The effectiveness of resistance, plyometric and sprint training at different stages of maturation in male youth athletes

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ABSTRACT

The trainability of youth at specific periods during growth and maturation has become a key issue in paediatric exercise science. The development of physical capacities such as movement speed, strength and power is difficult to predict in youth meaning that the structuring of training can be a significant challenge for coaches. Accordingly, methodologically sound research is required to underpin a more informed approach to the formulation of programmes of physical development. To this end, the purpose of this work was to investigate the trainability of youth athletes at specific stages during maturation (pre-, mid-, and post-peak height velocity) by addressing some of the shortcomings of the existing body of literature.

Short-term controlled interventions were undertaken and they extended from the findings of three meta-analytical reviews, all of which examined the effect of training on the development of speed, strength and power in youths aged 9 to 18. These investigations were focused on the manipulation of modifiable factors, such as the training stimulus, as opposed to non-modifiable factors, such as maturity (which was generally controlled for). With some exceptions, which are potentially explainable, speed, strength and power were, on the whole, more trainable in youths as they advanced in maturation with the mid-peak height velocity phase being a particularly important time for the development of these capacities. This could indicate the presence of a maturational threshold which moderates responses to training but this can also be coincident with a period of impaired performance potentially related to reduced motor control due to rapid growth rates.

Because of the way speed, strength and power can develop in youth athletes, the pre-peak height velocity phase of development may be more conducive to neuromuscular training with a coordinative component which establishes the movement competency required for more advanced techniques. An intensification of resistance (strength) training can be of benefit during mid-peak height velocity though impaired movement or a higher susceptibility to injury could compel coaches to reduce sprint (speed) and/or plyometric (power) training at this time. During the post-peak height velocity phase, athletes can be transitioned to more advanced training techniques, that are traditionally used with adults, if they possess the necessary coordination and experience to do so. Regardless of the results in this work, at every stage of development it is important for coaches to make programming decisions for youth athletes based, primarily, on training age and movement competency with the above maturity-related recommendations being suitable for those who have been exposed to high quality training from an early age.

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Abbreviations

1RM	1 repetition maximum
3RM	3 repetition maximum
10 m	10 metres
15 m	15 metres
20 m	20 metres
30 m	30 metres
CMJ	Countermovement jump
ES	Effect size
MID	Mid-peak height velocity
PHV	Peak height velocity
POST	Post-peak height velocity
PRE	Pre-peak height velocity
PT	Plyometric training
RT	Resistance training
SSC	Stretch-shortening cycle
ST	Sprint training

CHAPTER 1

Introduction

1.1 Introduction

Evidence suggests that exercise training can enhance (Franco-Márquez *et al.*, 2015; Lloyd *et al.*, 2016b; Meylan *et al.*, 2014a; Radnor, Lloyd and Oliver, 2016; Ramirez-Campillo *et al.*, 2015b; Ramirez-Campillo *et al.*, 2015c; Rodriguez-Rosell *et al.*, 2016; Rumpf *et al.*, 2015) or even expedite (Low *et al.*, 2015; Vänttinen *et al.*, 2011; Wrigley *et al.*, 2014) the physical development of youths to a level that is greater than that which could be realised through biological maturation alone. However, to date the degree of trainability of youths at different stages of maturation remains unclear due to a number of limitations of existing literature.

According to MacKelvie, Khan and McKay (2002), the magnitude and the specific timing of developmental changes can vary by as much as six years amongst youths of the same chronological age and this may affect the manner in which they respond to training (Anderson and Twist, 2005; Lloyd *et al.*, 2011; Meylan *et al.*, 2014a; Pearson, Naughton and Torode, 2006). Faigenbaum (2008) states that because the myelination of motor nerves does not reach a peak until sexual maturation, youth athletes do not respond to training in the same manner as adults, meaning that training methods typically assigned to older athletes may be inappropriate for younger athletes.

The biological maturity of an individual is indicated by the degree to which they have progressed towards the adult state with a combination of sexual, somatic and skeletal factors denoting status (Claessens, Beunen and Malina, 2008). Historically, maturation status has either been unaccounted for or has been inconsistently measured and reported in studies of exercise training in youths. For example, some researchers have used Tanner staging (Baxter-Jones, Eisenmann and Sherar, 2005), whilst others have utilised skeletal age or the maturity offset method to assess status. Though correlations between many of these measures are relatively strong (Baxter-Jones, Eisenmann and Sherar, 2005), it is nonetheless difficult to compare biologically-related changes in performance across studies because, ultimately, these methods measure different maturational qualities. Such limitations have impeded progress in this research area and, relatedly, there seems to be little evidence that outlines the degree to which youths should be exposed to particular training stimuli as they grow and mature. This has implications for the manner in which training programmes are structured with peak height velocity (PHV) considered an important signpost in the programming of adolescents' exercise regimes (Fujii, Demura and Matsuzawa, 2005). Occurring roughly between the ages of 13 and 15 in males (Malina and Geithner, 2011), PHV can be characterised as "the period of most accelerated growth during puberty" (Portas *et al.*, 2016). It is characterised by an initial growth of the legs, which is then followed by the lengthening of the trunk (Malina, Bouchard and Bar-Or, 2004). This could affect the way an individual responds to particular training stimuli (Meylan *et al.*, 2014a). In the current work, the maturity offset, as denoted by years to and from PHV is the preferred method of maturity assessment, however, Table 1 outlines a variety of measures and their relative strengths and weaknesses.

Method	Strengths	Weaknesses	Comments
Maturity offset	Fast, inexpensive and non-invasive. Also facilitates the construction of categorical variables to create maturity groups (Baxter-Jones, Eisenmann and Sherar, 2005).	Underestimates age at PHV at younger ages and overestimates it at older ages (Malina and Kozieł, 2014).	The maturity offset is a practicable method of assessing the status of youth athletes and is commonly used in youth sport. It can predict age at PHV to within 1 year 95% of the time (Mirwald *et al.*, 2002).
Skeletal age	The assessment of skeletal age seems to be the most accurate method of maturity estimation in youth (Baxter-Jones, Eisenmann and Sherar, 2005).	Expensive and requires exposure to radiation (Sherar *et al.*, 2005).	Though accurate, this method can also be undermined by the subjective assessment of results as well as within-subject variability in the maturity of different bones (Baxter-Jones, Eisenmann and Sherar, 2005).
Secondary sex characteristics	Growth of pubic hair and rising testicular volume tend to be accurate measures of pubertal development in young males (Rasmussen *et al.*, 2015).	The assessment of genitals for maturity assessment can be invasive and the method is undermined by the potential misalignment of sexual and somatic maturation (Baxter-Jones, Eisenmann and Sherar, 2005).	As this method is more suitable for a clinical setting, it may be difficult for coaches to comfortably use it within a practical setting.
Predicted adult height (Khamis-Roche)	This method is reasonably accurate with high correlations between height predicted during adolescence and young adult height (Malina, Bouchard and Bar-Or, 2004).	This measure requires the retrieval of parental heights which could be inaccurate, or even impossible to obtain.	Though a viable and non-invasive alternative to the maturity offset, the Khamis-Roche method can underestimate predicted adult height in late-maturing children and can overestimate it in early-maturing children (Fragoso *et al.*, 2014).

Table 1.1 Comparison of measures of biological maturity status

The planning, or 'periodisation', of physical training is defined as "the logical integration and sequencing of specific training factors into interdependent training periods in order to optimise specific physiological and performance outcomes at predetermined time points in accordance with the athlete's individual needs and position in the long term athlete development model (LTAD)" (Haff, 2014). Accordingly, this research aims to outline the degree to which youths of *differing* maturity status adapt to *similarly* structured training programmes. Studies that incorporate this design feature may help to reveal the effectiveness of specific training methods at different stages of maturation.

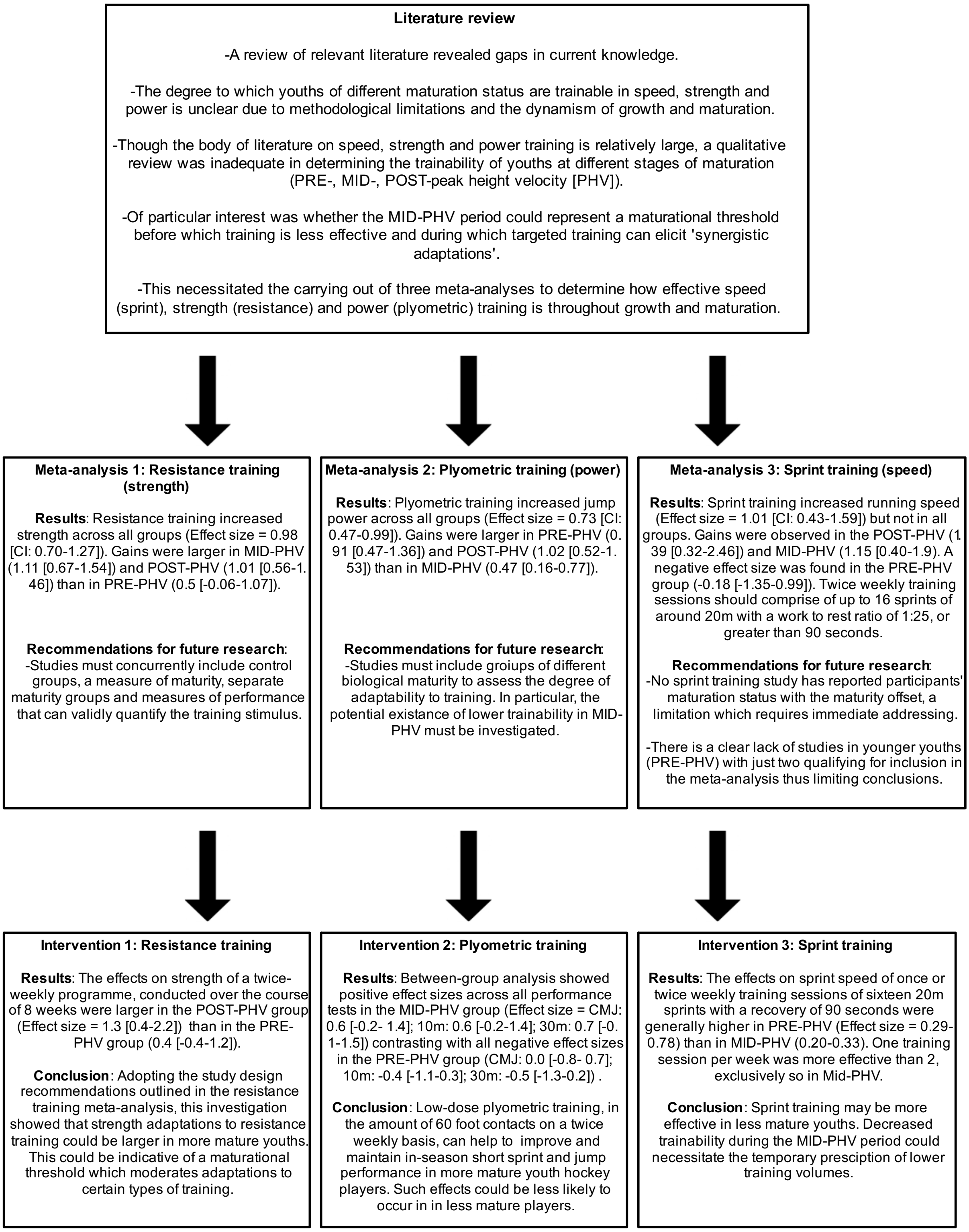
1.2 Aims of the research

This research aims to assess the trainability of youths in strength, power and speed before, during and after PHV. This can assist practitioners in constructing effective exercise programmes for youth athletes with a view to maximising adaptations. To this end the research will concurrently address some of the key recommendations for future research put forward by the British Association of Sport and Exercise Sciences (McNarry *et al.*, 2014):

- The inclusion of control groups to differentiate the concurrent effects of training and maturation.
- The utilisation of an assessment of biological maturity status.
- The investigation of trainability across all maturation stages to facilitate the direct comparison of responses in different maturity groups.
- The utilisation of performance tests that serve as valid and reliable measures of the adaptations due to training.

Several studies (Franco-Márquez *et al.*, 2015; Lloyd *et al.*, 2016b; Meylan *et al.*, 2014a; Radnor, Lloyd and Oliver, 2016; Ramirez-Campillo *et al.*, 2015b; Ramirez-Campillo *et al.*, 2015c; Rodriguez-Rosell *et al.*, 2016; Rumpf *et al.*, 2015) have satisfied one or more, but not all, of the above criteria and this research looks to address these shortcomings. Referring to the LTAD model (Balyi and Hamilton, 2004), Bailey *et al.* (2010) recently suggested that "participant development should not be driven by windows of opportunity as there is a lack of cause-and-effect evidence" pertaining to their efficacy. However, only by undertaking an in-depth and coherent investigation of youth athlete trainability can this assertion be truly evaluated.

According to several authors (Geithner *et al.*, 2004; Matos and Winsley, 2007; Philippaerts *et al.*, 2006; Vamvakoudis *et al.*, 2007) it is difficult to distinguish the effects of training from those of biological maturation. Indeed, research supports the phenomenon of 'synergistic adaptation' (Lloyd *et al.*, 2016b) whereby there is a combined effect of training and maturation on physical performance. A better understanding of the interdependent relationship between these two variables would go a way to determining the success or failure of a given programme of physical training. In adding to the methodologically limited body of scientific knowledge relating to this matter, it is anticipated that this research will inform coaches and mentors about appropriately structuring youths' fitness programmes. A schematic of the schedule of studies can be seen in Figure 1.1.



Literature review

-A review of relevant literature revealed gaps in current knowledge.

-The degree to which youths of different maturation status are trainable in speed, strength and power is unclear due to methodological limitations and the dynamism of growth and maturation.

-Though the body of literature on speed, strength and power training is relatively large, a qualitative review was inadequate in determining the trainability of youths at different stages of maturation (PRE-, MID-, POST-peak height velocity [PHV]).

-Of particular interest was whether the MID-PHV period could represent a maturational threshold before which training is less effective and during which targeted training can elicit 'synergistic adaptations'.

-This necessitated the carrying out of three meta-analyses to determine how effective speed (sprint), strength (resistance) and power (plyometric) training is throughout growth and maturation.

Meta-analysis 1: Resistance training (strength)

Results: Resistance training increased strength across all groups (Effect size = 0.98 [CI: 0.70-1.27]). Gains were larger in MID-PHV (1.11 [0.67-1.54]) and POST-PHV (1.01 [0.56-1.46]) than in PRE-PHV (0.5 [-0.06-1.07]).

Recommendations for future research:
-Studies must concurrently include control groups, a measure of maturity, separate maturity groups and measures of performance that can validly quantify the training stimulus.

Meta-analysis 2: Plyometric training (power)

Results: Plyometric training increased jump power across all groups (Effect size = 0.73 [CI: 0.47-0.99]). Gains were larger in PRE-PHV (0.91 [0.47-1.36]) and POST-PHV (1.02 [0.52-1.53]) than in MID-PHV (0.47 [0.16-0.77]).

Recommendations for future research:
-Studies must include groiups of different biological maturity to assess the degree of adaptability to training. In particular, the potential existance of lower trainability in MID-PHV must be investigated.

Meta-analysis 3: Sprint training (speed)

Results: Sprint training increased running speed (Effect size = 1.01 [CI: 0.43-1.59]) but not in all groups. Gains were observed in the POST-PHV (1.39 [0.32-2.46]) and MID-PHV (1.15 [0.40-1.9). A negative effect size was found in the PRE-PHV group (-0.18 [-1.35-0.99]). Twice weekly training sessions should comprise of up to 16 sprints of around 20m with a work to rest ratio of 1:25, or greater than 90 seconds.

Recommendations for future research:
-No sprint training study has reported participants' maturation status with the maturity offset, a limitation which requires immediate addressing.

-There is a clear lack of studies in younger youths (PRE-PHV) with just two qualifying for inclusion in the meta-analysis thus limiting conclusions.

Intervention 1: Resistance training

Results: The effects on strength of a twice-weekly programme, conducted over the course of 8 weeks were larger in the POST-PHV group (Effect size = 1.3 [0.4-2.2]) than in the PRE-PHV group (0.4 [-0.4-1.2]).

Conclusion: Adopting the study design recommendations outlined in the resistance training meta-analysis, this investigation showed that strength adaptations to resistance training could be larger in more mature youths. This could be indicative of a maturational threshold which moderates adaptations to certain types of training.

Intervention 2: Plyometric training

Results: Between-group analysis showed positive effect sizes across all performance tests in the MID-PHV group (Effect size = CMJ: 0.6 [-0.2- 1.4]; 10m: 0.6 [-0.2-1.4]; 30m: 0.7 [-0.1-1.5]) contrasting with all negative effect sizes in the PRE-PHV group (CMJ: 0.0 [-0.8- 0.7]; 10m: -0.4 [-1.1-0.3]; 30m: -0.5 [-1.3-0.2]) .

Conclusion: Low-dose plyometric training, in the amount of 60 foot contacts on a twice weekly basis, can help to improve and maintain in-season short sprint and jump performance in more mature youth hockey players. Such effects could be less likely to occur in in less mature players.

Intervention 3: Sprint training

Results: The effects on sprint speed of once or twice weekly training sessions of sixteen 20m sprints with a recovery of 90 seconds were generally higher in PRE-PHV (Effect size = 0.29-0.78) than in MID-PHV (0.20-0.33). One training session per week was more effective than 2, exclusively so in Mid-PHV.

Conclusion: Sprint training may be more effective in less mature youths. Decreased trainability during the MID-PHV period could necessitate the temporary presciption of lower training volumes.

Figure 1.1 Schematic of thesis structure

1.3 Research questions

- Are adaptations to training in youth athletes mediated by stage of maturation as denoted by years to/from PHV?

- Can specific types of training be optimally programmed based on a youth's stage of maturation?
- Is there a maturational threshold below which adaptations to training in youth athletes are less apparent?

1.4 Outline of Study 1 - A meta-analysis of maturation-related variation in adolescent boy athletes' adaptations to short-term resistance training

This meta-analysis investigated the maturation-related pattern of adaptations to resistance training (RT) in boy athletes. Included were studies examining the effects of 4-16 week RT programmes in healthy boy athletes aged 10 to 18 years. Pooled estimates of effect size (ES) for change in strength across all studies (n = 19) were calculated using the inverse-variance random effects model for meta-analyses. Estimates were also calculated for groups based on likely biological maturity status ('before' [PRE], 'during' [MID] and 'after' [POST] PHV). Using the standardised mean difference, RT increased strength across all groups (ES = 0.98, [CI: 0.70-1.27]). Strength gains were larger in MID (1.11 [0.67-1.54]) and POST (1.01 [0.56-1.46]) than in PRE (0.5 [-0.06-1.07]). Adaptations to RT are greater in adolescent boys during or after PHV. These findings should help coaches to optimise the timing of training programmes that are designed to improve strength in boy athletes.

1.5 Outline of Study 2 - Age-related variation in male youth athletes' countermovement jump following plyometric training: a meta-analysis of controlled trials

Recent debate on the trainability of youths has focused on the existence of periods of accelerated adaptation to training. Accordingly, the purpose of this meta-analysis was to identify the age- and maturation-related pattern of adaptive responses to plyometric training (PT) in youth athletes. Thirty ESs were calculated from the data of 21 sources with studies qualifying based on the following criteria: (a) Healthy male athletes who were engaged in organised sport; (b) Groups of participants with a mean age between 10 and 18 years; (c) PT intervention duration between 4 and 16 weeks. Standardised mean differences showed

PT to be moderately effective in increasing countermovement jump (CMJ) height (ES = 0.73 95% confidence interval: 0.47-0.99) across PRE-, MID-, and POST-peak height velocity groups. Adaptive responses were of greater magnitude between the mean ages of 10 and 12.99 years (PRE) (ES = 0.91 95% confidence interval: 0.47-1.36) and 16 and 18 years (POST) (ES = 1.02 [0.52-1.53]). The magnitude of adaptation to PT between the mean ages of 13 and 15.99 years (MID) was lower (ES = 0.47 [0.16-0.77]), despite greater training exposure. Power performance as measured by CMJ may be mediated by biological maturation. Coaches could manipulate training volume and modality during periods of lowered response in order to maximise performance.

1.6 Outline of Study 3 - Variation in responses to sprint training in male youth athletes: a meta-analysis

The trainability of youths and the existence of periods of accelerated adaptation to training have become key subjects of debate in exercise science. The purpose of this meta-analysis was to characterise youth athletes' adaptability to sprint training (ST) across PRE-, MID-, and POST-PHV groups. Effect sizes were calculated as a measure of straight-line sprinting performance with studies qualifying based on the following criteria: (a) healthy male athletes who were engaged in organised sports; (b) groups of participants with a mean age between 10 and 18 years; (c) ST intervention duration between 4 and 16 weeks. Standardised mean differences showed ST to be moderately effective (ES = 1.01 95% confidence interval: 0.43-1.59) with adaptive responses being of large and moderate magnitude in the POST- (ES = 1.39; 0.32-2.46) and MID- (ES = 1.15; 0.40-1.9) PHV groups respectively. A negative ES was found in the PRE group (ES = -0.18; -1.35-0.99). Youth training practitioners should prescribe ST modalities based on biological maturation status. Twice weekly training sessions should comprise of up to 16 sprints of around 20 metre (20 m) with a work to rest ratio of 1:25, or greater than 90 seconds.

1.7 Outline of Study 4 - Maturation-related differences in adaptations to resistance training in young male swimmers

This study examined the effects of RT on muscular strength and jump performance in young male swimmers. It was hypothesised that adaptations would be of a lower magnitude in less mature (Pre-PHV) than in more mature (Post-PHV) participants. Fourteen Pre- (-1.8 ± 1.0 years) and 8 Post-PHV (1.6 ± 0.5 years) swimmers undertook a 30 minute, twice-weekly RT programme for 8 weeks. They were compared with matched control groups (Pre-PHV: -2.0 ± 1.1, n=15; Post-PHV: 1.2 ± 1.0, n=7). The effects on lower body isometric strength (LBS), measured with mid-thigh pull, and CMJ height in the Post-PHV group were large (ES: 1.3 [0.4 to 2.2]) and small (0.4 [-0.4 to 1.2]) respectively. Effects on LBS and CMJ height in the Pre-PHV group were moderate (0.8 [0.1 to 1.4]) and trivial (0.2 [-0.5 to 0.8]) respectively. Estimates in the Post-PHV control group (LBS: 0.7 [-0.2 to 1.6]; CMJ: 0.2 [-0.7 to 1.0]) and the Pre-PHV control group (LBS: 0.1 [-0.5 to 0.7]; CMJ: -0.3 [-0.9 to 0.3]) may indicate the extent to which maturation could contribute to the performance changes seen in the respective training groups. LBS and CMJ are trainable, but to different magnitudes, in Pre- and Post-PHV swimmers. Following appropriate foundational training to establish technical competency, twice-weekly RT sessions of 30 minutes duration, comprising 3 sets of 4 exercises can be effective in Pre-PHV and Post-PHV youth.

1.8 Outline of Study 5 - Maturation-related effect of low-dose plyometric training on performance in youth hockey players

The purpose of this intervention study was to investigate if a low-dose of PT could improve sprint and jump performance in groups of different maturity status. Male youth field hockey players were divided into Pre-PHV (from -1 to -1.9 from PHV; Experimental: n = 9; Control = 12) and Mid-PHV (0 to +0.9 from PHV; Experimental: n = 8; Control = 9) groups. Participants in the experimental groups completed 60 foot contacts, twice-weekly, for 6 weeks. PT exerted a positive effect (ES: 0.4 [-0.4 to 1.2]) on 10 metre (10 m) sprint time in the experimental Mid-PHV group but this was less pronounced in the Pre-PHV group (0.1 [-0.6

to 0.9]). Sprint time over 30 metres (30 m) (Mid-PHV: 0.1 [-0.8 to 0.9]; Pre-PHV: 0.1 [-0.7 to 0.9]) and CMJ (Mid-PHV: 0.1 [-0.8 to 0.9]; Pre-PHV: 0.0 [-0.7 to 0.8]) was maintained across both experimental groups. Conversely, the control groups showed decreased performance in most tests at follow up. Between-group analysis showed positive ESs across all performance tests in the Mid-PHV group, contrasting with all negative ESs in the Pre-PHV group. These results indicate that more mature hockey players may benefit to a greater extent than less mature hockey players from a low-dose PT stimulus. Sixty foot contacts, twice per week, seems effective in improving short sprint performance in Mid-PHV hockey players.

1.9 Outline of Study 6 - Maturation-related adaptations in running speed in response to sprint training in youth soccer players

This study investigated the effects of a previously recommended dose of ST in young male soccer players of differing maturity status who trained for 1 and 2 days per week. Male soccer players from two professional academies were divided into Pre-PHV (-3.9 to -2.4 years from peak height velocity [PHV]; 1 day: n = 12; 2 days: = 12; Control = 13) and Mid-PHV (-0.9 to +0.7 years from PHV; 1 day: n = 7; 2 days = 10; Control = 10) groups. The experimental groups completed 16 sprints of 20 m with 90 seconds recovery, either once or twice per week. Effect sizes were larger in Pre-PHV (10m [0.49, CI: 0.01 to 0.97]; 20 m [0.29, CI: -0.19 to 0.77]; 5-10-5 [0.78, CI: 0.29 to 1.27]) than in Mid-PHV (10m [0.33, CI: -0.24 to 0.89]; 20 m [0.22, CI: -0.35 to 0.78]; 5-10-5 [0.20, CI: -0.36 to 0.77]). Across all participants, 1 ST session per week (ES = 0.28 to 0.49) was generally more effective than 2 (ES = 0.09 to 0.43), exclusively so in Mid-PHV. The Pre-PHV groups (ES = 0.13 to 0.83) consistently outperformed their control group (ES = -0.08 to 0.25) while the Mid-PHV groups (ES = 0.08 to 0.51) did not outperform their control group (0.24 to 1.02). ST, in the amount of 16 sprints over 20 m with a 90 s rest, may be more effective in Pre-PHV youths than in Mid-PHV youths.

CHAPTER 2

Literature Review (Part 1)

2.1 Introduction

This literature review provides a summary of relevant research on the trainability of youth athletes and describes the roles of training and maturation at specific times along the developmental continuum, distinguishing between PRE-, MID-, and POST-PHV. With a view to clarifying this specific area of research, the literature review is divided into specific parts across chapters 2 to 6. This chapter offers an overview of the research area. Following on from this, and such is the nature of training intervention studies, a meta-analytical approach has been used to quantify the effects of specific training modalities to improve strength, power and speed at each identified stage of maturation (chapters 3 to 5). These meta-analyses included studies that conformed to strict parameters which were defined *a priori* but there are also a number of relevant studies which did not qualify for these analyses, in some cases due to non-conformation to a single criterion. Following presentation of the meta-analytical studies, Chapter 6 offers a further narrative review of these studies and contextualises them against the already-provided evidence.

The literature relating to exercise training within youth populations is affected by a number of limitations which have been elucidated by McNarry *et al*. (2014). Firstly, the absence of control groups in many studies has made it difficult to differentiate the effects of training and maturation. Moreover, whilst many studies have validated the use of certain training methods to enhance physical capabilities, the quality of inferences that can be derived from such studies is limited by a failure to account for participants' maturity status. This problem is exacerbated by a paucity of data that could reveal the extent to which certain physical abilities are trainable at specific stages of growth and maturation with few studies comparing adaptations between youths of differing maturity status. Also, a failure to use appropriate measures of performance to quantify training effects has further convoluted existing conclusions (de Hoyo *et al.*, 2016; Lloyd *et al.*, 2016b; Radnor, Lloyd and Oliver, 2016; Zouita *et al.*, 2016). Taken together, these limitations mean that certain training methods could ultimately be misapplied during key stages of youths' development, potentially resulting in a lack of adaptation, maladaptation or injury (Lloyd *et al.*, 2016a; Matos and Winsley, 2007).

Furthermore, a distinction must be made between youths who are considered as being athletes and those who are not. Hansen *et al.* (1999) found that elite youth soccer players were stronger than their non-elite counterparts, a difference that was independent of hormonal profile thus indicating the presence of other factors that determine the trainability of different populations of youths. This could potentially denote athletes as a subset of individuals whose biological characteristics differentiate them from the wider population of youths.

With the recent emergence of a number of intervention studies (Franco-Márquez *et al.*, 2015; Meylan *et al.*, 2014a; Ramirez-Campillo *et al.*, 2015b; Ramirez-Campillo *et al.*, 2015c; Rumpf *et al.*, 2015) that take account of the biological maturity status of the participants using the maturity offset method (Mirwald *et al.*, 2002), researchers are beginning to address the above-mentioned limitations pertaining to physical training in youths. However, whilst many studies go some way to addressing these issues, few have done so within a single investigation. For instance, some authors (Meylan *et al.*, 2014a; Rumpf *et al.*, 2015), despite incorporating measures of biological maturity status into their study designs, have not included control groups. This means that following a training intervention, it is difficult to conclude whether any changes in physical performance could be attributed to training adaptations or the natural development of physical attributes independent of training activities. Those authors (Franco-Márquez *et al.*, 2015; Ramirez-Campillo *et al.*, 2015b; Ramirez-Campillo *et al.*, 2015c; Rodriguez-Rosell *et al.*, 2016) who did include control groups in their research designs predominantly conducted within-group comparisons of athletes of the same age or maturity status, meaning that despite a training effect being discernible from the natural development of physical performance, a comparison of youths of varying maturity status was not possible. Some researchers have addressed these issues concurrently within the same study but did not incorporate measures of performance which could be considered as being appropriate to the programmed intervention. For example, Lloyd *et al.* (2016b) included control groups and biologically disparate training cohorts in their study of different types of strength and conditioning training but failed to incorporate a measure of muscular strength with which to assess the effectiveness of a traditional RT protocol. Accordingly, until such considerations are comprehensively addressed concurrently and repeatedly in the literature, it is unlikely that definitive conclusions can be made with regard to the trainability of youth athletes as they mature.

2.2 Overview

Training is a multifactorial, modifiable stimulus that promotes physical development, optimises sports performance and reduces injury risk (Lloyd and Oliver, 2012). Biological maturation refers to the development of the body's tissues, organs and systems, the variable timing and tempo of which can influence all three of the aforementioned factors (Malina, Bouchard and Bar-Or, 2004), particularly during adolescence (Malina *et al.*, 2015). Though training and maturation both impact physical development, with the exception of body mass, coaches can only affect variables relating to training. This means that these can be considered as 'modifiable' (training) and 'non-modifiable' (maturation) factors. Though coaches must be aware of the non-modifiable factors as a signposting mechanism for the programming of training activities, they are likely to be more interested in factors upon which they can exert a direct influence.

The trainability of youths seems to be underpinned by a number of biological processes that occur non-linearly throughout the course of growth and maturation. For example, Frost *et al.* (1997) found that cocontraction of the musculature of the lower extremities was greater in younger children when expressed relative to speed and VO_2max, concluding that this may be why children experience a greater metabolic cost due to movement than adolescents or adults. Buchheit *et al.* (2011) observed differences in the way that members of a group of Pre-PHV soccer players (n = 15) recovered from the exertions of match play when compared to older players (n = 13) in a Post-PHV group. These authors found that high-intensity match running performance during a soccer game played 48 hours after an initial game was improved following a recovery protocol in younger participants (+27%) whilst performance in older participants decreased (-9%). The researchers theorised that this could be due to a reduced metabolic cost and lower degree of homeostatic perturbations owing to smaller stores of muscle mass and associated inability to exert comparable levels of muscular force. Gabbett, Johns and Riemann (2008) found that training adaptations were of a greater magnitude in under 15 rugby league players (n = 14, mean age = 14.1 ± 0.2 years) than they were in under 18 players (n = 21, mean age = 16.9 ± 0.3 years) in response to training over a 10 week period. Indeed, whilst the younger group saw improvements in running speed over 10, 20 and 40 metres, CMJ and $\dot{V}O_2$max, the older group improved only in CMJ and $\dot{V}O_2$max. It was recommended by Gabbett, Johns and Riemann (2008) that to elicit optimal adaptations, older players may need to train as much as 8 weeks longer during the preseason preparation period, placing a greater priority on the development of aerobic, strength and power qualities than comparatively younger players, possibly due to a lower ceiling of adaptation to training (Hawley, 2008). However, Wrigley *et al*. (2012) state that the mismatch between training and match intensity makes optimal programming of appropriate training loads a difficult task amongst older age-grade athletes (under 18) who spend a greater proportion of time above 90% of maximal heart rate than younger players (under 14). This introduces an interesting dilemma for coaches who are responsible for the formulation of youth athletic development programmes.

More specific to the current work, interventions for RT (Meylan *et al.*, 2014a), resisted ST (Rumpf *et al.*, 2015) and combined training (Lloyd *et al.*, 2016b) revealed that more mature youths seemed more responsive to the effects of the applied stimuli, indicating an effect of maturation on adaptations. Further complicating the relationship between training and maturation is the finding that PHV coincides with an increased vulnerability to injury in active youth (van der Sluis *et al.*, 2014) with this potentially attributed to the phenomenon of adolescent awkwardness whereby motor coordination is temporarily disrupted due to rapid growth (Lloyd *et al.*, 2011). These contrasting findings underline the dynamic nature of the interacting processes that determine adaptations to exercise, complicating practitioners' approach to programming, given that too much training may lead to maladaptation (Matos and Winsley, 2007), whilst too little could result in lower fitness levels and an associated greater risk of injury (Gabbett and Domrow, 2005). Accordingly, the trainability of youth athletes can present challenges to practitioners which are potentially more difficult to negotiate than those seen in adult populations.

Based on this evidence, optimising the timing and delivery of training while respecting maturational status and avoiding overtraining and injury is paramount for coaches nurturing talented youth athletes toward meeting their full potential. However, the ways and means to achieve this goal can be complicated and this represents a sizeable challenge within the context of LTAD: coaches need to apply an appropriately weighted training stimulus whilst also respecting the underpinning principles that govern modern utilised models of youth physical development (Bailey *et al.*, 2010; Balyi and Hamilton, 2004; Lloyd and Oliver, 2012). This means that strategically timed training is a high priority and it is, therefore, vital that programming parameters such as mode, duration, intensity and frequency are more rigorously investigated at specific times of biological maturation (Lloyd *et al.*, 2015b). This supports the well-accepted assertion that youth trainees should be exposed to a wide range of motor-activities throughout the process of biological development in order to comprehensively develop abilities such as decision-making and the anticipation of movement patterns (Lloyd *et al.*, 2015b). Such an approach greatly enhances movement competence and is the foundation for future sporting performance (Lloyd *et al.*, 2015b). Given that the responses to training can be highly variable amongst children who are of a similar age but who may differ in terms of maturational status (Anderson and Twist, 2005; Lloyd *et al.*, 2011; Meylan *et al.*, 2014a; Pearson, Naughton and Torode, 2006), acknowledgement of the specific physical and biological profile of an individual athlete may inform the prescription of appropriate training programmes and the realisation of optimal fitness potential in the long term.

2.3 The trainability of youths and the trigger hypothesis

An article by Katch (1983) discussed the ‘trigger hypothesis’ which holds that during the prepubertal period of development, the magnitude of fitness gain due to training is only small due to what is termed as a lack of hormonal control. Because of this, the author suggested that skill acquisition activities would be more beneficial to prepubertal children than physical conditioning as their hormonal and physiological profiles are not conducive to developing the latter. Summarising the evidence on the subject of aerobic training in youth, Matos and Winsley (2007) argued in favour of this stance highlighting that in training intervention studies, children typically improved aerobic capacity by no more than 10% whilst young adults often showed increases of between 15% and 20%. Indeed, previously, a similar pattern of long-term adaptation had been observed in a meta-analysis of the effects of training on $\dot{V}O_2$max in children (Payne and Morrow Jr, 1993) and another review (Payne *et al.*, 1997) by the same authors highlighted sources which claimed that a similar phenomenon existed in relation to other types of physical activity such as RT. However, Armstrong and Barker (2011) suggest that the relative intensity of the exercise that is undertaken is a key determinant of adaptation meaning that adults and children who undertake training programmes of relatively equalised training loads can increase fitness levels at a similar rate. In this way, the apparent manifestation of the trigger hypothesis may merely be representative of a difference in the way that older and younger individuals adapt to different volumes or intensities of training, as opposed to different modalities. Tolfrey, Campbell and Batterham (1998) suggest that a blunted response to exercise in prepubertal children either validates the theory of Katch (1983) or indicates the need to impose a more intense training stimulus on youths. In line with this assertion, a study carried out by McNarry, Mackintosh and Stoedefalke (2014) may be demonstrative of the criticisms previously highlighted by Ford *et al*. (2011) with regard to the existence of sensitive periods of adaptation and a critical maturational threshold above which adaptations to training are more apparent (Katch, 1983). These researchers also demonstrated that a more important consideration may be the overall training load and the magnitude of the applied stimulus as they found that the difference in performance levels between trained (n = 19, mean age = 10.4 ± 1.1 years, 8 males) and untrained (n = 15, mean age = 9.8 ± 0.9 years, 5 males) swimmers in their study cohort was unaffected by maturity. In years 1, 2 and 3 of the study, children reported training loads of 6 ± 3, 8 ± 3 and 12 ± 4 hours per week and when body size was controlled for, increases in VO_2max were not mediated by maturation status. This would seem to challenge the trigger hypothesis as a main factor in adaptations to endurance training with the researchers suggesting that previous studies that have reported the potential existence of a maturational threshold for athletic development (Lloyd and Oliver, 2012; Mirwald *et al.*, 1981; Ostojic *et al.*, 2009) may merely be reflective of inadequately low training loads amongst younger participants.

It must be highlighted that much of the above evidence on the trigger hypothesis relates to endurance training only which necessitates the further investigation of training modalities to improve speed, strength and power. In relation to this, there has been some compelling evidence of the presence of a specific trigger point for other physical capacities in youth presented by Philippaerts *et al*. (2006). These researchers tracked long term changes in youth soccer players (n = 33, mean age = 12.2 ± 0.7 years) whilst controlling for maturation status as denoted by years to/from PHV and found that the peak rate of development of most measured performance variables occurred at the same time as PHV. Balance, power and endurance tests were undertaken with only flexibility reaching peak development outside the PHV phase, achieving its fastest rate 12 months after the growth spurt. Based on playing level, players in this study undertook between 3 and 6 hours of soccer training and/or play on a weekly basis, though more telling conclusions are difficult to make as the composition of this training was not reported. Nevertheless, the study seems to expand on the trigger hypothesis by extending its applicability beyond the development of VO_2max, suggesting that other physical competencies may also be regulated by similar physiological or hormonal phenomena. However, the differentiating of training adaptations from biological maturation was not possible due to the lack of a control group.

On the contrary, the development of different performance characteristics over 8 weeks of RT or endurance training was investigated by Marta *et al.* (2014) These researchers found no evidence to suggest that non-athletic children who were more biologically mature (Tanner stage 2 vs. stage 1) adapted to exercise at a greater magnitude than their less mature peers, however the age range of the study participants (10-11 years) may not have been diverse enough to reveal any differentials in the magnitude of the training response. The results of Marta *et al.* (2014) may therefore have occurred because both groups were too young to have yet surpassed any maturational threshold, or because the Tanner method of maturity assessment may not have categorised participants in an appropriately sensitive way (Malina, 2002).

On the whole, though there exists evidence for and against the presence of a maturational threshold that regulates responses to exercise training in youth, much of the evidence against is centred on aerobic capacity and endurance exercise. To date, it is unclear as to whether the trigger hypothesis applies to training methods aimed at increasing muscular strength, speed and power and this work seeks to address this issue.

2.4 Long Term Athlete Development

The primary purpose of the LTAD model is to establish guidelines relating to the need to balance training stimuli and competition schedules throughout the periods of childhood and adolescence (Ford *et al.*, 2011). Seemingly, the model serves as a framework within which objective measures of physiological maturity, such as PHV, can be used to estimate an individual's maturation status so that an appropriate training stimulus can be applied at the four primary stages of the model: the 'FUNdamental' phase, the 'Training to Train' phase, the 'Training to Compete' phase and the 'Training to Win' phase. This means that training, in theoretical terms at least, should coincide with so-called sensitive periods of adaptation, leading to optimal adaptations to the imposed demands of physical activity (Balyi, Way and Higgs, 2013).

A practical example of this is described by Lloyd *et al*. (2014b) who recommend that longitudinal tracking of PHV could assist in the identification of a period of impaired motor control, or ‘adolescent awkwardness’ (Beunen and Malina, 1988; Eckrich and Strohmeyer, 2006), which is related to increased growth rates and could result in greater susceptibility to injury (van der Sluis *et al.*, 2014). Measurements such as this could, in turn, inform the regulation of training and facilitate the avoidance of excessive strain at a time when safe movement could be compromised, whilst also providing the necessary latitude to preserve and reinforce important movement patterns (Lloyd *et al.*, 2014b) such as pushing, pulling, rotating, jumping and running (Lloyd *et al.*, 2015b).

