44$) and moderate increase for the post-PHV EXP ($p < 0.05$, $d = 1.19$) groups. The pre-PHV EXP group significantly decreased duration in the concentric phase ($p < 0.05$, $d = 0.50$) while also increasing concentric power ($p < 0.05$, $d = 0.37$); while the post-PHV EXP group significantly increased concentric impulse ($p < 0.05$, $d = 0.32$) and concentric power ($p < 0.05$, $d = 0.35$). However, only the post-PHV EXP group significantly increased PF_{abs} ($p < 0.05$, $d = 0.66$) and peak landing force ($p < 0.05$, $d = 0.46$). There were no differences between the pre-PHV EXP and CON groups at baseline for any variables ($p > 0.05$); however, at post-testing, the pre-PHV EXP had a significantly shorter duration of eccentric phase than the CON group ($p < 0.05$). There was a significant difference between the post-PHV EXP and CON groups at baseline for eccentric impulse and eccentric power ($p < 0.05$); however, at post-testing, there were also significant differences between the groups for PF_{abs} and concentric impulse in addition to the eccentric variables ($p < 0.05$).

Insert table 5 here

DISCUSSION

The results of this study have demonstrated that both pre- and post-PHV EXP boys significantly improved various isometric and dynamic force-time characteristics following 12-week neuromuscular training programs; however, responses were somewhat different between the maturity groups. The initial hypothesis that the pre-PHV EXP group would have greater improvements than the post-PHV group in BSA movement competency following the training intervention was incorrect. Movement competency remained unchanged in all groups following the intervention, however, both EXP groups lowered their BSA total scores suggesting maintained movement competency. The hypothesis that the post-PHV group would achieve greater gains in force-time characteristics following the combined resistance and plyometric training program was correct. The training intervention stimulated significant gains in isometric PF_{abs} ($d = 0.79$) for the post-PHV EXP group only; however, there were non-significant changes in PF_{rel} for both groups which suggests that increased mass due to maturity status effects maximal force production. Both EXP groups improved their ability to produce force quickly as observed by the significant increases in peak force at all time epochs after 90 ms in the IMTP. Improvements in countermovement jumping height appeared to be similar in both EXP groups based on the magnitude of effect sizes; however, maturity-related differences were observed within the CMJ force-time characteristics. Specifically, the post-PHV EXP group increased PF_{abs} while the pre-PHV EXP group did not. In conjunction with the IMTP, it seems the ability to improve PF_{abs} was greater in the post-PHV group. The changes observed by both EXP groups are likely the result of specific adaptive responses from the training program which focused more on absolute strength and movement competency. Notably, neither CON groups showed any significant changes in any of the variables across all tests during the intervention period.

The present study provides novel data regarding the effects of neuromuscular training on isometric force-time characteristics in pre-and post-PHV males. The IMTP is a valid and reliable assessment of maximal strength in young athletes (9, 33); however, the effects of neuromuscular training on isometric force-time variables during the IMTP have yet to be reported. In the present study, while within-group analysis revealed moderate improvements in peak force at all time points after 90 ms within both the pre- and post-PHV EXP groups, only the post-PHV EXP group significantly improved PF_{abs}, tPF, and PRFD following training. Yet, PF_{rel} was unchanged in the pre- and post-PHV EXP group. Effect sizes indicated that the post-PHV EXP also had greater increases in PF_{abs} and PF200 and PF250 during the IMTP than the pre-PHV EXP group, which were likely underpinned by the significant decrease in tPF as well as increased PRFD. Cumulatively, these findings suggest that the training intervention enhanced maximal absolute force producing capacities to a larger extent in the post-PHV EXP group compared to the less mature group, which is indicative of the child-adolescent differences in training responsiveness (18, 39). For example, Meylan et al. (29) compared estimated squat 1RM strength in pre- and post-PHV males and reported greater changes in maximum strength in the older cohort following an 8-week training intervention. Although the findings by Meylan and colleagues (29) were not based on kinetic data, the findings suggest that gains in absolute strength are generally greater in post-PHV athletes than in pre-PHV athletes following a short term training period. This notion is also supported by recent meta-analyses reporting smaller strength gains in pre-PHV males than post-PHV males following short-term resistance training programs (18, 34). Resistance training in post-PHV males typically results in greater increases in muscle mass and strength, invariably due to their advanced hormonal profile (7). However, in a more recent meta-analysis, Peitz et al (39) reported that although absolute strength gains are smaller in pre-PHV cohorts, relative strength gains are comparable and can be even larger than older cohorts. This was observed in a study by Brownlee et al. (5) who found no difference in relative isometric strength in pre- and post-PHV soccer players following 8 weeks of training. In the current study the post-PHV EXP group increased relative strength to a slightly greater extent (0.50) than the pre-PHV group (0.10). However, when accounting for maturation there were no noticeable differences in relative force production between the training groups. Therefore, these results suggest that relative force production and relative gains in strength may not be dependent on maturation and are likely a result of the training intensities throughout the 12-week program. Also, this could suggest that exposure to a longer training program may enable larger gains in relative strength for both children and adolescents.

