

1 ABSTRACT

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

22

23 **Key words:** strength training, plyometric training, combined training, children,
24 adolescents

25

26 INTRODUCTION

27 It is well documented that developmentally appropriate, well supervised resistance
28 training interventions are safe and effective in stimulating positive adaptations on a
29 range of physical performance measures in children and adolescents (21, 22).

30 Resistance training is defined as a specialized method of conditioning whereby an
31 individual is working against a wide range of resistive loads in order to enhance
32 health, fitness and performance (21). Researchers have shown that a myriad of
33 resistance training modes have all been effective in eliciting beneficial training
34 responses in neuromuscular performance in youth, including, traditional strength
35 training (28) which involves the lifting of moderate to heavy loads with moderate
36 inter-set recovery using free weights or resistive machines (19), weightlifting (7),
37 plyometrics (26, 36) and combined strength and plyometric training (11, 37).

38 However, while studies have examined the efficacy of individual forms of resistance
39 training (e.g. plyometrics), minimal evidence exists that compares the effectiveness of
40 different resistance training modes and their potential interaction with maturation in
41 youth populations.

42
43 Previous meta-analyses have attempted to examine the effects of resistance training
44 on muscular strength (3) and motor skill performance (2) in youth of different
45 maturational status. Combined these meta-analyses showed that while adolescents
46 were able to make greater adaptations with respect to muscular strength, the
47 transference of resistance training gains to motor skill performance were more
48 pronounced in children (2). Such findings may reflect the heightened neural plasticity
49 and increased sensitivity for motor control and coordinative adaptation during
50 childhood (34, 35), versus the enhanced hormonal profile and greater muscle mass

51 associated with adolescence_(10). However, it should be noted that neither meta-
52 analysis showed differential responses to different resistance training modes in
53 relation to maturation. Additionally, very few studies have specifically examined the
54 interaction of training responses with maturation (20, 28, 31). These studies focused
55 solely on the interaction of maturation with strength training and combined_ showed
56 varying results.

57

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

71

72 Therefore, the purpose of this study was to determine the effectiveness of different
73 resistance training modes (traditional strength training, plyometric training or
74 combined training) on measures of neuromuscular performance (squat jump height,
75 reactive strength index, acceleration and maximal running velocity) in boys of

76 different maturational status. We hypothesized that boys that were pre-PHV would
77 respond more favorably to plyometric training, whereas boys that were post-PHV
78 would show a greater training response to traditional strength training or combined
79 training.

81 METHODS

82 **Experimental approach to the problem**

83 A between-group, repeated measures design was used to examine the effects of
84 different resistance training programs on measures of sprinting and jumping. Pre and
85 post-PHV male youth were placed within one of three experimental groups (traditional
86 strength training, plyometric training, combined training) or a control group. The
87 experimental groups participated in their respective training programs twice-weekly for
88 6 weeks, while the control group completed their regular physical education lessons.

89 The training period of 6 weeks was selected to match the typical duration of a school
90 term, while also reflecting a recognized mesocycle duration (13). All participants were
91 tested before and after the 6-week intervention for the following independent variables:
92 squat jump height, reactive strength index, acceleration and maximal running velocity.

93 Repeated measures of analyses of variance were used to test for possible changes in test
94 scores across the 6-week intervention period, while inferential statistics were used to
95 examine the qualitative meaning of the observed changes in the independent variables.

97 **Subjects**

98 Eighty young male school children (n = 40 pre-PHV and n = 40 post-PHV) from a local
99 secondary school in the United Kingdom volunteered to participate in the study and
100 were subsequently divided into one of three training groups (traditional strength

101 training, plyometric training or combined strength and plyometric training) or a control
102 group (n = 10 x pre-PHV and 10 x post-PHV per group). Participant characteristics per
103 maturation group and training intervention are presented in *table 1*. All participants had
104 previously engaged in physical education-based activities, however they were not
105 involved in any formalized strength and conditioning program. The training groups
106 completed 2 training sessions per week for 6-weeks instead of their regular physical
107 education classes. Conversely, the control group continued with their physical
108 education curricula. Parental informed consent and participant assent were obtained in
109 advance of the study and ethical approval for the research was granted by the University
110 Research Ethics Committee in accordance with the Declaration of Helsinki.