Appropriate manipulation of a youth athlete’s environmental conditions has been advocated by way of recommendations for stage-appropriate training programmes that cater to the specific developmental needs of the individual concerned (Ford *et al.*, 2011; Vaeyens *et al.*, 2008). Systematic approaches to the development of talent in youth populations, such as the LTAD model, are not a novel concept with several former Soviet bloc countries exposing children to concentrated sport training to exploit pre-identified athletic potential (Malina *et al.*, 2015). Though physiological changes during puberty are determined hereditarily, the development of characteristics associated with biological maturation can also be influenced by conditions in the surrounding environment (Krivolapchuk, 2011). The LTAD model could be considered to be an appropriate framework within which such programmes could be constructed and prescribed but it seems that it lacks the necessary facility to achieve the level of individualisation that could see this objective realised (Ford *et al.*, 2011).

The LTAD model has not been subjected to extensive academic scrutiny at this juncture and the veracity of its claims have been questioned by several authors (Ford *et al.*, 2011; Gulbin *et al.*, 2013; Lloyd and Oliver, 2012). Nevertheless, the principles that underpin the development of physical competencies within an athletic context (Lloyd and Oliver, 2012) should be conformed to throughout the Pre-, Mid- and Post-PHV periods and so, at the current time, the LTAD model may represent the most appropriate mechanism to guide the formulation of biological age-appropriate training programmes.

The effective prescription of such programmes represents a highly important component in the transition of athletes to the senior level of sport with exposure to training seen as a critical determinant of a youth's ability to operate successfully into adulthood (Capranica and Millard-Stafford, 2011; Vaeyens *et al.*, 2008). A meticulous approach to training prescription would be to pinpoint those physical attributes, such as sport-specific skills and physical capabilities, which may be required for a youth athlete to continue to demonstrate excellence into adulthood and to channel resources into sequentially developing these specific characteristics as less emphasis is placed on more general and transferable skills over time. However, the extent to which these skills and physical attributes should receive attention within the training programme has yet to be determined as there is little academic guidance on what constitutes the optimal timing, dose and type of training required to elicit positive adaptations in youth athletes (Capranica and Millard-Stafford, 2011; Wrigley *et al.*, 2014). Accordingly, prospective, sport-specific research, which outlines optimal training parameters, must be carried out to clarify how best to approach exercise programming in youth.

2.5 Maturation status and training

When body mass and biological maturation are controlled for (Mendez-Villanueva *et al.*, 2011a), performance still varies in youths suggesting that several other factors can influence the trainability of youths. Oliver and Rumpf (2014) suggest that neuromuscular training may be more beneficial prior to the growth spurt whilst RT may be more effective after. Indeed the plasticity of the neuromuscular system is said to be heightened during childhood (Lloyd *et al.*, 2015a) and this could have implications for the structuring of youth athletic training and associated development. Bailey *et al*. (2010) state that training practitioners should be mindful of training all elements of physical fitness throughout the critical and non-critical periods of development alike but this does not explicitly suggest that specific emphasis cannot, or does not need to, be placed on the cultivation of certain physical competencies at key junctures along the developmental continuum. Indeed, a study that was undertaken by Krivolapchuk (2011) suggests that younger participants were more dependent on aerobic pathways for energy production in contrast to older participants who were more reliant on anaerobic processes. This may affect the prescription of training as it has been argued that bouts of activity that exceed 15 seconds duration are difficult for prepubertal youths to sustain owing to low energy delivery due to an immature glycolytic capacity (Boisseau and Delamarche, 2000). As youths mature, increases in the thickness of type IIb muscle fibres occur and they also begin to proliferate in proportion to type I fibres which remain largely constant in number. Three months after the elongation of the body begins, muscle mass starts to increase and three months after that, body mass starts to rise. This could explain a preferential shift towards higher performance in anaerobic activities in and around the growth spurt (Philippaerts *et al.*, 2006). Factors such as these must be clarified from a performance perspective so that coaches can assess the effectiveness of different training types at different stages of maturation.

The LTAD framework suggests that measures of biological maturity status, such as maturity offset (Mirwald *et al.*, 2002), can facilitate practitioners in accounting for the non-linear development of individual athletes and can serve as a signposting mechanism for the prescription of appropriate training modalities at relevant stages of the model (Ford *et al.*, 2011). Though there is not enough evidence to explicitly advocate this approach, the maturity offset is thought to provide valuable reference points which denote critical periods of development during which sensitivity to the demands of training could be potentially heightened (Lloyd and Oliver, 2012). This could serve as a way of individualising training prescription (Philippaerts *et al.*, 2006) and the method is used to differentiate youths of varying maturity status in this work. A number of authors (Franco-Márquez *et al.*, 2015;

Meylan *et al.*, 2014a; Rodriguez-Rosell *et al.*, 2016; Rumpf *et al.*, 2015) have also categorised their study participants by biological age with the maturity offset. Given the highly variable timing and tempo of anthropometric and morphological changes in male youths (Baxter-Jones, Eisenmann and Sherar, 2005; Beunen and Malina, 1988; te Wierike *et al.*, 2015), this could be seen as a more accurate way of accounting for biological maturation than chronological age (Philippaerts *et al.*, 2006; Till and Jones, 2015).

2.6 Limitations of current research

To date, there has been a lack of intervention studies that incorporate control groups whilst using a measure of biological maturity status to partition the effects of training and maturation and to compare maturation-dependent responses to exercise. Additionally, researchers have generally failed to compare the effects of training in groups of disparate age or maturity status meaning that it has been difficult to determine whether or not specific types of exercises stimulate different responses across the developmental continuum. Lastly, researchers have often failed to include measures of performance that can appropriately measure the extent of the training effect if any. An example of this can be seen in the case of a researcher who applies a RT programme but does not measure strength before and after the intervention. Some studies address some of these issues but to date, the author is unaware of any that addresses all. To make clear conclusions on the trainability of youths, these issues must be explicitly addressed.

In interpreting this work the reader must be mindful that the physical and physiological changes that are associated with growth and maturation can differ substantially in youth with the magnitude of development showing variability across age groups. This can exert an effect on the degree of response to, and recovery from, training (Lloyd *et al.*, 2016a). In addition to this, when interpreting the presented research on exercise training in youth, the reader must be mindful that variability in data analysis techniques and the characteristics, histories and abilities of study participants could potentially convolute findings and interpretations (Beunen and Malina, 1988; Buchheit and Mendez-Villanueva, 2013).

CHAPTER 3

A meta-analysis of maturation-related variation in adolescent boy athletes' adaptations to short-term resistance training

Citation

Moran, J., Sandercock, G. R., Ramírez-Campillo, R., Meylan, C., Collison, J. and Parry, D. A. (2017). A meta-analysis of maturation-related variation in adolescent boy athletes’ adaptations to short-term resistance training. *Journal of Sports Sciences*. 35(11), 1041-1051.

Abstract

This meta-analysis investigated the maturation-related pattern of adaptations to RT in boy athletes. Included were studies examining the effects of 4-16 week RT programmes in healthy boy athletes aged 10 to 18 years. Pooled estimates of ES for change in strength across all studies (n = 19) were calculated using the inverse-variance random effects model for meta-analyses. Estimates were also calculated for groups based on likely biological maturity status (PRE, MID and POST-PHV). Using the standardised mean difference, RT increased strength across all groups (ES = 0.98, [CI: 0.70-1.27]). Strength gains were larger in MID- (1.11 [0.67-1.54]) and POST- (1.01 [0.56-1.46]) PHV than they were in PRE (0.5 [-0.06-1.07]). Adaptations to RT are greater in adolescent boys during or after PHV. These findings should help coaches to optimise the timing of training programmes that are designed to improve strength in boy athletes.

3.1 Introduction

Maximal strength is defined as the maximum force or torque that can be exerted by skeletal muscles in a given movement (Knuttgen and Komi, 2003) or action. High muscular strength is an integral element of sport performance for young athletes (Lloyd *et al.*, 2015a; Sander *et al.*, 2013) and RT is an effective way to enhance this quality (Chelly *et al.*, 2009; Christou *et al.*, 2006). However, there is variation in how children and adolescents of different biological maturity status adapt to the demands of RT (Meylan *et al.*, 2014a).

A recent meta-analytical review (Behringer *et al.*, 2010) reported that RT was effective for increasing strength in general population youths, with a combined weighted ES of 1.1 (0.9-1.3). Later, Behringer *et al.* (2011) conducted a meta-analysis on the effects of training on the motor skills of running, jumping and throwing, and identified that younger participants and non-athletes had greatest improvement after RT exercise. More recently, Harries, Lubans and Callister (2012) focused exclusively on RT in youth athletes and identified a mean difference in CMJ performance (cm) of 3.0 (1.6-4.5). This reinforced an earlier review that demonstrated similar results (Payne *et al.*, 1997). Most recently, Lesinksi, Prieske and

Granacher (2016) conducted a meta-analysis on the dose-response and programming variables of RT in youths, finding small to medium ESs across various physical qualities.

Despite these studies, when combined, the meta-analytical literature on RT with respect to biological maturation in youths is affected by several key limitations. Researchers have tended not to explicitly address mediating effects of biological maturity on adaptations to RT. Those that have implicitly addressed the issue (Behringer *et al.*, 2011; Behringer *et al.*, 2010; Lesinski, Prieske and Granacher, 2016) have treated it only as a categorical moderator variable with boys and girls analysed in the same subgroups, making any conclusions largely redundant. Boys experience different maturational changes to girls (Marceau *et al.*, 2011) and these changes give rise to differentials in performance throughout biological maturation (Ford *et al.*, 2011). In addition, the inclusion of trials of long duration, in some cases in excess of one year (Behringer *et al.*, 2011; Behringer *et al.*, 2010; Lesinski, Prieske and Granacher, 2016), distorts any maturation-related conclusions as participants can undergo substantial biological changes throughout the study period. Furthermore, the grouping of training methods, such as PT and traditional RT, to make inferences about a single outcome measure (Lesinski, Prieske and Granacher, 2016), is erroneous given the independent nature of training adaptations to different exercise modalities (Vissing *et al.*, 2008), and the principle of training specificity (Gamble, 2006). On this, the principle of specificity is also often ignored for outcome measures with many reviewers including studies that reported no measure of muscular strength. These factors are important for practitioners to consider when research informs the prescription of RT.

In youths, the optimal long-term timing of RT is not well described. Adaptations to RT vary according to biological maturation (Behringer *et al.*, 2010; Malina, 2006) and this type of activity seems less effective in increasing the strength of young athletes when performed in PRE-PHV (Meylan *et al.*, 2014a). This review builds on previous analyses by focusing specifically on boy athletes and adopts a novel approach to characterise the pattern and specificity of adaptations to RT throughout biological maturation. Biological maturity and training status are important considerations in the prescription of this type of exercise. Accordingly, this study seeks to account for shortcomings in a way that is relevant to practitioners. No meta-analysis has adopted this multidimensional perspective.

3.2 Methods

3.2.1 Experimental Approach to the Problem

This study was approved by the University of Essex Ethics Committee. The review was carried out in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) statement (Liberati *et al.*, 2009). A comprehensive literature search was conducted before the results were analysed using a random-effects model.

3.2.2 Literature search

The search process is shown in Figure 3.1. With no date restrictions, an extensive search of the PubMed, Google Scholar, Sport Discus, Medline, CINAHL and Science Direct databases was conducted. Words used either as individual search terms or in conjunction with each other included 'strength', 'power', 'weightlifting', 'resistance', 'training', 'exercise', 'paediatric', 'youth', 'young', 'children', 'adolescence', 'athletes', 'sport', 'volume', 'intensity', 'fitness', 'high', 'load', 'rest', 'sets' and 'repetitions'. Only articles published in peer-reviewed journals were selected. Study selection involved a review of all seemingly relevant article titles and was followed by an evaluation of article abstracts and, then, full published articles. After this, article reference lists were searched.

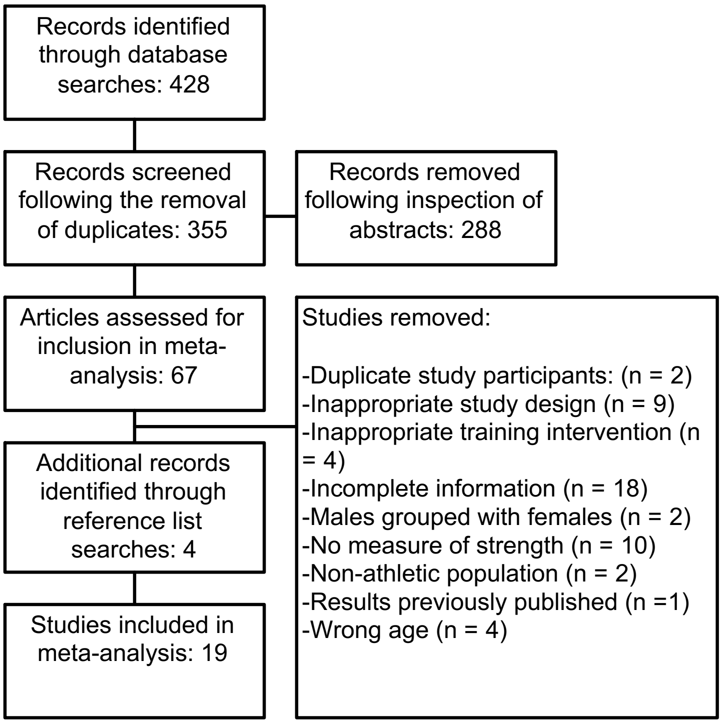


Figure 3.1 Flow chart for inclusion and exclusion of studies

Specific criteria determined studies' eligibility for inclusion. Studies must have included healthy sport-playing boys. Ages must have been stated for all within-study groups and participants must have been no younger than the mean age of 10 and no older than the mean age of 18 years: the adolescent growth spurt occurs at the age of approximately 11 years in boys (Malina, 1999) but can be preceded by several markers of sexual maturation, such as pubic hair and genitalia development at approximately the age of 10 years (Sun *et al.*, 2002). By age 18 years, full adult stature is usually attained (de Onis *et al.*, 2007; Sherar *et al.*, 2005). Studies must also have included a RT programme that conformed to descriptions used in previous reviews: exercise that "requires the musculature to contract (sic.) against an opposing force generated by some type of resistance" (Behringer *et al.*, 2010) and "resistance training using body mass or additional external weights" (Rumpf *et al.*, 2012). Programmes must have been between 4 and 16 weeks in duration and authors must have provided means and standard deviations for a measure of muscular strength for before and after the intervention.

Resistance training can improve strength in six weeks (Faigenbaum *et al.*, 2007) therefore a minimum training programme duration of four weeks was chosen to capture short-term effects. Biological maturation has a substantial impact on physical performance over an extended period of time (Beunen and Malina, 1988; Yagüe, La Fuente and Manuel, 1998). To minimise this impact on the estimates, an upper limit programme duration of 16 weeks was imposed to distinguish between the effects of training and advancing maturation.

The physical characteristics of groups are in Table 3.1 and the study characteristics are in Table 3.2. Nineteen studies provided enough information to be included.

Group	**All**	**PRE**	**MID**	**POST**
	n = 496	*n* = 57	*n* = 279	*n* =160
Age (y)	15.1 ± 2.0	11.1 ± 1.1	14.9 ± 1.2	16.9 ± 1.0
Stature (cm)	170.7 ± 14.4	145.4 ± 8.4	173.2 ± 9.9	176.2 ± 12.7
Mass (kg)	65.2 ± 16.0	38.3 ± 11.2	60.4 ± 21.5	74.5 ± 9.8

PRE: 10-12.99 year olds; MID: 13-15.99 year olds; POST: 16-18 year olds.

Table 3.1 Descriptive data for participants from resistance training studies included in meta-analysis

3.3.3 Maturity status

In order to estimate the likely maturity status for the participants in each study, the age groups used by previous researchers (Meylan *et al.*, 2014b; Rumpf *et al.*, 2012) were utilised (10-12.99 years = pre-PHV [PRE], 13-15.99 years = mid-PHV [MID], 16-18 years = post-PHV [POST]). Existing studies of exercise training in youths are limited by an absence of controls for the biological maturity status of trial participants. This justified the use of the current method on the basis that 'the interval of maximal growth' occurs between the ages of 13 and 15 years in males (Malina, Bouchard and Bar-Or, 2004; Malina and Geithner, 2011), a period defined here as MID. Peak height velocity usually occurs around the age of 14 in a

North American/European population (Malina, Bouchard and Bar-Or, 2004; Rumpf *et al.*, 2012) and despite youth athletes having a tendency to be more biologically mature than non-athletes (Malina, 2011), a number of longitudinal studies have estimated the PHV of this population to occur around this time (Bell, 1993; Froberg, Anderson and Lammert, 1991; Philippaerts *et al.*, 2006; Šprynarová, 1987). In and around the age of 14 years is a critical period for training-related physiological development in youth (Deprez *et al.*, 2015a). The onset of the growth spurt usually occurs one year prior to this (Tanner, Whitehouse and Takaishi, 1966) whilst up to 94% of full adult height is attained by age 15 (Malina *et al.*, 2005; Malina *et al.*, 2004). At this time, the highest degree of diversity in biological maturity amongst boys is apparent, with these differences typically levelling off after the age of 16 years (Malina *et al.*, 2015), a period defined here as POST.

3.3.4 Data Extraction

The extraction of data from gathered articles, displayed in Figure 3.2 and Table 3.2, was undertaken by two reviewers. The first reviewer collected the data before the second reviewer investigated its accuracy and the eligibility of studies for inclusion.

Where data were incompletely or unclearly reported, study authors were contacted for clarification. Where more than one relevant performance test was carried out, ESs were calculated by selecting the most relevant measure of muscular strength “based on theory or a logically defensible rationale” (Turner and Bernard, 2006). To account for the specificity of the training adaptation, surrogate measures such as a CMJ were not considered, unlike in a previous meta-analysis (Harries *et al.*, 2012). Where possible, a maximal squat, or similar, was chosen because of that exercise’s validity in measuring strength, its specificity to athletic movements and muscle actions, the large amount of muscle mass it recruits and its common prescription in exercise training programmes (Hoffman, 2006).

Reference	Age (years)	Maturation	Stature (cm)	Mass (kg)	Sport	Group	Group Identifier	Number of Participants	Resistance Training Experience (years)	Training frequency (per week)	Number of Weeks	Mean Total sessions	Test
Chaouachi *et al.* (2014b)	11 (1)	Pre	145.5 (8.1)	35.9 (9.7)	Judo and Wrestling	Olympic-style weightlifting	OWL	17		2	12	24	Isokinetic leg strength at 60 degrees per second (kg)
Chaouachi *et al.* (2014b)	11 (1)	Pre	145.1 (8.8)	39 (11.4)	Judo and Wrestling	Resistance training	Trad. RT	16		2	12	24	
Meylan *et al.* (2014a)	12.4 (0.7)	Pre	152 (4.7)	41.5 (4)	Sports Academy	Pre-PHV	Pre	10		2	8	16	1RM Leg Press (kg)
Rumpf *et al.* (2015)	10.4 (0.8)	Pre	141 (7.93)	38.2 (15.6)	Various	Pre-peak height velocity	PHV	14		2.66	6	16	Peak Horizontal Force (N)
Behringer *et al.* (2013)	15.1 (1.8)	Mid	175.8 (12.9)	62.3 (13.9)	Tennis	Resistance-training	RG	13		2	8	16	10RM Leg Press (kg)
Behringer *et al.* (2013)	15.5 (0.9)	Mid	177.1 (8.2)	65.2 (9.6)	Tennis	Plyometric training	PG	10		2	8	16	
Channell and Barfield (2008)	15.7 (1.23)	Mid	175.51		American Football	Olympic Lifting	OT	11	1.87 (0.81)	3	8	24	1RM Squat (kg)
Channell and Barfield (2008)	15.6 (0.6)	Mid	180.59		American Football	Powerlifting	PT	10	1.87 (0.81)	3	8	24	
Christou *et al.* (2006)	13.8 (0.4)	Mid	162 (3.8)	52 (3.3)	Soccer	Strength-soccer	STR	9		2	16	32	1RM Leg Press (kg)
Gabbett, Johns and Riemann (2008)	14.1 (0.2)	Mid	169.5 (2.1)	65.9 (2.7)	Rugby League	Under 15	Under 15	14	0	3	10	30	20 second Chin Ups Test (Chin Ups)
Gorostiaga *et al.* (1999)	15.1 (0.7)	Mid	173.1 (5.3)	62.4 (7.1)	Handball	Strength training	ST	9		2	6	12	1RM Leg Press (kg)
Ignjatovic *et al.* (2011)	15.7 (0.8)	Mid	183.6 (6.1)	73.5 (10.1)	Basketball	Experimental	E	23	0	2	12	24	1RM Bench Press (60% intensity)

													(N)
Meylan *et al.* (2014a)	13.6 (0.6)	Mid	165 (5.8)	53.6 (10)	Sports Academy	Mid-PHV	Mid	11		2	8	16	1RM Leg Press (kg)
Meylan *et al.* (2014a)	14.3 (0.7)	Mid	174 (4.2)	66 (9.1)	Sports Academy	Post-PHV	Post	12		2	8	16	
Rumpf *et al.* (2015)	15.2 (1.6)	Mid	173 (5.32)	62.7 (11)	Various	Mid-/post-peak height velocity	Mid-/post-PHV	18		2.66	6	16	Peak Horizontal Force (N)
Sarabia *et al.* (2015)	15.4 (0.8)	Mid	171.9 (4.1)	65.5 (6.9)	Tennis	Experimental	EG	11	0	2	6	12	Parallel half-squat (N)
Szymanski *et al.* (2004)	15.3 (1.2)	Mid	176.6 (7.8)	72.3 (13.4)	Baseball	Strength	Group 1	23		3	12	36	1RM Parallel Squat (kg)
Szymanski *et al.* (2004)	15.4 (1.1)	Mid	179 (5)	72.1 (7.9)	Baseball	Strength and Wrist Training	Group 2	20		3	12	36	
Szymanski *et al.* (2007)	15.3 (1.2)	Mid	178.4 (7.8)	76.2 (13.4)	Baseball	Strength	Group 1	24		3	12	36	1RM Parallel Squat (kg)
Szymanski *et al.* (2007)	15.4 (1.1)	Mid	176.4 (5)	72.5 (7.9)	Baseball	Strength and Medicine Ball Training	Group 2	25		3	12	36	
Takai *et al.* (2013)	13.6 (0.6)	Mid	158.00	49.30	Various	Training	Training	36		5.625	8	45	Maximal Knee Extension Strength (kg)
Campos Vázquez *et al.* (2015)	18 (0.9)	Post	177.9 (4.8)	70.6 (5)	Soccer	Squat	SG	10		2	8	16	Mean Velocity in Full Squt - 77.5kg (m/s)
Chelly *et al.* (2009)	17 (0.3)	Post	173 (3)	59 (6)	Soccer	Resistance training	RTG	11	0	2	8	16	1RM Half Squat (kg)
Coutts, Murphy and Dascombe (2004)	16.6 (1.2)	Post	168 (6.4)	74.7 (8.6)	Rugby League	Unsupervised	UNSUP	21		3	12	36	3RM Squat (kg)
Coutts, Murphy and Dascombe (2004)	16.8 (1)	Post	170 (5.4)	77.9 (8.7)	Rugby League	Supervised	SUP	21		3	12	36	
Gabbett, Johns and	16.9 (0.3)	Post	179.7 (1.3)	80.1 (2.3)	Rugby League	Under 18	Under 18	21	0	3	10	30	20 second

Riemann (2008)													Chin Ups Test (Chin Ups)
Harries, Lubans and Callister (2016)	16.8 (1)	Post	180.4 (3.3)	88.7 (18.2)	Rugby Union	Linear periodised	LP	8	0.5	2	12	24	1RM Box Squat (kg)
Harries, Lubans and Callister (2016)	17 (1.1)	Post	181.3 (7)	82.4 (12.6)	Rugby Union	Daily undulating periodised	DUP	8	0.5	2	12	24	
Kotzamanidis *et al.* (2005)	17 (1.1)	Post	178 (35)	73.50	Soccer	Combined Training	COM	12		2.3	13	29.9	1RM Half Squat (kg)
Kotzamanidis *et al.* (2005)	17.1 (1.1)	Post	175 (25)	72.50	Soccer	Strength Training	STR	11		2.3	13	29.9	
Prieske *et al.* (2016)	16.6 (1.1)	Post	182 (0.05)	72.5 (6.3)	Soccer	Stable surface core	CSTS	19		2.4	9	21.6	Trunk Flexion Isometric Force (N)
Prieske *et al.* (2016)	16.6 (1)	Post	179 (0.07)	69.4 (7.2)	Soccer	Unstable surface core	CSTU	18		2.3	9	20.7	

Table 3.2 Characteristics of the reviewed studies and their participants

3.3.5 Statistical analysis

The meta-analysis was carried out using the RevMan software (Review Manager Version 5.3). The inverse-variance random-effects model for meta-analyses was chosen because it assigns a proportionate weight to studies based on the magnitude of their respective standard errors (Deeks, Higgins and Altman, 2008) and permits analysis while controlling for heterogeneity across trials (Kontopantelis, Springate and Reeves, 2013). As researchers used different outcome measures to assess muscular strength, effects are represented by the standardised mean difference between pre- and post-intervention measures in training groups only (Sedgwick and Marston, 2013), and are presented alongside 95% confidence intervals. Effect sizes were evaluated according to Hopkins, *et al*. (2009) i.e. <0.2 = trivial; 0.2-0.59 = small, 0.6-1.19 = moderate, 1.2-1.99 = large, 2.0-3.99 = very large, ≥4.0 = extremely large.

Study heterogeneity was confirmed via the I^2 statistic. This represents the proportion of "the total variation in estimated effects across studies that is due to heterogeneity rather than to chance" (Liberati *et al.*, 2009). Higgins *et al*. (2003) stated that low, moderate and high heterogeneity correspond to I^2 values of 25%, 50% and 75%, however, these thresholds are considered tentative.

A risk of bias quality scale was not used. The Cochrane Collaboration discourages the use of such scales, stating that they are not supported by empirical evidence and can be inaccurate (Higgins, Altman and Sterne, 2011). Studies of physical training have methodological constraints that can lead to lower scores relating to bias (Bolger *et al.*, 2015). This can affect the blinding of participants, trainers and assessors. Previous meta-analyses on RT in youths have reported low study quality and a medium to high risk of bias (Behringer *et al.*, 2010; Harries, Lubans and Callister, 2012).

3.3.6 Analysis of moderator variables

To identify other sources of heterogeneity, moderator variables were determined and assessed (Sandercock, Bromley and Brodie, 2005). A summary of these can be seen in Table 3.3. Analysed with a random-effects model, moderator variables were selected based on differences in training programme configuration that could influence outcome measures (Wernbom, Augustsson and Thomee, 2007). Programme duration and mean total training sessions were selected because longer training programmes could lead to sustained performance improvements (Kraemer and Ratamess, 2004). Mean weekly training frequency was selected as this could have an impact on the magnitude of adaptation to training (Ross and Leveritt, 2001). All programme variables were grouped using a median split.

3.4 Results

3.4.1 Primary effects

The pooled mean estimate for all groups (n = 3) showed an increase in muscular strength (0.98 [0.70-1.27], Z = 6.81 [$p < 0.001$]). The overall estimate was moderate but there was heterogeneity among studies (I^2 = 75% [$p < 0.001$]).

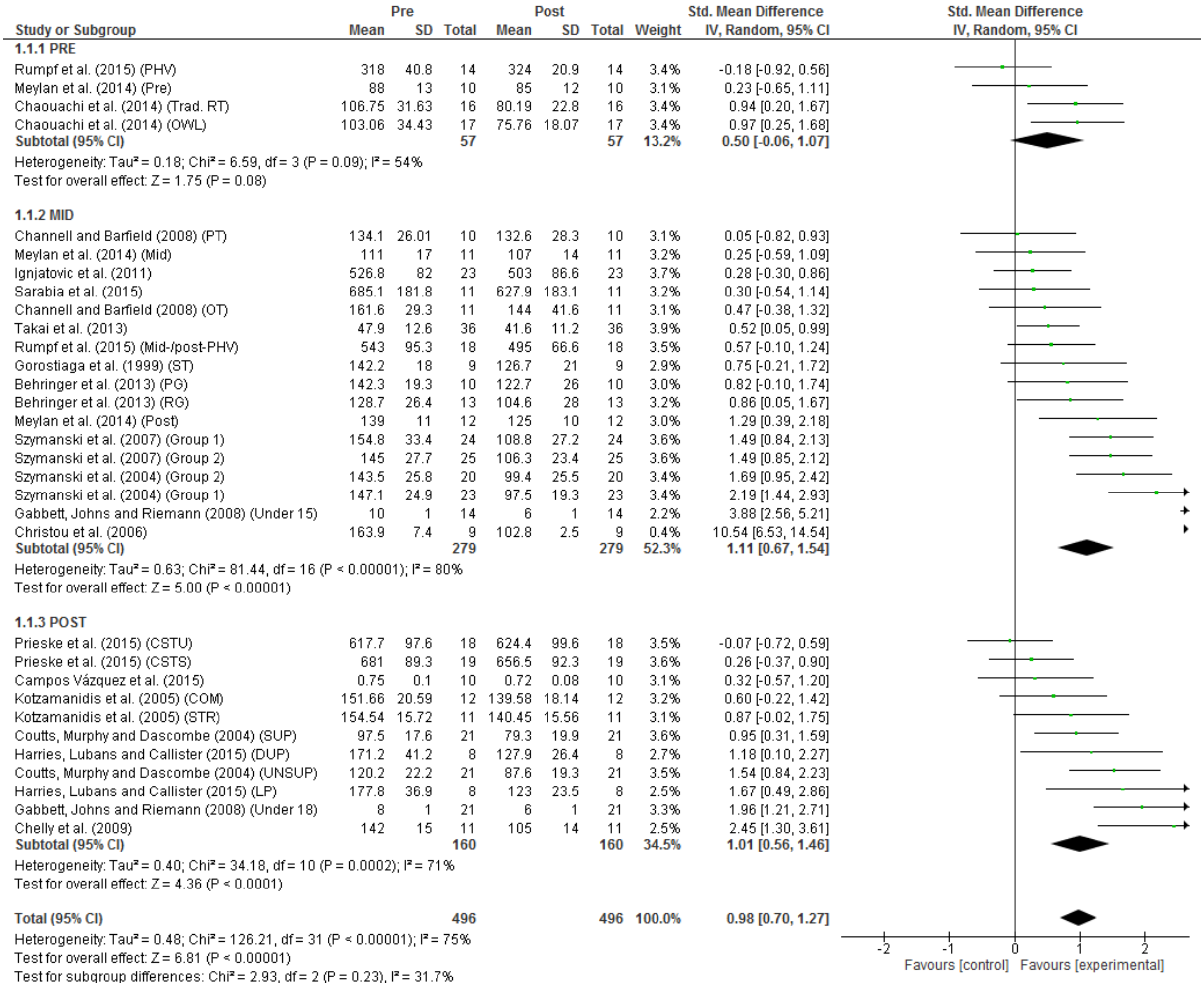
3.4.2 Effects across and in maturity groups

In the PRE group, the ES for change in strength was small (ES = 0.50 [-0.06-1.07], Z = 1.75 [p = 0.08]). The MID group demonstrated a moderate increase in strength (ES = 1.11 [0.67-1.54], Z = 5.00 [$p < 0.001$]). This ES was the largest of the three groups but the estimate was highly heterogeneous (I^2 = 80% [$p < 0.001$]). The POST group estimate was also moderate (ES = 1.01 [0.56-1.46], Z = 4.36 [$p < 0.001$]) and highly heterogeneous (I^2 = 71% [$p < 0.001$]).

Heterogeneity between maturity groups was moderate I^2 = 31.7% [p = 0.23]).

3.4.3 Effect of moderator variables

Subgroup analysis indicated that programme duration accounted for a large proportion of the between-group heterogeneity (I^2 = 93.7%, $p < 0.001$) with longer (>9.5 weeks) programmes producing greatest gains in strength (ES = 1.48 [1.06-1.9], Z = 6.89 [p < 0.001]). Total training sessions was also a source of between-study heterogeneity (*I*² = 92.1%, p < 0.001). Studies reported that more than 24.5 training sessions produced the largest mean estimate (ES = 1.63 [1.10-2.15], Z = 6.11 [p < 0.001]). Training frequency explained a moderate proportion of between-group heterogeneity (*I*² = 55.5%, p = 0.13). Mean estimates remained heterogeneous in all subgroups and heterogeneity was less in subgroups with smaller ESs shorter programmes, fewer training sessions and less frequent training.



	Pre			Post				Std. Mean Difference
Study or Subgroup	**Mean**	**SD**	**Total**	**Mean**	**SD**	**Total**	**Weight**	**IV, Random, 95% CI**
1.1.1 PRE								
Rumpf et al. (2015) (PHV)	318	40.8	14	324	20.9	14	3.4%	-0.18 [-0.92, 0.56]
Meylan et al. (2014) (Pre)	88	13	10	85	12	10	3.1%	0.23 [-0.65, 1.11]
Chaouachi et al. (2014) (Trad. RT)	106.75	31.63	16	80.19	22.8	16	3.4%	0.94 [0.20, 1.67]
Chaouachi et al. (2014) (OWL)	103.06	34.43	17	75.76	18.07	17	3.4%	0.97 [0.25, 1.68]
Subtotal (95% CI)			**57**			**57**	**13.2%**	**0.50 [-0.06, 1.07]**
Heterogeneity: Tau² = 0.18; Chi² = 6.59, df = 3 (P = 0.09); I² = 54%								
Test for overall effect: Z = 1.75 (P = 0.08)								
1.1.2 MID								
Channell and Barfield (2008) (PT)	134.1	26.01	10	132.6	28.3	10	3.1%	0.05 [-0.82, 0.93]
Meylan et al. (2014) (Mid)	111	17	11	107	14	11	3.2%	0.25 [-0.59, 1.09]
Ignjatovic et al. (2011)	526.8	82	23	503	86.6	23	3.7%	0.28 [-0.30, 0.86]
Sarabia et al. (2015)	685.1	181.8	11	627.9	183.1	11	3.2%	0.30 [-0.54, 1.14]
Channell and Barfield (2008) (OT)	161.6	29.3	11	144	41.6	11	3.1%	0.47 [-0.38, 1.32]
Takai et al. (2013)	47.9	12.6	36	41.6	11.2	36	3.9%	0.52 [0.05, 0.99]
Rumpf et al. (2015) (Mid-/post-PHV)	543	95.3	18	495	66.6	18	3.5%	0.57 [-0.10, 1.24]
Gorostiaga et al. (1999) (ST)	142.2	18	9	126.7	21	9	2.9%	0.75 [-0.21, 1.72]
Behringer et al. (2013) (PG)	142.3	19.3	10	122.7	26	10	3.0%	0.82 [-0.10, 1.74]
Behringer et al. (2013) (RG)	128.7	26.4	13	104.6	28	13	3.2%	0.86 [0.05, 1.67]
Meylan et al. (2014) (Post)	139	11	12	125	10	12	3.0%	1.29 [0.39, 2.18]
Szymanski et al. (2007) (Group 1)	154.8	33.4	24	108.8	27.2	24	3.6%	1.49 [0.84, 2.13]
Szymanski et al. (2007) (Group 2)	145	27.7	25	106.3	23.4	25	3.6%	1.49 [0.85, 2.12]
Szymanski et al. (2004) (Group 2)	143.5	25.8	20	99.4	25.5	20	3.4%	1.69 [0.95, 2.42]
Szymanski et al. (2004) (Group 1)	147.1	24.9	23	97.5	19.3	23	3.4%	2.19 [1.44, 2.93]
Gabbett, Johns and Riemann (2008) (Under 15)	10	1	14	6	1	14	2.2%	3.88 [2.56, 5.21]
Christou et al. (2006)	163.9	7.4	9	102.8	2.5	9	0.4%	10.54 [6.53, 14.54]
Subtotal (95% CI)			**279**			**279**	**52.3%**	**1.11 [0.67, 1.54]**
Heterogeneity: Tau² = 0.63; Chi² = 81.44, df = 16 (P < 0.00001); I² = 80%								
Test for overall effect: Z = 5.00 (P < 0.00001)								
1.1.3 POST								
Prieske et al. (2015) (CSTU)	617.7	97.6	18	624.4	99.6	18	3.5%	-0.07 [-0.72, 0.59]
Prieske et al. (2015) (CSTS)	681	89.3	19	656.5	92.3	19	3.6%	0.26 [-0.37, 0.90]
Campos Vázquez et al. (2015)	0.75	0.1	10	0.72	0.08	10	3.1%	0.32 [-0.57, 1.20]
Kotzamanidis et al. (2005) (COM)	151.66	20.59	12	139.58	18.14	12	3.2%	0.60 [-0.22, 1.42]
Kotzamanidis et al. (2005) (STR)	154.54	15.72	11	140.45	15.56	11	3.1%	0.87 [-0.02, 1.75]
Coutts, Murphy and Dascombe (2004) (SUP)	97.5	17.6	21	79.3	19.9	21	3.6%	0.95 [0.31, 1.59]
Harries, Lubans and Callister (2015) (DUP)	171.2	41.2	8	127.9	26.4	8	2.7%	1.18 [0.10, 2.27]
Coutts, Murphy and Dascombe (2004) (UNSUP)	120.2	22.2	21	87.6	19.3	21	3.5%	1.54 [0.84, 2.23]
Harries, Lubans and Callister (2015) (LP)	177.8	36.9	8	123	23.5	8	2.5%	1.67 [0.49, 2.86]
Gabbett, Johns and Riemann (2008) (Under 18)	8	1	21	6	1	21	3.3%	1.96 [1.21, 2.71]
Chelly et al. (2009)	142	15	11	105	14	11	2.5%	2.45 [1.30, 3.61]
Subtotal (95% CI)			**160**			**160**	**34.5%**	**1.01 [0.56, 1.46]**
Heterogeneity: Tau² = 0.40; Chi² = 34.18, df = 10 (P = 0.0002); I² = 71%								
Test for overall effect: Z = 4.36 (P < 0.0001)								
Total (95% CI)			**496**			**496**	**100.0%**	**0.98 [0.70, 1.27]**
Heterogeneity: Tau² = 0.48; Chi² = 126.21, df = 31 (P < 0.00001); I² = 75%								
Test for overall effect: Z = 6.81 (P < 0.00001)								
Test for subgroup differences: Chi² = 2.93, df = 2 (P = 0.23), I² = 31.7%								

Figure 3.2 Forest plot of strength change in each maturation group with 95% confidence intervals

Legend for group identifiers within studies: OWL: Olympic-style weightlifting, Trad. RT: Resistance training, Pre: Pre-PHV, PHV: Pre-peak height velocity, PG: Plyometric training, RG: Resistance-training, OT: Olympic Lifting, PT: Powerlifting, ST: Strength training, Mid: Mid-PHV, Post: Post-PHV, Mid-/post-PHV: Mid-/post-peak height velocity, SUP: Supervised, UNSUP: Unsupervised, DUP: Daily undulating periodised, LP: Linear periodised, COM: Combined Training, STR: Strength Training, CSTS: Stable surface core, CSTU: Unstable surface core.

Moderator variable	**Subgroup**	**Effect Size (95% C.I.)**	***N***	***P***	**Between-group I^2**	**Between-group *P***	**Within-group I^2**	**Within-group *P***
Programme duration	> 9.5 weeks	1.48 (1.06-1.9)	16	<0.001	93.7%	<0.001	77%	<0.001
	< 9.5 weeks	0.48 (0.24-0.73)	16	<0.001			38%	0.06
Mean total sessions	>24.5 sessions	1.63 (1.10-2.15)	12	<0.001	92.1%	<0.001	82%	<0.001
	< 24.5 sessions	0.59 (0.35-0.83)	20	<0.001			42%	<0.001
Mean weekly training frequency (sessions)	>2.5 sessions	1.22 (0.76-1.68)	13	<0.001	55.5%	0.13	81%	<0.001
	< 2.5 sessions	0.78 (0.45-1.12)	19	<0.001			65%	<0.001

Table 3.3 Effects of moderator variables on effect size for change in strength

3.5 Discussion

This meta-analysis investigated the maturation-related pattern of adaptations to RT in boy athletes. Based on the presented results, strength, though trainable in boys, is sensitive to maturity status. Several controlled trials (Behringer *et al.*, 2013; Chaouachi *et al.*, 2014b; Chelly *et al.*, 2009) demonstrated that RT is moderately to largely effective in sport-playing boys with the diversity of age profiles in these studies suggesting that enhancements in strength occur regardless of biological maturity status. Throughout childhood and adolescence, factors that have been cited in support of this are broadly attributed to morphological and neurological changes (Behm *et al.*, 2008). Morphological adaptations include changes in muscle fibre size and composition, changes in myosin heavy-chain, greater tendon stiffness and increases in the angle of muscle pennation. Neurological adaptations include increased activation of motor units, enhanced intermuscular coordination and neuromuscular learning (Behm *et al.*, 2008). Ultimately, as demonstrated by the primary effects, these mechanisms can lead to increases in strength in boys of any age, although the increases vary throughout growth and maturation (Lloyd *et al.*, 2012a).