In terms of SJ performance, the pre-PHV EXP group displayed small, significant improvements in jump height; however, no other changes were evident for either of the EXP groups. Previous studies assessing SJ height between pre- and post-PHV males following short-term training interventions have found similar results (23, 42). In the present study, the pre-PHV cohort improved SJ performance following exposure to a combination of resistance and plyometric training. This trend was also observed by Radnor *et al.* (42), who reported a greater number of pre-PHV boys improved squat jump height in response to combined training than post-PHV boys. Of note, the post-PHV EXP group did not show improvements in any of the SJ force-time characteristics despite also being exposed to combined training. Similar results were observed by Meylan et al. (28) who reported no change in SJ height in 12-14 year old youth soccer players following an 8-week plyometric training program. Correct SJ performance requires a vertical jump in the absence of an eccentric phase contribution (49), however the current 12-week training program appears to have failed at enhancing this ability. Considering the content of the training program, which relied predominantly on dynamic (eccentric-concentric) and plyometric exercises as opposed to solely concentric exercises. It appears that the program has thus elicited specific adaptations to the imposed training demands.

Both training groups made significant improvements in the CMJ for jump height and $\mathrm{RSI}_{\mathrm{mod}}$. However, the effect-sizes were greater in the post-PHV EXP group for both variables indicating the more mature group was more responsive to the training program. Also, because time to take off was unchanged in both training groups, the increased RSI_{mod} was primarily due to an increased jump height. The results of this study slightly contradict a meta-analysis by Moran et a. (35) which stated that children make greater changes in CMJ performance than adolescents when experiencing similar training loads. This notion is also supported by Rumpf et al. (45) who reported that prepubertal athletes may have more pliable musculotendinous tissue which allows for more efficient energy storage during slow stretch-shortening cycles (SSC) such as the CMJ. However, in addition to plyometric training the post-PHV EXP group were exposed to larger loads and training intensities than the pre-PHV group during the 12-weeks which resulted in greater force-production capabilities. Therefore, the greater change in CMJ jump height by the post-PHV group is likely due to a larger force-related adaptation.

Maturational differences in kinetic force-time phase analysis of the CMJ have not previously been reported. The adaptations to concentric and eccentric variables within the CMJ appear to have been somewhat different in both maturity EXP groups. Specifically, while both maturity groups increased concentric power output, only the pre-PHV group significantly decreased the duration of concentric phase, indicating a greater ability to produce force during a relatively shorter amount of time. The post-PHV group had no changes to duration in the concentric or eccentric phases; however, they significantly increased PF_{abs}. The CMJ is governed by a slow SSC and with regards to youth athletes, appears to be utilized differently by pre- and post-PHV athletes (43, 45). A review of the SSC by Radnor *et al.* (43) indicated that adolescents have a greater RFD as a result of less agonist-antagonist co-contraction than pre-adolescents. In addition, more mature children have greater efficiency at recruiting high-threshold type II motor units, resulting in heightened explosive force production during SSC activities.

Of note, the post-PHV EXP group significantly increased PF_{abs} production during the CMJ which likely influenced the improved jump performance. It is worth mentioning that the significant increase in peak landing force may be an unwanted adaptation from improved CMJ performance. An increase in force production and jump height will lead to athletes experiencing greater forces during landing. Based off BSA scores, the post-PHV group had good competency and were also coached on landing and rebounding mechanics throughout training. This may indicate that although peak landing force increased, the force was mitigated through competent landing technique. Therefore, in terms of maturity-related differences it appears that post-PHV athletes are likely to increase in more force-related adaptations to training, whereas pre-PHV athletes may will improve in more time-related variables.