111
112 *****Table 1 near here*****

114 Testing procedures

115 Prior to the start of the intervention period, all participants took part in a
116 familiarization session, which provided opportunities to practice both jumping and
117 sprinting test protocols. Participants were allowed to complete as many practice trials
118 as required to ensure they fully understood the protocols and could demonstrate
119 consistent technical execution as determined by the principal investigator. For the
120 purposes of the actual test sessions, participants completed a standardized 10-min
121 dynamic warm-up inclusive of 3 min of sub-maximal multidirectional running and 7
122 min of light dynamic mobilization and activation exercises targeting the main muscle
123 groups of the upper and lower extremities. Following the warm-up and practice
124 attempts of the test protocols, participants completed the battery of tests in the
125 following order: anthropometrics, squat jump test, 5-maximal rebound test, 10 m and

126 flying 20 m sprint tests. For each test, participants completed three trials with the best
127 of three trials being used for further analysis. Two and five minute rest periods were
128 given between each trial and test respectively to limit the effects of fatigue on
129 consecutive efforts.

130

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

136

137 *Jump protocols.* Squat jump height (cm) and reactive strength index (mm/ms) were
138 calculated from a squat jump and 5-maximal rebound test respectively, both of which
139 were performed on a mobile contact mat (Smartjump, Fusion Sport, Australia). Both
140 protocols have been shown to be valid and reliable means of assessing neuromuscular
141 performance in youth (squat jump, ICC = 0.93; reactive strength index, ICC= 0.90
142 (24)). The squat jump was performed starting from an initial semi-squat position (90°
143 knee flexion as determined subjectively by the principal researcher), with participants
144 holding the position for approximately two seconds before jumping vertically for
145 maximum height on the command of the tester (24). Hands remained akimbo for the
146 entire movement to eliminate any influence from arm swing and participants were
147 instructed to maintain fully extended lower limbs throughout the flight period.
148 Reactive strength index was determined during a 5-maximal rebound test, with
149 participants required to perform five consecutive maximal vertical rebounds on the
150 mobile contact mat. Participants were instructed to maximize jump height and

151 minimize ground contact time (8). The first jump in each trial served as a
152 countermovement jump and consequently was discounted for analysis, while the
153 remaining four rebounds were averaged for analysis of reactive strength index (24).
154
155 Sprinting protocols. Sprint times were recorded using wireless timing gates (Smart
156 Speed, Fusion Sport, Australia) in an indoor sports hall. Data was instantaneously
157 collected via a handheld PDA (iPAQ, Hewlett Packard, USA). Acceleration was
158 measured over 0-10 m with a stationary start from a line 30 cm behind the first timing
159 gate. Maximal running velocity was measured over a 20 m distance with a flying start.

160

161 **Training programs**

162 Training took place twice per week for 6-weeks and training sessions were designed
163 and implemented by a fully accredited strength and conditioning coach (ASCC).
164 Training sessions were separated by at least 48 hours to enable full recovery. Within
165 each session, a fully qualified physical education teacher was present, which enabled
166 a staff-to-pupil ratio of 1:10. To be included in the final analyses, participants were
167 required to complete at least 80% of the total training sessions within their respective
168 program. Correct technical execution was stressed at all times throughout the program
169 with relevant feedback provided on an individual basis; while intensity was never
170 increased at the expense of technical competency. In the event of participants being
171 unable to competently perform any given exercise, relevant exercise regressions were
172 prescribed on an individual basis. Within all training programs, training sessions
173 lasted no longer than 60 minutes and prescribed inter-set rest periods ranged between
174 1-2 minutes dependent on the relative intensity of the exercise; an approach that is
175 commensurate with recommended guidelines for youth resistance training (21).

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

180
181 *Traditional strength training group.* Within traditional strength training sessions,
182 participants completed 3 sets of 10 repetitions of a barbell back squat, barbell lunge,
183 dumbbell step up and leg press. In order to enable the prescription of individualized
184 training intensities, 10-repetition maximum (10RM) loads were calculated for
185 participants in the traditional strength training group prior to the start of the training
186 period using a protocol previously identified in the literature (16). In the event of
187 technical failure, where the coach deemed that competent technique was no longer
188 maintained to a satisfactory standard, the set was stopped to avoid potential risk of
189 injury to the participant. To progressively overload the training stimulus, intensity
190 was increased each week via a 5% increment in external load for all participants on
191 the proviso that technical competency was maintained. In the event of a particular
192 exercise being too difficult or failing to provide enough challenge, loads were reduced
193 or increased respectively on an individual basis.