The LTAD Model (Balyi, Way and Higgs, 2013) describes sensitive periods of adaptation when boys are more responsive to certain types of training. Indeed, an increase in growth hormones and androgens during puberty could indicate a maturational threshold that signals peak growth of several indicators of performance (Malina *et al.*, 2015; McNarry, Mackintosh and Stoedefalke, 2014). This could signal the onset of heightened sensitivity to the demands of RT. However, the lack of empirical evidence to support the claims of the LTAD Model has drawn criticism (Ford *et al.*, 2011). Despite this, there is evidence (Lloyd *et al.*, 2011; Meylan *et al.*, 2014a; Rumpf *et al.*, 2015) that specific periods of heightened adaptation do exist. The results of this meta-analysis seem to support these studies (Lloyd *et al.*, 2011; Meylan *et al.*, 2014a) and could have implications for the way RT is planned for boy athletes.

Group	**All**	**PRE**	**MID**	**POST**
Training frequency (per week)	2.5 ± 0.7	2.2 ± 0.33	2.7 ± 0.9	2.4 ± 0.4
Number of weeks	9.9 ± 2.6	9.5 ± 3.0	9.4 ± 2.8	10.7 ± 2.0
Total sessions	24.7 ± 8.8	20.0 ± 4.6	25.1 ± 10.3	25.8 ± 7.0

PRE: 10-12.99 year olds; MID: 13-15.99 year olds; POST: 16-18 year olds.

Table 3.4 Mean training programme characteristics

3.5.1 Resistance training before peak height velocity

The small ES for strength gains in the PRE group indicates that RT is less effective in younger athletes. The PRE athletes completed programmes of a similar length to the MID and POST groups but were exposed to fewer total training sessions (approximately 20%) (Table 3.4). Preadolescent boys can increase muscular strength but because their hormonal profile is not conducive to increasing muscle mass (Faigenbaum *et al.*, 2009), their potential for building strength is less than in older boys. Reflecting the pattern of strength development in the current review, a previous meta-analysis examining general-population boys and girls identified that younger participants had smaller increases in muscular strength (Behringer *et al.*, 2010). Two intervention studies (Meylan *et al.*, 2014a; Rumpf *et al.*, 2015) that measured biological maturity status (Mirwald *et al.*, 2002) reported similarly small (or negative) ESs in PRE (0.23 [-0.65-1.11] and -0.18 [-0.92-0.56]) than in MID and POST (1.29 [0.39-2.18] and 0.57 [-0.10-1.24]).

Together, these results could have occurred because of several factors. Lower concentrations of androgens and growth factors in younger athletes could mean that morphological changes that arise from RT were less likely to occur. Biological maturity status is heavily influenced by these hormones that are associated with increased strength (Hansen *et al.*, 1999) and impulse development in boys (Baldari *et al.*, 2009).

Muscle hypertrophy can enhance muscular strength (Zatsiorsky and Kraemer, 2006). However, as preadolescents' ability to increase muscular size is less, they could be more dependent on neural mechanisms (Payne *et al.*, 1997) to become stronger. For example, tendon cross sectional area remained unchanged after RT of the plantar flexors in children, despite an increase in tendon stiffness of 29% (Waugh *et al.*, 2014). In addition, maximal strength in upper and lower body muscle actions increased by 35% and 22% respectively in boys aged 9 to 11 years (Ramsay *et al.*, 1990). These adaptations were independent of increases in muscular size despite a 30% improvement in the twitch torque of the knee extensor and elbow flexor muscles.

Given the above, Meylan *et al.* (2014a) suggested that impulsive muscular actions could be optimally developed before PHV because of increased fascicle length and faster development of the central nervous system. Accordingly, a preferential emphasis on training with an impulsive component is warranted (Lloyd *et al.*, 2011; Meylan *et al.*, 2014a) alongside a programme of fundamental movement skills training (Lloyd and Oliver, 2012). However, this should not be completely at the expense of RT as this is considered a prerequisite for effective impulsive performance (Stone *et al.*, 2003).

Despite smaller ESs seen in the PRE group, RT should still be considered an important part of any sport preparation programme for younger children as it could be particularly effective in offsetting injury risk (Myer *et al.*, 2011) because of enhanced tendon stiffness (Waugh *et al.*, 2014). On this, a diversity of physical activities forms the basis for more intense activities later in life (Bergeron *et al.*, 2015). A wide-ranging programme such as that of Faigenbaum *et al*. (2011) incorporates elements of basic strength exercises and neuromuscular coordination and addresses fundamental movement skills in prepubertal boys in a developmentally appropriate way.

The results seen in PRE are not suitable to generalise about the magnitude of adaptation to RT at that time of maturation because of the small body of research that examines the modality in athletes between the ages of 10 and 13 years. Additional controlled intervention studies are needed to improve descriptions of adaptations of athletes in that age range to RT.

3.5.2 Resistance training during and after peak height velocity

Larger ESs seen in the more mature groups mirror results reported by the few studies in this meta-analysis that saw boys of differing maturity status presented with an identical RT stimulus (Meylan *et al.*, 2014a; Rumpf *et al.*, 2015). Resistance training could be more effective during and after the time of the growth and strength spurts (De Ste Croix, 2007) as these are denoted by increases in muscle mass because of rising concentrations of anabolic hormones (Rogol, Roemmich and Clark, 2002). Peak height velocity coincides with the greatest gain of relative strength in boys (Viru *et al.*, 1999) and is followed by peak weight velocity that is characterised by gains in bone and skeletal muscle tissues (Malina, Bouchard and Bar-Or, 2004; Malina *et al.*, 2015). At this time, muscle mass grows at its greatest rate and hypertrophic gains are associated with enhanced force production capability (Zatsiorsky and Kraemer, 2006).

As RT is more effective in MID and POST, it could be beneficial to conduct a higher volume of exercise during these times, after appropriate foundational training at a younger age. However it is important to consider that PHV can also coincide with higher susceptibility to traumatic and overuse injuries because of joint stiffness, impaired motor coordination and a differential in the ratio of limb growth to muscle strength (van der Sluis *et al.*, 2014). This means that coaches must be cautious when programming RT as any increased trainability can coincide with a greater vulnerability to injury that can also persist after PHV (van der Sluis *et al.*, 2014). Regardless of the magnitude of trainability, it is important that the training age of the athlete is taken into account when making programming decisions as increased training intensity and volume during and after PHV might not be advisable for inexperienced athletes (Lloyd *et al.*, 2012a).

The slightly lower ES seen in POST could be because of greater training experience and, thus, a lower ceiling of adaptation attributable to the accumulation of more training over greater durations (Deschenes and Kraemer, 2002; Hawley, 2008; Peterson, Rhea and Alvar, 2004). Further research could identify if there is a difference in the size of adaptations among boys of similar training ages, but of different biological ages.

3.5.3 Effects of moderator variables

In meta-analysis, examination of potential moderator variables can gauge the influence of ES modifiers, such as training intensity and duration, on primary effects (Ryan, 2014). The moderator variables of programme duration and mean total sessions had high heterogeneity. Mean weekly training frequency was a source of moderate heterogeneity. As anticipated, programmes of longer duration and more training sessions had greater effect. Also, a higher mean training frequency per week was more effective than a lower mean training frequency per week. High heterogeneity after subgroup analysis implies that moderators of the primary effect had not been identified meaning that other factors could account for training adaptations (Sandercock, Bromley and Brodie, 2005). This implies a synergy between programming variables and other factors, such as biological maturity, in determining the magnitude of adaptation to RT. Less variation among maturity groups than moderator variables was an anticipated outcome because of the highly variable nature of training programmes across studies. However, high heterogeneity in maturity groups could also be evidence of differing mechanisms of physiological adaptation to training. This could be particularly applicable when ESs of maturity groups are similar despite high heterogeneity, as can be observed in the MID and POST groups.

3.5.4 Limitations

A lack of uniformity in how training programmes were prescribed could contribute to high heterogeneity. Additionally, the method of calculating ESs whereby baseline and post-training measures of muscular strength were compared only in intervention groups means that it is more difficult to differentiate between the effects of training and advancing maturation. On this, a sub-analysis of the minority of studies that did include a comparable control group showed an ES of 0.7 (0.2-1.2). This could reveal the proportion of strength gains that arise from training as opposed to those attributed to maturation.

The classifications used to account for biological maturity are related to chronological age and so can account for only some of the developmental diversity that is seen across groups. Relationships between physical performance and chronological age have been demonstrated (Deprez *et al.*, 2015b; Mendez-Villanueva *et al.*, 2011a; Valente-dos-Santos *et al.*, 2014), implying that biologically-mediated changes in physical performance can be captured via the used method. In relation to subgroup analysis, dichotomisation of continuous data (particularly by median split) may lead to residual confounding and reduced statistical power (Altman and Royston, 2006).

3.6 Conclusions

The results of this study show that RT is more effective during and after PHV in boy athletes and this means such exercise should be strategically programmed at this time. A practical measure of biological maturity, such as that put forward by Mirwald *et al.* (2002), can assist practitioners in assessing maturation status so that training can be prescribed in optimal doses at appropriate times.

Practitioners are advised to increase the intensity and volume of RT in MID and POST-PHV when adaptations are greater (Meylan *et al.*, 2014a). However, an athlete’s training history and greater likelihood of sustaining injuries during PHV must also be carefully considered. Accordingly, a practitioner should ultimately make programming decisions based on movement proficiency and ability to display correct technique (Lloyd *et al.*, 2012a). Indeed, this approach should be prioritised across all youths, regardless of sex or maturity status. Before PHV it could be beneficial to develop impulsive or neural qualities (Lloyd *et al.*, 2011; Lloyd and Oliver, 2012) as specific types of training can vary in their effectiveness at different times throughout maturation (Meylan *et al.*, 2014a). A well-rounded integrative neuromuscular training programme could be an effective way to address foundational strength and movement skills before PHV (Faigenbaum *et al.*, 2011) and prior to more advanced and voluminous training in later years. To summarise, this meta-analysis could assist coaches in determining the optimal time to programme RT as boys grow and mature in the long term. Its results can be considered complementary to those of other reviews (Behringer *et al.*, 2010; Lesinski, Prieske and Granacher, 2016) which can help to determine appropriate programming variables for specific training session prescription.

CHAPTER 4

Age-related variation in male youth athletes' countermovement jump following plyometric training: a meta-analysis of controlled trials

Citation

Moran, J., Sandercock, G. R. H., Ramírez-Campillo, R., Meylan, C., Collison, J. and Parry, D. A. (2017). Age-related variation in male youth athletes' countermovement jump following plyometric training: a meta-analysis of controlled trials. *Journal of Strength and Conditioning Research*. 31(2), 552-565.

Abstract

Recent debate on the trainability of youths has focused on the existence of periods of accelerated adaptation to training. Accordingly, the purpose of this meta-analysis was to identify the age- and maturation-related pattern of adaptive responses to PT in youth athletes. Thirty ESs were calculated from the data of 21 sources with studies qualifying based on the following criteria: (a) Healthy male athletes who were engaged in organised sport; (b) Groups of participants with a mean age between 10 and 18 years; (c) PT intervention duration between 4 and 16 weeks. Standardised mean differences showed PT to be moderately effective in increasing CMJ height (ES = 0.73 95% confidence interval: 0.47-0.99) across PRE-, MID-, and POST-peak height velocity groups. Adaptive responses were of greater magnitude in PRE (ES = 0.91 95% confidence interval: 0.47-1.36) and POST (ES = 1.02 [0.52-1.53]). The magnitude of adaptation to PT in MID was lower (ES = 0.47 [0.16-0.77]), despite greater training exposure. Power performance as measured by CMJ may be mediated by biological maturation. Coaches could manipulate training volume and modality during periods of lowered response in order to maximise performance.

4.1 Introduction

The stretch forces that occur during movement give rise to eccentric muscle contractions, with the resultant stored elastic energy contributing to a potentiation of force in subsequent concentric contractions, a mechanism referred to as the stretch-shortening cycle (SSC) (Knuttgen and Komi, 2003; Nicol, Avela and Komi, 2006). An athlete's ability to leverage this mechanism is an important determinant of good athleticism considering its influence on sprinting (Rumpf *et al.*, 2013), jumping (Jakobsen *et al.*, 2012) and change of direction ability (Marshall *et al.*, 2014).

Plyometric training, which uses SSC exercises such as jumps, bounds and hops (Chu and Myer, 2013), has been validated as an effective way of enhancing power performance in youth (Chelly *et al.*, 2014; Chelly, Hermassi and Shephard, 2015; Meylan and Malatesta, 2009; Michailidis *et al.*, 2013; Ramirez-Campillo *et al.*, 2015d; Santos and Janeira, 2011;

Zribi *et al.*, 2014). However, previous meta-analyses (de Villarreal *et al.*, 2009; de Villarreal, Requena and Newton, 2010; Harries, Lubans and Callister, 2012; Markovic, 2007; Rumpf *et al.*, 2012) examining the efficacy of PT as a training method across a wide range of age groups in both genders have revealed variable results. Examining the effect of PT in males and females between the ages of 11 and 29 years, Markovic (2007) reported a pooled ES of 0.88 (95% confidence interval: 0.64-1.11) in relation to jump performance. Later, de Villarreal *et al.* (2009) found PT to have varying degrees of effectiveness on CMJ height, ranging from small (0.31) to large (1.22) across sport, sport level, fitness, gender and training experience. However, the researchers did not disentangle the responses of youth athletes from those of adults. Harries *et al.* (2012) included a small number of studies on PT programmes in their meta-analysis on RT in youth athletes, finding a mean difference in CMJ performance of 5.47 cm (1.95-9.00) for PT programmes (n = 4) and 3.03 cm (0.83-5.24) for combined RT and PT and/or ST programmes (n = 7). Investigating the effect of PT on males and females of various ages and levels of training experience, de Villarreal, Requena and Cronin (2012) found that such methods had a small mean effect (g = 0.37) in training groups, compared with control participants (g = 0.03). Additionally, in an analysis of the effect of a wide number of training methods on sprint times in youth, Rumpf *et al.* (2012) found PT to have a small effect (-0.56 ± 1.26) on performance, however just four studies contributed data to this calculation.

There is only limited evidence to suggest that training at specific ages during maturation produces greater adaptations than at other ages. Lloyd *et al.* (2011) demonstrated that there may exist periods of accelerated adaptation for SSC development before (between the ages of 10 and 11) and near (between the ages of 14 and 16) the time of PHV. However, it is not clear if PT during these periods can elicit greater training adaptations than could be realised through maturation alone. It seems that maturation-dependent development of the neuromuscular system plays a role in the prospective pattern of adaptation to PT (Lloyd *et al.*, 2012b). This is particularly relevant given the recent academic debate on the trainability of youths, the timing of youth training and the potential existence of 'golden periods' of adaptation (McNarry *et al.*, 2014). However, as yet, there is not enough evidence to suggest that training prescription should be adapted to coincide with these supposed periods of maturation.

All of the above cited studies underline, to varying degrees, the efficacy of PT as a beneficial training method across a wide cross-section of populations. However, to date, no meta-analytical review has taken a focused approach to investigating the age-related effects of PT exclusively in male youth athletes. Systematic reviews to date have, therefore, not been precise enough to draw definitive conclusions about PT effectiveness and prescription within specialist populations. Addressing this shortfall in knowledge may be highly important within the context of athletic training prescription for young athletes.

This meta-analysis seeks to establish if PT is more effective at enhancing power performance in male youth athletes at specific junctures across childhood and adolescence. Accordingly, it looks to clarify the existence of periods of accelerated adaptation.

4.2 Methods

4.2.1 Experimental Approach to the Problem

This meta-analytical review was conducted in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) statement (Liberati *et al.*, 2009).

4.2.2 Literature Search

Extensive searches of the PubMed, Google Scholar, Sport Discus, Medline, CINAHL and Science Direct databases were undertaken. These searches imposed no date restrictions and were carried out between December 10th, 2014 and January 16th, 2015 with the searches being updated to April 23rd, 2015 throughout the course of the review. Words that were used as either individual search terms, or in conjunction with each other, included 'strength', 'power', 'plyometric', 'stretch-shortening cycle', 'jump', 'training', 'exercise', 'paediatric', 'youth', 'children', 'adolescence', 'athletes' and 'sport'. In the process of selecting studies for inclusion, a review of all seemingly relevant article titles within each database was conducted and this was followed by an evaluation of article abstracts and, then, full published articles. Following the further elimination of inappropriate studies for a variety of reasons (Figure 4.1), a search of article reference lists was carried out. Only peer-reviewed articles were selected. Additionally, in order to maintain a minimum standard of study quality in the meta-analysis, only articles published in journals that were included in Hopkins' (Hopkins, 2014) annual summary of impact factors in the fields of sport and exercise medicine and science were eligible for selection.

Specific criteria determined the eligibility of studies for inclusion in the meta-analytical review. Studies included healthy males, between the mean age of 10 and 18 years old, who were engaged in organised sport. Interventions were between 4 and 16 weeks in duration as previous work has seen beneficial effects due to RT and/or PT inside four (Hammett and Hey, 2003; Lloyd *et al.*, 2012b) to six weeks (Faigenbaum *et al.*, 2007). The upper limit reduced the likelihood of athletes being allocated to the wrong maturity group in the meta-analysis due to the passage of time during interventions. The PT interventions were required to conform to the following description: lower body unilateral and bilateral bounds, jumps and hops that utilise a pre-stretch or countermovement that incites usage of the SSC (Chu and Myer, 2013; Chu and Shiner, 2007). Means and standard deviations for a measure of post-intervention CMJ performance in experimental and control groups were used to calculate an ES. Studies that did not incorporate a control group into the study design were excluded from this analysis in order to allow for differentiation of the effects of training and maturation.

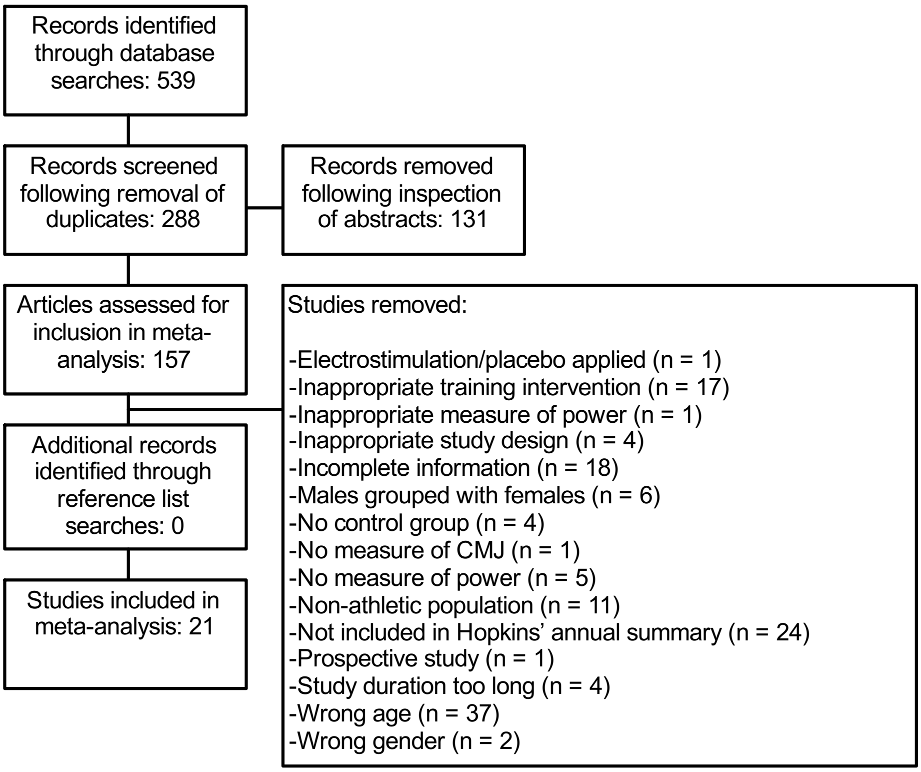


Figure 4.1 The search process

In relation to the criteria for study selection, any intervention studies that utilised assistive jumping apparatus or techniques such as electrostimulation were excluded. It is also worth noting that this study did not aim to examine the effects of RT, or other, training methods. However, a wide range of exercise types were carried out in several of the analysed studies as part of a formalised fitness programme. This means that any observed adaptations may not be solely attributable to PT.

4.2.3 Maturity Status

Assessment of maturity status followed the same protocol as in Chapter 3. A descriptive summary of each maturity group is shown in Table 4.1.

	All		PRE		MID		Post	
	Experimental (*n*=500)	**Control (n=339)**	**Experimental (*n*=178)**	**Control (n=98)**	**Experimental (*n*=277)**	**Control (n=205)**	**Experimental (*n*=45)**	**Control (n=36)**
Mean age (y)	13.3 ± 2.5	13.5 ± 2.4	11.3 ± 1.8	11.3 ± 1.6	14.0 ± 1.8	13.9 ± 1.8	17.1 ± 0.5	17.2 ± 0.6
Mean height (cm)	150.0 ± 37.9	159.5 ± 33.5	147.9 ± 11.1	148.3 ± 55.4	161.9 ± 12.1	162.1 ± 12.5	178.4 ± 5.3	176.5 ± 5.1
Body mass (kg)	49.1 ± 19.1	51.9 ± 13.9	41.9 ± 11.1	40.8 ± 10.0	54.9 ± 14.0	53.7 ± 9.8	73.7 ± 9.5	72.4 ± 12.2

Table 4.1 Descriptive data for male youth athletes from PT studies included in meta-analysis

4.2.4 Data extraction

The extraction of data from gathered articles was undertaken by two reviewers. The first reviewer collected the data before the second reviewer investigated its accuracy and the eligibility of studies for inclusion. Where required data was not clearly or completely reported, article authors were contacted for clarification. For consistency, a CMJ was used for the calculation of ESs due to its relevance to sport (Harman, 2006) and high reliability (Slinde *et al.*, 2008).

4.2.5 Analysis and interpretation of results

The analysis and interpretation of results mirrored that of Chapter 3. Table 4.2 displays all of the included studies whilst Figure 4.2 shows forest plots and their associated ESs. As in Chapter 3, the inverse-variance random effects model for meta-analyses was used. The calculated ESs were interpreted using the conventions outlined for standardised mean difference by Hopkins, *et al*. (2009) (<0.2 = trivial; 0.2-0.6 = small, 0.6-1.2 = moderate, 1.2-2.0 = large, 2.0-4.0 = very large, >4.0 = extremely large).

As in Chapter 3, to gauge the degree of heterogeneity amongst the included studies, the I^2 statistic was referred to. Similarly, funnel plots were subjectively analysed to assess publication bias however, a risk of bias quality scale was not utilised.

Study Name	Age (SD) (y)	Maturation	Height (SD) (cm)	Weight (SD) (kg)	Sport	Group	Group Identifier	Number of Participants	Training frequency (per week)	Number of Weeks	Mean total sessions
Chelly *et al.* (2015)	12.1 (1.0)	Pre	154.0 (3.0)	38.1 (4.1)	Track	Control	Control	13			
Chelly *et al.* (2015)	11.7 (1.0)	Pre	158.0 (20.0)	43.0 (16.6)	Track	Plyometric	Experimental	14	3	10	30
Michailidis *et al.* (2013)	10.6 (0.5)	Pre	145.0 (7.3)	41.7 (6.4)	Soccer	Control	CG	21			
Michailidis *et al.* (2013)	10.7 (0.7)	Pre	147.0 (8.6)	42.5 (7.2)	Soccer	Plyometric	PTG	24	2	12	24
Ramirez-Campillo *et al.* (2014a)	10.1 (2.0)	Pre	143.0 (10.0)	39.0 (9.3)	Soccer	Control	Control	14			
Ramirez-Campillo *et al.* (2014a)	10.4 (2.0)	Pre	141.0 (10.0)	37.0 (7.0)	Soccer	Plyometric - 30 second rest	G30	13	2	7	14
Ramirez-Campillo *et al.* (2014a)	10.4 (2.3)	Pre	141.0 (10.0)	37.2 (6.1)	Soccer	Plyometric - 60 second rest	G60	13	2	7	14
Ramirez-Campillo *et al.* (2014a)	10.3 (2.3)	Pre	142.0 (10.0)	38.0 (10.0)	Soccer	Plyometric - 120 second rest	G120	11	2	7	14
Ramirez-Campillo *et al.* (2015a)	11.2 (2.4)	Pre	143.0 (17.7)	41.8 (12.7)	Soccer	Control	CG	14			
Ramirez-Campillo *et al.* (2015a)	11.0 (2.0)	Pre	146.0 (13.7)	43.5 (14.9)	Soccer	Bilateral plyometrics	BG	12	2	6	12
Ramirez-Campillo *et al.* (2015a)	11.6 (1.7)	Pre	147.0 (11.1)	45.0 (9.3)	Soccer	Unilateral plyometrics	UG	16	2	6	12
Ramirez-Campillo *et al.* (2015a)	11.6 (2.7)	Pre	144.0 (17.5)	42.2 (16.9)	Soccer	Combined plyometrics	B+UG	12	2	6	12
Ramirez-Campillo *et al.*(2015b)	11.4 (2.4)	Pre	146.0 (16.2)	42.2 (13.2)	Soccer	Control	CG	10			
Ramirez-Campillo *et al* (2015b).	11.6 (1.4)	Pre	144.0 (9.6)	40.0 (5.9)	Soccer	Vertical plyometrics	VG	10	2	6	12
Ramirez-Campillo *et al.* (2015b)	11.4 (1.9)	Pre	150.0 (12.3)	44.6 (11.0)	Soccer	Horizontal plyometrics	HG	10	2	6	12
Ramirez-Campillo *et al.* (2015b)	11.2 (2.3)	Pre	141.0 (14.4)	40.1 (12.8)	Soccer	Vertical and horizontal plyometrics	VHG	10	2	6	12

Ramirez-Campillo *et al* . (2015c)	12.8 (2.8)	Pre	160.0 (13.4)	53.9 (14.1)	Soccer	Progressed volume	PPT	8	2	6	12
Zribi *et al.* (2014)	12.2 (0.4)	Pre	154.8 (7.6)	41.2 (7.8)	Basketball	Control	CG	26			
Zribi *et al.* (2014)	12.1 (0.6)	Pre	155.5 (6.7)	41.1 (8.2)	Basketball	Plyometrics	PG	25	2	9	18
Buchheit *et al.* (2010a)	14.5 (0.5)	Mid	174.0 (10.0)	64.7 (10.0)	Soccer	Repeated Sprints	RS	7			
Buchheit *et al.* (2010a)	14.5 (0.5)	Mid	173.0 (7.0)	64.2 (6.0)	Soccer	Explosive strength	ExpS	8	1	10	10
de Villarreal *et al.* (2015)	14.9 (0.2)	Mid	165.2 (8.5)	54.5 (6.6)	Soccer	Control	CG	13			
de Villarreal *et al.* (2015)	15.3 (0.3)	Mid	168.0 (7.8)	57.1 (8.3)	Soccer	Combined training	CombG	13	2	9	18
Faigenbaum *et al.* (2007)	13.6 (0.7)	Mid	166.0 (10.0)	58.6 (14.4)	Baseball and American Football	Resistance Training	RT (control)	14			
Faigenbaum *et al.* (2007)	13.4 (0.9)	Mid	164.0 (10.0)	61.5 (21.8)	Baseball and American Football	Plyometric Training	PRT	13	2	6	12
Garcia-Pinillos *et al.* (2014)	16.4 (1.5)	Mid*	169.0 (0.06)	61.5 (9.5)	Soccer	Control	CG	13			
Garcia-Pinillos *et al.* (2014)	15.5 (1.3)	Mid	172.0 (0.05)	68.3 (11.2)	Soccer	Contrast	EG	17	2	12	24
Marques *et al.* (2013)	13.2 (1.4)	Mid			Soccer	Control	Control	26			
Marques *et al.* (2013)	13.5 (1.3)	Mid			Soccer	Plyometric	Training	26	2	6	12
Meylan and Malatesta (2009)	13.1 (0.6)	Mid	163.0 (10.0)	47.4 (9.6)	Soccer	Control	CG	11			
Meylan and Malatesta (2009)	13.3 (0.6)	Mid	159.0 (9.0)	48.6 (9.6)	Soccer	Plyometric	TG	14	2	8	16
Ramirez-Campillo *et al* . (2015c)	13 (1.9)	Mid	159.0 (8.5)	53.2 (11.1)	Soccer	Control	CG	8			
Ramirez-Campillo *et al* . (2015c)	13 (2.1)	Mid	161.0 (10.1)	53.8 (7.6)	Soccer	Non-progressed volume	NPPT	8	2	6	12
Ramirez-Campillo et al. (2014b)	13.2 (1.8)	Mid	153.0 (12.0)	47.4 (11.9)	Soccer	Control	CG	38			

Ramirez-Campillo et al. (2014b)	13.2 (1.8)	Mid	154.0 (12.0)	47.9 (10.0)	Soccer	Plyometric	TG	38	2	7	14
Ramirez-Campillo et al.(2015d)	14.0 (2.3)	Mid	160.0 (13.1)	52.1 (12.1)	Soccer	Control	CG	55			
Ramirez-Campillo et al.(2015d)	14.2 (2.2)	Mid	158.0 (12.4)	50.3 (12.1)	Soccer	24 hours rest	PT24	54	2	6	12
Ramirez-Campillo et al.(2015d)	14.1 (2.2)	Mid	159.0 (12.3)	51.8 (12.2)	Soccer	48 hours rest	PT48	57	2	6	12
Santos and Janeira (2008)	14.2 (0.4)	Mid	173.2 (7.6)	61.1 (11.4)	Basketball	Control	CG	10			
Santos and Janeira (2008)	14.7 (0.5)	Mid	175.9 (9.3)	72.7 (16.9)	Basketball	Plyometrics	EG	15	2	10	20
Santos and Janeira (2011)	14.2 (0.4)	Mid	173.2 (7.6)	61.1 (11.4)	Basketball	Control	CG	10			
Santos and Janeira (2011)	15 (0.5)	Mid	172.9 (6.3)	62.6 (9.9)	Basketball	Plyometrics	EG	14	2	10	20
Alves *et al.* (2010)	17.6 (0.5)	Post	174.6 (6.2)	70.6 (10.3)	Soccer	G3	G3 (control)	6			
Alves *et al.* (2010)	17.3 (0.7)	Post	177.7 (5.6)	70.5 (9.1)	Soccer	G1	G1	9	1	6	6
Alves *et al.* (2010)	17.2 (0.4)	Post	173.5 (6.9)	69.8 (6.9)	Soccer	G2	G2	8	2	6	12
Chelly *et al.* (2014)	17.2 (0.4)	Post	177 (5.3)	78.0 (11.4)	Handball	Control	Control	11			
Chelly *et al.* (2014)	17.1 (0.3)	Post	181.0 (6.4)	80.1 (11.9)	Handball	Plyometric	Experimental	12	2	8	16
Fernandez-Fernandez *et al.* (2015)	17 (0.6)	Post	179.2 (2.8)	73.8 (4.8)	Tennis	Control	CG	8			
Fernandez-Fernandez *et al.* (2015)	16.8 (0.2)	Post	181.4 (4.5)	74.9 (6.1)	Tennis	Repeated Sprint/Explosive Strength	IG	8	2	8	16
Gorostiaga *et al.* (2004)	17.2 (0.7)	Post	175.1 (5.4)	66.8 (6.0)	Soccer	Control	C	11			
Gorostiaga *et al.* (2004)	17.3 (0.5)	Post	177.4 (4.9)	70.3 (6.7)	Soccer	Strength	S	8	2	11	22

Table 4.2 Characteristics of the reviewed studies and their participants

4.2.6 Analysis of moderator variables

In order to identify potential sources of heterogeneity, moderator variables were determined and assessed (Sandercock, Bromley and Brodie, 2005). The moderator variables were analysed with a random effects model and were selected based on differences in sport and training programme characteristics. A division was made between soccer and other sports as youth athletes may express a preference for sports that place a premium on the physical abilities in which they are most proficient (Malina *et al.*, 2007). The variables of programme duration and mean total sessions were grouped using a median split as longer training programmes may lead to more sustained performance improvements (Kraemer and Ratamess, 2004).

4.3 Results

4.3.1 Main effect

Across all groups included in the meta-analysis there was a significant improvement in CMJ height (ES = 0.73 [0.47-0.99], Z = 5.58 [$p < 0.00001$]). The overall estimate was of moderate magnitude but showed a significant level of between-study heterogeneity (I^2 = 61% [$p < 0.00001$]).

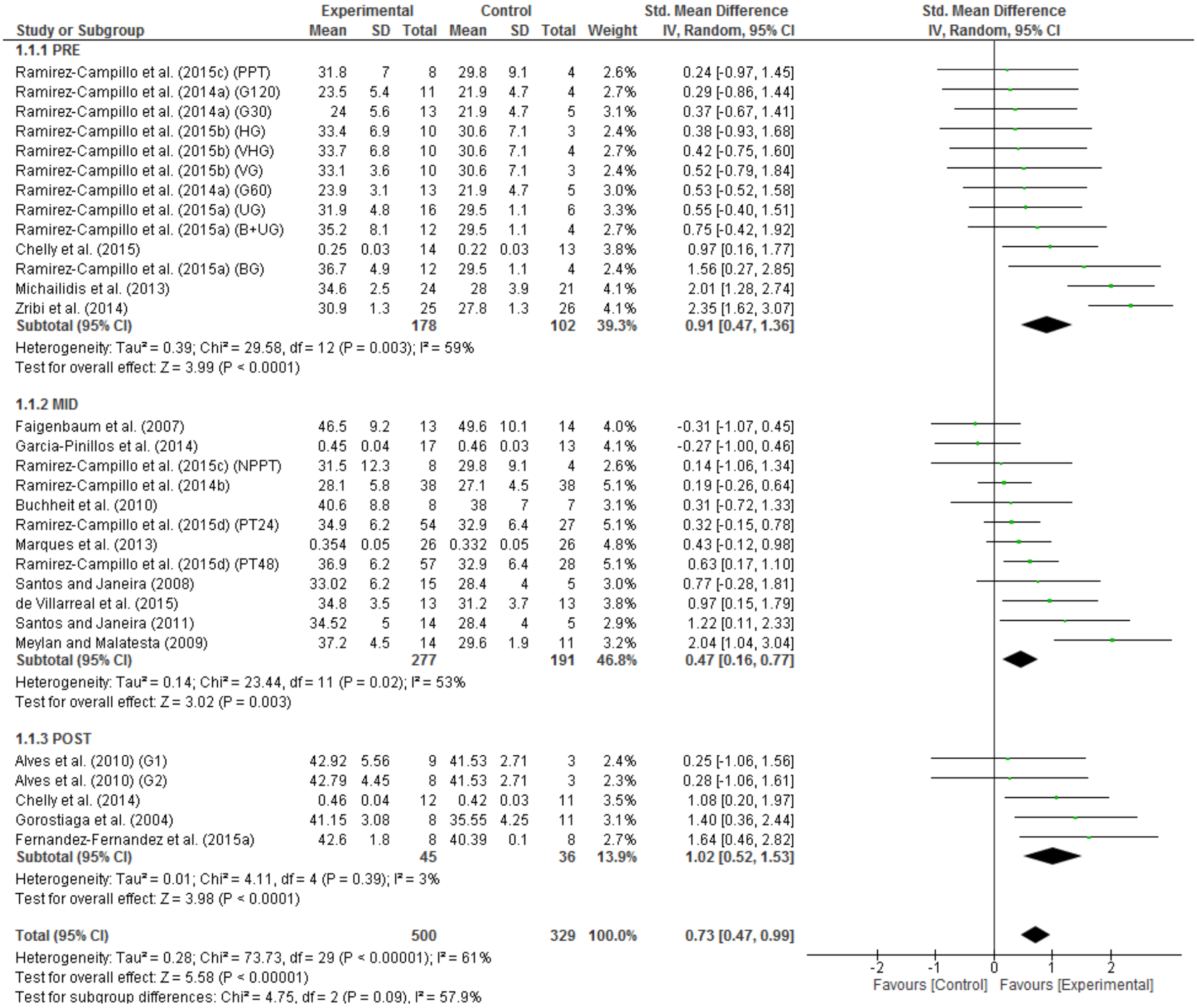
4.3.2 Effects between and within maturity groups

Table 4.3 summarises effects across groups. Maturity groups, which were determined *a priori*, were heterogeneous (I^2 = 57.9% [p = 0.09]).

In the MID group, the ES for change in CMJ was small (ES = 0.47 [0.16-0.77], Z = 3.02 [p = 0.003]) and heterogeneous (I^2 = 53% [p = 0.02]). The POST group showed the greatest increases in CMJ. The mean estimate for POST was of moderate magnitude (ES = 1.02 [0.52-1.53], Z = 3.98 [$p < 0.0001$]) with low heterogeneity not reaching statistical significance (I^2 = 3% [p = 0.39]). The PRE group estimate was moderate (ES = 0.91 [0.47-1.36], Z = 3.99 [$p < 0.0001$]) and heterogeneous (I^2 = 59% [p = 0.003]).

Moderator variable	Subgroup	Effect Size (95% C.I.)	*N*	*P*	Between-group I^2	Between-group *P*	Within-group I^2	Within-group *P*
Likely maturity status	PRE	0.91 (0.47-1.36)	13	<0.0001	57.9%	0.09	59%	0.003
	MID	0.47 (0.16-0.77)	12	0.003			53%	0.02
	POST	1.02 (0.52-1.53)	5	<0.0001			3%	0.39

Table 4.3 Effects of likely maturity status on effect size for change in CMJ



Study or Subgroup	Experimental Mean	Experimental SD	Experimental Total	Control Mean	Control SD	Control Total	Weight	Std. Mean Difference IV, Random, 95% CI
1.1.1 PRE								
Ramirez-Campillo et al. (2015c) (PPT)	31.8	7	8	29.8	9.1	4	2.6%	0.24 [-0.97, 1.45]
Ramirez-Campillo et al. (2014a) (G120)	23.5	5.4	11	21.9	4.7	4	2.7%	0.29 [-0.86, 1.44]
Ramirez-Campillo et al. (2014a) (G30)	24	5.6	13	21.9	4.7	5	3.1%	0.37 [-0.67, 1.41]
Ramirez-Campillo et al. (2015b) (HG)	33.4	6.9	10	30.6	7.1	3	2.4%	0.38 [-0.93, 1.68]
Ramirez-Campillo et al. (2015b) (VHG)	33.7	6.8	10	30.6	7.1	4	2.7%	0.42 [-0.75, 1.60]
Ramirez-Campillo et al. (2015b) (VG)	33.1	3.6	10	30.6	7.1	3	2.4%	0.52 [-0.79, 1.84]
Ramirez-Campillo et al. (2014a) (G60)	23.9	3.1	13	21.9	4.7	5	3.0%	0.53 [-0.52, 1.58]
Ramirez-Campillo et al. (2015a) (UG)	31.9	4.8	16	29.5	1.1	6	3.3%	0.55 [-0.40, 1.51]
Ramirez-Campillo et al. (2015a) (B+UG)	35.2	8.1	12	29.5	1.1	4	2.7%	0.75 [-0.42, 1.92]
Chelly et al. (2015)	0.25	0.03	14	0.22	0.03	13	3.8%	0.97 [0.16, 1.77]
Ramirez-Campillo et al. (2015a) (BG)	36.7	4.9	12	29.5	1.1	4	2.4%	1.56 [0.27, 2.85]
Michailidis et al. (2013)	34.6	2.5	24	28	3.9	21	4.1%	2.01 [1.28, 2.74]
Zribi et al. (2014)	30.9	1.3	25	27.8	1.3	26	4.1%	2.35 [1.62, 3.07]
Subtotal (95% CI)			**178**			**102**	**39.3%**	**0.91 [0.47, 1.36]**
Heterogeneity: Tau² = 0.39; Chi² = 29.58, df = 12 (P = 0.003); I² = 59%								
Test for overall effect: Z = 3.99 (P < 0.0001)								
1.1.2 MID								
Faigenbaum et al. (2007)	46.5	9.2	13	49.6	10.1	14	4.0%	-0.31 [-1.07, 0.45]
Garcia-Pinillos et al. (2014)	0.45	0.04	17	0.46	0.03	13	4.1%	-0.27 [-1.00, 0.46]
Ramirez-Campillo et al. (2015c) (NPPT)	31.5	12.3	8	29.8	9.1	4	2.6%	0.14 [-1.06, 1.34]
Ramirez-Campillo et al. (2014b)	28.1	5.8	38	27.1	4.5	38	5.1%	0.19 [-0.26, 0.64]
Buchheit et al. (2010)	40.6	8.8	8	38	7	7	3.1%	0.31 [-0.72, 1.33]
Ramirez-Campillo et al. (2015d) (PT24)	34.9	6.2	54	32.9	6.4	27	5.1%	0.32 [-0.15, 0.78]
Marques et al. (2013)	0.354	0.05	26	0.332	0.05	26	4.8%	0.43 [-0.12, 0.98]
Ramirez-Campillo et al. (2015d) (PT48)	36.9	6.2	57	32.9	6.4	28	5.1%	0.63 [0.17, 1.10]
Santos and Janeira (2008)	33.02	6.2	15	28.4	4	5	3.0%	0.77 [-0.28, 1.81]
de Villarreal et al. (2015)	34.8	3.5	13	31.2	3.7	13	3.8%	0.97 [0.15, 1.79]
Santos and Janeira (2011)	34.52	5	14	28.4	4	5	2.9%	1.22 [0.11, 2.33]
Meylan and Malatesta (2009)	37.2	4.5	14	29.6	1.9	11	3.2%	2.04 [1.04, 3.04]
Subtotal (95% CI)			**277**			**191**	**46.8%**	**0.47 [0.16, 0.77]**
Heterogeneity: Tau² = 0.14; Chi² = 23.44, df = 11 (P = 0.02); I² = 53%								
Test for overall effect: Z = 3.02 (P = 0.003)								
1.1.3 POST								
Alves et al. (2010) (G1)	42.92	5.56	9	41.53	2.71	3	2.4%	0.25 [-1.06, 1.56]
Alves et al. (2010) (G2)	42.79	4.45	8	41.53	2.71	3	2.3%	0.28 [-1.06, 1.61]
Chelly et al. (2014)	0.46	0.04	12	0.42	0.03	11	3.5%	1.08 [0.20, 1.97]
Gorostiaga et al. (2004)	41.15	3.08	8	35.55	4.25	11	3.1%	1.40 [0.36, 2.44]
Fernandez-Fernandez et al. (2015a)	42.6	1.8	8	40.39	0.1	8	2.7%	1.64 [0.46, 2.82]
Subtotal (95% CI)			**45**			**36**	**13.9%**	**1.02 [0.52, 1.53]**
Heterogeneity: Tau² = 0.01; Chi² = 4.11, df = 4 (P = 0.39); I² = 3%								
Test for overall effect: Z = 3.98 (P < 0.0001)								
Total (95% CI)			**500**			**329**	**100.0%**	**0.73 [0.47, 0.99]**

Heterogeneity: Tau² = 0.28; Chi² = 73.73, df = 29 (P < 0.00001); I² = 61%
Test for overall effect: Z = 5.58 (P < 0.00001)
Test for subgroup differences: Chi² = 4.75, df = 2 (P = 0.09), I² = 57.9%

Figure 4.2 Forest plot for all included studies

Legend: PPT: Progressed volume, G120: Plyometric - 120 second rest, G30: Plyometric - 30 second rest, HG: Horizontal plyometrics, VHG: Vertical and horizontal plyometrics, VG: Vertical plyometrics, G60: Plyometric - 60 second rest, UG: Unilateral plyometrics, B+UG: Combined plyometrics, BG: Bilateral plyometrics, NPPT: Non-progressed volume, PT24: 24 hours rest, PT48: 48 hours rest, G1: Group 1, G2: Group 2.