There are certain limitations within this study that should be considered when interpreting the results. *Firstly*, the low sample size in both the pre- and post-PHV cohorts indicate low statistical power, which may reduce the generalizability of the findings to wider populations of young athletes. *Secondly*, participants in both EXP groups failed to attend every training session, however, adherence was greater than the minimum threshold (> 14 training sessions) required to elicit increases in plyometric performance in youth athletes reported in a recent meta-analysis (35). *Thirdly*, the greater training load between the CON and EXP groups may be responsible for the improvements changes as opposed to the neuromuscular training itself. *Fourthly*, the 12-week training programs only provides insight into potential adaptations in response to short- to moderate-term training interventions. Meta-analytical data suggest that adaptations in strength and power are greater when training interventions are >23 weeks (18), and the interaction of maturity and training on isometric and dynamic force-time characteristics following longer-term interventions remains unclear. Despite these limitations, the current study makes an original and significant contribution to the literature, indicating the positive role neuromuscular training has on isometric and dynamic force-time characteristics in young male cricketers. Similarly, the incorporation of the isometric and dynamic tests provide novel insight on the changes within different regions within the force-velocity curve for pre- and post-PHV males.

PRACTICAL APPLICATIONS

The findings of this study suggest that the kinetic variables which drive strength and power performance in male youth might be influenced by maturity status. The combination of plyometric and resistance training stimulated a greater increase in strength-related responses for the post-PHV boys as observed by improvements in PF_{abs} in both the IMTP and CMJ. Of note, the post-PHV group also increased CMJ peak landing force following training, which highlights the importance for additional training with athletes to land safely as a result of improved jump performance. Therefore, practitioners improving strength and power in youth athletes must still train for proper landing technique so that athletes can continue to land effectively and are not at a greater risk of injury as a result of their improved force production capabilities. Although no group significantly decreased BSA total score, both EXP groups lowered their scores suggesting maintained movement competency whilst increasing maximal force production qualities. Alternatively, the pre-PHV boys increased early force-producing capabilities (< 250 ms) in the IMTP and CMJ. Practitioners aiming to develop specific qualities in young male athletes should understand the nuances and different strength and power adaptations that are likely to occur depending on maturational status and consider these adaptations when programming. Given the short-term nature of this study, it should also be noted that these results may only be relative to this training period, and that longer interventions are required to have a greater understanding on the interaction between training and maturity status. However, though it appears that pre- and post-PHV boys may have different training responses, the implementation of a varied, developmentally appropriate, and periodized training program should still be the primary goal of any long-term athletic development program.