194
195 *Plyometric training group.* Plyometric training prescription included a combination of
196 exercises that were geared towards developing both safe jumping and landing
197 mechanics (e.g. drop landings, vertical jumps in place, single leg forward hop and
198 stick) and to also stress stretch-shortening cycle activity (e.g. pogo hopping, drop
199 jumps, multiple horizontal rebounds). Within each session, participants were exposed
200 to multiple sets of 4 exercises to enable sufficient repetition to develop motor control

201 programs. The plyometric training program (*table 2*) was progressed conservatively
202 according to number of foot contacts completed within each session (week 1 foot
203 contacts = 74 per session; week 6 foot contacts = 88 per session).

204

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

206

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

215

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

217

218 **Statistical Analysis**

219 Descriptive statistics (means \pm *sd*) were calculated for all performance variables for
220 both pre- and post-training intervention data. Differences in all performance variables
221 were analyzed using separate 2 x 4 x 2 (time x training group x maturity) repeated
222 measures ANOVA, where 'time' denotes pre- to post-training data, 'training group'
223 represents plyometric training, traditional resistance training, combined training or
224 control groups, and 'maturity' refers to pre- vs post-PHV. Sphericity of data was
225 tested by Mauchly's statistic, and where violated, Greenhouse-Geiser adjustment was

226 used. Bonferroni and Games-Howell post hoc tests were used to determine the origin
227 of any between-group differences when equal variance was or was not assumed
228 respectively. Effect sizes were calculated for all performance variables in each
229 training group and assessed using the magnitude of effect sizes according to Cohen's
230 *d* statistic. Descriptive statistics and repeated measures ANOVA analysis were
231 computed using SPSS V.20 (SPSS Inc., Chicago, IL, USA), with statistical
232 significance for all tests set at an alpha level of $p < 0.05$.

233

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

247

248 RESULTS

249 Mean changes in sprint and jump performance, including effect sizes, are displayed in
250 *table 4* for pre- and post-PHV groups respectively and where significant, changes in

251 sprint and jump performance in both pre-PHV and post-PHV groups ranged from
252 small (<0.20) to large (>0.90). Irrespective of maturation, none of the control groups
253 made any significant changes in performance over the 6-week training period.

254 Attendance rates for pre-PHV (plyometric training = 91%, traditional strength training
255 = 89% and combined training = 90%) and post-PHV (plyometric training = 83%,
256 traditional strength training = 88% and combined training = 87%) experimental
257 groups and both control groups (>82%) were above the predetermined attendance
258 threshold across the intervention period.

259

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

261

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

272

273 Analysis of squat jump and reactive strength index data showed main effects for both
274 time and maturity. For both jumping variables, post-PHV youth demonstrated greater
275 performances following the training intervention period. Significant interactions were

276 found for time x maturity and time x training group for both squat jump and reactive
277 strength index. Additionally, there was a significant time x maturity x training group
278 interaction for squat jump performance. Significant improvements in squat jump
279 height and reactive strength index were seen in all pre-PHV training groups. In the
280 post-PHV cohort, squat jump height increased significantly in the resistance and
281 combined training groups, while reactive strength index improved significantly in the
282 plyometric and combined training groups.

283

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

293

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

295

296 DISCUSSION

297 From the results of this study it was observed that boys, both pre- and post-PHV, were
298 able to make significant improvements in jumping, sprinting, or both qualities
299 following a range of 6-week resistance-based training programs. Irrespective of
300 maturation, none of the control groups showed any significant changes in

301 performance across the intervention period. Plyometric training appeared to stimulate
302 the greatest gains in pre-PHV children, with significant improvements (range of % or
303 ES) reported for all sprinting and jumping variables. Across all pre-PHV training
304 groups, effect sizes were greater for changes in jumping versus sprinting performance.
305 For the post-PHV cohort, combined training appeared to be the most effective in
306 eliciting change across all performance variables, with moderate to large effects
307 reported in acceleration, maximal running velocity and squat jump height. Inferential
308 statistics showed that for almost all variables, comparable performance changes
309 between pre- and post-PHV boys were trivial following both resistance and combined
310 training interventions. However, following plyometric training, changes in squat jump
311 and acceleration performance were significant and very likely greater in pre-PHV
312 children versus their post-PHV peers.