4.3.3 Effect of moderator variables

A summary of the effect of moderator variables can be viewed in Table 4.4. Subgroup analysis suggested programme duration (I^2= 89.9%, p = 0.002) and total training sessions (I^2= 91.1%, p = 0.0008) accounted for a significant proportion of the between-group heterogeneity. Programmes with more than 14.5 total sessions produced greatest gains in CMJ (ES = 1.28 [0.78-1.78], Z = 5.04 [p < 0.00001]). Sport explained a lower proportion of between group heterogeneity (I^2= 36.8%, p = 0.21). Mean estimates remained heterogeneous in all subgroups and the level of heterogeneity was high in subgroups with larger ESs, longer programmes and more training sessions.

Moderator variable	**Subgroup**	**Effect Size (95% C.I.)**	***N***	***P***	**Between-group I^2**	**Between-group *P***	**Within-group I^2**	**Within-group *P***
Sport	Soccer	0.61 (0.36-0.86)	23	<0.00001	36.8%	0.21	45%	0.01
	Other	1.09 (0.38-1.80)	7	0.003			77%	0.003
Programme duration	>7.5 weeks	1.21 (0.72-1.69)	12	<0.0001	89.9%	0.002	71%	<0.0001
	<7.5 weeks	0.38 (0.19-0.56)	18	<0.0001			0%	0.93
Mean total sessions	>14.5 sessions	1.28 (0.78-1.78)	11	<0.00001	91.1%	0.0008	71%	0.0001
	<14.5 sessions	0.37 (0.19-0.56)	19	<0.0001			0%	0.95

Table 4.4 Effects of moderator variables on effect size for change in CMJ

4.4 Discussion

The primary moderator of interest on the main effect in the current meta-analysis was likely maturity status (Meylan *et al.*, 2014b; Rumpf *et al.*, 2012). Training-related mechanisms that could explain the main effect include changes to the stiffness of various elastic elements of the muscle-tendon complex, transition to Type II muscle-fibre, increases in the magnitude of muscle contractility, increased muscle size, altered fascicle angle, enhanced motor unit recruitment and discharge rate, greater inter-muscular coordination, higher stretch-reflex excitability, enhanced neural drive to agonist muscles and better utilisation of the SSC

(Markovic and Mikulic, 2010). However, a lack of clarity in how some of these mechanisms manifest (Markovic and Mikulic, 2010), in addition to the confounding effects of maturation-related physical changes (Lloyd *et al.*, 2011), mean that explanations of the effects are speculative. Based on the results of the gathered studies, it seems that PT is moderately effective during the PRE- and POST-PHV periods but seems to be less so around the time when growth achieves its greatest rate of progression in MID.

Of the studies included in this meta-analysis, only three (Ramirez-Campillo *et al.*, 2015a; Ramirez-Campillo *et al.*, 2015b; Ramirez-Campillo *et al.*, 2015c) controlled for biological maturity status using the PHV classification method of Mirwald *et al.* (2002). However, the results of these researchers support the findings of this work. Across these studies, athletes in MID-PHV demonstrated smaller ESs (PPT: 0.24 [-0.97-1.45]; NPPT: 0.14 [-1.06-1.34]) (Ramirez-Campillo *et al.*, 2015c) than in PRE-PHV (BG: 1.56 [0.27-2.85]; B+UG: 0.75 [-0.42-1.92]; UG: 0.55 [-0.40-1.51]; VG: 0.52 [-0.79-1.84]; VHG: 0.42 [-0.75-1.60]; HG: 0.38 [-0.93-1.68]) (Ramirez-Campillo *et al.*, 2015a; Ramirez-Campillo *et al.*, 2015b). These studies were carried out by the same research team. Regardless of maturity status, all of these groups trained twice per week for 6 weeks and though the composition of the applied PT programmes varied, in most cases the MID groups executed a greater than, or equal, amount of total foot contacts relative to the PRE groups. This would seem to imply that despite similar training loads, younger athletes experienced a larger response to training, as demonstrated in the current meta-analysis.

To contextualise the pattern of adaptation to PT in the current study, it is worth referring to the work of Philippaerts *et al*. (2006) and Lloyd *et al*. (2011) who showed lower body power performance to have two peaks of accelerated development which straddle a period of reduced development near the time of PHV. However, it should be noted that both of these studies focus on the natural development of power performance in youths, rather than the magnitude of adaptations due to PT. Despite this, the underlying processes of growth and maturation may influence the magnitude of trainability reported in studies such as those carried out by Ramirez-Campillo *et al.* (Ramirez-Campillo *et al.*, 2015a; Ramirez-Campillo *et al.*, 2015b; Ramirez-Campillo *et al.*, 2015c).

In a mixed longitudinal assessment of physical performance in male soccer players (n = 33, mean age = 12.2 ± 0.7 years), Philippaerts *et al.* (2006) found that lower body power, as measured by standing long jump, reached peak development (10.5 $\mathrm{cm \cdot year^{-1}}$) 18 months prior to PHV. This rate of growth decreased markedly to 6.3 $\mathrm{cm \cdot year^{-1}}$ prior to PHV, before recovering and reaching near pre-pubertal levels during and after the growth spurt. Similarly, Lloyd *et al.* (2011) reported a decline in power prior to the attainment of PHV with performance recovering almost to previously attained levels thereafter. A double-peaked pattern of power performance development can occur due to the emergence of 'adolescent awkwardness' prior to, and during, the growth spurt when motor coordination can be impaired due to differential timing in the development of the trunk and legs (Lloyd *et al.*, 2011), as well as rapid growth (Beunen and Malina, 1988; Eckrich and Strohmeyer, 2006). The fastest period of male adolescent growth typically occurs between the ages of 13 and 15 years and is characterised by an approximate 16.5 cm increase in height due to the trunk and the legs increasing in length (Dimeglio, 2001). The resultant change in body dimensions heightens the centre of mass making it more difficult to control the trunk during plyometric activity, whilst the sudden increase in body mass may also compound this problem (Chu and Myer, 2013). The associated lack of motor coordination could be due to the inability of the neurological pathways to adapt quickly enough to the substantial change in body dimensions (Quatman-Yates *et al.*, 2012). However, this *is* considered a temporary phenomenon (Philippaerts *et al.*, 2006) which could explain the restoration of a moderate level of trainability in the POST group. This may have negatively affected CMJ performance in the MID group, however, it must be stated that this phenomenon is not necessarily seen in all boys (Lloyd *et al.*, 2015c).

In relation to the PRE group, Rumpf *et al.* (2013) highlight that the musculotendinous tissue of athletes in the prepubertal stage of development is more pliable than that of older athletes, thus making it more efficient at storing energy in slow SSC movements, such as a CMJ (Knuttgen and Komi, 2003; Markovic and Mikulic, 2010) than in fast SSC movements, such as maximal ST. Kubo *et al*. (2001) found the tendons of younger boys (10.8 ± 0.9 years) to be more compliant than those of older boys (14.8 ± 0.3 years) and this could augment CMJ performance in PRE athletes (Lichtwark and Barclay, 2010; Markovic and Mikulic, 2010; Wilson, Elliott and Wood, 1992), which could influence responses to training. If younger athletes are comparatively more efficient at storing and reutilising elastic energy in slow SSC movements, a higher level of trainability before the growth spurt may be plausible for certain explosive movements.

It has also been suggested that, despite lower overall performance, prepubescent boys are better able to utilise the SSC than more physically mature athletes as evidenced by a higher percentage gain in CMJ height relative to performance on a squat jump during which the pre-stretch movement was eliminated (Lazaridis *et al.*, 2013). However, more evidence is required as the differences may merely be due to biomechanical factors such as knee flexion angle (Lazaridis *et al.*, 2013) rather than any underlying processes that may determine the degree of trainability. Nevertheless, Meylan *et al*. (2014a) demonstrated that there was a greater ability to maintain speed performance following a period of detraining prior to PHV in comparison to MID or POST PHV, arguing that this could be due to maturation-related development of the central nervous system and increased fascicle length. Along with more compliant musculotendinous tissues, the simultaneous occurrence of these natural processes prior to the growth spurt could contribute to the greater adaptive responses to training in the PRE group as compared to the MID group. However, it remains to be proved if training itself exerts an influence on these processes of natural development.

From the MID stage to the POST stage, the difference in ES from small to moderate could be explained by processes of natural development that may have had a mediating effect on the responses to PT: During POST, peak weight velocity is characterised by increases in muscle tissue owing to greater concentrations of anabolic hormones which can occur during and after the growth spurt (Malina, Bouchard and Bar-Or, 2004; Rogol, Roemmich and Clark, 2002). Previous research has shown the influence of age, lean leg volume and body mass on power performance in male youths whilst qualitative factors relating to muscle architecture and neuromuscular coordination also play a significant role at this stage of maturation (Martin *et al.*, 2004). Hypertrophy of Type II muscle fibres as well as the growth-spurt related increase in muscle coordination and motor unit activation greatly influence power performance (Martin *et al.*, 2004). This could be particularly applicable to the boys in the POST stage who may have been undergoing a spurt in body mass; and effects may have been further accentuated if this was concomitant with a dissipation of adolescent awkwardness after the MID stage. In this way, the described natural processes may have moderated training responses across the developmental continuum, resulting in the pattern of adaptation as reported in this meta-analysis.

Based on these observations, it seems that responses to training are maturation-dependent. However, it is less clear if the PRE and POST periods could be considered as phases of heightened development or adaptation (albeit not necessarily via the same processes) or, conversely, if the MID period represents an interruption to the otherwise normal trajectory of power development in youth. If this were to be the case, the larger magnitude of CMJ performance seen during the POST stage could merely be a biologically underpinned correction of the disruption to coordination seen during the MID period (Williams, Oliver and Faulkner, 2011).

Group	**All**	**PRE**	**MID**	**POST**
Training frequency (per week)	2.0 ± 0.3	2.0 ± 0.3	1.9 ± 0.3	1.8 ± 0.4
Number of weeks	7.6 ± 2.0	7.2 ± 1.9	8.0 ± 2.1	7.8 ± 2.0
Total sessions	15.0 ± 5.0	15.2 ± 5.6	15.2 ± 4.4	14.4 ± 5.9

Table 4.5 Mean training programme characteristics

PRE (10-12.9 year olds); MID (13-15.9 year olds); POST (16-18 year olds).

Another important factor to consider is the respective training programme parameters of each maturation group in the meta-analysis (Table 4.5). A systematic review (Johnson, Salzberg and Stevenson, 2011) of PT in young children previously suggested that two PT sessions per week is optimal in enhancing jumping performance and a large majority of the analysed studies conformed to that guideline. However, the MID group seemed less responsive to PT despite having the longest mean training duration in weeks and the highest mean number of training sessions per programme of the three groups. This could further suggest that maturation-related factors may play a role in impeding the development of lower body power performance around the time of the growth spurt. As all three maturation groups had similar programme parameters across studies, it could be that the PRE and POST groups were more sensitive to the applied training stimulus, though the volume and intensity of PT is likely to have been highly variable across studies. Accordingly, future research must clearly detail the number of foot contacts per session, as well as investigate both higher and lower training frequencies.

The reduction in the magnitude of the MID group's adaptation could also be due to modifications in PT design to accommodate the level of movement competency and/or the presence of adolescent awkwardness. Such an approach can reduce the level of complexity or intensity of PT. For example, a depth jump could be considered to be one of the more advanced plyometric exercises, requiring athletes to have adequate neuromuscular control and strength (Marshall, 2005). This could be replaced by coaches in the MID phase by a less demanding exercise such as a box jump which can reduce forces exerted on the involved joints (Van Lieshout *et al.*, 2014). Such manipulation of training variables, incorporating changes to volume, intensity and modality, could contribute to a reduced adaptive response. On this point, Meylan *et al.* (2014a) have previously executed a training intervention progression that was based on movement competency across Pre-, Mid- and Post-PHV groups and this would seem to be a prudent approach to LTAD.

From a statistical analysis perspective, it is important to discuss the potential effect of moderator variables. In meta-analysis, an evaluation of moderator variables can be undertaken to gauge the impact of ES modifiers, such as training intensity and duration, on the main effect (Ryan, 2014). However, difficulty in comparing the intensity of various programmes across studies, in addition to a lack of complete intervention information, necessitated the examination of alternative factors. In this meta-analysis, the moderator variables of programme duration and mean total sessions were shown to be significant sources of heterogeneity. As expected, larger effects were seen in programmes that lasted longer and had more training sessions per programme. High heterogeneity after subgroup analysis suggests that moderators of the main effect may not have been found, meaning other factors could account for training adaptations (Sandercock, Bromley and Brodie, 2005). This would seem to imply a potential synergy between programme characteristics and other factors, such as biological maturity, in determining the magnitude of response to PT in youth athletes. Generally lower variation between maturity groups when compared to moderator variables was an expected outcome as a result of the highly variable nature of training programmes across studies. However, it could be argued that the high level of heterogeneity within maturity groups could be evidence of differing mechanisms of physiological adaptation to training. This may be particularly applicable in cases in which the ESs of maturity groups are similar despite a large degree of heterogeneity.

There are some limitations to this study. Despite the relationship between age and power performance in youth (Nikolaidis, 2014), the classifications of maturation put forward are based on chronological age so can account for only some of the biological variability across groups. Biological and chronological age are not necessarily synchronous (Baxter-Jones, Eisenmann and Sherar, 2005) but until researchers begin to use a standardised and common method of estimating study participants' level of maturation, this will continue to be a limitation of future reviews. Also, these results relate only to the effects of PT on CMJ performance meaning that they may not be representative of the effects of training on other measures of lower body power such as unilateral, horizontal or depth jumps. Researchers and practitioners could incorporate each of these measures to obtain a more comprehensive overview of the effects of different types of PT in youth athletes.

4.5 Practical Applications

Jump power performance may be more trainable in the PRE and POST stages of maturation with periods of accelerated adaptation potentially occurring due to differing mechanisms of physiological development. When measured through CMJ, power performance may be lower during MID-PHV with a reduction of trainability being concurrent with this stage of development. Longitudinal tracking of PHV could assist in the identification of the MID-PHV period and this could help coaches to regulate training load at this time, facilitating the necessary latitude to preserve and reinforce important movement patterns during the interval of maximal growth.

Reduced trainability during the MID stage could compel trainers to instead prescribe exercise that is more likely to yield greater responses to training, such as RT (Meylan *et al.*, 2014a). This does not mean that PT should be discontinued, but the prescription of a maintenance dose could facilitate the retention of power performance whilst other qualities are developed and whilst the athlete has a window of time to address the movement challenges posed by adolescent awkwardness. This would potentially involve an overall reduction in PT load and could instead comprise movement competence training or strengthening of the trunk musculature. Such an approach may be more in keeping with a more applicable vision of LTAD.

In order to facilitate this approach, researchers and coaches must incorporate measures of biological maturity into their study designs and practices respectively. Though costly, skeletal assessment using x-ray is probably the most effective method (Baxter-Jones, Eisenmann and Sherar, 2005) but even if skeletal age cannot be ascertained, there are alternative options. Of direct relevance to the current study is the method proposed by Mirwald *et al.*

(2002) which reliably predicts years to or from PHV to within one year, 95% of the time. Tracking of the resultant PHV offset may enable coaches to implement the approach advocated in the current analysis. However, alternatives such as the Khamis-Roche method (Khamis and Roche, 1994) offer a similarly convenient and non-invasive way of predicting adult stature. Also, Tanner staging can provide estimates of sexual maturation (Herman-Giddens, Wang and Koch, 2001). Researchers and coaches who have access to athletes for an extended period of time can longitudinally track growth velocity curves which can identify the beginning, middle and end of the adolescent growth spurt (Balyi and Way, 2005).

CHAPTER 5

Variation in responses to sprint training in male youth athletes: a meta-analysis

Citation

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Abstract

The trainability of youths and the existence of periods of accelerated adaptation to training have become key subjects of debate in exercise science. The purpose of this meta-analysis was to characterise youth athletes' adaptability to ST across PRE-, MID-, and POST-PHV groups. ESs were calculated as a measure of straight-line sprinting performance with studies qualifying based on the following criteria: (a) healthy male athletes who were engaged in organised sports; (b) groups of participants with a mean age between 10 and 18 years; (c) ST intervention duration between 4 and 16 weeks. Standardised mean differences showed ST to be moderately effective (ES = 1.01 95% confidence interval: 0.43-1.59) with adaptive responses being of large and moderate magnitude in the POST- (ES = 1.39; 0.32-2.46) and MID- (ES = 1.15; 0.40-1.9) PHV groups respectively. A negative ES was found in the PRE group (ES = -0.18; -1.35-0.99). Youth training practitioners should prescribe ST modalities based on biological maturation status. Twice weekly training sessions should comprise of up to 16 sprints of around 20 m with a work to rest ratio of 1:25, or greater than 90 seconds.

5.1 Introduction

Sprinting velocity is an important factor in high performance in a variety of sports with acceleration requiring a high level of force production in order to propel the body forward (Lockie *et al.*, 2012). This quality may be a particularly influential factor in age grade sport where youths' sprint performance increases with age (Rumpf *et al.*, 2011) which, in turn, exerts a progressive impact on motor performance (Malina, Bouchard and Bar-Or, 2004; Mendez-Villanueva *et al.*, 2011a). Sprinting over a short distance is a common and important event in youth sport (Rumpf *et al.*, 2011) and Mendez-Villanueva *et al.* (2011b) observed youth soccer players to reach speeds of up to 29.5 ± 1.4 ($km \cdot h^{-1}$) in matches. Additionally, straight sprints have been shown to be the most common type of movement prior to goal-scoring (Aughey *et al.*, 2013; Faude, Koch and Meyer, 2012).

Improvements in sprinting velocity during youth occur due to growth and maturation (Oliver, Lloyd and Rumpf, 2013); however, training that specifically targets the physical, metabolic and neurological elements that facilitate short, impulsive movements can also be effective (Gevat *et al.*, 2012). Sprint training programmes commonly include sprinting itself, without external resistance, typically over short distances (30 m) and combined with longer rest periods (3 mins) (Kotzamanidis *et al.*, 2005). These programmes have been shown to enhance sprinting velocity over a commensurate distance in youth athletes (Kotzamanidis *et al.*, 2005) as they do in adults (Hansen, 2014).

To our knowledge, there are no studies which subject male youth athletes to a ST stimulus whilst also controlling for biological maturity status. This means that many of the principles that determine conventional programming of youth ST remain unfounded. To our knowledge, just one meta-analysis (Rumpf *et al.*, 2012) has specifically quantified the effect of ST on sprinting velocity in youth, however, just two studies were part of that review. The authors of that analysis found a favourable small averaged ES (-0.57 ± 0.31) on sprint velocity. Recent intervention studies have shown variable results for ST at different stages of maturation with limited evidence suggesting that this training modality could be less effective prior to the attainment of PHV (Rumpf *et al.*, 2015; Venturelli, Bishop and Pettene, 2008). This could indicate the presence of a maturational threshold (McNarry, Mackintosh and Stoedefalke, 2014) that mediates responses to training and longitudinal research suggests this could be concurrent with the onset of PHV (Philippaerts *et al.*, 2006). The current meta-analysis aims to clarify this observation by undertaking a comprehensive analysis of the effect of ST on sprinting velocity in young male athletes. A secondary aim is to determine whether the current literature supports the idea of specific periods of enhanced adaptation to this type of training.

5.2 Materials and Methods

5.2.1 Protocol

This review used similar methodology as the meta-analyses on RT and PT in Chapters 3 and 4.

5.2.2 Literature search

With no date restrictions, searches of the PubMed, Google Scholar, Sport Discus, Medline, CINAHL and Science Direct databases were undertaken. Words that were used as either individual search terms, or in conjunction with each other, included ‘speed’, ‘velocity’, ‘agility’, ‘sprint’, ‘sprinting’, ‘alactic’ ‘acceleration’, ‘running’, ‘training’, ‘exercise’, ‘change of direction’, ‘paediatric’, ‘youth’, ‘children’, ‘adolescents’, ‘athletes’ and ‘sport’. In selecting studies for inclusion, a review of all relevant article titles within each database was conducted before an examination of article abstracts and, then, full published articles. Following the further elimination of inappropriate studies for a variety of reasons (Figure 5.1), a search of article reference lists was carried out. Only peer-reviewed articles were selected.

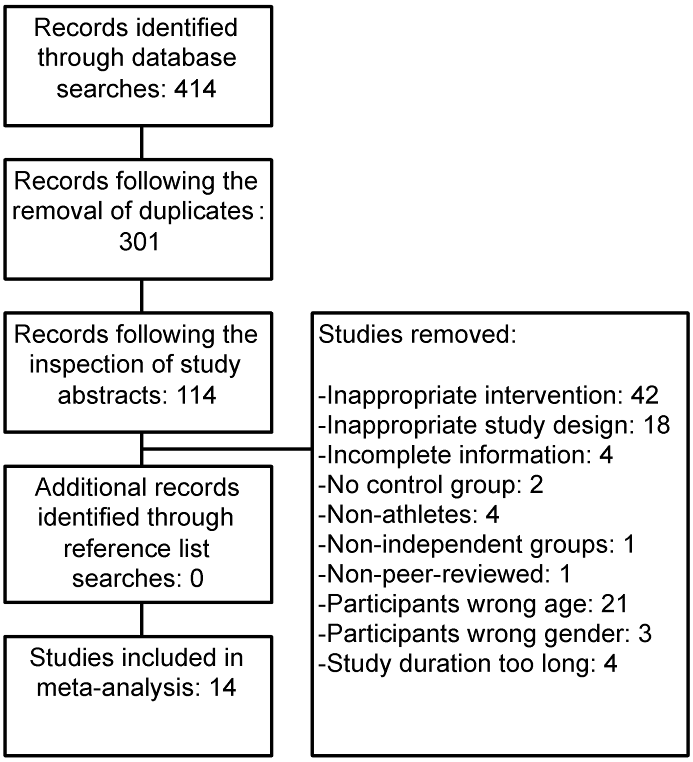


Figure 5.1 The search process

5.2.3 Selection of studies

The following criteria determined the eligibility of studies for inclusion in the review: healthy males, between the mean age of 10 and 18 years, who were engaged in organised sport. Interventions must have been between 4 and 16 weeks in duration and must have included a control group. The protocols of included studies must have comprised sprinting movements with recovery after each effort (Rumpf *et al.*, 2012) and must have focused on improving sprint performance. Studies that utilised resisted sprinting (which were considered as a form of RT), or repeated ST as a mechanism to improve sprint endurance, were not considered.

It should be noted that in some studies, specific ST was carried out alongside other training modalities as part of a wider fitness programme. Means and standard deviations for a measure of post-intervention sprinting performance were used to calculate an ES.

5.2.4 Maturity Status

Assessment of maturity status followed the same protocol as in Chapters 3 and 4. The characteristics of the participants of the studies are reported in Table 5.1.

5.2.5 Data extraction

For studies in which data were not clearly or completely reported, article authors were contacted for clarification. Where possible, 30 m sprint distance times were used to measure sprinting velocity. This was rationalised on the basis that sprinting over this distance is representative of sport specific maximal velocity (Cronin and Hansen, 2005). Where a 30 m sprint was not carried out, sprint times for the closest measured distance were utilised instead. Table 5.2 shows all of the included studies.

	All		PRE		MID		Post	
	Experimental (*n*= 166)	**Control (*n*=141)**	**Experimental (*n*=21)**	**Control (*n*=20)**	**Experimental (*n*=68)**	**Control (*n*=58)**	**Experimental (*n*=77)**	**Control (*n*=63)**
Mean age (y)	15.1 ± 2.1	15.1 ± 2.2	11.2 ± 0.3	11.2 ± 0.3	14.1 ± 0.7	13.9 ± 0.6	16.8 ± 0.7	16.9 ± 0.7
Mean height (cm)	170.4 ± 10.5	170.0 ± 10.8	151.8 ± 4.0	151.1 ± 3.0	164.8 ± 2.6	164.2 ± 2.4	179.2 ± 3.8	179.0 ± 4.8
Mean body mass (kg)	62.8 ± 11.8	63.2 ± 11.7	40.5 ± 5.0	40.5 ± 5.0	53.8 ± 3.1	54.3 ± 2.6	72.4 ± 4.8	72.7 ± 5.0

Table 5.1 Descriptive data for male youth athletes from sprint training studies included in meta-analysis

Study Name	Age (yrs) (SD)	Maturation	Height (cm) (SD)	Weight (kg) (SD)	Sport	Group	Group Identifier in study	Number of Participants	Training frequency (per week)	Number of Weeks	Mean Total sessions	Test
Pettersen and Mathisen (2012)	11.5 (0.3)	Pre	154.7 (4.6)		Soccer	Training	TG	14	1	6	6	20 m sprint (s)
Venturelli, Bishop and Pettene (2008)	11 (0.5)	Pre	149 (6)	40.5 (5)	Soccer	Sprint-training	STG	7	2	12	24	20 m sprint (s)
Chaouachi *et al.* (2014a)	14.2 (0.9)	Mid	167.2 (5.7)	54.1 (6.3)	Soccer	Change of direction	CODG	12	3	6	18	30 m sprint (s)
Christou *et al* (2006).	13.8 (0.4)	Mid	162 (3.8)	52 (3.3)	Soccer	Strength-soccer	STR	9	2	16	32	30 m sprint (s)
Christou *et al.* (2006)	13.5 (0.9)	Mid	163 (2.5)	54.1 (2)	Soccer	Soccer	SOC	9	2	16	32	30 m sprint (s)
de Villarreal *et al.* (2015)	15.33 (0.34)	Mid	168.04 (7.78)	57.13 (8.34)	Soccer	Combined	CombG	13	2	9	18	10 m sprint (s)
Mathisen (2014)	13.5 (0.24)	Mid	162.5 (8.1)	48.8 (10.1)	Soccer	Training	TG	14	1	8	8	20 m sprint (s)
Meckel *et al.* (2012)	14.3 (0.5)	Mid	166.1 (8.1)	56.5 (10.9)	Soccer	Short-sprint repetition	SST	11	3	7	21	30 m sprint (s)
Alves *et al.* (2010)	17.33 (0.71)	Post	177.67 (5.57)	70.54 (9.09)	Soccer	G1	G1	9	1	6	6	15 m sprint (s)

Alves *et al.* (2010)	17.22 (0.44)	Post	173.5 (6.86)	69.76 (6.93)	Soccer	G2	G2	8	2	6	12	15 m sprint (s)
Buchheit *et al.* (2010b)	16 (0.8)	Post	181 (6)	71.2 (10.3)	Handball	Speed/agility	S/A	7	2	4	8	10 m sprint (s)
Gottlieb *et al.* (2014)	16.3 (0.5)	Post	185.3 (4)	78.2 (5.9)	Basketball	Specific Sprint Training	SST	10	2	6	12	20 m sprint (s)
Kotzamanidis *et al.* (2005)	17 (1.1)	Post	178 (35)	73.5 (1.2)	Soccer	Combined	COM	12	2	9	18	30 m sprint (s)
Shalfawi *et al.* (2012a)	16.3 (0.5)	Post	178.5 (7.3)	68.1 (9.4)	Soccer	Training	Training	8	2	8	16	40 m sprint (s)
Tonnessen *et al.* (2011)	16.4 (0.9)	Post	176.3 (7.4)	67.2 (9.1)	Soccer	Training	TG	10	1	10	10	40 m sprint (s)
Tsimahidis *et al*. (2010)	18 (1.2)	Post	183 (1.3)	80.9 (10.2)	Basketball	Combined training programme	CTP	13	2	10	20	30 m sprint (s)

Table 5.2 Characteristics of the reviewed studies and their participants

5.2.6 Analysis and interpretation of results

The analysis and interpretation of results followed the same protocol as in Chapter 4.

5.2.7 Study quality

Funnel plots were subjectively analysed to assess publication bias which was apparent however, a risk of bias quality scale was not utilised. The Cochrane Collaboration has discouraged the use of such scales, saying that the practice is not supported by empirical evidence and assessment criteria may result in inaccurate study weights (Higgins, Altman and Sterne, 2011). Moreover, it has also been suggested that controls such as blinding are difficult to implement in training intervention studies (Bolger *et al.*, 2015). Previous reviews on training studies in youths have reported low study quality and a medium to high risk of bias (Behringer *et al.*, 2010; Harries, Lubans and Callister, 2012) and we adopted that assumption in this review.

5.2.8 Subgroup analysis

In order to identify potential sources of heterogeneity, moderator variables were determined *a priori* and assessed, a summary of which can be seen in Table 5.3. The moderator variables were analysed with a random effects model and were selected based on differences in sport, training programme characteristics and performance testing methods. A division was made between soccer and other sports on the basis that youth athletes may be more likely to partake in activities in which they excel, meaning faster athletes may express a preference for sports that place a premium on sprinting velocity (Malina *et al.*, 2007). The variables of programme duration and mean total sessions were divided at their medians as it was hypothesised that longer training programmes may lead to greater performance improvements. Training frequency was subdivided into 1, 2 and 3 sessions per week as this variable may have an impact on the magnitude of adaptation to short ST (Ross and Leveritt, 2001). Subgroups were also formed based on the total number of sprints per session, sprint distance and rest interval between sprints. Lastly, the distance used for performance testing was categorised as ‘0-20 m’ (inclusive of 20 m) and ’20-40 m’ as shorter distances may be more sensitive to detecting accelerative potential, whilst longer distances are more effective for measuring maximal velocity (Little and Williams, 2005).

Moderator	**Group**	***n***	***ES* (95%CI)**	***P***	**I^2**
Sport	Soccer	*13*	0.76 (0.43-1.59)	*0.001*	69%
	Other	*3*	4.34 (0.46-8.22)	*0.03*	
Programme duration (weeks)	>8	*7*	2.06 (0.58-3.53)	*0.006*	73.6%
	≤8	*9*	0.55 (0.24-0.87)	*<0.001*	
Total training sessions (*n*)	>17	*8*	1.69 (0.48-2.90)	*0.006*	65.5%
	<17	*8*	0.59 (0.24-0.95)	*<0.001*	
Training frequency (per week)	1	*4*	0.64 (0.07-1.21)	*0.03*	53.1%
	2	*10*	1.53 (0.51-2.54)	*0.003*	
	3	*2*	0.29 (-0.29-0.88)	*0.33*	
Total sprints per session (*n*)	>16	*5*	0.20 (-0.30-0.71)	*0.44*	67.0%
	<16	*6*	1.41 (0.15-2.68)	*0.03*	
Sprint distance (m)	≥20	*7*	0.94 (-0.07-1.95)	*0.07*	0%
	<20	*6*	0.80 (0.02-1.59)	*0.05*	
Rest interval (s)	≥90	*6*	1.13 (-0.07-2.34)	*0.07*	0%
	<90	*6*	0.58 (-0.02-1.19)	*0.06*	
Testing distance (m)	0-20	*8*	0.70 (0.14-1.26)	*0.01*	49.8%
	20-40	*8*	1.60 (0.48-2.72)	*0.005*	

Table 5.3 Effects of moderator variables on effect sizes

5.3 Results

Following the search process, 414 studies were identified. When duplicates were removed, this was reduced to 301 with this being further reduced to 114 following the inspection of abstracts. After full studies were individually inspected for eligibility, 14 remained. These were included in the meta-analysis, being allocated to one of the three maturity classifications (PRE, MID, POST). Eleven of the studies included soccer players with the remainder being basketball (n = 2) and handball (n = 1). In terms of biological maturity, there were two studies carried out in prepubertal children, five in midpubertal and seven in postpubertal athletes.

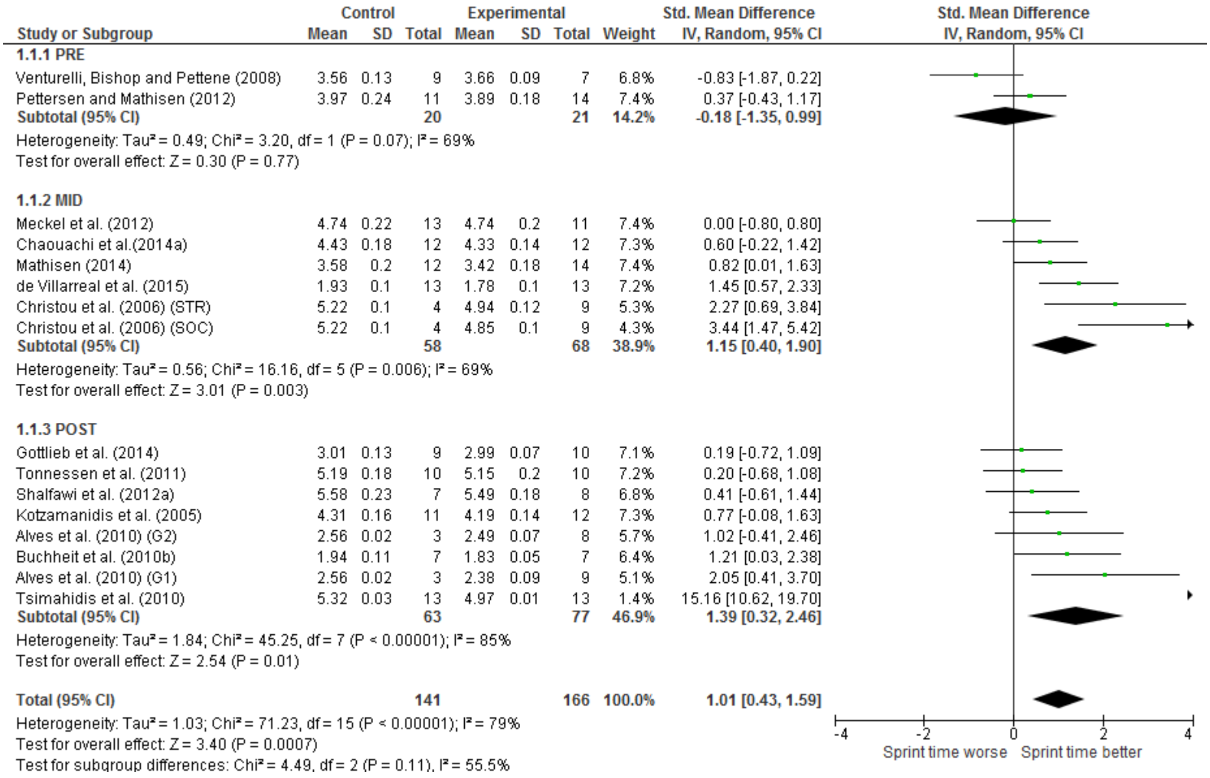
5.3.1 Main effect

Across all groups included in the meta-analysis there was a significant improvement in sprinting velocity (ES = 1.01 [0.43-1.59], Z = 3.40 [p = 0.0007]). The overall estimate was of moderate magnitude but showed a high level of between-study heterogeneity (I^2 = 79% [$p < 0.00001$]).

5.3.2 Effects between and within maturity groups

Heterogeneity between maturity groups was moderate (I^2 = 55.5% [p = 0.11]).

In the PRE group, the ES for change in sprinting velocity was trivial and non-significant (ES = -0.18 [-1.35-0.99], Z = 0.30 [p = 0.77]). The POST group showed the greatest effects for sprinting velocity. The mean estimate for POST was of large magnitude (ES = 1.39 [0.32-2.46], Z = 2.54 [p = 0.01]) but was highly heterogeneous (I^2 = 85% [$p < 0.00001$]). The MID group estimate was moderate (ES = 1.15 [0.40-1.90], Z = 3.01 [p = 0.003]) and was also highly heterogeneous (I^2 = 69% [p = 0.006]). Figure 5.2 shows forest plots with associated ESs.



Study or Subgroup	Control Mean	Control SD	Control Total	Experimental Mean	Experimental SD	Experimental Total	Weight	Std. Mean Difference IV, Random, 95% CI
1.1.1 PRE								
Venturelli, Bishop and Pettene (2008)	3.56	0.13	9	3.66	0.09	7	6.8%	-0.83 [-1.87, 0.22]
Pettersen and Mathisen (2012)	3.97	0.24	11	3.89	0.18	14	7.4%	0.37 [-0.43, 1.17]
Subtotal (95% CI)			**20**			**21**	**14.2%**	**-0.18 [-1.35, 0.99]**
Heterogeneity: Tau² = 0.49; Chi² = 3.20, df = 1 (P = 0.07); I² = 69%								
Test for overall effect: Z = 0.30 (P = 0.77)								
1.1.2 MID								
Meckel et al. (2012)	4.74	0.22	13	4.74	0.2	11	7.4%	0.00 [-0.80, 0.80]
Chaouachi et al.(2014a)	4.43	0.18	12	4.33	0.14	12	7.3%	0.60 [-0.22, 1.42]
Mathisen (2014)	3.58	0.2	12	3.42	0.18	14	7.4%	0.82 [0.01, 1.63]
de Villarreal et al. (2015)	1.93	0.1	13	1.78	0.1	13	7.2%	1.45 [0.57, 2.33]
Christou et al. (2006) (STR)	5.22	0.1	4	4.94	0.12	9	5.3%	2.27 [0.69, 3.84]
Christou et al. (2006) (SOC)	5.22	0.1	4	4.85	0.1	9	4.3%	3.44 [1.47, 5.42]
Subtotal (95% CI)			**58**			**68**	**38.9%**	**1.15 [0.40, 1.90]**
Heterogeneity: Tau² = 0.56; Chi² = 16.16, df = 5 (P = 0.006); I² = 69%								
Test for overall effect: Z = 3.01 (P = 0.003)								
1.1.3 POST								
Gottlieb et al. (2014)	3.01	0.13	9	2.99	0.07	10	7.1%	0.19 [-0.72, 1.09]
Tonnessen et al. (2011)	5.19	0.18	10	5.15	0.2	10	7.2%	0.20 [-0.68, 1.08]
Shalfawi et al. (2012a)	5.58	0.23	7	5.49	0.18	8	6.8%	0.41 [-0.61, 1.44]
Kotzamanidis et al. (2005)	4.31	0.16	11	4.19	0.14	12	7.3%	0.77 [-0.08, 1.63]
Alves et al. (2010) (G2)	2.56	0.02	3	2.49	0.07	8	5.7%	1.02 [-0.41, 2.46]
Buchheit et al. (2010b)	1.94	0.11	7	1.83	0.05	7	6.4%	1.21 [0.03, 2.38]
Alves et al. (2010) (G1)	2.56	0.02	3	2.38	0.09	9	5.1%	2.05 [0.41, 3.70]
Tsimahidis et al. (2010)	5.32	0.03	13	4.97	0.01	13	1.4%	15.16 [10.62, 19.70]
Subtotal (95% CI)			**63**			**77**	**46.9%**	**1.39 [0.32, 2.46]**
Heterogeneity: Tau² = 1.84; Chi² = 45.25, df = 7 (P < 0.00001); I² = 85%								
Test for overall effect: Z = 2.54 (P = 0.01)								
Total (95% CI)			**141**			**166**	**100.0%**	**1.01 [0.43, 1.59]**
Heterogeneity: Tau² = 1.03; Chi² = 71.23, df = 15 (P < 0.00001); I² = 79%								
Test for overall effect: Z = 3.40 (P = 0.0007)								
Test for subgroup differences: Chi² = 4.49, df = 2 (P = 0.11), I² = 55.5%								

Figure 5.2 Forest plot of effect sizes in each maturation group with 95% confidence intervals

Legend for group identifiers within studies: SOC: Soccer, STR: Strength-soccer, G1: Group 1 Soccer, G2: Group 2 Soccer

Subgroup analysis suggested programme duration accounted for a significant proportion of the between-group heterogeneity (I^2 = 73.6%) with longer (>8 weeks) programmes producing greatest gains in sprinting velocity (ES = 2.06 [0.58-3.53], Z = 3.40 [p = 0.006]). Sport (I^2 = 69%), total training sessions (I^2 = 65.5%), training frequency (I^2 = 53.1%), total sprints per session (I^2 = 67.0%) and sprint test distance (I^2 = 49.8%) all accounted for large proportions of between-group heterogeneity. Mean estimates remained heterogeneous in most subgroups and the level of heterogeneity was lower in subgroups with smaller ESs, shorter programmes, less training sessions, a greater number of sprints, shorter sprint distances, shorter rest intervals and shorter sprint test distances.