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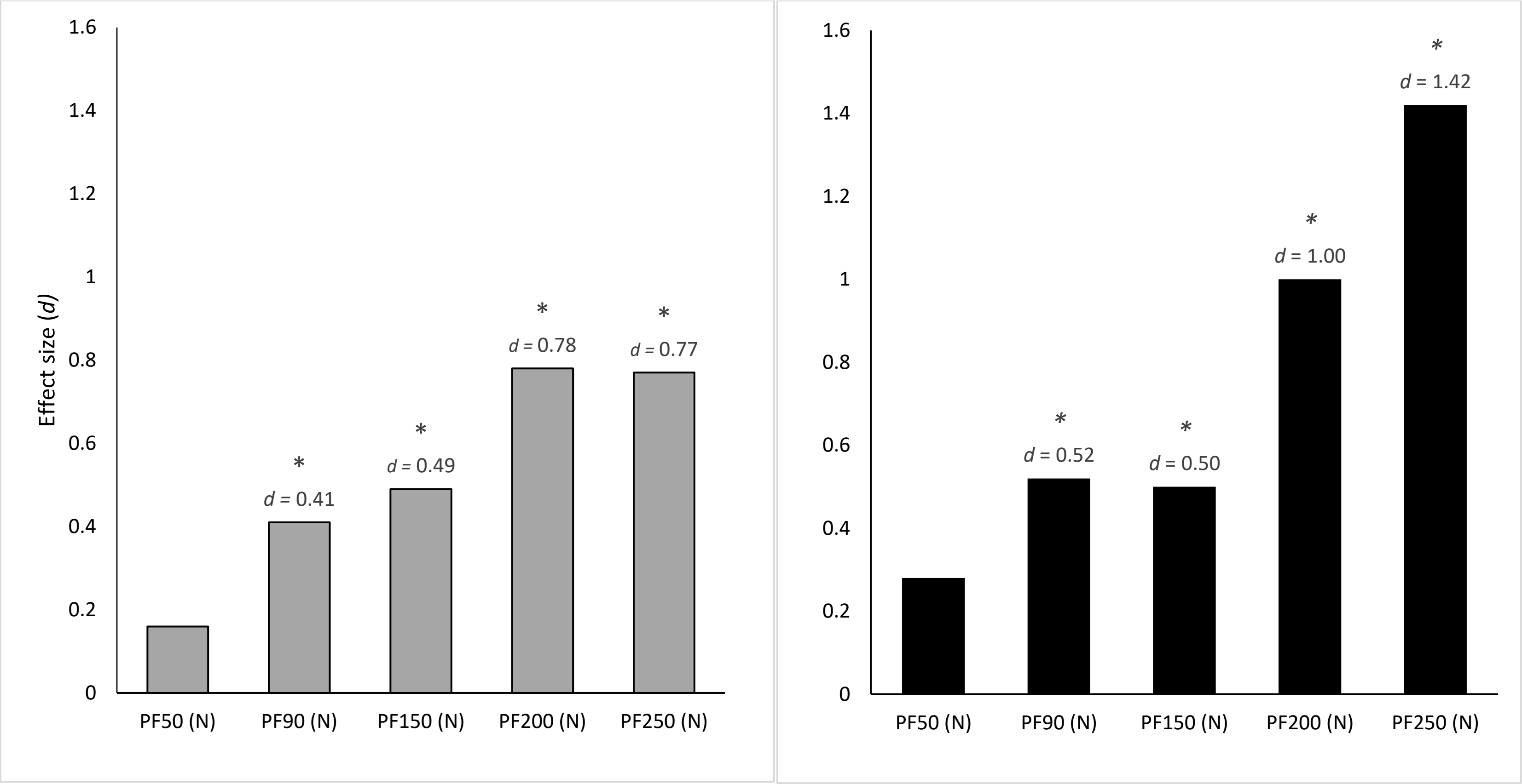

Figure 1. Effect sizes for pre- and post-PHV EXP within-group changes at PF for all time epochs for pre-PHV. * significant change from baseline to post-testing ($p < 0.05$).

Table 1. Mean (± SD) values for descriptive details of each maturity groups anthropometric data.

	N	Standing height (cm)	Mass (kg)	Maturity offset (years from PHV)
Pre-PHV EXP	14	151.26 ± 8.23	47.82 ± 16.62	-2.04 ± 0.83
Pre-PHV CON	10	146.82 ± 9.30	41.64 ± 6.99	-2.28 ± 0.67
Post-PHV EXP	7	174.41 ± 9.22	70.27 ± 13.39	1.80 ± 0.83
Post-PHV CON	7	174.05 ± 5.92	64.18 ± 4.82	1.20 ± 0.48

Table 2. Structure of 12-week training program for pre-PHV EXP.

		Session 1			Session 2		
	Week	Exercise	Sets	Repetitions	Exercise	Sets	Repetitions
Training Block 1	1-2	Pogo hops	3	10	Bear crawl holds	3	30 seconds
		Standing long jumps	3	5	Drop landings	3	5
		Single leg hop & stick	3	5 each leg	Barbell back squat	3	10
		Side planks	3	30 sec each side	Banded overhead press	3	10
		MB slams	3	10	Banded horizontal pulls	3	10
	3-4	Pogo hops	3	10	Bear crawl holds	3	30 seconds
		Split jumps	3	10	Drop landings	3	5
		Box jumps	3	5	Barbell deadlift	3	6-8
		Glute bridges	3	10	Banded overhead press	3	10
		MB Side tosses	3	5 each side	Single arm banded rows	3	10 each
Training Block 2	5-6	Pogo hops	4	10	Plank holds	4	30 seconds
		Standing long jumps	4	5	KB Squat jumps	4	5
		Deadbugs	4	20	Barbell back squat	4	6-8
		MB vertical throws	4	5	Press ups	4	8
		Side planks	4	30 sec each side	TRX rows	4	8
	7-8	Box jumps	4	5	Plank holds	4	30 seconds
		Drop jumps	4	5	KB Squat jumps	4	5
		Deadbugs	4	5	Barbell deadlift	4	5
		Glute bridges	4	15	Press ups	4	6-8
		MB horizontal throws	4	5	TRX rows	4	8
Training Block 3	9-10	Multidirectional hurdle jumps	4	6	Shoulder taps	4	20
		Drop jump to 10m sprint	4	3	Barbell back squat	4	3-5
		20m sprints	4	2	KB swings	4	8
		MB overhead throws	4	5	DB overhead press	4	5
		Single leg glute bridges	4	10 each leg	Horizontal rows	4	5
	11-12	Multidirectional hurdle jumps	4	6	Shoulder taps	4	20
		Drop jump to standing long jump	4	3	Barbell deadlift	4	3-5
		20m sprints	4	2	KB swings	4	8
		MB vertical throws	4	5	Single arm DB overhead press	4	5 each side
		MB horizontal throws	4	3 each side	DB Rows	4	5 each side