313

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

320

321 Developmentally appropriate strength training (28), weightlifting (7), plyometric
322 training (26) and combined training (9) have all been proven effective in mediating
323 beneficial adaptations in numerous measures of neuromuscular performance in youth.
324 In the current study, significant main effects for time across all variables indicated
325 that irrespective of resistance training mode, both pre- and post-PHV boys were able

326 to make worthwhile improvements in jumping and sprinting performance. The current
327 study also identified significant time x training group interactions for all jumping and
328 sprinting variables, with all training programs having a significant influence on the
329 performance changes reported following the 6-week intervention period.

330
331 Of greater interest to the youth practitioner however, was the significant time x
332 training group x maturity interaction for both squat jump and acceleration
333 performance. Furthermore, magnitude-based inferences confirmed that in response to
334 the plyometric training intervention, pre-PHV children had improvements in
335 acceleration and squat jump height that were very likely greater than post-PHV males.
336 Almost all other between-maturity group differences were non-significant and trivial,
337 irrespective of training intervention. Intuitively, this suggests that the pre-PHV boys
338 responded more favorably to the plyometric training program. These findings may
339 reflect the process of ‘synergistic adaptation’, which refers to the symbiotic
340 relationship between specific adaptations of an imposed training demand with
341 concomitant growth and maturity-related adaptations. It is acknowledged that
342 appropriately prescribed plyometric training enhances stretch-shortening cycle
343 function in youth (26). Stretch-shortening cycle activity is governed by efficient
344 neural regulation (18) and research shows that pre-pubescence is a timeframe during
345 which children experience a proliferation in neural coordination and central nervous
346 system maturation (5, 30, 34). It could be suggested that the high neural demand of
347 plyometric training provided a stimulus that coincided with the natural adaptive
348 response of the pre-PHV boys resulting from growth and maturation. Combined, this
349 synergistic relationship may have led to an amplified age-related training response
350 and suggests that training during this developmental period should include exposure

351 to plyometric training to complement motor skill and foundational strength
352 development.

353
354 Squat jump and acceleration performance are indicative of slower stretch shortening
355 cycle activity (6), while reactive strength index and maximal running velocity
356 typically utilize faster-stretch-shortening cycle actions (25). Interestingly, the
357 heightened training response shown by the pre-PHV group following the plyometric
358 training intervention resulted only in very likely greater adaptations in squat jump and
359 acceleration performance, but unlikely changes in measures of reactive strength index
360 and maximal running velocity. This may simply be a reflection of adaptations
361 emanating from specifics of program design and exercise selection. For example, the
362 plyometric training program included a number of exercises that targeted effective
363 landing mechanics and movements that recruited longer ground contact times (e.g.
364 drop landings, single leg forward hop and stick, horizontal jumps and multiple
365 horizontal rebounds), which may have led to a bias in adaptations of slower stretch-
366 shortening cycle mechanics. The notion of different jump protocol strategies eliciting
367 specific neuromuscular adaptations is supported by previous literature (17, 25).

368
369 While magnitude-based inferences indicated that the post-PHV boys failed to show an
370 enhanced training response compared to the pre-PHV children for any of the
371 performance variables, it is worth noting that statistical significance testing showed
372 that the training mode that led to the largest and highest number of significant
373 performance changes was combined training. Combined training incorporates both
374 plyometric and traditional strength training exercises, and while speculative, it could
375 be suggested that the stimulus of this training mode more closely reflected the internal

376 milieu of the post-PHV participants. Performance of plyometrics and traditional
377 strength training differs in the time available in which to produce force. Plyometrics
378 involve rapid movement speeds and high rates-of-force development, whereas
379 traditional strength training allows for much longer contraction times in order to attain
380 higher peak force outputs. Developmentally, post-PHV boys will experience
381 morphological changes that facilitate force generation (e.g. increased motor unit size
382 and pennation angles) in addition to continued neural adaptations as a consequence of
383 maturation (27). The synergistic relationship between the combined training and
384 natural adaptive processes may have provided a more potent maturity-related training
385 stimulus. Combined, the findings for both pre- and post-PHV cohorts support recent
386 meta-analyses that showed pre-PHV boys made the greatest gains in sprinting
387 performance following plyometric training (32), while post-PHV males benefitted
388 most from combined training modes.

389

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

399

400 PRACTICAL APPLICATIONS

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

416

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420

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535

536 **FIGURE LEGEND**

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