5.4 Discussion

In this meta-analysis, the main moderator of interest in youth trainability was maturity status. The results showed that ST improves sprint performance in youths, but results were heterogeneous. Sprint training became progressively more effective with increasing maturity.

During growth and maturation, the natural development of sprint performance occurs due to greater muscular size, increased limb length, changes to musculotendinous tissue, enhanced neural and motor development and better movement quality and coordination (Oliver and Rumpf, 2014). The timing and tempo of these factors is highly variable across individuals (Malina, Bouchard and Bar-Or, 2004) and manipulation or changing of any of the variables, through training or natural development, could result in improvements in sprinting velocity. However, given that there are so many variables that contribute to this quality, it has thus far been difficult to determine how best to structure training in youth (Rumpf *et al.*, 2012).

Sprint training was found to be moderately effective in the MID phase and largely effective in the POST phase. There was no evidence for the effectiveness of ST in the PRE group; however with only two studies included in this part of the analysis, any conclusions drawn from these data are limited. As highlighted by McNarry *et al.* (2014) in a statement by the British Association of Sport and Exercise Sciences, a review (Rumpf *et al.*, 2012) found that the trainability of sprinting velocity in youths was approximately 50% lower in MID than it was in PRE and POST groups. That investigation by Rumpf *et al*. (2012) examined the effects of multiple different training modalities, such as PT and RT, on sprinting and is opposed by the results of the current meta-analysis. This is possibly due to the multi-dimensional nature of the training methods examined, contrasting with the current study.

The pattern of trainability of sprinting velocity in this review is in line with that described in a previous investigation: Meyers *et al*. (2015) found that maximal sprinting velocity seemed to develop at quicker rates during and after the growth spurt. These authors identified maturation-related increases in stride length, accentuated by improved stabilisation of stride frequency and ground contact times, as potential mediators of sprinting velocity development around PHV. Greater leg length has previously been associated with higher sprinting velocity in youth (Mendez-Villanueva *et al.*, 2011a) and it seems that sprinting performance during and after the growth spurt may be further enhanced by increases in strength and power

(Meyers *et al.*, 2015). Also, Philipaerts *et al*. (2006), conducting a longitudinal evaluation of a number of different physical abilities in male youth soccer players, found that 30 m sprint time reached its fastest rate of development (-0.4 $s \cdot yr^{-1}$) around PHV, before levelling off after the growth spurt. The lack of improvement in younger athletes found in the current study and the large magnitude of response of the oldest athletes support the findings of Meyers *et al*. (2015) and could indicate the presence of a maturational threshold for the development of sprinting velocity around the time of PHV.

Greater levels of strength are related to faster sprinting performance in youth (Comfort *et al.*, 2014) which may explain why training was more effective with increasing age. During the growth spurt, elevated testosterone, growth hormone and IGF-1 contribute to the accumulation of fat free mass and relative reduction of body fat such that, by the age of 18 most males have obtained 90% of their total skeletal mass (Rogol, Roemmich and Clark, 2002). This results in enhanced levels of strength (Mero *et al.*, 1990; Rogol, Roemmich and Clark, 2002) and ultimately, given their dependent relationship, greater sprinting velocity (Armstrong, Welsman and Chia, 2001). This may explain why the development of sprinting velocity could be further expedited when specific ST is combined with RT as has been shown previously (Kotzamanidis *et al.*, 2005). The progressively increasing rate of muscle mass accumulation beyond the onset of the growth spurt (Silva *et al.*, 2013) could play a role in the higher rate of sprinting velocity development in the POST phase when both training and natural development are considered. Increases in muscle cross-sectional area can enhance force output capability, which in turn can have positive effects on sprinting performance (Suchomel, Nimphius and Stone, 2016). Given that both the current analysis, and the study by Meyers *et al*. (2015), showed a similar trajectory of development in the POST period, this may be one of the most influential elements of sprint performance as it can also interact with factors such as fascicle length, pennation angle and tendon stiffness (Meyers *et al.*, 2015). However, it should be noted that as youths grow, relative strength can decrease as height and body mass increase (Zatsiorsky and Kraemer, 2006). If this process outpaces that of maturation, a decrease in performance is possible, thus underlining the importance of continuous RT to uphold sprint performance throughout youth (Zatsiorsky and Kraemer, 2006).

A result of the current meta-analysis is that ST seemed to be ineffective in the PRE group and recent evidence seems to support this finding. Rumpf *et al*. (2015) showed that resisted ST was not effective in pre-pubertal athletes in contrast to a Mid/Post-PHV group. The latter group adapted to training to a similar extent to that observed in adult investigations (Lockie *et al.*, 2012; Zafeiridis *et al.*, 2005). In maximal sprinting, Rumpf *et al*. (2013) showed that SSC activity showed variability across the developmental continuum with leg stiffness being 44.5% and 18.4% higher in the POST-PHV period than it was in the PRE- and MID- periods respectively. The authors highlight that the musculotendinous tissue of younger boys is more compliant than that of older boys, meaning that as a youth physically matures, he is better able to utilise the SSC whilst sprinting. Also, concentric and eccentric power was greater in older participants than it was in younger participants and these factors, individually or combined, could have resulted in a lower response in younger athletes. Reinforcing the above evidence, Meylan *et al*. (2014a) recently demonstrated that a group of Pre-PHV athletes showed smaller improvements in sprint times than Mid-PHV and Post-PHV athletes following an eight week training programme.

In youth, short-distance acceleration is achieved through a combination of increased stride length and frequency (Korhonen, Mero and Suominen, 2003). However, Meyers *et al*. (2015) showed that running stride frequency decreases in the PRE stage and this could potentially reduce the effectiveness of ST at this stage. Accordingly, those researchers recommended that training in the pre-pubertal period should incorporate exercises to improve stride frequency, likely because younger athletes may be more dependent on that quality to generate sprinting velocity. Indeed the results of this meta-analysis could inform a long-term training strategy for sprinting performance in youth: boys who are undergoing the growth spurt, or who have already experienced it, could preferentially focus on improving strength and rate of force development in an effort to take advantage of a hormonal profile that is conducive to improving those particular qualities (Meyers *et al.*, 2015). Similarly, younger athletes could have a preferential focus on addressing their own unique limiting factors in sprinting performance, such as stride frequency.

It is important to note that many of the above observations relate to the natural development of sprinting velocity in youth, rather than the magnitude of adaptations due to training. Nevertheless, these underlying processes of growth and maturation seem to have mediating effects on trainability levels as it is possible that biological maturation can either enhance or limit the effectiveness of the training stimulus, as outlined in the results presented in Chapter 4. This means that practitioners must consider these factors when constructing developmentally-appropriate ST programmes.

A further factor to consider is the mean training loads of the maturity groups. As displayed in Table 5.4, the PRE and POST groups had largely similar training loads when measured by total distances sprinted and total sessions per programme; yet they adapted at different magnitudes. However, the POST group underwent a substantially lower volume of sprints per session at almost double the distance of the PRE group, indicating that a lower volume of sprints over a longer distance may be a more effective training protocol in youth athletes. The MID group had a substantially higher volume of training than the PRE or POST groups and this could mean that MID athletes may require a ST stimulus of greater duration or magnitude in order to realise the benefits of training.

	ALL	PRE	MID	POST
Number of sprints	16.7 ± 8.6	25.0 ± 7.1	21.9 ± 7.3	11.4 ± 6.1
Sprint distance (m)	22.7 ± 15.0	13.5 ± 2.1	30.3 ± 20.0	22.2 ± 15.0
Total load (m [sprints x distance])	418.8 ± 301.7	330.0 ± 42.4	742.6 ± 364.1	340.4 ± 290.8
Work interval (s)	4.5 ± 0.7	5.0	4.0	-
Rest interval (s)	116.2 ± 52.5	100.0 ± 35.4	88.0 ± 39.6	140.3 ± 58.6
Training frequency (per week)	1.9 ± 0.6	1.5 ± 0.7	2.2 ± 0.8	1.8 ± 0.5
Number of weeks	8.7 ± 3.5	9.0 ± 4.2	10.3 ± 4.5	7.4 ± 2.2
Total sessions	16.3 ± 8.3	15.0 ± 12.7	21.5 ± 9.2	12.8 ± 4.9

Table 5.4 Mean training programme characteristics in reviewed studies

Another factor to consider is the potential impact of moderators of the training effect. In meta-analysis, moderator analysis can be utilised to evaluate the impact of ES modifiers, such as training intensity and duration, on the main effect (Ryan, 2014). However, difficulty in comparing the intensity of various programmes across studies, in addition to incomplete information, necessitated the examination of alternative factors. In the current analysis, the moderator variables of sport, programme duration, total training sessions, training frequency, total sprints per session and testing distance were all shown to be potential sources of moderate to high heterogeneity. As expected, larger effects were seen in programmes that lasted longer and had more training sessions per programme. ESs were of greater magnitude in programmes with less than 16 sprints performed over distances greater than 20 m and with rest intervals higher than 90 seconds. Also, 2 sessions per week seemed more effective than 1 whilst distances of between 20 m and 40 m were more sensitive to measuring changes in sprinting performance following an intervention when compared to 0 m to 20 m. Three sessions per week had a lower ES than 2 sessions per week and this could be explained by an imbalance of studies in the respective subgroups or a suboptimal response to progressively higher training volumes: higher volumes of training are not necessarily more beneficial (Cadore *et al.*, 2013). The presence of high heterogeneity after subgroup analysis suggests that moderators of the main effect may not have been found, meaning other factors could account for training adaptations. This would seem to imply a potential synergy between programming variables and other factors, such as biological maturity, in determining the magnitude of response to ST in youth athletes. Predominantly lower variation between maturity groups when compared to moderator variables was an expected outcome as a result of the highly variable nature of training programmes across studies. Heterogeneity within maturity groups could also be evidence of differing mechanisms of physiological adaptation to training. This may be particularly applicable in cases in which the ES of maturity groups was similar despite a large degree of heterogeneity, as can be observed in the MID and POST groups.

This study does have some limitations. The categories used to account for biological maturity (Rumpf *et al.*, 2012) are based on chronological age and can account for only some of the developmental diversity that is seen across groups. Examination of the I^2 statistics revealed high levels of heterogeneity between studies, indicating a level of inconsistency amongst results which can negatively impact the confidence of study recommendations (Higgins *et al.*, 2003). However, heterogeneity is likely always present in meta-analyses (Deeks, Higgins and Altman, 2008). The relatively small body of data relating to ST in youth means that more research is required to make more definitive conclusions based on maturation status. However, this is potentially offset by the finding that, based on current literature, ST does generally increase performance in youth athletes. Researchers should therefore use this review as a basis for formulating future training interventions.

Based on the available literature, it seems that training sessions to improve sprinting velocity should comprise of up to 16 sprints of around 20 m with a work to rest ratio of 1:25, or greater than 90 seconds. Two sessions per week would seem to be adequate in enhancing sprinting performance over an 8 week period. However, these parameters may need to be varied based on the maturity status of the athlete, with ST across all ages occurring alongside exercises that address the effects of performance limiters or leverage the positive changes associated with maturation.

As ST may vary as youth athletes grow, a concentrated approach to offsetting negative confounding factors during times of lower trainability, prior to PHV, could be used. Following this, practitioners could directly target key times of heightened response to increase the efficiency of training, focusing efforts on improving strength and sprinting performance during and after PHV. During the PRE stage of development, coaches should directly address the factors that could result in reduced adaptive responses, focusing training on activities that improve fundamental movements such as running, skipping, jumping and balancing (Lloyd *et al.*, 2015b). This can be combined with training that enhances stride frequency (Meyers *et al.*, 2015) such as assisted or downhill sprinting. However, the suitability of this training method for athletes who are not advanced has been questioned (Sheppard, 2013). Additionally, fast leg drills (at intervals or on command) to facilitate faster limb motion than would be typically possible during standard sprinting could be combined with bounding movements (Cissik, 2005). This can form the basis to advance onto more complex tasks as the youth develops skill and dexterity (Lloyd *et al.*, 2015b). Training that targets concentric strength may underpin sprint performance over shorter distances, whilst SSC activities may have more influence as distance increases (Harris *et al.*, 2008). As the athlete advances, such work could be transitioned into more specialised squat and weightlifting variations, higher intensity plyometric exercises (Myer *et al.*, 2013) and resisted ST (Rumpf *et al.*, 2015). In this way, a multi-modal approach across all youths seems best with ST occurring alongside complimentary exercises in order to support the development of sprinting velocity throughout growth and maturation.

CHAPTER 6

Literature Review (Part 2)

6.1 Introduction

With a view to establishing the clearest possible overview of the trainability of youth athletes, a dual-purpose literature review format has been adopted in this work. Meta-analyses can be superior to narrative reviews of the literature as they establish clear and systematic criteria for study selection and facilitate a robust statistical analysis of similar studies in a given field of research (Fagard, Staessen and Thijs, 1996). Narrative reviews can be biased by personal experiences and it may not necessarily be obvious to the reader how large a proportion of a particular body of literature was evaluated, with selective citation and bias being potential downfalls of the approach (Garg, Hackam and Tonelli, 2008). However, systematic methods of reviewing literature can be restrictive, with adherence to a defined set of search criteria for studies potentially resulting in the oversight of important details relating to how a given trial was conducted, leading to a lack of validity (Hopayian, 2001). In light of this information, it was decided that a narrative review, conducted with less restrictive search criteria, would allow the evaluation of studies which failed to meet all of the selection criteria for the meta-analytical reviews, but could still add valuable context to the reported results. Such an approach could also facilitate the assessment of studies which were published after the systematic searches had been conducted. To this end, the following sections offer a complementary narrative review of studies on RT, PT and ST in youth athletes in the PRE, MID and POST periods.

6.2 The Effects of Training and Maturation in the PRE PHV Stage

6.2.1 Strength

The results of the RT meta-analysis in Chapter 3 showed that strength was less trainable during PRE than it was in both MID and POST, however, only three studies met the inclusion criteria for that part of the work. Included were 19 studies which were chosen from the wider literature but in contrast to the meta-analyses on PT and ST, it was decided to calculate ESs based on baseline and follow-up data with a view to being as inclusive as possible with regard to the available studies. This was because of many researchers' failure to include appropriate control groups in their interventions. Of the studies included in the meta-analysis, just two (Meylan *et al.*, 2014a; Rumpf *et al.*, 2015) measured maturity status using the offset method (Mirwald *et al.*, 2002). Both of these interventions showed that strength was less trainable prior to PHV, potentially indicating the presence of a maturational threshold that mediates responses to RT exercise. However, reflective of the limitations of the wider body of literature, neither study included a control group meaning that the quality of the inferences that can be made are limited. Despite this, there are a number of studies of RT in PRE youths that warrant investigation either because they failed to meet the inclusion criteria set out in the meta-analysis or because they were published after that investigation was carried out.

Thompson *et al.* (2017) found that strength is trainable in PRE athletes (mean age: 11.8 ± 0.9), though after a twice-weekly, 16 week programme they only reported a small effect that was in line with that reported in the meta-analysis (ES = 0.5). However, these researchers highlighted athlete motivation as a potential confounding factor in substandard test performance. A study by Lloyd *et al.* (2016b) also reinforced the results of the RT meta-analysis, and supports those of Rumpf *et al.* (2015) and Meylan *et al.* (2014a), finding that younger non-athletes could be less trainable than older athletes in sprinting and jumping performance in response to a twice-weekly programme of 6 weeks duration. However a measure of strength was not utilised in that study, limiting the applicability and specificity of the results. Similarly, Radnor, Lloyd and Oliver (2016) exposed PRE (mean age: ~13 years) and POST (mean age: ~16 years) physical education students to different types of training with groups in each maturity classification allocated to PT, RT and combined training conditions. Though these researchers also did not utilise a measure of muscular strength, they did find that the resistance-trained PRE participants had smaller increases in acceleration, maximal running velocity, squat jump height and reactive strength index than the PT and combined training conditions. This could indicate that the latter methods could be more effective than traditional RT in PRE youths. Moreover, the resistance-trained PRE participants also showed lower increases in acceleration and maximal running velocity than their POST counterparts. The researchers suggested that PRE youths may be more responsive to a PT stimulus owing to the maturation-related increase in neuromuscular control resulting in a synergistic adaptation due to training. This is largely in line with the findings of the PT meta-analysis (Chapter 4).

Unlike Lloyd *et al.* (2016b) and Radnor, Lloyd and Oliver (2016), Amaro *et al.* (2017) failed to measure the maturity status of their swimmer participants (mean age: ~12.7 years) with the maturity offset. The researchers did, however, include a measure of functional strength though the effects of the twice-weekly 6 week programme on tethered front crawl were trivial, possibly because the test was conducted in water to assess potential transferability to swimming. Nevertheless, the programme did seem to enhance explosive medicine ball throwing performance (ES = 1.4) though this was only obvious in a group that trained with explosive movements with imposed time constraints. A group which undertook traditional RT did not adapt much more than the control group (ES = 0.5 vs. 0.3). Once again, these results seem to confirm those of the meta-analyses in that PRE athletes may be relatively more responsive to exercise with a velocity component. It is, however, curious that the traditional RT group achieved much larger increases in jump height (ES = 1.1 vs. 0.45) though this may be due to the slow SSC nature of the CMJ test that was utilised, meaning it could be more responsive to exercise in which slower muscle actions are prevalent. In relation to this, because the musculotendinous tissue of PRE youths is more pliable than that of MID or POST youths, it could be more efficient at storing energy in slow SSC movements, such as a CMJ (Knuttgen and Komi, 2003; Markovic and Mikulic, 2010) than in fast SSC movements, such as maximal ST. Alternatively, the group which adapted to a greater extent in each case had substantially lower baseline scores, possibly indicating greater room for improvement and, thus, a relatively higher ceiling for potential adaptation when compared to the more accomplished group which could have reached an upper limit for performance. In relation to this point, at any stage of maturation it must also be considered that a lower response to training could occur because of greater training experience and, thus, a lower ceiling of adaptation attributable to the accumulation of more training over longer durations (Deschenes and Kraemer, 2002; Hawley, 2008; Peterson, Rhea and Alvar, 2004). Potentially compounding this, lower ESs in the PRE stage could also be attributed to the aforementioned maturational threshold which could moderate responses to training (Katch, 1983).

Tsolakis *et al.* (2006) filled most criteria for inclusion in the RT meta-analysis but this study was ultimately excluded because it took place over a 12 month period, almost guaranteeing that strength increases would be seen due to maturation in a group of fencers straddling the divide between the PRE and MID periods of maturation. Supporting this, the researchers found a very large ES of 2.18 but because of the aforementioned issue relating to study design, the result has limited use for judging the effect of training in a PRE group of athletes.

Rodriguez-Rosell *et al.* (2016) subjected PRE soccer players (mean age: 12.7 ± 0.5) to 6 weeks of concurrent RT, PT and ST, becoming one of the first studies to use maturity offset in a controlled trial. This study would have met the criteria for inclusion in the meta-analysis but for its date of publication which was outside the window of time in which the systematic search was undertaken. Contrary to the results of the meta-analysis, the researchers reported a large ES (1.30), for 1 repetition maximum (1RM) strength in the squat exercise, indicating a high level of trainability in PRE athletes in response to concurrent training types on a twice-weekly basis. Potential confounders to these results can be seen in the types of exercises included in the training programme with ST and PT also serving as potential stimuli to the observed performance changes. Importantly, because the measure of strength (squat) was also utilised as an exercise in the programme itself, it is unclear as to what extent a learning effect would have influenced testing performance. This issue was considered in the research design of the RT intervention in the current work.

Examining the effect of RT in nine physically active boys (mean age: 10.4 ± 0.5 years), Cunha *et al.* (2015) found that a 3 day per week programme carried out over a 12 week period resulted in substantially larger increases in leg strength in the experimental group (ES = 3.95) than in the control group (ES = 0.72). Interestingly, the researchers observed changes in lean body mass in both cohorts with these being of generally greater magnitude in the training group, potentially indicating hypertrophic gains in a prepubertal population. However, despite these changes the participants were biologically classified with the Tanner method which is not coherent with measures of PHV. Interventions that only take account of participants' Tanner stage are not entirely sufficient as this method has limited use, referring only to stages of pubic hair and/or genital development (Malina, 2002). Accordingly, despite the young age profile of the participants, it is therefore more difficult to discern whether or not these PRE participants could have been classified as very early-maturing. One potential explanatory factor in the substantial ESs seen in this study is the volume, frequency and intensity of the training that the participants undertook: the RT meta-analysis showed that programmes that were longer than 9.5 weeks and had more than 24.5 sessions per programme and 2.5 sessions per week were more effective and the intervention of Cunha *et al.* (2015) exceeded these parameters. These results could indicate that younger children may need a larger training stimulus in order to adapt at the same, or greater, a rate than older children with changing hormonal profiles exerting an increasingly important influence as a child matures. Indeed this is implied by McNarry, Mackintosh and Stoedefalke (2014) in relation to endurance training in youth, the authors suggesting that the ostensible presence of a maturational threshold for adaptations could be no more than the application of insufficient training volumes in younger populations.

Large effects were also reported by Negra *et al.* (2016a) in PRE soccer players (mean age: 12.8 ± 0.25 years) with a control group showing only small improvements over a 12 week period during which the training group carried out 2 low-to-moderate load, high-velocity RT sessions on a weekly basis. Another study by Negra *et al.* (2016b), assessed the effects of

RT and PT on strength and power in PRE soccer players (mean age: 12.8 ± 0.3) years. Carrying out 2 training sessions per week, the researchers reported large (ES = 1.21) positive changes in half-squat 1RM strength in the RT group whilst the PT group showed moderate improvements (ES = 0.7). However, despite these results, it is worth noting that similar to Rodriguez-Rosell *et al.* (2016), the performance test used (half-squat) was also a programmed exercise in the RT group, potentially affording that cohort a learning advantage over the PT group. This was also a confounding factor in a study carried out in non-athletic school children (mean age: 12.1 + 0.3 years) by Ingle, Sleap and Tolfrey (2006). These authors noted very large (ES = 2.21) increases in squat strength following 12 weeks of thrice weekly complex RT, contrasting with only trivial changes in a control group (ES = 0.19). The researchers speculated that changes could have occurred due to increased motor neuron firing rates, improved neuromuscular coordination, greater muscle activation and more efficient transfer between concentric and eccentric muscle actions. However, once again, because the training group undertook back squats so regularly over the 12 week intervention period and the control group did not, conclusions relating to greater levels of neuromuscular control or coordination are rather facile given that exercises such as the back squat were also part of the testing protocol for the experimental and control groups alike. In this context, it is also worth noting that jumping performance increases in the respective groups were relatively equal across various tests. For these reasons it is worthwhile for researchers to use tests of muscular strength which are not directly incorporated into the intervention as a regularly performed exercise as this might confound results between groups which are exposed to different interventions.

6.2.2 Speed

There is a distinct lack of research relating to the development of sprint sprinting speed via direct training interventions in youth athletes and this is particularly pervasive in the PRE stage of maturation. Two studies which did investigate this were those of Pettersen and Mathisen (2012) and Venturelli, Bishop and Pettene (2008), both of which met the criteria for inclusion in the ST meta-analysis. Another study (Thompson *et al.*, 2017) saw PRE athletes (mean age: 11.8 ± 0.9) exposed to various types of resisted and assisted sprints with the authors reporting small (ES = 0.5) changes in sprint time over a 16 week period. The authors concluded that sprint mechanics could have been improved from the training programme allied to increased ground contact times and stride lengths which could particularly have improved agility performance. However, agility performance did not differ between training and control conditions. Similarly, and in line with the results of the meta-analysis, Trecroci *et al.* (2016) reported only a small ES (0.4) for improvement in 20 m sprint performance following 12 weeks of twice weekly speed and agility training. Interestingly, the control group also achieved a similar result (ES = 0.3). These small ESs slightly contrast with the moderate effect (0.75) reported for 20 m sprint performance by Rodriguez-Rosell *et al.* (2016). Though these researchers saw a substantial difference between the training and control groups, the applied training also comprised of RT and PT, making it somewhat difficult to isolate an effect due to ST. Substantially more research is required in this maturity group before more definitive conclusions can be made.

6.2.3 Power

Hammami *et al.* (2016) subjected 24 young male soccer players (age range: 12 to 13 years) to alternating 4 week blocks of balance training and PT, or PT and balance training, on a twice weekly basis. In line with the PT meta-analysis (Chapter 4), these researchers reported moderate ESs for CMJ in PRE athletes, indicating trainability at this stage of maturation. They attributed these changes to improvements in neuromuscular control and enhanced ability to control postural sway. These are important factors to consider for athletes before they enter the growth spurt as they could potentially offset injury and poor movement quality during the interval of maximal growth when susceptibility to injury could be higher (van der Sluis *et al.*, 2014). This could be an important factor in preserving maximal trainability when the chances of negative events occurring due to adolescent awkwardness are highest. Rodriguez-Rosell *et al.* (2016) also subjected PRE soccer players (mean age:

12.7 ± 0.5) to 6 weeks of twice weekly training which included PT. These researchers also reported a moderate ES (0.71) that was substantially larger than that of a control group (-0.2). Despite these results, one confounder to the observed effects is that PT was only part of a wider programme of training that also included RT and ST. Nevertheless, comparing their findings to those of other studies, the authors attributed their results to the potential existence of a window for the heightened adaptation to PT that occurs prior to the onset of the growth spurt.

Radnor, Lloyd and Oliver (2016) exposed PRE (mean age: ~13 years) and POST (mean age: ~16 years) participants to PT over a period of 6 weeks during which training was carried out on a twice weekly basis. The researchers reported that the training programme elicited greater responses in PRE participants for both squat jump (16.56% vs. 1.41%) and reactive strength index (10.21% vs. 4.64%). Previously, a study (Lloyd *et al.*, 2016b) with a similar design produced comparable findings with the authors concluding that maturation-related increases in performance could have played a role in stimulating a synergistic response to training in younger participants which was not experienced by the older participants who had likely experienced the growth spurt. Amaro *et al.* (2017) also subjected participants (mean age: ~13 years) to 6 weeks of training which included twice weekly box jumps of progressively increasing repetitions (30-54). The data presented by the researchers revealed a moderate ES of 1.1 though only small changes, similar to those seen in the control group, were observed in a separate group which undertook the same programme with a time constraint on each set. This is a curious observation though it could be argued that the constraint imposed upon performance, whereby as many repetitions as possible were performed within a given timeframe, could have impacted negatively on exercise technique.

The results of the PT meta-analysis are largely in line with the above findings from various researchers though there does exist some contradictory data: some subsequent studies have still found relatively low ESs in response to PT over a 6 week period in PRE participants. For example, Rosas *et al.* (2016) reported an ES of 0.26 in CMJ for loaded and unloaded intervention conditions in youth soccer players (mean age: 12.1±2.2 years), with similarly small changes relating to other jump types. However, the 6 week study period may be representative of the lower end of the timescale in terms of the appearance of adaptations (Negra *et al.*, 2016b) and so longer interventions may be required. Supporting this, in a study that was omitted from the meta-analysis on the basis that the applied intervention was considered to be an injury prevention programme and not specifically a PT programme, Kilding, Tunstall and Kuzmic (2008) showed that a warm-up protocol in PRE soccer players (mean age: 10.4 ± 1.4 years), which was predominantly unsupervised, seemed to have little to no effect (ES = 0.14) on CMJ and a small effect on three-step jump performance (ES = 0.6). These results seem to make sense in that the included jumps in the programme were not vertical, but horizontal in nature; but they are nonetheless worth considering. This is also a potential issue in a study by Thompson *et al* (2017) who found that CMJ performance was not improved in PRE athletes (mean age: 11.8 ± 0.9) who were exposed to 16 weeks of PT, in addition to RT and ST. This was despite a relatively long intervention period of 16 weeks but with CMJ being used to measure the potential effect of depth jumping and jumps with a horizontal component, it is perhaps not surprising that changes were not seen given that the utilised test may not have been appropriately specific to the stimulus. In relation to these studies, the previous point about the lower pliability of the musculotendinous tissue of PRE athletes may again be applicable.

Continuing on the issue of PT programme characteristics, Fukuda *et al.* (2013) reported negative effects (ES = -0.6) on performance over a 4 week period in younger participants (mean age: 9.9 ± 1.5) though it must be noted that increases in CMJ power and velocity were reported. In this case it could be that the plyometric stimulus was not of the required intensity or volume as it was carried out for only 5 minutes, albeit on 4 days during the week (Fukuda *et al.*, 2013). Indeed, Negra *et al.* (2016b) reported that improvements in jump capability generally took 8 to 12 weeks to manifest in response to PT in youth soccer players (mean age: 12.7 ± 0.3 years), eventually resulting in statistical significance ($p < 0.001$) and

EZs of between 0.54 and 1.03 across a variety of different measures of explosive power. Similarly, a PT intervention carried out in youth tennis players (mean age: age 12.5 ± 0.3 years) by Fernandez-Fernandez *et al.* (2016) showed increased CMJ performance (ES = 0.46) after 8 weeks though the relative volume of jumps in that intervention (180 foot contacts in week 1 to ~350 foot contacts in week 8) was larger than that utilised by Negra *et al.* (2016b) (112 foot contacts in week 1 to 280 foot contacts in week 12). Despite the differences, these results are in line with the meta-analysis in that programmes longer than 7.5 weeks resulted in a large ES (1.21) contrasting with that in programmes that were shorter than 7.5 weeks (0.38). In another, non-controlled, study that exposed PRE soccer players (mean age: age ~13 years; maturity offset: ~-1.6) to high or low volumes of PT, Chaabene and Negra (2017) found that a lower amount of foot contacts (50-120 per session) elicited a greater response in CMJ performance (ES = 1.14 vs. 0.55) than a higher amount (110-220 per session). Oddly, the authors claimed that there existed no significant difference between the two protocols despite the fact that the lower volume method resulted in an ES that was more than twice that of the higher volume method. This is likely due to the statistical approach used. The authors allude to the presence of an upper threshold training volume above which adaptations to PT can diminish. Whether or not such a threshold is apparent in more mature youths is unclear at this time (Chaabene and Negra, 2017).

A 10 week study undertaken by Kotzamanidis (2006), which incorporated a mean of around 80 foot contacts per week, resulted in a large effect (ES = 1.85) in PRE (mean age: ~11 years) youth. A control group demonstrated only a trivial decrease in jump performance. The participants in this study were not classified as athletes but the researchers nonetheless concluded that the observed changes could have been due to enhancements in tendon stiffness despite children displaying a greater degree of compliance of elastic tissue than adults. Similarly to Kotzamanidis (2006), Diallo *et al.* (2001) subjected soccer players (mean age: 12.3 ± 0.4 years) to a PT programme conducted over a period of 10 weeks but conducted training on 3 days instead of 2. The researchers reported a moderate ES (0.93) for CMJ which was almost identical to that seen in PRE athletes in the meta-analysis. Interestingly, they used a very large volume of jumps per training session with a mean of 750 being performed over the 10 week course of the study. Both the experimental and control groups in this study experienced relatively similar increases in lean leg volume which would seem to suggest that the performance gains seen in the training group were due to neural factors such as an increases in neuromuscular activation and coordination. An investigation on the effect of complex training, including PT, showed that neither the experimental or control groups achieved meaningful changes in lean body mass over a 12 week training period, however, the experimental group did demonstrate small (ES = 0.2) increases in CMJ performance (Ingle, Sleap and Tolfrey, 2006). Though the results of these studies differ, both demonstrate that changes in power performance seem to occur independent of lean mass in PRE youths.

Chaouachi *et al.* (2014b) also observed a moderate (ES = ~1.0) change in CMJ over an intervention period of 12 weeks, performing training sessions on 2 days per week. In PRE judo and wrestling athletes (mean age: 11.0 ± 1.0 years), PT was generally found to be more effective than traditional RT across a variety of measures of strength, speed and power though Olympic-style weightlifting, which is analogous to weighted jumps, was found to be the most effective form of training. These results are interesting as they generally reflect the results of the RT and PT meta-analyses in that they support the findings that the latter may be more effective than the former in PRE athletes.

Keiner *et al.* (2014) seem to be the only researchers who have undertaken a long-term study on the effects of PT in PRE athletes (age: 9-12 years) though the lack of presented ES and graphical representation of results make definitive conclusions on trainability difficult to make. Moreover, as the maturation status of the participants would be likely to change over the course of the two year study period, the usefulness of this type of investigation can be surprisingly limited because age-specific conclusions are difficult to pinpoint. Tsolakis *et al.* (2006) seem to be the researchers who have come closest to replicating this timescale, exposing young fencers (mean age: 12.4 ± 0.47 years) to a multidimensional programme over the course of 12 months. Though the training group demonstrated a very large ES of 3.5, it is interesting to note that the control group (mean age: 12.1 ± 0.36 years) also exhibited a very large ES that was more than double that of the experimental group (ES = 7.2). This would seem to demonstrate the substantial effect of maturation on performance over an extended period of time and further underlines the importance of contextualising physical performance through the use of control groups. In this particular instance, it is unclear why there was seemingly no effect of training but the authors did suggest that the applied training stimulus, which was multimodal, may not have been sufficient to elicit adaptations. Relatively sparse details on the features of the programme make it difficult to comment on the quality of the PT intervention relative to other studies. Interestingly, despite the performance results and the conclusions of the authors that there were no differences in post-intervention muscle cross-sectional area, the training group demonstrated a large effect (1.7) for increase in arm size whilst the control group only achieved a moderate change. Similarly, though both groups experienced very large increases in serum testosterone, that of the training group was larger (3.0 vs. 2.2). These ESs make it difficult to reconcile the authors' conclusion that training had no effect on hormonal profile or physique. It's important to concede that increases in growth hormone were far higher in the control group but the above ESs nevertheless demonstrate the limitations of hypothesis testing (Hopkins *et al.*, 2009) in training studies, particularly those with small sample sizes as in the study of Tsolakis *et al*. (2006). This is also an issue in a study by Marta *et al.* (2013) whose visual presentation of results makes it difficult to interpret the practical effects of the applied training programme in a much larger sample of PRE children who were not athletes.

Omitted from the meta-analysis on the basis that its participants were too young, Ferrete *et al.* (2014) carried out a study which examined the effect of resisted and un-resisted jumping on physical performance in prepubertal soccer players (9.32 ± 0.25 years). Though the researchers did not assess the effects of the programme on a measure of strength, they found that following 9 weeks of training, the experimental group had achieved a small ES of 0.4 for CMJ. In contrast, the control group saw no change in performance. Interestingly, this remained the case after another 9 weeks of training but by the time the 26 week intervention had concluded, the training group had maintained its performance whilst the control group demonstrated diminished jump height (-0.6). It is important to note the effects of training over and above that of growth and maturation given the relatively long timescale of this intervention.

6.3 The Effects of Training and Maturation in the MID PHV Stage

6.3.1 Strength

As boys transition into puberty, strength increases in line with growth and maturation with this process being partly attributed to increases in serum testosterone (Hansen *et al.*, 1999). However, other factors are also highly influential with an intertwining number of processes such as stature, mass, muscular size, hormones and neurological characteristics also playing an important role (Hansen *et al.*, 1999). Excluded from the meta-analysis on the basis that the intervention took place over a two year period, Alvarez San-Emeterio *et al.* (2011) subjected participants (mean age = 14.04 ± 0.88 years) to RT three times per week. Training was not performed maximally with 56% of 1RM used for three sets of 8 squats with 3 minutes of recovery between each. At follow up there was a 39.47% increase in strength on a 1RM squat test thought the large EZ (2.12) could be due to maturational factors over time rather than the real effects of the training programme. This is particularly possible given the relatively low intensity of the training and the long study duration. Importantly, Alvarez San-Emeterio *et al.* (2011) did not include a control group but this was a limitation that was addressed by Sander *et al.* (2013). These researchers carried out a two year long RT programme in under 15 (MID), under 17 (MID) and under 19 (POST) soccer players, with EZs being of very large magnitude in all groups, demonstrating the effects of RT over time. Similarly, Keiner *et al.* (2014) reported verifiable changes in strength over time in cohorts of the same ages as those in the study of Sander *et al.* (2013), noting few differences between the absolute gains in strength across all experimental groups. Together these studies demonstrate the long term benefits of RT in MID and POST though the ability to isolate maturation-specific mechanisms for the changes in strength seen is hampered by the especially long study duration of 2 years in both cases.

Smart and Gill (2013) exposed supervised (mean age: 15.4 ± 1.4 years) and unsupervised (mean age: 15.1 ± 1.3 years) rugby players to a 15 week training programme during an off-season period. There were distinct differences between the groups with the supervised cohort registering very large changes in strength (ES = 2.83) whilst the unsupervised group experienced only small increases (ES = 0.53). It is likely that the lower ES in the unsupervised group was due to the lack of any direct coaching and overseeing of the programme meaning that there was a confounding effect on the results in terms of understanding the mediating effect of maturation. Moraes *et al.* (2013) also reported very large increases in strength in MID participants (mean age: ~15.5 years). Tested for 1RM on the leg press exercise, a group subjected to periodised training showed a slightly larger ES (6.3) than a group subjected to unperiodised training (ES = 5.2), 3 times per week over a 12 week period. In contrast, the control group showed small (ES = -0.62) decreases in strength over the same period. The training status of the participants in this study is an important factor to consider as the dramatic increases in strength reported could partly be due to the fact that all were considered to be untrained. Indeed, in the study discussion it is implied by the authors that these results may only be reflective of what could be achieved in inexperienced trainees. Given that the playing of a given sport could result in a training stimulus for athletic tasks such as jumping due to the fact that jumping occurs multiple times during the course of play (Mohr, Krustrup and Bangsbo, 2003), this is not an insignificant issue because it could mean that sport-playing youths who do not have a history of specific strength and conditioning training could still possess a training age that is related to the carrying out of those types of modalities. This could have implications for trainability.

Gonzalez-Badillo *et al.* (2015) carried out a RT programme in MID athletes (mean age: 14.9 ± 0.3 years) but was excluded from the meta-analysis on the basis of the long study duration and because the measure of performance utilised was related to speed-strength and not strength alone (Mann, 2015), thus limiting its applicability to other included studies. Nevertheless, the researchers found that training induced a very large ES of 2.86 though this result is limited by the lack of an age-matched control group. Similarly, Santos and Janeira (2008) exposed MID youths to a RT stimulus, however, because the effects of the programme were only measured through changes in muscular power, it is difficult to judge the extent to which the programme could have developed muscular strength.

Previously, Hetzler *et al.* (1997) divided 20 baseball players into novice (mean age = 13.2 ± 0.9) and experienced (mean age = 13.8 ± 0.6) RT groups and subjected them to 3 weekly sessions over the course of a 12 week programme. Excluded from the meta-analysis on the basis that the necessary quantitative data could not be obtained from the study paper or its authors, this intervention was nevertheless in line with the results of the meta-analysis, showing a high level of trainability during MID with both training groups demonstrating strength increases of around 40%. This contrasted with increases of 14% in the control group. Interestingly, ESs for peak power and CMJ were smaller in the more experienced participants than they were in novice participants (0.0 vs. 0.3 and 0.2 vs. 0.5 respectively), potentially indicating the importance of training age on adaptations to RT in this population.

More recently, Franco-Marquez *et al.* (2015) exposed 20 MID soccer players to a programme that was comparable to that of Rodriguez-Rosell *et al.* (2016). Following twice weekly training sessions for a period of 6 weeks, the researchers reported a moderate ES of 1.16 which was smaller than that reported in PRE soccer players by Rodriguez-Rosell *et al.* (2016). Together these two studies are the best example of a valid comparison between disparate maturity groups whose status and physical performance levels were measured in ways that were appropriate to the applied stimulus. Franco-Marquez *et al.* (2015) suggested that puberty-related increases in anabolic hormones may have been responsible for the higher ESs seen in comparison to a study undertaken in older players by Lopez-Segovia *et al.* (2010) but it is unfortunate that there is no such comparison with the study of Rodriguez-Rosell *et al.* (2016), which was carried out by the same group of researchers, likely due to the respective articles' near-simultaneous publication dates. The higher ESs seen in the study of PRE athletes by Rodriguez-Rosell *et al.* (2016) could have called the hormone-based argument and comparison to the study of Lopez-Segovia *et al.* (2010) into question given the larger adaptability of an even younger cohort.