Table 3. Structure of 12-week training program for post-PHV EXP.

		Session 1			Session 2		
	Week	Exercise	Sets	Repetitions	Exercise	Sets	Repetitions
Training Block 1	1-2	Standing long jumps	3	4	Box jumps	3	5
		Pogos	3	10	Barbell back squat	3	10
		Single leg hop & stick	3	5 each	Horizontal rows	3	6-10
		Barbell hip thrusts	3	10	Romanian deadlift	3	10
		Chest supported DB rows	3	10	Kneeling landmine press	3	8 each side
	3-4	Multidirectional hurdle jumps	3	3	Box jumps	3	5
		Split jumps	3	10	Barbell deadlift	3	6-10
		Single leg hop & stick	3	5 each	Horizontal rows	3	6-10
		KB split squats	3	10 each side	Barbell step ups	3	5 each side
		DB bench press	3	10	Kneeling landmine press	3	8 each side
Training Block 2	5-6	Pogos	4	10	Bounding	4	3 each leg
		Drop Jumps	4	3	Barbell back squat	4	5-8
		KB Squat jumps	4	3	Bent over rows	4	8
		Chest supported DB rows	4	10	Romanian deadlift	4	6
		Barbell bench press	4	6-8	Weighted dead bugs	4	10
	7-8	Multidirectional hurdle jumps	4	3	Bounding	4	4 each leg
		Drop Jump to 10m sprint	4	3	Hex bar deadlift	4	5
		Standing long jumps	4	4	Bent over rows	4	6-8
		Barbell hip thrusts	4	6-8	Barbell step ups	4	5 each side
		Barbell bench press	4	5	Weighted dead bugs	4	10
Training Block 3	9-10	Drop Jump to standing long jump	4	3	20m sprints	4	2
		Single leg box jumps	4	2 each side	Barbell back squat	4	3
		Rear foot elevated DB squats	4	8 each side	Pull Ups	4	5
		KB swings	4	10	Barbell overhead press	4	5-8
		DB rows	4	8 each side	Weighted plank holds	4	30 sec
	11-12	Multidirectional hurdle jumps	4	3	20m sprints	4	2
		Standing long jumps	4	3	Hex bar deadlift	4	3
		DB lunges	4	2	Pull Ups	4	AMRAP
		Barbell hip thrust	4	5	Single arm DB overhead press	4	5 each
		Barbell bench press	4	5	Weighted plank holds	4	30 sec

Table 4. Group means (± SD) for IMTP kinetic force-time variables and effect-sizes (ES) for within-group difference from baseline to post-testing.

	Pre-PHV EXP			**Pre-PHV CON**			**Post-PHV EXP**			**Post-PHV CON**		
	Baseline	**Post**	**ES (*d*)**	**Baseline**	**Post**	**ES (*d*)**	**Baseline**	**Post**	**ES (*d*)**	**Baseline**	**Post**	**ES (*d*)**
Peak Force (N)	1253.14 ± 261.12	1320.93 ± 247.47	**0.26**	1153.54 ± 239.40	1168.98 ± 246.10	**0.06**	2205.93 ± 313.96[α]	2452.78 ± 441.60*[α]	**0.79**	1862.47 ± 292.33	1811.29 ± 254.15	**0.18**
Relative Peak Force (N/kg)	30.13 ± 5.47	30.72 ± 4.68	**0.10**	27.68 ± 3.48	28.00 ± 3.52	**0.09**	32.68 ± 4.10	34.74 ± 5.09	**0.50**	30.58 ± 4.37	29.72 ± 3.69	**0.19**
Time to Peak Force (s)	1.67 ± 0.66	1.40 ± 0.42[α]	**0.41**	2.13 ± 1.08	2.33 ± 1.43	**0.18**	1.93 ± 0.46	1.47 ± 0.46*	**1.00**	1.32 ± 0.84	1.55 ± 0.92	**0.27**
Peak RFD ($N\cdot s^{-1}$)	5612.70 ± 1726.90[α]	6715.70 ± 2273.38[α]	**0.64**	4074.74 ± 1272.22	4622.25 ± 2164.90	**0.43**	8729.83 ± 883.48	11026.10 ± 2428.47*	**2.60**	7631.28 ± 1675.76	7698.74 ± 1877.09	**0.04**
Time to Peak RFD (s)	0.70 ± 0.78	0.83 ± 0.96	**0.17**	0.50 ± 0.94	0.55 ± 1.06	**0.05**	0.46 ± 0.71	0.40 ± 0.57	**0.08**	0.52 ± 0.05	0.59 ± 1.01	**1.14**