Using a crossover study design in which MID surfers (mean age: 14.0 ± 1.1 years) undertook either stable or unstable surface strength and power training, Tran *et al.* (2015) found that a twice-weekly programme conducted over a 7 week period resulted in increases in isometric strength of 12.7% and 5.5% in stable and unstable conditions respectively. The study underlines the trainability of strength during the MID period but it is difficult to make more robust conclusions in terms of this review given the unknown effect of the 4 week wash out period on the subsequent training phase.

Makhlouf *et al.* (2016) divided 57 young male soccer players (mean age: 13.7 ± 0.5 years) into four conditions, one of which performed endurance training before RT on the same training day; one which performed RT before endurance training; one which performed both types of training on alternate days; and a control group. Training twice per week over a 12 week period resulted in large to very large ESs in all training groups. In contrast, the control group showed a borderline medium-large effect improving to the extent that the observed changes could be representative of maturation-related improvements in strength. This can be reconciled with the ESs reported in MID soccer players by Franco-Marquez *et al.* (2015), however, those researchers saw comparable ESs in half the time with a substantially lower volume of RT. In light of this, if maturation or training volume did not exert the most influential effect on the results of these studies, differences relating to training experience could be the next obvious factor.

6.3.2 Speed

There are few studies on ST to improve sprint time in youth athletes and those that have been conducted have not compared adaptations between training groups of different maturity status. Chaalali *et al.* (2016) carried out a study which examined the effect of agility or change of direction training in youth soccer players (mean age: 14.5 ± 0.9 years) finding small (ES = 0.57) and moderate (ES = 0.89) ESs for 15 metre (15 m) sprint time and moderate effects (ES =1.15; ES = 1.05) for 15 m agility sprint respectively in both conditions. Over the 6 week study duration, the trivial (0.14) and moderate ES (0.96) seen in the control group for straight sprinting and agility sprinting respectively suggest that the training programme was effective. However, this was less pronounced for the agility sprinting. The authors attributed these changes to increases in the power of the leg extensors and an ability to produce force more efficiently though the lack of PRE or POST maturity groups in the study make it difficult to conclude if the observed changes are due to training or a synergistic interaction of training and maturation (Lloyd *et al.*, 2016b). Modest decreases in sprint time were also reported by Franco-Marquez *et al.* (2015) in an intervention in which MID soccer players (mean age: 14.7 ± 0.5 years) carried out two training sessions per week over a 6 week period. With 3 to 4 sprints being conducted in each session, the very low training volume could have been a factor in the small EZ for 20 m sprint time improvement (ES = 0.29).

Gonzalez-Badillo *et al.* (2015) subjected MID soccer players (mean age: 14.9 ± 0.3 years) to 26 weeks of concurrent strength, speed and power training, using sprint performance over 20 m as a measure of performance. Conforming to the running distance recommendations (20 m) of the sprint meta-analysis, the researchers reported small ESs in MID and POST soccer players with a similar, but larger, effect (0.4 vs. 0.2) in the POST group. Given that these researchers did not include age-matched control groups, it is difficult to attribute these changes solely to the training programme, particularly given the relatively long study duration of 26 weeks. This would seem to be sufficient time for the effects of maturation on performance to become apparent.

Smart and Gill (2013) undertook a multi-modal training intervention on supervised (15.4 ± 1.4 years) and unsupervised (mean age: 15.1 ± 1.3 years) rugby players who undertook ST. Omitted from the meta-analysis on the basis that the researchers did not include a control group, the 15 week off-season programme comprised of between 6 and 12 short (< 50m) sprints, with a 3 minute rest after each effort, once per week. However, both groups made only trivial improvements in sprint performance over 30 m.

6.3.3 Power

Extensive research has been carried out on the development of power in youth athletes but methodological issues persist in limiting the quality of inferences that can be made. In line with the PT meta-analysis, moderate ESs have been reported for CMJ performance in MID participants by Gonzalez-Badillo *et al.* (2015) but this study included no control group and took place over a period of 26 weeks, severely limiting its utility to gauge the trainability of the its participants in response to the applied stimuli, which were varied. Chaouachi *et al.* (2014c) addressed both of these issues in their study but the population was somewhat different in that it comprised of physical education students (mean age: ~13.5 years) who had no background in training or sport outside of their school curriculum, limiting the applicability of the results to a trained youth population. In response to PT and balance interventions, the authors reported moderate ESs of 0.72 and 0.88 respectively, contrasting with that of the control group which demonstrated an ES of 0.1 for CMJ. These effects took place over an 8 week period during a periodised programme which was carried out on an unusually high 3 days. This is not an insignificant factor given that only one study (Chelly, Hermassi and Shephard, 2015) included in the PT meta-analysis used such a training frequency. That study was carried out in PRE athletes and also over a longer period of 10 weeks. This could indicate that MID athletes could be as trainable as PRE athletes if training is administered at a higher volume, however, to date this evidence remains scant. Franco-

Marquez *et al.* (2015) improved even further on the research designs of Gonzalez-Badillo *et al.* (2015) and Chaouachi *et al.* (2014c) from a youth development perspective by being one of the first to include a measure of participants' biological maturity status. Carrying out CMJs and triple jumps in a programme that also included RT and ST, these researchers reported a small effect (0.58) that was, again, in line with the PT meta-analysis.

Tran *et al.* (2015) undertook a twice-weekly 7 week crossover study on the effect of strength and power training in youth surfers (mean age: 14.0 ± 1.1 years) finding that the applied stimulus resulted in increases in CMJ of 5.7% (ES = 0.4) when undertaken on a stable surface. Unstable surface training resulted in a 6.5% decrease in CMJ (ES = -0.75) but despite these results being in line with the PT meta-analysis, the 4 week washout period utilised in the crossover design could confound results. Moreover, the study did not include a true control group. The same can be said of a study by Leporace *et al.* (2013) who reported a small ES of 0.5 in MID volleyball players (mean age: 13.0 ± 0.7 years). This change in performance is also in line with the meta-analysis and the higher training frequency of 3 days per week, along with the potentially large volume of jumps which were prescribed predominantly with a time guideline, would suggest that training efficiency was not especially high.

Like Tran *et al.* (2015), Granacher *et al.* (2015) also subjected groups of MID athletes (mean age: 15.0 ± 1.0 years) to PT on stable and unstable surfaces finding that the stable surface was more effective in eliciting improvements in CMJ performance. Again, because a control group was not utilised, it is difficult to determine the extent to which the observed changes over the 8 week intervention could be attributed to the training programme. On this, the authors' claim that the inclusion of a control group was not feasible because it would not be possible to get youths to abstain from training or avoid exposure to plyometric activity during the course of soccer playing and training is erroneous. As any training group would also be exposed to the same secondary stimuli not imposed in the study, the inclusion of an age- and activity-matched control group, or even a passive group of non-athletes, would have facilitated isolation of the effect of the plyometric stimulus only, in addition to accounting for the effect of maturation, regardless of any additional exercise.

Bishop *et al.* (2009) examined the effect of 8 weeks of PT, twice per week, on measures of functional swimming skills, finding moderate increases in swimming block start velocity (ES = 1.1) in MID participants (mean age: 13.1 ± 1.4 years). In contrast, the control group, which maintained habitual swimming activity showed performance decreases in this measure and conceded to the experimental group on all other performance measures. The researchers attributed the performance increases to the stimulation of muscle spindles resulting in preloading of agonist muscles and a resultant storage of elastic energy. Combined with the development of the elastic muscular components and greater motor unit firing, the subsequent potentiation of explosive muscle actions seemingly results in improved power performance. This is a process previously described by Komi (2003) and others (Nicol, Avela and Komi, 2006) but it is important to consider underlying biological components in growing children and adolescents that could potentially impact upon its functioning. For example, the accumulation of muscle or fat mass can affect relative strength throughout maturation, potentially resulting in a negative impact on jump performance if body mass begins to exceed an individual’s ability to move that mass (Zatsiorsky and Kraemer, 2006). Though this is likely not a factor in the results that were reported in a study undertaken by Santos *et al.*, (2012) these researchers nonetheless presented data in MID youths (mean age: 13.3 ± 1.04 years) which showed that over an 8 week period, a control group showed larger increases in CMJ performance than two experimental groups (0.4 vs. 0.2 vs. 0.2). However, it must be highlighted that both experimental groups demonstrated larger increases in horizontal jumping performance (0.2 vs. 0.2 vs. -0.2). Regardless of the conclusions made by the researchers via null hypothesis testing it must be noted that the training effect in these MID participants was in line with the meta-analysis in being relatively low and only marginally beyond the ‘smallest worthwhile change’ (Hopkins *et al.*, 2009; Spencer *et al.*, 2006).

The same can be said of a study carried out by Brown, Mayhew and Boleach (1986) who exposed MID basketball players (mean age: 15.0 ± 0.7 years) to 12 weeks of undefined depth-jump training. Omitted from the PT meta-analysis on the basis that the ages and the amount of participants in each study group were not provided, the authors reported larger increases in arms (ES = 1.3 vs. 0.7) and no-arms (ES = 1.23 vs. 0.58) CMJ performance in the experimental group as compared to the control group. However, in line with the results of the meta-analysis, if these ESs were based on post-training between-group analyses of ESs, it can be seen that the no-arms jump showed no improvement whilst the with-arms jump showed only a small increase. This offers further evidence of a decreased level of trainability for power in MID given that the experimental group did not improve substantially more than the control group. One potential reason for this is the nature of the training stimulus with depth-jumping considered to be an advanced plyometric exercise that may not be suitable for young athletes who do not possess the requisite strength or neuromuscular coordination to leverage the full benefits of the method (Chu, 1998; Shiner, Bishop and Cosgarea, 2005).

Similar to Brown, Mayhew and Boleach (1986), Aoki *et al*. (2017) examined the effects of PT (twice weekly for 9 weeks) on CMJ performance with, and without, an arm swing movement. Though the MID group (mean age: 15.2 ± 0.8 years) demonstrated slightly larger ESs than the POST group (mean age: 17.4 ± 1.2 years), the increases in performance were only of moderate magnitude (ES = 0.73 to 0.99) in both cohorts. The application of these results are limited given the absence of a control group and it is also unclear how the sport of basketball, which is characterised by multiple jumping movements (Blache, Beguin and Monteil, 2011), could have affected jumping ability in the years preceding the study. For example, if basketball play was regularly carried out by these players over a long period of time prior to their participation in the intervention, the execution of the sport itself could have provided a PT stimulus which brought the participants closer to their ceiling of adaptation for that motor ability owing to a higher training age (Till *et al.*, 2017).

Matavuji *et al.* (2001) also subjected MID basketball players (mean age: 15-16 years) to drop jump training which was applied 3 times per week over a period of 6 weeks with 30 foot contacts per session. This number of foot contacts is lower than that used in the PT intervention in the current piece of work but the nature of these jumps renders them substantially more intense than those used with the youth hockey players. Matavuji *et al.* (2001) reported increases in experimental groups which performed jumps from heights of 50 cm and 100 cm though the graphical representation of results prevented a calculation of ES. Similarly, an investigation by Ramirez-Campillo *et al.* (2013) subjected participants to 120 jumps per week over a 7 week period but this intervention, too, included higher-intensity drop jumps. In this case, 120 foot contacts per week was considered a 'medium volume'.

As part of a 12 week RT programme, Makhlouf *et al.* (2016) performed a 4 week block of power training which incorporated PT into the routine of young male soccer players (mean age: 13.7 ± 0.5 years). Measuring the effect of the programme on CMJ, the researchers found small to moderate effects in the training groups whilst the control group improved only trivially. These results are somewhat reflective of the PT meta-analyses with strength seeming to be substantially more trainable than power in these MID soccer players. However, given that RT was performed for 8 weeks and PT for just 4, the differential in the results seen could be attributable to the composition of the applied stimuli. A similar limitation can be seen in the study of Wong, Chamari and Wisloff (2010) who examined the effect of on-field strength and power training in youth soccer players (mean age: 13.5 ± 0.7 years). However, only the final 4 weeks of that intervention included a plyometric element to the training programme and this resulted in a small ES of 0.5 on CMJ. This is an important consideration in the interpretation of the results of studies such as that of Wong, Chamari and Wisloff (2010). Traditional RT has been shown to be inferior to explosive training in enhancing CMJ performance in MID American footballers (15.9 ± 1.2 years) (Channell and Barfield, 2008) and, indeed, Wong, Chamari and Wisloff (2010) highlight work (Gorostiaga *et al.*, 1999) which seems to indicate that RT which stimulates only slow or normal muscle actions was ineffective for increasing CMJ performance. This underlines the importance of utilising a concurrent approach to programming for multiple physical capabilities at one time throughout the course of a youth training intervention. This is particularly important during periods of maturation in which the effects of training may be enhanced or hampered by biological processes.

Also carrying out a training intervention over a 4 week period, Fukuda *et al.* (2013) found that CMJ height was reduced as demonstrated by an ES of -0.2 for CMJ in MID judo athletes (mean age: 15.2 ± 2.0). Interestingly, there were positive changes in CMJ power, force and velocity. The researchers did not seem to address this discrepancy but it is unlikely that it was due to negative changes in relative strength (Zatsiorsky and Kraemer, 2006) due to growth given the short timescale of the study and because both body mass and body fat decreased. It could be tentatively speculated that the emergence of adolescent awkwardness could have influenced CMJ performance but this too is doubtful given that a similar pattern of change was seen in in a younger cohort (mean age: 9.9 ± 1.6). It could be that the plyometric element of the applied training programme was not intense or voluminous enough given that it was performed only as a part of pre-exercise warm-up, though it was carried out on a relatively high 4 days per week. In line with the findings of Fukuda *et al.* (2013), Smart and Gill (2013) exposed supervised (mean age: 15.4 ± 1.4 years) and unsupervised (mean age: 15.1 ± 1.3 years) rugby players to a 15 week off-season training programme. Despite being exposed to a wide spectrum of training modalities, the respective groups experienced only small (ES = 0.23) and trivial (ES = 0.1) changes in CMJ performance with the difference being attributed to the presence, or lack thereof, of a supervising professional. Again, this seems in line with the results of the PT meta-analysis with a combination of RT and PT, as seen in the study of Radnor, Lloyd and Oliver (2016), failing to overcome the potential suppressants of trainability during the MID stage of maturation, even over the course of a relatively longer study.

An interesting exception to the findings of the meta-analysis is a study carried out by Sohnlein *et al.* (2014) who found that 16 weeks of PT resulted in very large effects in a group of soccer players (mean age: 13.0 ± 0.8 years) who carried out training twice per week. These effects were substantially larger than those seen in other MID athletes in the PT meta-analysis but it must be highlighted that they related to a different performance measure (long jump) and the control group was almost a year younger than the training group. Also, the 16 week duration of the study was longer than all others included in the PT meta-analysis. Similarly, Amara *et al.* (2015), using a different measure of ES than that demonstrated above, reported large increases in CMJ performance in soccer players (mean age: 15.41 ± 1.23 years) following two PT sessions per week over a period of 8 weeks. Interestingly, percentage increases in performance were greater in participants who were classified as being 'underweight' with this possibly due to the inhibitory effect of additional body mass in 'healthy weight' participants. This has interesting implications for the trainability of youths of varying maturity status given that in the PT meta-analysis, the mean weight of the PRE group was 41.9 ± 11.1 kg whilst those of the MID and POST groups were 54.9 ± 14.0 kg and 73.7 ± 9.5 respectively. It could be this factor that results in a lowered response to PT in MID athletes with this issue being overcome in POST by maturation-related changes in muscle architecture (Enright *et al.*, 2015).

6.4 The Effects of Training and Maturation in the POST PHV Stage

6.4.1 Strength

Gonzalez-Badillo *et al.* (2015) included POST athletes in their study of RT and found that speed-strength was highly trainable during that period, recording a large ES of 1.31. In line with the results of the RT meta-analysis, this ES, though large, was lower than that in the MID group (ES = 2.86) and is reflective of a previous description of a ceiling for performance that could be partly related to the training age of the individual (Till *et al.*, 2017). This was demonstrated in a study (Hetzler *et al.*, 1997) in MID baseball athletes (mean age: ~13.6 years) in which ESs for peak power and CMJ were smaller in participants who had 8 months of RT experience in comparison to another training group which had no experience. Also, research has shown that after the age of 16, physical performance increases can cease whilst skill performance continues to improve (Huijgen *et al.*, 2010). However, the study of Gonzalez-Badillo *et al.* (2015) has a major flaw in that it did not include age-matched control groups to account for progressing maturation, a particularly important factor given the relatively long duration of the study. If control groups had been included in the study, statistical comparisons could have revealed the degree to which the observed changes could be attributed to maturation and, in such a case, it is theoretically possible that the POST group would have demonstrated larger performance increases.

This was not an issue for Sander *et al.* (2013) who reported very large ESs for squat strength in POST athletes, only slightly smaller than those seen in a MID group in response to twice-weekly RT over a two-year period. The same researchers (Keiner *et al.*, 2014) adopted a similar study design over the same time period in groups of MID and POST (under 19 and under 17) soccer players reporting largely similar changes in back squat strength at the end of the study. Crucially for an investigation of this duration, age- and activity-matched control groups achieved far smaller gains in strength, underlining the effects of the training programme over time. Similarly, Tsimahidis *et al.* (2010) also noted substantial increases in strength (approx. 30%) in youth basketball players (mean age: 18.0 ± 1.2 years) after 10 weeks of twice-weekly training. However, the authors' failure to include the raw data for 1RM performance prevented the calculation of an ES and resulted in the study being omitted from the RT meta-analysis.

In a similar study design to that undertaken in MID soccer players by Makhlouf *et al.* (2016), Enright *et al.* (2015) subjected POST soccer players (mean age: 17.3 ± 1.6 years) to 5 weeks of either RT (strength) and endurance training (S+E) or endurance and RT (E+S). The researchers found highly contrasting results in each of the training groups with the E+S group demonstrating a large effect which contrasted with the small effect seen in the S+E group. This differential could be due to the sequencing of the training that was carried out, with the E+S group being given a longer between-session rest period and experiencing a lower RT load; but it is interesting to note that the effects on squat jump performance were the direct opposite of those reported for strength with the S+E group performing better. The E+S group showed generally larger ESs across various measures of muscle thickness and fascicule angle of pennation, potentially indicating the important role played by architectural alterations to skeletal muscle in the observed changes. However, as both groups were of a similar age, this is more likely due to the configuration of training and recovery periods than the maturity status of the respective groups. One important feature of the study is that it was carried out in well-trained POST athletes meaning that the large ES seen in relation to strength and muscle architecture seem to challenge the previous longitudinal finding that more mature athletes are only likely to see improvements in skills performance (Huijgen *et al.*, 2010), potentially due to the exhaustion of all physiological avenues of adaptation.

A study by Drinkwater *et al.* (2005), which was omitted from the RT meta-analysis only on the basis that the author could not provide a mean age for each training group separately (mean age: 17.4 ± 0.5 years) found a moderate effect, almost exactly in line with that of the quantitative investigation (ES = 1.02), in POST soccer players. Training to repetition failure on 3 occasions per week over a 6 week period, the authors did not include a disparately aged comparison group though it is interesting to note that a group that did not train to repetition failure achieved only a small increase in strength (ES = 0.43). In this case it would seem that training programme configuration was an important factor in the results that were reported. However, despite the age of these athletes, the authors conceded that these changes were probably reflective only of early-onset adaptations to RT because the participants did not have significant training experience. In this way, the adaptations and ESs that were apparent might also be seen in much younger athletes with a similar training age.

Despite the above evidence, and that presented in the RT meta-analysis, low strength increases in response to RT in POST are not without precedent. Examining the effects of a twice weekly, 6 week RT programme in soccer players (mean age: ~17 years), Śliwowski *et* *al.* (2015) yielded predominantly small increases in strength in groups with and without muscular imbalances. In this study, the participants had approximately 7 years of training experience and despite the authors not characterising the nature of this experience, it could underline the importance of training age in moderating the effects of RT on the magnitude of adaptations seen. Similarly, only borderline small to moderate (ES = 0.63) changes in 3 repetition maximum (3RM) squat strength were reported in a study undertaken by Weakley *et al*. (2017) in 35 youth rugby players (mean age: 16.9 ± 0.4) whose RT activities were monitored over a 12 week period. Undertaking an average of 1.4 training sessions per week, the players in this observational study were not carrying out a uniform prescribed RT programme which could have created variability in the degree to which they adapted to their utilised training methods. Indeed, the wide confidence interval for 3RM squat (0.22 to 1.03) would seem to support this assertion whilst the lack of a control group and the method whereby participants reported their own training activities means that the reported EZ (0.63) can only be considered with caution. Greater changes in strength may have been apparent if the study was conducted with a traditional intervention design, or if supervision of training was explicitly undertaken (Smart and Gill, 2013).

6.4.2 Speed

As in the PRE and MID stages of PHV, studies that examine the effects of ST on running speed in POST are relatively scarce. Certainly there is a paucity of investigations that isolate the effects of ST on running speed without the additive effects of other training methods such as RT and PT. One research group (Mujika, Santisteban and Castagna, 2009) that did achieve this did so in a group that was too old (mean age: 18.5 ± 0.7) to be included in the ST meta-analysis but nonetheless found that contrast training was more effective than ST in eliciting changes in sprinting speed. No ES could be calculated from the graphically presented data but it must be highlighted that despite exceeding the daily recommended ST load of 16 sprints over a 20 m distance, supported in the ST meta-analysis, only a total of 6 training sessions were performed. This could indicate that the applied stimulus was not of the correct volume.

Gonzalez-Badillo *et al.* (2015) examined the effects of concurrent RT, ST and PT in MID and POST (mean age: 17.8 ± 0.4 years) soccer players reporting a slightly higher, but small, positive effect on sprint time over 20 m (ES = 0.4) in the older group in contrast to the trivial effect (ES = 0.2) in the MID group. Given that this study was carried out over a 26 week period, these would seem to be relatively modest gains given the results of the ST meta-analysis which reported much larger effects over a shorter period of time. Moreover, the lack of an age-matched control group for either one of the experimental cohorts limits this study's utility in examining the trainability of youths to the applied training stimuli. de Hoyo *et al.* (2016) reported only a small ES (0.28) on 30 m sprint performance in elite youth soccer players (mean age: 18.0 ± 1.0 years) who undertook 2 sessions of ST and PT over the course of 8 weeks; though ESs were larger over the 50 m distance (ES = 0.4).

6.4.3 Power

Subjecting physically active youths to PT in the amount of 74 to 88 foot contacts in twice-weekly sessions over a period of 6 weeks, Lloyd *et al.* (2016b) found that POST (mean age: ~16 years) saw only trivial and small increases in squat jump and reactive strength index respectively in response to the applied PT stimulus. This contrasted with the moderate and small increases seen in PRE (mean age: ~13 years) participants, the authors suggesting that the maturation-related increase in performance could have augmented adaptations in the younger participants. Interestingly, the POST group fared better when PT was combined with RT potentially indicating that a more diverse and comprehensive training stimulus is required to elicit adaptations in more mature youths. In this way, POST trainees may benefit to a greater extent with a range of training exercises that span the force-velocity continuum (Lloyd *et al.*, 2016b). This is reflective of a similar study by Radnor, Lloyd and Oliver (2016) which made comparable conclusions, POST (mean age: ~16 years) showing substantially lower percentage increases in squat jump and RSI in response to PT when compared to

PRE (mean age: ~13 years). Once again, a combined training stimulus brought adaptive responses somewhat more in line with each other. Indeed, the effectiveness of more intense forms of PT in POST athletes was demonstrated by Thomas, French and Hayes (2009), who showed that volume-equalised programmes of drop jump and CMJ training were generally equally effective in increasing jump performance in youth soccer players (mean age: 17.3 ± 0.4 years), though the pre- and post-intervention performance of the drop jump group was higher. These results could be indicative of the need to incorporate more advanced or intense training methods into the programmes of more mature athletes with a higher training age, however, the lack of a control group precludes more robust conclusions relating to the effect of maturation on the changes seen. This is also a limitation of the study by Gonzalez-Badillo *et al.* (2015) which reported only a moderate effect (ES = 0.9) in a study that was more than four times longer than that of Thomas, French and Hayes (2009). In a similarly uncontrolled study, Aoki *et al*. (2017) reported only moderate (ES = 0.73 to 0.99) increases in CMJ after PT (twice weekly for 9 weeks) though a MID group (mean age: 15.2 ± 0.8 years) demonstrated slightly larger ESs than a POST group (mean age: 17.4 ± 1.2 years). Though beyond the scope of this literature review, the authors did report that the MID group showed higher levels of tension, depression, anger, fatigue and total mood disturbance, potentially suggesting that the POST group were more psychologically robust in adapting to the applied training stimulus. This could partly explain why MID trainees can experience lower levels of adaptation than their PRE and POST counterparts in response to PT with psychological stress manifesting in a physical manner.

The study of Mujika, Santisteban and Castagna (2009) offers potential evidence on the effects of more advanced training methods in POST soccer players (mean age: ~18.3 years) with a contrast training group achieving substantially larger performance changes in CMJ than a ST group (ES = 0.5 vs. 0.1); however, it must be highlighted that the ST group saw larger effects when an arm swing was allowed in the performance of the CMJ (ES = 0.2 vs. 0.1). Supporting this, previous work has demonstrated that after the age of 16, physical performance increases can diminish whilst skill performance continues to advance (Huijgen *et al.*, 2010).

Similarly, de Hoyo *et al*. (2016) observed only a borderline small to moderate ES (0.6) on CMJ performance in elite youth soccer players (mean age: 18.0 ± 1.0 years) who undertook 2 sessions of ST and PT over the course of 8 weeks. However, in a similar population (mean age: 18.4 ± 1.1 years), Sedano *et al.* (2011) reported large increases in CMJ (ES = 1.5) indicating that even in supposedly advanced athletes, substantial gains in performance can be achieved. As the researchers did not investigate potential mechanisms of action, they could only speculate about the factors that could underpin such large changes at an advanced developmental age. A similar finding was also presented by Asadi *et al.* (2016) who conducted an investigation that saw experienced national level youth basketball players (mean age: 18.5 ± 0.8 years) undertake between 350 and 550 foot contacts per week over an 8 week period. Divided into three sessions per week, the researchers reported a very large EZ for CMJ performance of 2.93, demonstrating experienced youths' ability to adapt, albeit with a much higher training volume than was used in the PT investigation by de Hoyo *et al.* (2016) who reported far smaller effects (ES = 0.6). Once again, Asadi *et al.* (2016) could only speculate on the potential mechanisms of action, highlighting enhanced neural drive to agonist muscles and intermuscular coordination, alterations to tendon stiffness and changes to muscle size and fibre mechanics as potential mechanisms. These results are particularly encouraging for youth athletes with a higher training age as one of the inclusion criteria for the study was the requirement to be able to leg press 2.5 times one's body mass, indicating a high level of baseline strength. Indeed it could have been this high level of strength that enabled the athletes to sustain such a high number of foot contacts, potentially suggesting that more advanced youth athletes can continue to progress if they have the necessary robustness to withstand necessary larger training volumes.

6.5 Summary

Based on the evidence cited in this chapter, it seems that there may be key periods in childhood and adolescence during which specific physical qualities could be preferentially targeted due to the idiosyncratic progression of biological functions and mechanisms. For example, a coach who is training an athlete at the PRE stage of maturation could preferentially target the development of slow SSC movements owing to the increased pliability of musculotendinous tissue and the associated efficiency of energy storage for such movements (Rumpf *et al.*, 2013). At the same time, exposure to aerobic training could be limited until the MID stage is reached, owing to the reported increase in males' VO_2max that is concurrent with maximum PHV, thus leveraging the benefits of 'synergistic adaptation' (Lloyd *et al.*, 2016b). This is an issue relating to periodised planning and training efficiency as previously described by Haff (2014). Hypothetically, it may make little sense to prescribe training types towards improving physical capacities which may not be optimally developed at certain stages of maturation. This could potentially result in suboptimal adaptations in the future and, by extension, overtraining. In this way, the goal of LTAD training programmes may not only be to exploit sensitive periods of adaptation in the manner described by Balyi and Hamilton (2004), but to prevent maladaptation due to misapplied training loads or modalities at inappropriate times. The evidence cited in the previous sections could be used to make inferences with regard to how youth training could be structured but until more training-based empirical evidence is attained, traditional principles of sport periodisation (Lloyd *et al.*, 2015b) should be adopted. Accordingly, the purpose of the following experimental chapters is to elucidate the effect of particular types of training at specific stages of maturation, paying particular attention to the period of the growth spurt, or the 'interval of maximal growth' (Malina, 2011; Malina, Bouchard and Bar-Or, 2004). This is considered to be a crucial time in the development of athletic abilities in youth.

CHAPTER 7

Maturation-related differences in adaptations to resistance training in young male swimmers

Citation

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Abstract

This study examined the effects of RT on muscular strength and jump performance in young male swimmers. It was hypothesised that adaptations would be of a lower magnitude in less mature (Pre-PHV) than in more mature (Post-PHV) participants. Fourteen Pre- (-1.8 ± 1.0 years) and 8 Post-PHV (1.6 ± 0.5 years) swimmers undertook a 30 minute, twice-weekly RT programme for 8 weeks. They were compared with matched control groups (Pre-PHV: -2.0 ± 1.1, n=15; Post-PHV: 1.2 ± 1.0, n=7). The effects on lower body isometric strength (LBS), measured with mid-thigh pull, and CMJ height in the Post-PHV group were large (EZ: 1.3 [0.4 to 2.2]) and small (0.4 [-0.4 to 1.2]) respectively. Effects on LBS and CMJ height in the Pre-PHV group were moderate (0.8 [0.1 to 1.4]) and trivial (0.2 [-0.5 to 0.8]) respectively. Estimates in the Post-PHV control group (LBS: 0.7 [-0.2 to 1.6]; CMJ: 0.2 [-0.7 to 1.0]) and the Pre-PHV control group (LBS: 0.1 [-0.5 to 0.7]; CMJ: -0.3 [-0.9 to 0.3]) may indicate the extent to which maturation could contribute to the performance changes seen in the respective training groups. LBS and CMJ are trainable, but to different magnitudes, in Pre- and Post-PHV swimmers. Following appropriate foundational training to establish technical competency, twice-weekly RT sessions of 30 minutes duration, comprising 3 sets of 4 exercises can be effective in Pre-PHV and Post-PHV youth.

7.1 Introduction

Maximal strength is the maximum force skeletal muscles can exert in an action (Knuttgen and Komi, 2003). Strength is well correlated with sprint (r = 0.672) and jump (r = 0.760) performance (Comfort *et al.*, 2014) and can help to reduce injury rates (Faigenbaum and Myer, 2010). Physical strength is also required to carry out fundamental movement skills and to underpin long term commitment to physical activity (Lloyd *et al.*, 2014a). Recommendations suggest no minimum age for participation in RT but youth should be technically proficient before embarking on a programme (Dahab and McCambridge, 2009). On this, and as highlighted in Chapter 3, neuromuscular coordination can vary in athletes of the same chronological age whilst adaptations can differ between youth of disparate maturity status (Meylan *et al.*, 2014a; Rumpf *et al.*, 2015) due to issues relating to movement efficiency and hormonal profile. These are important considerations in programing as guidelines for exercise in youth have thus far been generic, particularly for less mature or experienced children who may need to overcome issues relating to strength and motor control to optimise performance.

Current literature is affected by a number of limitations relating to the biological maturity status of youth in addition to the specificity of the training stimulus with respect to stages of maturation. Historically, controlled trials (Lillegard *et al.*, 1997; Pfeiffer and Francis, 1986; Vrijens, 1978) have demonstrated improvements in strength following exposure to RT but have measured maturity status in different ways making comparisons to recent studies difficult. Over the last number of years, researchers have started reporting the maturity offset (years before and after PHV) (Mirwald *et al.*, 2002) of trial participants (Meylan *et al.*, 2014a; Rumpf *et al.*, 2015) and more recently, the first controlled studies, which report maturity offset in resistance-training athletes (Franco-Márquez *et al.*, 2015; Rodriguez-Rosell *et al.*, 2016), have emerged. Both of these studies involved youth soccer players who were subjected to concurrent training modalities including squat, sprint and jump exercises on a twice-weekly basis with the authors examining the effects on equivalent performance parameters. However, only one resisted exercise was performed in the programme each day.

Maturity offset (Mirwald *et al.*, 2002) is an objective and practical method to assess maturation and is used in professional sports (Till *et al.*, 2014; Wrigley *et al.*, 2014). Though not without limitations (Mirwald *et al.*, 2002), the method has been used to form grouping variables in a variety of recently published interventions and reviews examining training types in youth (Lloyd *et al.*, 2016b; Meylan *et al.*, 2014a; Radnor, Lloyd and Oliver, 2016; Rumpf *et al.*, 2015; Rumpf *et al.*, 2012). Additionally, many researchers have failed to measure programmes' effects on a measure of maximum muscular strength, preferring instead to assess responses in jumping and sprinting performance (Gonzalez-Badillo *et al.*, 2015; Lloyd *et al.*, 2016b; Radnor, Lloyd and Oliver, 2016; Santos and Janeira, 2008). This is an important consideration in light of the specificity of adaptive responses to different training modalities (Vissing *et al.*, 2008). Also, recent controlled trials in youth demonstrated moderate to large gains in strength over a 6 week period but because RT was combined with ST and PT, it is difficult to specify the effect of RT in youth of a certain maturity status (Franco-Márquez *et al.*, 2015; Rodriguez-Rosell *et al.*, 2016). Furthermore, controlled studies have generally not compared adaptations in groups of different maturity status as delineated with the maturity offset. Two recent studies (Meylan *et al.*, 2014a; Rumpf *et al.*, 2015) did adopt this approach but did not include control groups making it difficult to partition the effects of training and maturation. On this, Radnor, Lloyd and Oliver (2016) and Lloyd *et al.* (2016b) did include control groups and a measure of maturity status but preferred to assess RT's effect on jumping and sprinting performance.

To date, no researchers have sought to address all of the above limitations within the same study and this limits the quality of inferences that can be made from the literature. The purpose of this study was to examine the effects of RT, deliberately without ST and PT, on performance in Pre-PHV and Post-PHV male participants, incorporating control groups and a measure of muscular strength. Recent evidence on RT in youth has been somewhat equivocal. A meta-analysis by Behringer *et al.* (2011) showed that younger trainees had greater increases in motor performance in response to RT. However, recent non-controlled trials have shown that RT has had greater effects on muscular strength in more mature youth athletes (Meylan *et al.*, 2014a; Rumpf *et al.*, 2015). On that basis, it was hypothesised that adaptations in strength and power would be of a larger magnitude in more mature (Post-PHV) than in less mature (Pre-PHV) youth swimmers.

7.2 Methods

7.2.1 Experimental approach to the problem

This study was carried out to assess the effects of RT on performance in Pre-PHV and Post-PHV male swimmers with a view to testing the hypothesis that the more mature group (Post-

PHV) would demonstrate greater adaptations. Addressing the limitations of previous research, it was a deliberate design feature to include training groups of different maturation status to facilitate testing of the hypothesis. Accordingly, the groups were divided on the basis that synergistic adaptations to RT may occur due to the combined effects of training and maturation in more mature (Post-PHV) youth (Faigenbaum *et al.*, 2016). Additionally, control groups were incorporated to account for non-training related changes in performance while a measure of biological maturity and, also, muscular strength was used to determine if changes in strength were dependent on maturity status. The measure of biological maturity status proposed by Mirwald *et al.* (2002) was utilised to differentiate the study groups as it is a commonly used method in youth sport. Before and after the 8 week training intervention period, tests were carried out to assess upper body strength (UBS [hand grip peak force]), CMJ and lower body strength (LBS [isometric mid-thigh pull peak force]) as these were considered to be measures that would be likely to show an effect due to the training stimulus (Faigenbaum *et al.*, 2016).

7.2.2 Participants

The study was approved by the university's ethics committee and written informed consent was obtained from parents and participants. It was undertaken in accordance with the Declaration of Helsinki. Youth swimmers were recruited through local swimming clubs. The experimental group (n = 22) was recruited from a single club to provide access to training facilities. To avoid contamination, the control group (n = 22) was drawn from multiple clubs (n = 4). Because of this, randomisation was not feasible. The characteristics of the participants are in Table 1. Participants ranged from -3.9 to +3.1 years either side of PHV and were divided into Pre-PHV (Experimental: n = 14; Control = 15) and Post-PHV (Experimental: n = 8; Control = 7) groups for analysis, as recommended by Mirwald *et al.* (2002) (Pre-PHV = <0.0 years from PHV; Post-PHV = ≥ 0.0 years from PHV).

Pre-PHV Group	**Experimental (n = 14)**	**Control (n = 15)**	**Effect size**
Age (years)	11.9 ± 1.2	11.3 ± 1.2	0.5 (-0.1 to 1.1)$_{\text{small}}$
Age range (years)	10.4-13.2	9.6-13.9	
Maturity offset (years)	-1.8 ± 1.0	-2.0 ± 1.1	0.2 (-0.4 to 0.8)$_{\text{trivial}}$
Height (cm)	152.5 ± 6.6	152.4 ± 12.1	0.0 (-0.6 to 0.6)$_{\text{trivial}}$
Sitting height (cm)	75.2 ± 4.4	75.5 ± 5.6	-0.1 (-0.7 to 0.6)$_{\text{trivial}}$
Mass (kg)	44.7 ± 10.0	47.4 ± 13.3	-0.2 (-0.8 to 0.4)$_{\text{small}}$
Post-PHV Group	**Experimental (n = 8)**	**Control (n = 7)**	**Effect size**
Age (years)	15.0 ± 1.1	14.9 ± 1.2	0.1 (-0.8 to 0.9)$_{\text{trivial}}$
Age range (years)	15.4-17.0	14.7-17.5	
Maturity offset (years)	1.6 ± 0.5	1.2 ± 1.0	0.5 (-0.3 to 1.4)$_{\text{small}}$
Height (cm)	176.4 ± 3.6	173.9 ± 6.5	0.5 (-0.4 to 1.3)$_{\text{small}}$
Sitting height (cm)	89.9 ± 2.5	87.1 ± 3.7	0.9 (0.0 to 1.8)$_{\text{moderate}}$
Mass (kg)	68.5 ± 5.6	66.4 ± 9.7	0.3 (-0.6 to 1.1)$_{\text{small}}$

Table 7.1 Descriptive data for participants

7.2.3 Procedures

Participants performed fitness tests in the week before and the week after the training intervention. Testing was carried out by a team of sports scientists from the university's Sports and Exercise department. To estimate maturity status, anthropometric measurements were taken and entered into an equation to predict maturity offset (Mirwald *et al.*, 2002). Following this, the tests of UBS, CMJ and LBS were undertaken. Sitting and standing height were measured with a stadiometer (Seca, Leicester, United Kingdom) and body mass with a portable scales (HoMedics Group Limited, Kent, United Kingdom).

Upper body strength was measured with a Takei T.K.K.5001 Grip A handgrip dynamometer (Takei Scientific Instruments Co. Ltd, Tokyo, Japan). Excellent test-retest reliability (r = 0.96-0.99) was observed for this measure which was in line with previous work (Ortega *et al.*, 2008). The dynamometer was adjusted to the hand size of each participant (Cohen *et al.*, 2010). Hand span was measured with tape and was taken as the distance between the little finger and the thumb when the hand was widely opened, with optimal grip spans corresponding to previous measurements (España-Romero *et al.*, 2008). The dominant hand was used with the participant in a standing position, the elbow extended and the wrist held neutral. The used arm was allowed to deviate from 180 degrees of flexion to near 0 degrees. The participants were given a verbal countdown to performance of “3, 2, 1, squeeze” and exerted maximal force for a period of 5 seconds. Following two efforts with at least 2 minutes of rest between each, the highest observed score was recorded for analysis (Cohen *et al.*, 2010). The digital version of this equipment has been shown to be acceptably reliable across trials (inter-trial difference: 0.3 ± 2.5 kg) (Ortega *et al.*, 2008).

To assess CMJ, a Newtest Powertimer jump mat (Newtest OY, Oulu, Finland) was used. Excellent test-retest reliability (r = 0.97-0.98) was observed for this measure which was in line with previous work (Thomas, Mather and Comfort, 2014). Jump tests in youth have shown this apparatus to be highly reliable (McNeal and Sands, 2003). Participants executed a downward movement to a self-selected depth before performing an explosive extension of the lower-body limbs to jump as high as possible (Dabbs *et al.*, 2011). To facilitate maximal performance, participants were permitted to utilise an arm-swing movement as desired during the jump (Hara *et al.*, 2008). There was at least one minute’s rest between efforts and the highest of three trials was used in the analysis.