[*] significant within-group change from pre to post testing ($p < 0.05$).

[α] significant between-group difference with CON group of same maturity status ($p < 0.05$).

Table 5. Group means (± SD) for CMJ kinetic force-time variables and effect-sizes (ES) for within-group diffe

	Pre-PHV EXP			**Pre-PHV CON**			**Post-PHV EXP**	
	Baseline	**Post**	**ES (*d*)**	**Baseline**	**Post**	**ES (*d*)**	**Baseline**	**Pos**
Jump Height (m)	17.44 ± 4.23	18.79 ± 4.86	**0.32***	17.84 ± 3.09	17.14 ± 3.50	**0.22**	25.27 ± 6.09	29.72 ±
Time to take off (s)	0.56 ± 0.09	0.53 ± 0.09$^\alpha$	**0.33**	0.57 ± 0.06	0.63 ± 0.10	**0.68**	0.63 ± 0.06	0.62 ±
RSI modified (JH/time to take off)	0.23 ± 0.09	0.27 ± 0.09	**0.44***	0.24 ± 0.04	0.21 ± 0.05	**0.75**	0.32 ± 0.08	0.41 ±
Peak Force (N)	484.34 ± 182.64	540.03 ± 183.36	**0.30**	477. 32 ± 108.23	464.93 ± 160.68	**0.11**	874.13 ± 226.13	1022.8 237.8
Eccentric Impulse (Ns)	39.64 ± 11.30	41.42 ± 12.78	**0.16**	35.00 ± 7.46	36.10 ± 8.58	**0.15**	79.71 ± 19.22$^\alpha$	83.42 ±
Duration of Eccentric Phase (s)	0.26 ± 0.05	0.27 ± 0.05$^\alpha$	**0.20**	0.28 ± 0.05	0.32 ± 0.06	**0.80**	0.34 ± 0.05	0.32 ±
Concentric Impulse (Ns)	79.78 ± 20.18	84.42 ± 20.63	**0.22**	76.20 ± 13.22	76.00 ± 11.37	**0.02**	157.00 ± 35.58	168.2 35.8
Duration of Concentric Phase (s)	0.30 ± 0.06	0.27 ± 0.04	**0.50***	0.28 ± 0.04	0.30 ± 0.06	**0.50**	0.29 ± 0.02	0.29 ±
Peak Landing Force (N)	1478.90 ± 469.17	1418.04 ± 556.88	**0.13**	1425.61 ± 200.20	1418.18 ± 340.86	**0.04**	2418.81 ± 763.43	2768. 930.
Peak Power (W)	1449.81 ± 382.51	1575.54 ± 408.68	**0.33***	1365.05 ± 247.98	1416.35 ± 241.69	**0.20**	2997.89 ± 877.68	3335. 744.
Eccentric Power (W)	-189.50 ± 52.55	-204.82 ± 63.75	**0.29**	-185.05 ± 41.68	-171.42 ± 48.42	**0.32**	-383.40 ± 90.21$^\alpha$	-402. 108.
Concentric Power (W)	764.57 ± 227.53	848.64 ± 197.89	**0.37***	711.20 ± 133.30	709.70 ± 136.70	**0.01**	1611.42 ± 411.75	1753.8 507.

* significant within-group improvement from Pre to Post Testing ($p < 0.05$).

$^\alpha$ significant between-group difference with CON Group ($p < 0.05$).