Lower body strength was measured with a portable cable pull apparatus (Takei A5002, Fitness Monitors, Wrexham, United Kingdom) which has a high intraclass correlation coefficient (r = 0.98) (Kibele and Behm, 2009). Excellent test-retest reliability (r = 0.95-0.96) was observed for this measure which was in line with previous work (Kibele and Behm, 2009). The apparatus can be viewed in Figure 7.1. Participants were instructed to assume an upright body position with the knees bent to approximately 160 degrees (Kibele and Behm, 2009). The lumbar spine was arched and the trunk was inclined forward such that the pulling handle rested halfway up the thigh between the midpoint of the patella and the iliac crest (Comfort *et al.*, 2015). Following the assumption of a safe body-position (Beckham *et al.*, 2013), participants were given a verbal countdown to performance of “3, 2, 1, pull”. With verbal encouragement (Beckham *et al.*, 2013), each participant exerted maximal force for a period of 5 seconds (Comfort *et al.*, 2015). Between each effort, participants were instructed to rest for 3 minutes (Comfort *et al.*, 2015) and the best of two trials was used for analysis. The unit of measurement for the mid-thigh pull was kilogram-force (kgf) with one unit being the equivalent of 9.806N (Thompson and Taylor, 2009).

The three performance tests were undertaken in the order described with the difference between the coefficient of variation for baseline and follow-up measures ranging from 2.4% to 3.9%.

Figure 7.1 Portable cable pull apparatus

7.2.4 Training

The RT programme (Table 7.2) conformed to the guidelines for youth of the National Strength and Conditioning Association (Faigenbaum *et al.*, 2009) and was delivered every day by the lead researcher who is an accredited strength and conditioning coach (United Kingdom Strength and Conditioning Association), and other qualified personnel. Prior to the beginning of each session a general warm-up (5-10 mins), consisting of skipping, crawling and various other upper and lower body movements, was performed. Training sessions were scheduled on four days each week and participants were instructed to attend on two non-consecutive days. Prior to undertaking the 8 week intervention study, participants engaged in an introductory week during which they were familiarised with the session format and proper exercise technique.

Phase 1	**Week 1**		**Week 2**		**Week 3**		**Week 4**	
	Sets	**Repetitions**	**Sets**	**Repetitions**	**Sets**	**Repetitions**	**Sets**	**Repetitions**
Goblet squats	3	8	3	10	3	12	3	max
Push ups	3	8	3	10	3	12	3	max
Supine weighted hip thrusts	3	8	3	10	3	12	3	max
Side planks	3	15 secs e/s	3	20 secs e/s	3	20 secs e/s	3	30 secs e/s
Rest	2-3 mins following continuous execution of all four exercises with mobility work		2-3 mins following continuous execution of all four exercises with mobility work		2-3 mins following continuous execution of all four exercises with mobility work		2-3 mins following continuous execution of all four exercises with mobility work	
Phase 2	**Week 5**		**Week 6**		**Week 7**		**Week 8**	
	Sets	**Repetitions**	**Sets**	**Repetitions**	**Sets**	**Repetitions**	**Sets**	**Repetitions**
Goblet split squats	3	8 e/s	3	10 e/s	3	12 e/s	3	max e/s
Push ups	3	10	3	12	3	max	3	max
Supine isometric weighted hip thrusts	3	45 secs	3	60 secs	3	75 secs	3	90 secs
Spiderman planks	3	6 e/s	3	8 e/s	3	10 e/s	3	12 e/s
Rest	2-3 mins following continuous execution of all four exercises with mobility work		2-3 mins following continuous execution of all four exercises with mobility work		2-3 mins following continuous execution of all four exercises with mobility work		2-3 mins following continuous execution of all four exercises with mobility work	

Table 7.2 Resistance training programme

e/s: each side

During the sessions, participants were instructed to use manageable loads such that safe and technically proficient performance was not compromised. Each participant was encouraged to lift the maximum weight possible for the prescribed number of repetitions. When participants were capable of performing more than the prescribed number of repetitions, they were asked to increase the load by between 5% and 10%. In such cases, they were permitted to perform the work set to near muscular failure before adjusting the load to the higher level. Conversely, if they were unable to complete the work set, they were instructed to decrease the load by 5% to 10%. For the push up exercise, participants were given a repetition guideline but were encouraged to continue performance until near muscular failure or until one of the coaches had judged that technical breakdown could occur. For the side plank and plank exercises, time guidelines were provided but participants were allowed to extend performance up to a maximum of 30 seconds (each side), and 1 minute respectively. In the final week of each four week cycle, maximum repetitions or time were encouraged up to the point that proper technique could be maintained on each exercise.

As available training time was limited, sessions followed a specific format. The first sets of all four exercises were performed in a continuous manner with low-intensity mobility exercises used as active rest between each. These included side-lying rotations, leg lowering, floor slides and hip-flexor stretching. Using phase 1 as an example, the participants would perform a single set of goblet squats, using side-lying rotations as a means of active rest before performing a single set of push ups, followed by the leg-lowering mobility exercise and continuing on to the third and fourth exercises accordingly. After this, 2 to 3 minutes of complete rest was taken before moving on to the second set of goblet squats and performing all subsequent exercises in a continuous manner once again. This form of "super-setting" is considered to be effective for carrying out RT when available time is a limiting factor (Kelleher *et al.*, 2010) and exercises were arranged in such a way that upper and lower body movements were alternated to preserve technical competency in each. After 4 weeks of the intervention, the resistance exercises were progressed to maintain participants' engagement and to increase the demands of the program.

The average ratio of participants to coaches in the intervention was approximately 5 to 1. The average attendance rate during the intervention was 89.2%. To complete the study, a participant must have attended 75% of all training sessions to ensure that a sufficient volume of training was undertaken. Participants tracked progress in a diary which was observed by the lead researcher. Also, to estimate workload, immediately after each training session, participants reported their rating of perceived exertion (RPE) for the entire session on a 1 to 10 scale. This figure was multiplied by the training session duration in minutes to establish a 'session-RPE' score (Foster *et al.*, 1996).

7.2.5 Statistical analysis

Magnitude-based inferences were preferred to traditional null hypothesis testing which can be biased by small sample sizes (Rhea, 2004) and can be ineffective in gauging practical importance (Hopkins *et al.*, 2009). Effect sizes were interpreted using previously outlined ranges (<0.2 = trivial; 0.2-0.6 = small, 0.6-1.2 = moderate, 1.2-2.0 = large, 2.0-4.0 = very large, >4.0 = extremely large) (Hopkins *et al.*, 2009). An EZ of 0.2 was considered to be the 'smallest worthwhile change' (Spencer *et al.*, 2006). The estimates were considered unclear when the chance of a beneficial effect was high enough to justify use of the intervention, but the risk of impairment was unacceptable. An odds ratio of benefit to impairment of <66 was representative of such unclear effects (Meylan *et al.*, 2014a). This odds ratio corresponds to an effect that is borderline possibly beneficial (25% chance of benefit) and borderline most unlikely detrimental (0.5% risk of harm). This was calculated using an available spreadsheet (Hopkins, 2007). Otherwise, the effect was considered as clear and was reported as the magnitude of the observed value, with the qualitative probability that the true value was at least of this magnitude (Meylan *et al.*, 2014a). The scale for interpreting the probabilities was as follows: possible = 25–75%; likely = 75–95%; very likely = 95–99.5%; most likely>99.5% (Hopkins *et al.*, 2009).

Uncertainty in the ESs was represented by 90% confidence limits. Effects were considered unclear if the confidence interval overlapped thresholds for substantial positive and negative values. Otherwise, the effect was clear and reported as the magnitude of the observed value with a qualitative probability (Hopkins *et al.*, 2009; Meylan *et al.*, 2014a). The utilised confidence limits of 90% are important in intervention studies in which one is presented with an inexpensive intervention that is most unlikely to be harmful, but likely to be at least trivially beneficial (Hopkins, 2007).

7.3 Results

Effect sizes and their descriptors and likelihood estimates of beneficial effects are shown in Tables 7.3 (baseline to follow up) and 7.4 (follow up only).

Variable	Group	Baseline (SD)	Follow-up (SD)	Effect size	Confidence limits	Likelihood effect is beneficial	Effect description	Odds ratio of benefit to harm
Mid-thigh pull (kgf)	All (Experimental)	94.9 (35.1)	115.6 (38.3)	0.6	0.1 to 1.1	86.1%	Small increase	407
	All (Control)	87.0 (32.8)	96.1 (33.3)	0.3	-0.2 to 0.8	67.9%	Small increase	576
	Pre-PHV Experimental	74.0 (20.7)	92.5 (26.4)	0.8	0.1 to 1.4	89.5%	Moderate increase	374
	Pre-PHV Control	78.2 (30.2)	82.0 (28.1)	0.1	-0.5 to 0.7	18.1%	Trivial increase	828
	Post-PHV Experimental	131.3 (22.6)	156.0 (13.1)	1.3	0.4 to 2.2	92.4%	Large increase	359
	Post-PHV Control	105.9 (32.1)	126.4 (21.8)	0.7	-0.2 to 1.7	89.8%	Moderate increase	350
Hand grip (kgf)	All (Experimental)	27.8 (10.6)	27.6 (9.8)	0.0	-0.5 to 0.5	0.0%	Trivial decrease	0
	All (Control)	24.8 (9.0)	25.0 (7.7)	0.0	-0.5 to 0.5	0.0%	Trivial increase	43
	Pre-PHV Experimental	20.9 (4.8)	21.7 (5.1)	0.2	-0.5 to 0.8	34.0%	Trivial increase	636
	Pre-PHV Control	20.3 (5.4)	21.2 (5.3)	0.2	-0.4 to 0.8	37.2%	Trivial increase	677
	Post-PHV Experimental	39.9 (5.6)	37.9 (6.7)	-0.3	-1.2 to 0.5	0.9%	Small decrease	0
	Post-PHV Control	34.5 (7.3)	33.1 (5.6)	-0.2	-1.1 to 0.7	0.5%	Small decrease	0
CMJ (cm)	All (Experimental)	37.3 (6.8)	38.8 (7.1)	0.2	-0.3 to 0.7	56.9%	Small increase	713
	All (Control)	32.9 (6.2)	32.0 (7.4)	-0.1	-0.6 to 0.4	0.0%	Trivial decrease	0
	Pre-PHV Experimental	35.6 (7.0)	36.8 (7.3)	0.2	-0.5 to 0.8	37.0%	Trivial increase	620
	Pre-PHV Control	30.7 (5.4)	28.9 (5.4)	-0.3	-0.9 to 0.3	0.7%	Small decrease	0
	Post-PHV Experimental	40.1 (5.7)	42.4 (5.4)	0.4	-0.4 to 1.2	82.0%	Small increase	344

Post-PHV Control	37.6 (5.6)	38.6 (7.1)	0.2	-0.7 to 1.0	30.4%	Trivial increase	196

Table 7.3 Within-group analysis baseline and follow-up scores, effect sizes, confidence limits, likelihood effects and odds ratios for performance data

The within-group baseline to follow-up analysis showed LBS increased across both groups and was of large magnitude in the Post-PHV group and moderate in the Pre-PHV group. Comparison of follow-up tests in both Pre-PHV and Post-PHV groups and their controls were reflective of this finding. The Post-PHV control group improved LBS to a greater extent than the Pre-PHV control group. Predominantly small and trivial changes were seen in UBS across experimental and control groups in both maturity categories. The Post-PHV group showed a small 'likely beneficial' effect for CMJ and the Pre-PHV group showed a trivial effect in the within-group analysis. However, the between-group comparisons showed substantially larger post-intervention changes in the Pre-PHV group than in the Post-PHV group. Once again, the Post-PHV control group showed larger changes than the Pre-PHV group.

Variable	Comparison	Effect size	Confidence limits	Likelihood effect is beneficial	Effect description	Odds ratio of benefit to harm
Mid-thigh pull (kgf)	Experimental vs. Control (All)	0.5	0.0 to 1.0	85.5%	Small increase	411
	Experimental vs. Control (Pre-PHV)	0.4	-0.2 to 1.0	79.0%	Small increase	486
	Experimental vs. Control (Post-PHV)	1.7	0.7 to 2.7	92.9%	Large increase	364
Hand grip (kgf)	Experimental vs. Control (All)	0.3	-0.2 to 0.8	71.4%	Small increase	540
	Experimental vs. Control (Pre-PHV)	0.1	-0.5 to 0.7	3.8%	Trivial increase	5092
	Experimental vs. Control (Post-PHV)	0.8	-0.1 to 1.7	89.4%	Moderate increase	374
CMJ (cm)	Experimental vs. Control (All)	0.9	0.4 to 1.5	90.5%	Moderate increase	377
	Experimental vs. Control (Pre-PHV)	1.2	0.6 to 1.9	91.8%	Large increase	372
	Experimental vs. Control (Post-PHV)	0.6	-0.3 to 1.5	87.2%	Moderate increase	383

Table 7.4 Between-group analysis effect sizes, confidence limits, likelihood effects and odds ratios for performance data

The training load data for the training intervention can be viewed in Figure 7.2 and Table 7.5. Only small and trivial changes were found between both experimental groups.

Figure 7.2 Weekly Training Load for Pre- and Post-PHV groups

AU: arbitrary units

	All	Pre-PHV	Post-PHV	Effect size
Mean session duration (mins)	31.0 ± 3.2	31.0 ± 3.1	30.9 ± 3.3	0.0 (-0.8 to 0.7)$_{\text{trivial}}$
Mean RPE	6.6 ± 1.0	6.5 ± 1.1	6.9 ± 0.9	0.4 (-0.3 to 1.1)$_{\text{small}}$
Mean session load (AU)	204.8 ± 38.0	200.4 ± 38.1	212.8 ± 36.6	0.3 (-0.4 to 1.1)$_{\text{small}}$
Mean attendance (%)	89.2 ± 7.8	89.7 ± 8.7	88.3 ± 6.2	-0.2 (-0.9 to 0.6)$_{\text{trivial}}$

Table 7.5 Descriptive data for training load

7.4 Discussion

This study compared the effects of a RT programme in male swimmers of differing biological maturation status. It was hypothesised that more mature (Post-PHV) participants would adapt to a greater magnitude than less mature (Pre-PHV). The study sought to account for limitations in previous research by including control groups, measures of muscular strength and comparable maturity groups within the same investigation, something which has not previously been achieved. The most important finding was that strength seems more trainable in Post-PHV youth than in Pre-PHV and the ESs for LBS in each group confirmed this. Also notable was that despite the pure intervention effect on CMJ being smaller in the Pre-PHV group, CMJ performance could be more responsive to RT in Pre-PHV.

Previous interventions in youth athletes (Meylan *et al.*, 2014a; Rumpf *et al.*, 2015) have shown that RT in the Pre-PHV stage may be less effective for increasing strength than it is in the Post-PHV stage. Meylan *et al.* (2014a) found that maximal strength was less trainable in Pre-PHV athletes and more transient following a detraining period when compared to Mid- and Post-PHV athletes. Similarly, Rumpf *et al.* (2015) reported that Pre-PHV athletes failed to improve resisted sprint performance as compared to a Mid-/Post-PHV group which showed significant increases. However, neither of these studies included a control group which makes it difficult to fully evaluate the training methods and impossible to differentiate between changes due to training and biological maturation.

Structural development of muscle mass can occur in response to hormonal changes during adolescence (Lloyd *et al.*, 2014a). Also, an influential factor in the ability to exert force is the cross-sectional area of a muscle (Folland and Williams, 2007). Accordingly, as the Pre-PHV group's ability to increase muscular size was likely lower than the Post-PHV group's, the less mature participants may have been more dependent on neural mechanisms for the enhancement of strength. The lower ES seen in Pre-PHV could be indicative of fewer available pathways of adaptation in comparison to the Post-PHV group. This is supported by previous research (Waugh *et al.*, 2014) which revealed that tendon cross-sectional area remained unaffected following RT in prepubertal children, despite an increase in tendon stiffness of 29%. Moreover, it has been demonstrated that increased strength in prepubertal boys can occur without changes in muscular size with strength adaptations attributed to enhanced excitation-contraction coupling (Ramsay *et al.*, 1990).

Performance improvements are likely to occur due to the interaction between training and maturation (Faigenbaum *et al.*, 2009; Naughton *et al.*, 2000). Interestingly, moderate changes in LBS were seen in the Post-PHV control group. This contrasts with the changes in LBS in the Pre-PHV control group, which improved only trivially. The disparate effects observed in the control groups could suggest that maturation-related increases in strength influenced performance in the Post-PHV group though over the short study period this could also be argued to be unlikely. Alternatively, the size of the observed effect means that a learning effect or increased desire to perform well on the test cannot be ruled out as confounding factors.

Trivial increases and small decreases in UBS in the Pre-PHV and Post-PHV groups were matched by almost identical results in their respective control groups. This suggests that training exerted no effect on this measure, likely due to the nature of the training programme which, based on its configuration, seemed more likely to increase LBS than UBS. This underlines the importance of the specificity of the training stimulus; however, even in interventions that included exercises that targeted the wrist flexors, effects as measured by hand grip strength, were non-existent and small in 1-day (0.0, [-0.5 to 0.5]) and 2-days (0.33 [-0.2 to 0.9]) per week training groups (Faigenbaum *et al.*, 2002).

The results of this study show that RT can enhance CMJ performance in both Pre- and Post-PHV swimmers. Despite the pure intervention effect being lower in Pre-PHV, the between-group analysis showed that the effects on CMJ were far larger in that group. However, it must be considered that accumulation of muscle mass during Post-PHV could lead to increases in absolute strength and body mass which could result in decreases in relative strength (Zatsiorsky and Kraemer, 2006) and, thus, a reduced effect on CMJ. Research has shown the effects of age, lean leg volume, body mass, altered muscle architecture and neuromuscular coordination on performance in youth (Martin *et al.*, 2004) and this could partly explain why the Post-PHV group showed larger increases in LBS, which is dependent on absolute strength (McGuigan and Winchester, 2008), than in CMJ, which is dependent on relative strength (Nuzzo *et al.*, 2008). Conversely, as hypertrophic gains were less likely to play a role in Pre-PHV, CMJ in that group may have been uninhibited by changes in bodyweight and reductions in relative strength. Reinforcing this, Lloyd *et al.* (2016b) reported predominantly larger changes in jump height in Pre-PHV youth in response to a variety of different training types, citing maturation-related changes in SSC regulation as a potential mechanism. Nevertheless, the reader must consider that despite there being a larger post-intervention difference in the Pre-PHV groups, the raw increase in CMJ was still greater in the Post-PHV group.

It is also important to note that the increases in CMJ performance were far less than LBS over the 8 week intervention and PT studies of similar duration have reported larger effects on jump performance, as shown in Chapter 4. This underlines the independent nature of different physical qualities (Vissing *et al.*, 2008) and suggests a need to incorporate a range of modalities into training programmes to specifically target multiple abilities. This may be particularly important in Post-PHV (Lloyd *et al.*, 2016b) when youth seem more receptive to a wider range of training adaptations, as highlighted in Chapters 3 and 4. Resistance training has been shown to be effective in increasing jump performance (Lloyd *et al.*, 2016b; Meylan *et al.*, 2014a). However, in many interventions training is carried out alongside sprint or PT meaning that it is difficult to partition the effects of RT from those of other modalities. This is further convoluted by many researchers implementing a RT programme but measuring only its effects on jumping or sprinting performance, and not strength.

In terms of RT programing, current recommendations for youth are broad (Faigenbaum *et al.*, 2009; Lesinski, Prieske and Granacher, 2016; Lloyd *et al.*, 2014a) and dose responses remain unclear (Lesinski, Prieske and Granacher, 2016). Furthermore, quantifying RT loads is a difficult task (Lesinski, Prieske and Granacher, 2016) and several methods have been proposed (Day *et al.*, 2004; McBride *et al.*, 2009). To establish a basis for comparison with other studies, participants provided RPEs following each training session. Meylan et al. (2014a) reported mean RPEs as low as 3.7 ± 1.3 arbitrary units (AU) in light training weeks and as high 6.1 ± 1.5 AUs in heavy training weeks. In comparison, this intervention showed mean RPEs of 6.6 ± 1.0 AUs with little variation over time despite the periodised nature of the training program. In adult males, RPEs of this magnitude have been equated to a mean exercise intensity of around 90% of 1RM across a RT session (Day *et al.*, 2004), but it remains to be proved if this is directly applicable to a youth population. The reported training RPEs and session-RPEs seem to indicate that training loads across both groups were relatively equal. In future studies, the reporting of RPEs could be a simple, but useful, way of standardising training loads for comparison across interventions to approximate training intensity in heterogeneous programmes. The method has been shown to be reliable in measuring RT intensities in adults (Day *et al.*, 2004).

As highlighted recently (McNarry *et al.*, 2014), research into the trainability of youth must satisfy several criteria such as the inclusion of control groups, the utilisation of an assessment of biological maturity status and the direct comparison of responses in different maturity groups. A strength of this study is that it meets all of these criteria and also uses a measure of performance that is specific to the applied training stimulus. Many studies have met one or some of the above criteria but to our knowledge, no previous study achieves all. However, it does have some limitations. Several training studies (Buchheit *et al.*, 2010b; Fernandez-Fernandez *et al.*, 2015; Ramirez-Campillo *et al.*, 2015c) have used similar statistical methods but with a smaller sample size (<10 paticipants) than that recommended by Hopkins (2006) such that the sample does not misrepresent the population. In the current study, the Post-PHV training and control groups also have less than 10 participants potentially limiting the findings' applicability to a wider population. Future research could replicate this study with a larger sample. Also, the randomisation of participants was not possible, though this is also a common drawback in many interventions studies. Mirwald's (2002) method of measuring biological maturity status, though reliable, can lack precision. The division made between the maturity groups in the current study was made at the point of 0.0 years to/from PHV meaning that any individual who fell within 6 months proximity to this could have been wrongly categorised. However, as only 3 out of 44 individuals were within this range, it is unlikely that this affected the results to a great extent. Assessments of biological maturity may be reinforced with alternative measures such as that of Khamis and Roche (1994) whilst a wider divison between groups may also be beneficial in research settings (Lloyd *et al.*, 2016b; Radnor, Lloyd and Oliver, 2016). Also, though the performance measures utilised showed clear differences between groups, they do not necessarily explain the underlying mechanisms meaning more research is required. Lastly, though the participants in the experimental groups were not carrying out another RT programme, and just two reported informal RT experience, many were involved in other sports such as soccer and rugby. This could confound the results and their applicability to other populations, though almost all control participants were also involved in other sports and did not demonstrate extensive performance changes.

Overall, strength and power are trainable to different degrees in Pre-PHV and Post-PHV swimmers but more mature individuals could be more sensitive to applied stimuli potentially owing to a greater contribution from maturational factors.

7.5 Practical Applications

The current results advocate the use of 4 compound (Beardsley and Contreras, 2014) and core exercises in supporting strength and power (McGill, 2010) in this population. Exercises consisted of 3 sets of 8-12 repetitions (or up to 1 minute on timed exercises) and participants were encouraged to increase repetitions to more challenging ranges when possible. Twice-weekly RT sessions of 30 minutes duration is sufficient to provide the necessary stimulus. However, adaptations of Post-PHV youth may be larger than those in Pre-PHV.

Less experienced youth can engage in a general programme of integrative neuromuscular training to lay a foundation of technical competency for higher training loads and volumes as they mature. Mature youth who have undergone appropriate foundational training can engage in more advanced training techniques and can be exposed to higher training loads and volumes. Given that Pre-PHV youth may adapt at a lower magnitude, it may be more appropriate to subject them to alternative types of neuromuscular training (Faigenbaum *et al.*, 2011) to yield increases in performance. Such training is considered a prerequisite to further participation in physical activity and is representative of a more focused approach to athletic development. In summary, youth of all ages can engage in RT but practitioners may see differences in the magnitude of adaptation across the developmental continuum.

CHAPTER 8

Maturation-related effect of low-dose plyometric training on performance in youth hockey players

Citation

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Abstract

The purpose of this intervention study was to investigate if a low-dose of PT could improve sprint and jump performance in groups of different maturity status. Male youth field hockey players were divided into Pre-PHV (from -1 to -1.9 from PHV; Experimental: n = 9; Control = 12) and Mid-PHV (0 to +0.9 from PHV; Experimental: n = 8; Control = 9) groups. Participants in the experimental groups completed 60 foot contacts, twice-weekly, for 6 weeks. PT exerted a positive effect (ES: 0.4 [-0.4 to 1.2]) on 10 m sprint time in the experimental Mid-PHV group but this was less pronounced in the Pre-PHV group (0.1 [-0.6 to 0.9]). Sprint time over 30 m (Mid-PHV: 0.1 [-0.8 to 0.9]; Pre-PHV: 0.1 [-0.7 to 0.9]) and CMJ (Mid-PHV: 0.1 [-0.8 to 0.9]; Pre-PHV: 0.0 [-0.7 to 0.8]) was maintained across both experimental groups. Conversely, the control groups showed decreased performance in most tests at follow up. Between-group analysis showed positive EZs across all performance tests in the Mid-PHV group, contrasting with all negative ESs in the Pre-PHV group. These results indicate that more mature hockey players may benefit to a greater extent than less mature hockey players from a low-dose PT stimulus. Sixty foot contacts, twice per week, seems effective in improving short sprint performance in Mid-PHV hockey players.

8.1 Introduction

Field hockey is a high-intensity team sport that requires players to engage in multiple short-distance sprints intermittently over the course of a competitive game (Elferink-Gemser *et al.*, 2004; Lythe and Kilding, 2011). With similar physiological demands to soccer (Lythe and Kilding, 2011), the performance of skills such as tackling and ball striking require players to express high force output with jumping, accelerating and decelerating also dependent on this ability (Elferink-Gemser *et al.*, 2007; Manna, Khanna and Dhara, 2009). In movement terms, the sport is characterised by multiple changes of direction, often in a semi-crouched posture which increases energy demand (Elferink-Gemser *et al.*, 2004). Directly related to this, sprinting and jumping are important determinants of athletic performance in youth sport and should thus be targeted through physical training (Buchheit *et al.*, 2010c). An individual's ability to efficiently utilise the SSC in such movements is an indicator of good athleticism and PT has been shown to be an effective way in which to enhance this ability as evidenced by the meta-analysis in Chapter 4.

Because adaptations to PT may differ between youths of different maturity status, appropriate planning is likely to be a crucial element in the long-term periodisation of training. Previously, a trigger hypothesis has been proposed (Katch, 1983), suggesting that a maturational threshold may moderate responses to training around the time of PHV. A longitudinal investigation (Philippaerts *et al.*, 2006) of physical parameters in youths supports this position, suggesting that an interaction between training and maturation may enhance sprint and jump performance at the time of PHV. This is supported by an earlier review (Viru *et al.*, 1999) which stated that the greatest increase in physical performance was concomitant with progressing maturation in boys. However, the results in Chapter 4 are suggestive of a lowered response to PT around the time of PHV, contrasting with a higher level of trainability in the Pre-PHV phase (<13 years of age).

The PT meta-analysis results are also in line with PT studies (Ramirez-Campillo *et al.*, 2015a; Ramirez-Campillo *et al.*, 2015b; Ramirez-Campillo *et al.*, 2015c) that have measured biological maturity status with the maturity offset (Mirwald *et al.*, 2002). However, because very few researchers have compared groups of heterogeneous maturity status within the same study, it has thus far been difficult to accurately gauge the effect of biological maturation on adaptations to PT. Furthermore, comparisons between studies which use the maturity offset and those which account for participants' Tanner stage (Marta *et al.*, 2013; Marta *et al.*, 2014) can be difficult to make as the latter measure refers to stages of pubic hair and genital development (Malina, 2002) whilst the former is related to anthropometric variables (Mirwald *et al.*, 2002).

In addition, the minimum effective dose of PT has not been rigorously described in the literature. In their recent meta-analysis on the dose response between RT and physical performance in youth athletes, Lesinski, Prieske and Granacher (2016) included several studies of PT. However the authors' method of grouping PT studies with those that examined other training modalities makes it difficult to draw definitive conclusions with regard to exercise dosing. Previously, in their systematic review, Bedoya *et al.* (2015) had recommended a minimum starting dose of 50 to 60 foot contacts per session though this was based on a very narrow range of studies and the authors did not elaborate on the dose which could be minimally effective. This is also true of the wider body of literature which has not investigated the effectiveness of this suggested dose. This has implications for athletic programing as the application of the minimum effective dose could be an integral element of athletic development given the recent debate on overuse injury and burnout in youth sport (DiFiori *et al.*, 2014). The importance of this is further emphasised by recent guidelines on strength and conditioning training in youths which broadly suggest 2, 3 or more sessions per week whilst acknowledging the confounding variables of volume, intensity, exercise type and degree of difficulty on the stimulated response (Faigenbaum *et al.*, 2009). To date, the guidelines on PT in youth remain vague, particularly for the sport of field hockey with most PT research on male youths carried out in soccer.

Because of these limitations and conflicting results, it is unclear if there is an optimal time for the prescription of the minimum effective dose of PT in youth hockey players and this warrants further investigation. In light of these observations, the current investigation sought to examine the effects of a low-volume, low-intensity plyometric warm-up protocol on sprint and jump performance in youth hockey players, comparing responses in Pre-PHV and Mid-PHV male participants. A second objective was to examine the effectiveness of a minimum effective dose of PT that could be conveniently applied within a short timeframe around primary sports training.

8.2 Methods

8.2.1 Participants

Thirty-eight male youth field hockey players completed this study. They were recruited through a local school which competes against other schools in the area and were allocated into experimental (n = 17) and control (n = 21) conditions. This was based on the school team that they played for and the number of participants that could be recruited from each. Playing position was not used either as an inclusion or exclusion criteria. The participants carried out two hockey training sessions per week in addition to one competitive game against other school opposition. None of the participants in either group were carrying out a systematic fitness programme. However, aside from their primary sport, they were involved in an intensive physical education programme and military-style exercises on a daily basis. The characteristics of the participants are shown in Table 8.1. The study was approved by the institutional review board and participants provided informed parental consent to take part.

Pre-PHV Group	**Experimental (n = 9)**	**Control (n = 12)**
Age (years)	12.6 ± 0.7	12.8 ± 0.8
Maturity offset (years)	-1.5 ± 0.3	-1.4 ± 0.3
Maturity offset range (years)	-1 to -1.9	-1 to -1.9
Height (cm)	155.4 ± 5.1	160.4 ± 5.5
Sitting height (cm)	76.6 ± 2.9	76.7 ± 2.4
Mass (kg)	50.9 ± 8.7	52.9 ± 9.0
Mid-PHV Group	**Experimental (n = 8)**	**Control (n = 9)**
Age (years)	14.3 ± 0.6	14.4 ± 0.5
Maturity offset (years)	0.3 ± 0.2	0.4 ± 0.3
Maturity offset range (years)	0.1 to 0.5	0 to 0.9
Height (cm)	173.1 ± 5.4	171.2 ± 6.0
Sitting height (cm)	85.1 ± 3.0	84.6 ± 2.0
Mass (kg)	58.8 ± 3.4	64.0 ± 8.1

Table 8.1 Descriptive data for participants

8.2.2 Procedures

Participants attended performance testing sessions in the week before and the week after the training intervention. Anthropometric measurements were taken prior to tests of physical performance. To estimate participant maturity status, anthropometric measurements were taken and entered into an equation to predict maturity offset (Mirwald *et al.*, 2002). This equation is: Maturity Offset = -9.236 + (0.0002708 x leg length and sitting height interaction) + (-0.001663 x age and leg length interaction) + (0.007216 x age and sitting height interaction) + (0.02292 x weight by height ratio). The equation can measure maturity offset within an error of ± 1 year, 95% of the time (Mirwald *et al.*, 2002). Sitting and standing height were measured with a stadiometer (Seca, Leicester, United Kingdom) and body mass with a portable scales (HoMedics Group Limited, Kent, United Kingdom). The participants ranged from -1.9 to +0.9 years either side of PHV and were divided into Pre-PHV (Experimental: n = 9; Control = 12) and Mid-PHV (Experimental: n = 8; Control = 9) groups for analysis (Mirwald *et al.*, 2002). The Pre-PHV group had an offset range from -1 to -1.9 years relative to PHV. The Mid-PHV group had an offset range of 0 to +0.9 years relative to PHV.

Countermovement jump was measured with a Newtest Powertimer jump mat (Newtest OY, Oulu, Finland). For the test, the arms were positioned akimbo and participants executed a downward movement to a self-selected depth before performing a vigorous extension of the lower-body limbs to jump as high as possible. There was at least one minute's rest between efforts and the highest of three trials was used in the analysis (Ramirez-Campillo *et al.*, 2014a).

The 10 m and 30 m running times of the participants were measured using TC System timing gates (Brower Timing Systems, Draper, Utah, United States). These distances were chosen based on their identification by Cronin and Hansen (2005) as appropriate for measuring acceleration (10 m) and maximal speed (30 m). Participants positioned the big toe of their lead foot behind the start line and initiated performance when desired, triggering the timer when passing through the system gates. There was at least one minute of rest between efforts and the best of three trials was used for analysis.

Similar to Zech *et al.* (2014), the PT programme was incorporated into the warm up prior to the in-season hockey practice of the experimental groups. It was delivered by the school fitness coach and the coaches of the respective groups. The control groups concurrently executed low intensity hockey skills work. Displayed in Table 8.2, the programme was formulated based on the recommendations of previous systematic reviews of PT in children (Johnson, Salzberg and Stevenson, 2011), youth athletes (Bedoya, Miltenberger and Lopez, 2015) and general population (de Villarreal *et al.*, 2009). These studies have suggested a minimum dose of PT in youths but to date, the effectiveness of this dose has not been examined. Accordingly, the current programme comprised 60 foot contacts per session on two days per week, for 6 weeks with exercises chosen based on the recommendations of de Villarreal *et al.* (2009) who advocate a varied PT stimulus that includes CMJs along with bilateral and unilateral hops. By programming in this way it was ensured that participants were exposed to vertical, horizontal, bilateral and unilateral movements thus ensuring a well-rounded training stimulus. No more than 10 repetitions for each exercise were assigned based on the recommendations of Faigenbaum *et al.* (2009) who highlight the importance of minimising fatigue to perform PT safely and effectively. The total duration of the programme was 7 weeks as training was temporarily interrupted for 7 days by the school's mid-term break after week 4. After the mid-term break, another training block of 2 weeks was performed. Under school rules, all participants were required to partake in the hockey training as part of the sport curriculum.

Exercise	**Sets**	**Repetitions**
High knees	1 x 15 m	n/a
Heel flicks	1 x 15 m	n/a
Russian marches	1 x 15 m	n/a
Walking single leg deadlift	1 x 15 m	n/a
Cariocas	1 x 15 m on each side	n/a
Lateral shuffles	1 x 15 m on each side	n/a
	60 second rest prior to plyometric program	
Countermovement jumps	**1**	**10**
Standing shoulder abductions	1	20
Countermovement jumps	**1**	**10**
Standing shoulder abductions	1	20
Bilateral forward hops	**1**	**10**
Quadruped thoracic rotations	1	20 each side
Bilateral forward hops	**1**	**10**
Quadruped thoracic rotations	1	20 each side
Unilateral forward hops	**1**	**5 each side**
Quadruped scapula push ups	1	30
Unilateral forward hops	**1**	**5 each side**

Table 8.2 Order and arrangement of warm up and plyometric protocol

The PT element of the warm-up was preceded by a number of dynamic mobility drills performed over a 15 m distance. Between each PT exercise, upper body mobility drills were performed to afford the lower body musculature adequate rest between each set of jumps or hops. This equated to around 60 seconds of rest between each plyometric drill. During the PT exercises, participants were encouraged to be as “explosive” as possible within the boundaries of their own capabilities, being requested to take a brief pause (2 secs approx.)

between repetitions if required, or if elastically repetitive jumps proved difficult to perform. As their capabilities improved, participants were encouraged to undergo fewer pauses between repetitions and to transition seamlessly from one jump into the next. The entire warm-up took approximately 12 minutes to complete.

8.2.3 Statistical Analysis

As in Chapter 7, magnitude-based inferences were used to quantify changes in each group (Hopkins *et al.*, 2009). Analyses were conducted within all groups to examine the effectiveness of the PT programme and between training and control groups to examine effectiveness of the PT programme at different maturity levels compared to the control condition.

Reliability of performance measures was assessed using the intraclass correlation coefficient which was 0.95-0.97, 0.91-0.93 and 0.96-0.99 for the CMJ, 10 m and 30 m respectively.

8.3 Results

Effect sizes and their descriptors, in addition to likelihood estimates of beneficial effects for the respective analyses are shown in Tables 8.3 and 8.4.

Within-group analysis showed that the PT programme was specifically effective in enhancing 10 m performance in the Mid-PHV group. All performance parameters in the experimental groups were at least maintained with effects generally of greater magnitude in the Mid-PHV group. Control groups demonstrated decrements in most performance parameters but this was more pronounced in the Pre-PHV group. Decrements were generally of a similar magnitude to performance improvements.

Between-group analysis showed that the Mid-PHV group had small to moderate increases in all performance parameters with effects largest and most likely in CMJ and 30 m sprint. The Pre-PHV group showed performance decreases across all tests.

Variable	Group	Pre	SD	Post	SD	Effect size	Confidence limits	Likelihood effect is beneficial	Effect description	Odds ratio of benefit to harm
CMJ (cm)	Pre-PHV Experimental	28.0	4.0	28.1	4.0	0.0	-0.7 to 0.8	0.0%	Trivial increase	9
	Pre-PHV Control	29.9	7.0	28.3	6.6	-0.2	-0.9 to 0.4	0.4%	Small decrease	0
	Mid-PHV Experimental	32.5	6.0	32.8	3.7	0.1	-0.8 to 0.9	0.0%	Trivial increase	25
	Mid-PHV Control	30.0	5.9	29.7	5.8	-0.1	-0.8 to 0.7	0.0%	Trivial decrease	0
10 m sprint (s)	Pre-PHV Experimental	2.26	0.13	2.25	0.12	0.1	-0.6 to 0.9	22.8%	Trivial increase	296
	Pre-PHV Control	2.19	0.11	2.20	0.10	-0.1	-0.8 to -0.6	0.0%	Trivial decrease	0
	Mid-PHV Experimental	2.15	0.15	2.10	0.10	0.4	-0.4 to 1.2	80.3%	Small increase	341
	Mid-PHV Control	2.21	0.15	2.19	0.21	0.1	-0.7 to 0.9	1.1%	Trivial increase	125
30 m sprint (s)	Pre-PHV Experimental	5.46	0.34	5.43	0.31	0.1	-0.7 to 0.9	4.6%	Trivial increase	196
	Pre-PHV Control	5.19	0.43	5.24	0.39	-0.1	-0.8 to -0.6	0.0%	Trivial decrease	0
	Mid-PHV Experimental	4.96	0.29	4.94	0.27	0.1	-0.8 to 0.9	0.4%	Trivial increase	54
	Mid-PHV Control	5.26	0.47	5.23	0.52	0.1	-0.7 to 0.8	0.2%	Trivial increase	69

Table 8.3 Pre and post scores, effect sizes, confidence limits, likelihood effects and odds ratios for performance data

Variable	Group	Effect size	Confidence limits	Likelihood effect is beneficial	Effect description	Odds ratio of benefit to harm
CMJ (cm)	Pre-PHV	0.0	-0.8 to 0.7	0.0%	Trivial decrease	0
	Mid-PHV	0.6	-0.2 to 1.4	87.3%	Moderate increase	390
10 m sprint (s)	Pre-PHV	-0.4	-1.1 to 0.3	0.8%	Small decrease	0
	Mid-PHV	0.6	-0.2 to 1.4	86.4%	Small increase	395
30 m sprint (s)	Pre-PHV	-0.5	-1.3 to 0.2	1.4%	Small decrease	0
	Mid-PHV	0.7	-0.1 to 1.5	88.4%	Moderate increase	384

Table 8.4 Between-group effect sizes, confidence limits, likelihood effects and odds ratios for performance data

8.4 Discussion

The objective of this study was to examine the effects of a low-volume, and low-intensity PT programme on sprint and jump performance in youth hockey players, comparing responses in Pre-PHV and Mid-PHV male participants. A second objective was to examine the effectiveness of a low-dose of PT that could be conveniently applied within a short timeframe in conjunction with primary sports training.

The finding of most interest in the within-group analysis was that the applied dose of PT resulted in larger increases in 10 m sprint performance in the Mid-PHV than in the Pre-PHV group with the latter failing to exceed the ‘smallest worthwhile change’ of 0.2 (Spencer *et al.*, 2006). Of note, 30 m sprint time and CMJ were maintained in both experimental groups whereas the control groups experienced decrements across most tests. The between-group analysis indicated that the programme was generally only effective in the Mid-PHV group suggesting that more mature players were more responsive to the PT stimulus.

Marta *et al.* (2013) recently demonstrated that a variable training stimulus that included PT was an effective way to improve CMJ (ES = 0.22) and sprint performance (ES = 0.45) over an 8 week period in prepubescent children. A similar study undertaken by the same research group (Marta *et al.*, 2014), suggested that older children had no maturational-related advantage in terms of their sensitivity to the applied training stimulus. However, differences in the way that various researchers have traditionally assessed biological maturity is likely to influence the inferences that can be made from a study and more recently, several interventions which measured maturity with the offset method have shown different results (Meylan *et al.*, 2014a; Rumpf *et al.*, 2015).

In line with these latter interventions, the larger effects in the Mid-PHV group in the current study could be explained by the potential existence of a maturational threshold which is signalled by the development of hormonal profiles and the musculoskeletal system around the time of PHV, and which may regulate responses to training (Lloyd *et al.*, 2016b; Meylan *et al.*, 2014a). In youths, the development of impulsive movement capability has been shown to increase in line with PHV (Philippaerts *et al.*, 2006). After the growth spurt, an increase in the cross-sectional area of type II muscle fibres could underpin impulsive performance increases in older youths (Martin *et al.*, 2004). The lower concentrations of circulating androgens and growth factors in prepubertal youth could make morphological changes in the Pre-PHV group less likely. This is relevant to our analysis as lean leg volume, body mass, altered muscle architecture and greater neuromuscular coordination have been associated with enhanced impulsive movement performance in male youths (Martin *et al.*, 2004). Rumpf *et al*. (2013) showed that SSC activity progressively increased as youths matured with vertical tendon stiffness (33.3%), leg stiffness (22%), eccentric muscle action (89.6%) and concentric muscle action (56.6%) all greater in Mid-PHV than they were in Pre-PHV. The authors found that the musculotendinous tissue of younger boys is more compliant than that of older boys, meaning that maturation exerts an effect on the ability to utilise the SSC. It may be that the hormonal and musculotendinous profiles of the Mid-PHV group could have made them more receptive to the effects of the low volume PT stimulus.

The current results are also in line with previous longitudinal research in youths that suggests that sprint and jump performance improves in line with PHV (Philippaerts *et al.*, 2006). The authors of that study did imply that training could interact with maturation to have an effect on adaptations to exercise but the work generally referred to the natural development of physical performance only. In contrast, the results of the PT meta-analysis in

Chapter 4 suggest that jump performance during the Mid-PHV phase could be negatively affected by the emergence of growth spurt-related ‘adolescent awkwardness’ in some participants. As suggested in Chapter 5, physical performance could also be inhibited due to a decrease in relative strength that is associated with increasing body size during the Mid-PHV period, a trend that can continue despite increases in absolute strength (Zatsiorsky and Kraemer, 2006). However, in support of the current results, not all youths do experience disrupted sensorimotor abilities during growth and maturation (Quatman-Yates *et al.*, 2012) and it is not beyond possibility that this study’s small sample size resulted in the Mid-PHV group being unaffected by this particular phenomenon. Similarly, the 7 week duration of the study may not have been long enough for any potential maturation-related decreases in relative strength to impact upon jump and sprint performance (Gabbett, Johns and Riemann, 2008). It seems that independent of the potentially disruptive effects of these physiological processes, sprint and jump performance may be more likely to be enhanced by PT in Mid-PHV youths than in Pre-PHV youths (Meylan *et al.*, 2014a; Philippaerts *et al.*, 2006; Rumpf *et al.*, 2015).

Another finding of interest was the small decrements in performance generally seen across the respective control groups of the Pre- and Mid-PHV cohorts. The extensive amount of physical activity of the study participants could have resulted in a temporary decrement in performance across the school term, with low volume PT being an effective means with which to offset this effect in the experimental groups. In the Pre-PHV control group, sprint and jump performance decreased in all measures whilst the Mid-PHV control group experienced decrements in CMJ. Short-term decreases in performance in youths have been documented numerous times in the literature (Faude *et al.*, 2013; Faude *et al.*, 2014; Ferrete *et al.*, 2014; Gabbett, 2006; Montgomery *et al.*, 2008; Santos *et al.*, 2012; Santos and Janeira, 2008). It is possible that these decrements were due to fatigue (Faude *et al.*, 2014) or an interference effect between multi-dimensional training modalities (Faude *et al.*, 2014; Montgomery *et al.*, 2008; Santos *et al.*, 2012) resulting in a reduction of the effects of neuromuscular training. However, the concurrent execution of RT and PT with sports training was sufficient to preserve CMJ performance in other studies (Gabbett, 2006; Santos *et al.*, 2012). This is in line with the results of this investigation.

A second objective of the current intervention was to examine the effectiveness of a minimum effective dose of PT in youths. Moderate volumes of PT can be as effective as higher volumes (Cadore *et al.*, 2013; de Villarreal, González-Badillo and Izquierdo, 2008) however there is little consensus on the size of ‘low’, ‘moderate’ and ‘high’ doses. An eight month intervention incorporating 300 jumps per session, twice per week showed only small effects in Mid-PHV boys. Lower volumes of PT have been associated with similar increases in jumping performance and greater training efficiency (de Villarreal *et al.*, 2009). Demonstrating this, Ramirez-Campillo *et al.* (2014b) applied a similar dose of PT to the current study over a 7 week period, reporting ES of a similar magnitude in adolescent males. The current results support the addition of 60 foot contacts to the warm-up of sport training and this was found to be as beneficial as previous interventions of higher volume (Weeks, Young and Beck, 2008) and intensity (Ramirez-Campillo *et al.*, 2014b). The applied stimulus was generally only effective in enhancing sprint performance in Mid-PHV over the 6 weeks of training. However, it did enable all training groups to maintain performance regardless of maturation status and may thus be suitable for an in-season training programme when the volume of other training modalities is high.

This maintenance of performance occurred despite a one week break in the programme which could potentially have had a detraining effect on the experimental groups. Meylan *et al.* (2014a) found that a detraining period had a greater negative effect on performance in Pre-PHV than in Mid-PHV, however those researchers documented these changes over an 8 week period of training abstinence. Over a shorter detraining period of two weeks in a training study on physical education students, Herrero *et al.* (2010) found that jumping height decreased by 5.5% whilst sprint time improved by 0.8%. If the one week detraining period in the current study did exert an impact on performance, the results of Herrero *et al.* (2010)

could explain why sprint time may have been less affected than CMJ. These are important factors to consider for youth training within a school environment as this study demonstrates the intermittent nature of performance training due to vacation periods and planned breaks in the academic semester. It could therefore be suggested that breaks of at least one week may not be detrimental to overall performance.

It is likely that coaches would need to prescribe higher volumes of PT to achieve greater changes in sprinting and jumping performance across maturity groups but this may be more relevant to off- or pre-season periods when competitive sport loads may be lower. Coaches may also want to increase the volume of jumps that youth athletes are exposed to: a deliberate feature of this study was that PT volume was fixed from week to week to establish a base dose of jumps as a platform from which future research can build. This may have reduced the potential magnitude of the EZ and so coaches might consider the impact that a periodised approach could have on adaptive responses. It is important to highlight that the nature of the PT program, which incorporated movements in a predominantly horizontal direction, may have been a factor in Mid-PHV participants increasing 10 m sprint to a greater extent than CMJ. Also, it is likely that the nature of the PT program, which incorporated many slow SSC movements, was the reason that improvements in sprint performance was restricted to the act of accelerating, rather than that of maximal speed running (Flanagan and Comyns, 2008). Regardless of training dose, PT should not be prescribed at the expense of safe exercise technique at any age and a programme of integrative neuromuscular training may be required to address foundational strength and movement skills prior to the execution of more advanced training (Faigenbaum *et al.*, 2011).

This study does have a number of limitations. It was not possible to randomise the participants because training had to be administered by the coaches within their own specific training groups. This is also a common drawback in many interventions studies. The utilised measurement of biological maturity status, though reliable, can lack precision (Malina and Koziel, 2014) and may therefore be of more use if combined in a battery of maturity assessments which could include that of Khamis and Roche (1994). Also, though the performance measures utilised showed differences between the maturity groups, they do not necessarily explain the mechanism of adaptation meaning more research in this area is required.

8.5 Conclusion

Low-dose PT, in the amount of 60 foot contacts on a twice weekly basis, can help to improve and maintain in-season short sprint and jump performance in Mid-PHV youth hockey players. Such effects could be less likely to occur in Pre-PHV hockey players. This could be reflective of maturation-related differences between older and younger players but could also imply that the applied stimulus in younger children could be insufficient. Similar doses of PT have been proposed for injury prevention in youths (Myklebust and Steffen, 2009) and there is no suggestion that the dose of PT in the current study would not be sufficient for that purpose. However, in the interests of outright performance improvement, youth hockey players may benefit from higher PT loads. This should not be at the expense of efficient movement technique and should be secondary to foundational fitness training which can act as a base for more complex forms of training at a later stage (Faigenbaum *et al.*, 2011). To conclude, responses in the groups in this study indicate that a near-minimum effective dose of PT could have been found, though its successful application may be contingent on the maturity status of the individual and their volume of physical activity.

CHAPTER 9

Maturation-related adaptations in running speed in response to sprint training in youth soccer players

Abstract

Male soccer players from two professional academies were divided into Pre-PHV (-3.9 to -2.4 years from peak height velocity [PHV]; 1 day ST: n = 12; 2 days ST: = 12; Control = 13) and Mid-PHV (-0.9 to +0.7 years from PHV; 1 day ST: n = 7; 2 days ST = 10; Control = 10) groups. The experimental groups completed 16 sprints of 20 m with 90 seconds recovery, either once or twice per week. Effect sizes were larger in Pre-PHV (10m [0.49, CI: 0.01 to 0.97]; 20 m [0.29, CI: -0.19 to 0.77]; 5-10-5 [0.78, CI: 0.29 to 1.27]) than in Mid-PHV (10m [0.33, CI: -0.24 to 0.89]; 20 m [0.22, CI: -0.35 to 0.78]; 5-10-5 [0.20, CI: -0.36 to 0.77]). Across all participants, 1 ST session per week (ES = 0.28 to 0.49) was generally more effective than 2 (ES = 0.09 to 0.43), exclusively so in Mid-PHV. The Pre-PHV groups (ES = 0.13 to 0.83) consistently outperformed their control group (ES = -0.08 to 0.25) while the Mid-PHV groups (ES = 0.08 to 0.51) did not outperform their control group (0.24 to 1.02). ST, in the amount of 16 sprints over 20 m with a 90 s rest, may be more effective in Pre-PHV youths than in Mid-PHV youths.

9.1 Introduction

The term ‘speed’ is defined as distance divided by time and in athletic terms refers to the movement of a body or part of a body over a given distance (Newton, Laursen and Young, 2009). Depending on this distance, a differentiation can be made between ‘acceleration speed’ (5 to 20 m) and ‘maximum speed’ (30 to 60 m) (Newton, Laursen and Young, 2009) with good performance over these distances being associated with greater sporting ability (Coen *et al.*, 1998). As sprinting is a common event in youth sport (Rumpf *et al.*, 2011), its inclusion in a training programme is an important factor in the fitness of young athletes. This is reinforced by the potential existence of windows of trainability in youth. For example, it may be necessary to ingrain particular motor skills prior to the emergence of ‘synaptic pruning’. This process, which cultivates higher-order cognitive processes, is affected by environmental stimuli which exert an influence over which synapses will, and will not, be required as a youth develops. Theoretically, this could result in impaired motor skill development if particular movements aren’t ingrained prior to its onset in the first and second decades of life (Balyi, Way and Higgs, 2013; Luna, 2009).

Evidence suggests that youths of differing maturity status could respond to ST (to improve sprint times as opposed to endurance) to different magnitudes with more mature individuals seeming more responsive to this type of exercise, as demonstrated in the meta-analysis in Chapter 5. This could be due to the variability of intertwined maturational factors relating to the development of muscle mass, the growth of limbs, changes to musculotendinous tissue, enhanced neural and motor development and greater neuromuscular coordination (Oliver and Rumpf, 2014). In support of this, Meyers *et al*. (2015) reported that maximal sprinting speed tends to develop at a quicker rate after the initiation of the growth spurt, highlighting increases in stride length, and stabilisation of stride frequency and ground contact times, as influencers of sprinting speed in youth. Such factors could potentially be indicative of the presence of a maturational threshold which moderates adaptations to ST around PHV (McNarry *et al.*, 2014). However, these factors are related to growth and maturation rather than training and the lack of ST studies carried out in prepubertal youths means that conclusions on trainability at this stage of maturation remain speculative.

Current literature is affected by a number of limitations. The search process for the ST meta-analysis in Chapter 5 did not identify any qualifying studies which measured the biological maturity status of youths with one of the most commonly used methods in sport (Mirwald *et al.*, 2002). The results of that meta-analysis suggest that ST in prepubertal youth athletes may be ineffective, and though this is in line with other studies in youth training (Meylan *et al.*, 2014a; Rumpf *et al.*, 2015), a lack of data prevent definitive conclusions being made. Also, recommendations on the optimal load of ST in youth are scarce. Subgroup analyses in the ST meta-analysis showed that an effective dose for increasing sprinting speed across the spectrum of maturation is 16 sprints of approximately 20 m distance, with a recovery period of 90 seconds or greater (or work to rest ratio of 1:25), on a twice weekly basis. Previous evidence on RT in youth suggests that training on two days per week is more effective than on one day (Faigenbaum *et al.*, 2002) but it is unclear if this also applies to ST due to the variability of training parameters. Indeed, de Villarreal, González-Badillo and Izquierdo (2008) reported greater improvements in 20 m sprint time in students who were exposed to 1- and 2-day(s) per week protocols of PT in comparison to 4-days per week over a 7 week period, indicating a more beneficial effect of lower training volumes.

The purpose of this study was to examine the effects of ST on sprint times before (Pre-PHV) and during (Mid-PHV) the growth spurt in youth soccer players. In an effort to address the limitations of previous research, disparate groups, whose maturity status was reported, were exposed to 1-day or 2-days per week ST programmes comprising sixteen 20 m sprints with 90 seconds recovery. The objective was to elucidate the trainability of youths of differing maturation status to alternative volumes of training, something which has not previously been achieved in any investigation relating to the development of sprinting speed. It was hypothesised that adaptations would be of larger magnitude in Mid-PHV and when training was carried out on 2 days per week instead of 1.

9.2 Methods

9.2.1 Participants

The study was approved by the university's ethics committee and participants and their parents granted consent to partake. The study was undertaken in accordance with the Declaration of Helsinki. The experimental cohort comprised of youth soccer players from an English professional category three academy (n = 41) who were randomised into 1 day per week and 2 days per week training groups. To prevent cross-group contamination, the control group were members of a nearby category three academy (n = 23). English football academies are divided into four categories by independent audit with category 1 being the highest and category 4 the lowest. The characteristics of the participants are in Table 9.1. Participants ranged from -3.9 to +0.8 years either side of PHV and were divided into Pre-PHV (Experimental: n = 24; Control = 13) and Mid-PHV (Experimental: n = 17; Control = 10) groups for analysis, as recommended by Mirwald *et al*. (2002) (Pre-PHV = ≥ -4.0 and <-1 years from PHV; Mid-PHV = ≥ -1.0 and < +0.99 years from PHV). The experimental cohorts were further divided into groups which undertook ST either once (Pre-PHV: n=12; Mid-PHV: n=7) or twice (Pre-PHV: n=12; Mid-PHV: n=10) per week.

Pre-PHV Group	**All (n = 24)**	**1 session (n = 12)**	**2 sessions (n = 12)**	**Control (n = 13)**
Age (years)	10.4 ± 0.7	10.4 ± 0.8	10.4 ± 0.7	10.0 ± 1.0
Age range (years)	9.4 to 11.8	9.4 to 11.8	9.5 to 11.5	8.7 to 11.3
Maturity offset (years)	-3.3 ± 0.4	-3.4 ± 0.4	-3.3 ± 0.4	-3.2 ± 0.6
Height (cm)	139.1 ± 4.6	139.0 ± 5.6	139.1 ± 3.5	139.7 ± 6.7
Mass (kg)	31.9 ± 3.3	31.3 ± 3.8	32.4 ± 2.8	34.4 ± 4.4
Mid-PHV Group	**All (n = 17)**	**1 session (n = 7)**	**2 sessions (n = 10)**	**Control (n = 10)**
Age (years)	13.8 ± 0.8	13.6 ± 0.7	13.8 ± 0.8	14.5 ± 1.0
Age range (years)	12.3 to 14.9	12.9 to 14.9	12.3 to 14.8	12.8 to 15.5
Maturity offset (years)	-0.2 ± 0.6	-0.3 ± 0.5	-0.1 ± 0.7	0.0 ± 0.6
Height (cm)	161.8 ± 11.5	166.9 ± 5.5	158.2 ± 13.4	163.5 ± 5.6
Mass (kg)	55.4 ± 7.8	55.4 ± 9.2	55.4 ± 7.1	53.2 ± 5.7

Table 9.1 Descriptive data for participants

9.2.2 Procedures

Testing was carried out by the soccer clubs' sports science staff and was in accordance with the English Premier League's Elite Player Performance Plan. To estimate participant maturity status, anthropometric measurements were entered into an equation to predict maturity offset (Mirwald *et al.*, 2002): Maturity Offset = -9.236 + (0.0002708 x leg length and sitting height interaction) + (-0.001663 x age and leg length interaction) + (0.007216 x age and sitting height interaction) + (0.02292 x weight by height ratio). The equation can measure maturity offset within an error of ± 1 year, 95% of the time (Mirwald *et al.*, 2002).

To measure linear (10 m and 20 m) and multidirectional (5-10-5 test) sprinting speed, electronic timing gates were used (Brower Timing Systems, Draper, Utah, United States). This equipment has shown excellent test-retest reliability (ICC = 0.91 to 0.99) in the measurement of linear sprint speed in athletes (Shalfawi *et al.*, 2012b). Participants began each sprint in a front-facing, crouched, standing 'two-point position' behind the start line. They were instructed to sprint straight through each timing gate line (10 m, 20 m) maximally until they were past target markers placed 5m after the final line. There was 3 minutes of recovery between trials and the best of 3 was recorded for each distance and used in the analysis.

To measure multidirectional sprint times, the pro agility (5-10-5) test was used with the aforementioned timing equipment and start protocol. The test mirrored that of a previous investigation (Nesser *et al.*, 2008). A 10 m distance was measured and bisected to indicate the timing gate's start point. Timing started when the participant initiated movement to his left or right and he was required to run to the end of the 10 m line before changing course to run to the opposite end. Changing direction once more, the test concluded when the participant crossed the middle line for a second time, culminating in a total run distance of 20 m. There was 3 minutes of recovery between trials and the best of 3 was used in the analysis.

9.2.3 Training

The ST intervention was based on the findings of the ST meta-analysis in Chapter 5 which suggested that effective speed development programmes for youth athletes consisted of 16 sprints over a distance of 20 m with 90 seconds recovery time between each effort. This protocol was thus adopted with experimental groups exposed to either 1 or 2 ST sessions per week. All experimental groups trained once per week under the supervision of a qualified sport scientist and those who trained twice undertook an additional unsupervised session carried out to the same specifications. Those who were tasked with completing some unsupervised training were reminded of their responsibilities weekly and were requested to provide regular feedback to the coach on their individual sessions. The control group continued with their usual soccer training schedule but did not carry out any specific ST during the course of the period of observation.

9.2.4 Statistical analysis

As in Chapters 7 and 8, magnitude-based inferences were preferred to traditional null hypothesis testing (Hopkins *et al.*, 2009).

9.3 Results

Effect sizes and their descriptors and likelihood estimates of beneficial effects are shown in Table 9.2.

Performance was increased to a greater extent in the Pre-PHV group, with 1 training session per week generally more beneficial than 2 sessions per week across all participants, exclusively so in Mid-PHV. Sprint training improved 10 m, 20 m and 5-10-5 performance, though there was variability in the magnitude of response across groups. Improvements in 10 m performance were ‘small’ and ‘likely’ in Pre-PHV though only ‘small’ and ‘possible’ in Mid-PHV. One training session per week was substantially more effective than 2 per week and was ‘likely’ beneficial in the Mid-PHV group, though there was little difference between these conditions in Pre-PHV. 10 m performance improvements in the Mid-PHV group which performed 2 sessions per week were no larger than its control group.

For 20 m performance, 2 sessions per week was also inferior to 1 session per week in both groups. For that test, improvements were ‘small’, but practically important, in Pre-PHV and Mid-PHV, being slightly larger in Pre-PHV. There were few differences between all Mid-PHV groups and their control group. In contrast, the Pre-PHV groups experienced better performance increases than their control group, particularly in the 1 session per week condition which demonstrated a ‘small’ and ‘likely’ beneficial improvement in 20 m sprint.

5-10-5 test performance was improved across the entire cohort but showed large variability. Both Pre-PHV groups experienced ‘moderate’ and ‘likely’ beneficial increases though only the Mid-PHV group which performed 1 session per week demonstrated improved performance. Despite this, this was still less than the ES in the Mid-PHV control group which was of ‘moderate’ magnitude. In contrast, the Pre-PHV control group experienced only borderline ‘trivial’ to ‘small’ changes.

Variable	Group	Baseline (SD)	Follow-up (SD)	Effect size	Confidence limits	Likelihood effect is beneficial	Likelihood effect is harmful	Effect description	Odds ratio of benefit to harm
10 m sprint	All experimental	2.05 ± 0.13	2.01 ± 0.13	0.32	-0.04 to 0.69	73.7%	0.5%	Small increase	592
	All (1 session)	2.06 ± 0.14	2.01 ± 0.15	0.34	-0.19 to 0.88	76.1%	0.7%	Small increase	473
	All (2 sessions)	2.04 ± 0.13	2.00 ± 0.13	0.30	-0.20 to 0.79	70.8%	0.4%	Small increase	545
	All (Control)	2.11 ± 0.19	2.10 ± 0.22	0.05	-0.43 to 0.54	0.0%	0.0%	Trivial increase	2386
	Pre-PHV (All experimental)	2.12 ± 0.09	2.08 ± 0.11	0.49	0.01 to 0.97	83.9%	1.2%	Small increase	428
	Pre-PHV (1 session)	2.13 ± 0.11	2.08 ± 0.13	0.44	-0.24 to 1.12	82.5%	1.2%	Small increase	388
	Pre-PHV (2 sessions)	2.12 ± 0.08	2.07 ± 0.08	0.56	-0.12 to 1.24	86.4%	1.7%	Small increase	378
	Pre-PHV (Control)	2.25 ± 0.09	2.26 ± 0.10	-0.08	-0.73 to 0.57	0.0%	1.0%	Trivial decrease	0
	Mid-PHV (All experimental)	1.94 ± 0.11	1.91 ± 0.10	0.33	-0.24 to 0.89	74.6%	0.6%	Small increase	469
	Mid-PHV (1 session)	1.93 ± 0.10	1.89 ± 0.07	0.51	-0.38 to 1.40	85.9%	1.8%	Small increase	338
	Mid-PHV (2 sessions)	1.95 ± 0.12	1.92 ± 0.13	0.23	-0.51 to 0.97	59.5%	0.4%	Small increase	383
	Mid-PHV (Control)	1.92 ± 0.11	1.89 ± 0.13	0.29	-0.45 to 1.03	71.3%	0.7%	Small increase	377
20 m sprint	All experimental	3.62 ± 0.31	3.57 ± 0.29	0.18	-0.19 to 0.54	41.9%	0.0%	Trivial increase	1536
	All (1 session)	3.64 ± 0.30	3.56 ± 0.28	0.28	-0.26 to 0.81	68.4%	0.4%	Small increase	538
	All (2 sessions)	3.60 ± 0.32	3.57 ± 0.30	0.09	-0.40 to 0.59	3.5%	0.0%	Trivial increase	2763
	All (Control)	3.71 ± 0.38	3.69 ± 0.41	0.05	-0.44 to 0.53	0.0%	0.0%	Trivial increase	1952
	Pre-PHV (All experimental)	3.81 ± 0.24	3.74 ± 0.21	0.29	-0.19 to 0.77	69.9%	0.4%	Small increase	571

	Pre-PHV (1 session)	3.82 ± 0.22	3.72 ± 0.22	0.45	-0.23 to 1.13	82.9%	1.2%	Small increase	387
	Pre-PHV (2 sessions)	3.80 ± 0.27	3.77 ± 0.19	0.13	-0.54 to 0.80	18.1%	0.0%	Trivial increase	526
	Pre-PHV (Control)	3.99 ± 0.17	4.00 ± 0.15	-0.04	-0.68 to 0.61	0.0%	0.0%	Trivial decrease	0
	Mid-PHV (All experimental)	3.35 ± 0.16	3.31 ± 0.18	0.22	-0.35 to 0.78	55.2%	0.2%	Small increase	616
	Mid-PHV (1 session)	3.35 ± 0.14	3.30 ± 0.15	0.33	-0.56 to 1.21	76.0%	1.0%	Small increase	310
	Mid-PHV (2 sessions)	3.35 ± 0.17	3.32 ± 0.20	0.15	-0.59 to 0.88	27.0%	0.1%	Trivial increase	373
	Mid-PHV (Control)	3.33 ± 0.22	3.28 ± 0.23	0.24	-0.50 to 0.97	60.7%	0.4%	Small increase	382
5-10-5 m agility	All experimental	5.55 ± 0.41	5.37 ± 0.39	0.45	0.09 to 0.82	82.4%	1.0%	Small increase	466
	All (1 session)	5.58 ± 0.39	5.40 ± 0.36	0.49	-0.05 to 1.03	84.0%	1.2%	Small increase	415
	All (2 sessions)	5.52 ± 0.43	5.34 ± 0.43	0.43	-0.08 to 0.93	81.4%	1.0%	Small increase	445
	All (Control)	5.65 ± 0.41	5.50 ± 0.51	0.33	-0.16 to 0.82	74.5%	0.6%	Small increase	514
	Pre-PHV (All experimental)	5.77 ± 0.29	5.51 ± 0.38	0.78	0.29 to 1.27	89.2%	2.1%	Moderate increase	387
	Pre-PHV (1 session)	5.77 ± 0.30	5.55 ± 0.32	0.69	0.00 to 1.38	88.6%	2.1%	Moderate increase	372
	Pre-PHV (2 sessions)	5.77 ± 0.28	5.46 ± 0.45	0.83	0.13 to 1.53	90.0%	2.4%	Moderate increase	369
	Pre-PHV (Control)	5.93 ± 0.26	5.85 ± 0.34	0.25	-0.39 to 0.90	64.3%	0.4%	Small increase	461
	Mid-PHV (All experimental)	5.24 ± 0.35	5.17 ± 0.32	0.20	-0.36 to 0.77	50.6%	0.2%	Small increase	656
	Mid-PHV (1 session)	5.26 ± 0.31	5.14 ± 0.26	0.43	-0.46 to 1.32	83.1%	1.5%	Small increase	330

	Mid-PHV (2 sessions)	5.22 ± 0.39	5.19 ± 0.38	0.08	-0.66 to 0.81	0.9%	0.0%	Trivial increase	175
	Mid-PHV (Control)	5.29 ± 0.25	5.04 ± 0.24	1.02	0.24 to 1.79	91.2%	2.8%	Moderate increase	363

Table 9.2 Baseline and follow-up scores, effect sizes, confidence limits, likelihood effects and odds ratios for performance data

9.4 Discussion

This study compared the effects of a ST programme in male soccer players of differing biological maturation status. Its objective was to address limitations of previous research by including a measure of biological maturity status and comparable maturity groups within the same ST intervention. This has not previously been achieved and would go some way to clarifying previous suggestions that youth of differing maturity status adapt to ST to different magnitudes. A concurrent aim was to establish if the described guidelines for ST session configuration in Chapter 5 differed in effectiveness based on participant maturity status. The most important findings were that ST was more effective in the Pre-PHV group than in the Mid-PHV group and that 1 session per week was generally more effective than 2 per week in eliciting performance improvements. It is interesting to note that despite largely similar ES being observed in the Pre-PHV and Mid-PHV groups, the overall trainability of the Mid-PHV group seems lower given that in many cases, performance changes in the control condition were roughly equal, or larger, than in the experimental condition. This suggests that biological processes could have played a greater role than training in the improvements in sprint time that were observed in Mid-PHV. Conversely, the Pre-PHV control group experienced substantially lower changes than the experimental group indicating a far larger effect of the ST intervention whereby training seemed to have a greater influence than growth and maturation.

Though mechanistic factors were not assessed, there exists some evidence to potentially explain this finding. The lower trainability in the Mid-PHV stage could be attributed to the phenomenon of adolescent awkwardness whereby a youths' motor coordination is temporarily disrupted due to rapid growth of the limbs and trunk (Lloyd *et al.*, 2011). Associated increases in body dimensions can heighten the centre of mass making it more challenging to control the trunk during impulsive movements and this can be compounded by rapid increases in body mass (Chu and Myer, 2013). If an increase in body mass is not concurrently offset by a rise in relative strength, an athlete may find himself relatively less capable of producing the requisite force to propel the body forward (Zatsiorsky and Kraemer, 2006) during sprinting movements. Given that, in several tests, the Mid-PHV control group's EZ equalled and exceeded one, or both, of the Mid-PHV experimental groups, it could be argued that biological processes played a role in the performance changes that were observed, albeit over a very short period of time. In light of this it seems that growth and maturation could negate some of the detrimental impact that is associated with impaired motor coordination during the growth spurt. If indeed this is the case, it could indicate that performing relatively high volumes of ST during the Mid-PHV period may not be optimal, particularly given that sprint times could be upheld/improved by biological processes, and standard sport training, during this period.

It was previously reported that maximal sprinting velocity may develop more rapidly during and after the interval of maximal growth in males with maturation-related increases in stride length, better stabilisation of stride frequency and ground contact times serving as mediators of this quality around PHV (Meyers *et al.*, 2015). Greater leg length has also been positively associated with sprinting velocity in youth (Mendez-Villanueva *et al.*, 2011a) and it seems that sprinting performance during and after PHV may be further enhanced by increases in muscular strength (Meyers *et al.*, 2015). With all of these concurrently occurring positive and negative factors being considered in what is a time of dynamic physical change for the young male, it may be prudent to decrease the volume of ST and increase the volume of RT to optimise development. Indeed, the results of the RT meta-analysis in Chapter 3 identified the Mid-PHV period as the time during which adaptations to RT are maximised in youth which potentially validates this as an important strategy to develop relative strength at a time when the trainability of sprint ability could be temporarily impeded. In light of this, it is important to differentiate between increases in sprint time that can be attributed to growth and maturation and those which can be attributed to ST. The Mid-PHV period may well be the time at which sprint ability is maximally developed through biological processes but it may not necessarily be the time at which ST is most effective. This is evidenced by the faster sprint times in the Mid-PHV group, as compared to the Pre-PHV group, in all tests despite lower ESs.

In relation to the Pre-PHV group this data was much needed given the lack of investigations of ST in youths of this maturity status. Previous literature has suggested that there exists a prepubertal critical training period for speed development which is facilitated by the maturation of the central nervous system through increased myelination of nerve cell axons and enhanced inter- and intramuscular coordination (Lloyd *et al.*, 2014a; Negra *et al.*, 2016a; Rumpf *et al.*, 2012). This could mean that the Pre-PHV period is the optimal time at which to develop sprint ability, a stance strengthened by the suggestion that bouts of activity that exceed 15 seconds duration are difficult for prepubertal youths to sustain owing to low energy delivery due to an immature glycolytic capacity (Boisseau and Delamarche, 2000). Accordingly, it may be more beneficial for Pre-PHV youth to carry out training that is more suited to their physiological profiles thus lending credence to the concept of ‘synergistic adaptation’ (Lloyd *et al.*, 2016b). The distinct lack of improvement in the Pre-PHV control group offers strong support to the assertion that the ST stimulus was much more effective in the Pre-PHV cohort than it was in the Mid-PHV cohort.

Beyond the maturation-specific adaptations, it is interesting to note that 1 ST session per week was generally more effective than 2 ST sessions per week, particularly during Mid-PHV. The ST meta-analysis demonstrated that 2 ST sessions per week was most effective in youth athletes though it was also apparent that 1 session was more beneficial than 3 thus indicating that there may be an optimal threshold above which adaptations are reduced. Indeed, it has also been shown that such a threshold may exist for PT in youths with lower volumes being potentially more effective than higher volumes for the development of jumping performance, as discussed in Chapter 8. This has important implications for training prescription for youth athletes because it suggests that higher training loads do not necessarily result in larger adaptations meaning that coaches can apply an optimal stimulus that both enhances physical capabilities and avoids the development of burnout or overtraining. This finding is particularly important for youths in the Mid-PHV period of maturation who may be more susceptible to injury at this time (van der Sluis *et al.*, 2014). Indeed while adaptations were similar in the 1 session and 2 sessions per week Pre-PHV groups, in the Mid-PHV group 2 sessions per week elicited only 'trivial' and borderline 'trivial' to 'small' changes. Though this training was not considered 'harmful' in and of itself, when compared to the 1 session per week group in Mid-PHV, it could be argued to be relatively detrimental to performance. On that basis, 1 training session per week during Mid-PHV may not only be more beneficial, it can also reduce the degree to which youths of this age are exposed to potentially injurious levels of physical activity.

It is also notable that 5-10-5 performance may not have been impacted by the applied ST stimulus in the Mid-PHV group. Across the entire cohort, improvements were seen in this test but did not differ substantially between control and experimental conditions. Though this did not necessarily hold within the individual groups, the changes in 5-10-5 performance could have occurred due to soccer-specific training rather than the linear ST programme which may have had less of an impact on the multi-directional 5-10-5 test owing to the specificity of motor abilities (Salaj and Markovic, 2011). Indeed, despite larger increases in the Pre-PHV experimental groups than were seen in their control group, the increase in 5-10-5 performance in the Mid-PHV control group was larger than that seen in its respective experimental groups. This could again be indicative of reduced trainability in the Mid-PHV cohort but could also be due to their soccer training schedule with typical game-based training exercises also being effective for the improvement of agility performance (Chaouachi *et al.*, 2014a). Because the control groups continued with their usual soccer training activities, it is plausible that general sport training continued to exert a positive effect on multidirectional performance in the absence of a linear ST stimulus. Nevertheless, important 'moderate' changes were still seen in the 5-10-5 test in the Pre-PHV cohort indicating trainability.

This study has some limitations. Due to resource constraints, the groups that performed 2 ST sessions per week only received supervision for one of those training sessions meaning the quality of the unsupervised sessions may have been limited (Smart and Gill, 2013). Nevertheless, the finding that showed 2 training sessions per week to be generally inferior to 1 indicates that these sessions did seem to exert an impact, albeit negative. A similar study could assess the effect of a full supervised schedule of training sessions. The method by which biological maturity status was assessed, though reliable, can lack accuracy (Malina and Koziel, 2014) and may be reinforced if used in conjunction with predictions of full adult height (Khamis and Roche, 1994). Lastly, though the measures of sprint time showed important differences between the Pre- and Mid-PHV groups, they do not necessarily describe the underlying mechanisms of adaptation, necessitating the need for more in-depth investigations. A strength of this study is that it is the first to compare adaptations to ST in youth athletes of differing maturity status. By extension, it is the first to compare different volumes of ST in youth athletes with a view to informing coaches of optimal programming parameters at different stages of maturation.

9.5 Conclusion

Based on the results of this study, ST, in the amount of 16 sprints over 20 m with a 90 s rest, may be more effective in Pre-PHV youths than in Mid-PHV youths. In general, 1 session per week may be more beneficial than 2 sessions per week but it seems that Pre-PHV youths may be more responsive to the higher of those two loads. In Mid-PHV, 2 sessions per week is not harmful but could be detrimental to performance when compared to 1 session per week. On the basis of these findings, Pre-PHV youths can carry out 2 ST sessions per week which could potentially be reduced to 1 during Mid-PHV. If coaches decide to undertake this course of action, it may be beneficial to replace 1 ST session with RT with a view to reducing injury risk and developing the requisite relative strength to overcome the rapid changes in body mass and dimensions which may temporarily impair performance during the growth spurt. Regardless of the configuration of training, coaches should administer multidimensional programmes that address all physical capabilities in youth athletes.

CHAPTER 10

Conclusion and Summary

10.1 Summary

Based on the results presented in this work, it can be concluded that there do seem to be specific junctures, during growth and maturation of the male youth, at which particular types of training are more or less effective than they are at other times. In the context of the current work, this is described in detail in Table 10.1. Youth athletes must be afforded the opportunity to build a wide-ranging set of motor skills and physical capabilities from a young age in order to underpin optimal health and athletic performance, particularly in the interests of offsetting the negative outcomes associated with adolescent awkwardness, overuse or traumatic injury. In general terms, RT should be carried out during the Pre-, Mid- and Post-PHV periods of maturation and can be advanced in its volume and complexity as greater proficiency is attained. Development of hormonal profiles can facilitate this increase in complexity as a youth matures, ensuring that adaptations can be sustained into, and beyond, the growth spurt. This can be combined with varying volumes of ST and PT that should be prescribed more cautiously depending on the maturity status of the individual athlete. Due to the rapid development of the central nervous system, both of these types of training can be carried out alongside fundamental movement training during the Pre-PHV period but may have to be reduced in volume to varying degrees as a youth approaches Mid-PHV, the adolescent growth spurt. At this time, accelerated growth rates could interfere with the effectiveness of ST and PT so coaches may need to devote less time to one or both of these whilst devoting more time to movement training and RT with a view to upholding relative strength and reducing the chances of injury. However, if disrupted motor coordination does not manifest, ST and PT may not be negatively affected and can be progressed on the basis of physical competency. As the growth rate slows down, the complexity of RT can be further increased alongside higher volumes of ST and PT but coaches must continue to carefully monitor an athlete’s movement quality and susceptibility to injury at all times as this can continue to be a risk following the growth spurt. It is doubtful that any one type of training needs to be discontinued in healthy athletes but coaches must remain attentive to these recommendations so as to expose the athlete to the optimal mix of activities at the right time. The results of this work support the LTAD model as a framework for exercise prescription but only on the basis that technical competency is given a higher priority than windows of physiological development. Furthermore, the LTAD model seems to lack provision for the development of physical qualities such as muscular power, meaning that future versions of the could take a more comprehensive approach to addressing the training modalities typically used by modern coaches. This is vital for the area of LTAD in general given the large body of knowledge that has been accrued since its original formulation.

		Group		
Study	**Measure**	**Pre-PHV**	**Mid-PHV**	**Post-PHV**
Resistance training meta-analysis	Squat	0.50 (-0.06 to 1.07)$_{\text{small}}$	1.11 (0.67 to 1.54)$_{\text{moderate}}$	1.01 (0.56 to 1.46) $_{\text{moderate}}$
Plyometric training meta-analysis	CMJ	0.91 (0.47 to 1.36)$_{\text{moderate}}$	0.47 (0.16 to 0.77)$_{\text{small}}$	1.02 (0.52 to 1.53)$_{\text{moderate}}$
Sprint training meta-analysis	30 m sprint	-0.18 (-1.35 to 0.99)$_{\text{trivial}}$	1.15 (0.40 to 1.90)$_{\text{moderate}}$	1.39 (0.32 to 2.46)$_{\text{large}}$
Resistance training intervention	Mid-thigh pull	0.8 (0.1 to 1.4)$_{\text{moderate}}$	-	1.3 (0.4 to 2.2)$_{\text{large}}$
Plyometric training intervention	10 m sprint	0.1 (-0.6 to 0.9)$_{\text{trivial}}$	0.4 (-0.4 to 1.2)$_{\text{small}}$	-
Sprint training intervention	5-10-5	0.78 (0.29 to 1.27)$_{\text{moderate}}$	0.20 (-0.36 to 0.77)$_{\text{small}}$	-

Table 10.1 Summary of most significant results from each study

10.2 Research question 1: Are adaptations to training in youth athletes mediated by stage of maturation as denoted by years to/from PHV?

Yes, as evidenced by the variability of the ESs reported across the six studies in this work, it seems that adaptations to training in youth athletes are mediated by maturation status. However, the extent to which this is the case is likely to be dependent on the individual characteristics of the youth athlete with some, for example, likely to be affected by the phenomenon of adolescent awkwardness whilst others may be less likely to be affected by this. This has implications for the way in which a young athlete’s physical activities should be programmed and it is likely that technical proficiency is a more important factor to consider than maturation itself. Coaches must also consider whether a low response to a given training method necessitates its omission from a training programme owing to the potential for burnout or injury and concurrent lack of adaptation. This could lead to a poor risk to reward ratio.

10.3 Research question 2: Can specific types of training be optimally programmed based on a youth's stage of maturation?

Yes. As a direct extension from the maturational factors considered in the evaluation of question 1, different types of training can, and should, be prescribed based on the degree to which a given athlete responds to a modality. For example, if a youth athlete in the Mid-PHV stage of maturation does not respond to PT, it may be beneficial to temporarily eliminate this type of training from the programme in order to concentrate on RT which seems to be effective at all times and may offset the impediments to power performance. By the same token, RT may be somewhat less effective in Pre-PHV meaning low volumes can be prescribed at this time whilst other physical competencies, such as neuromuscular control and movement speed, are addressed before the onset of the growth spurt. With good foundational training, an athlete may be able to safely undertake all types of training at higher volumes and intensities during Post-PHV.

10.4 Research question 3: Is there a maturational threshold below which adaptations to training in youth athletes are less apparent?

Partly, as it seems that training that is more metabolically challenging, such as RT, increases in effectiveness as a youth enters and goes beyond Mid-PHV. However, despite some confounding evidence, it seems that training with a predominant neuromuscular component, such as PT and ST, can be very effective prior to the growth spurt. The potential existence of a maturational threshold that moderates adaptations to training does not necessarily mean certain modalities should be eliminated; however, it does require a coach to repeatedly evaluate the magnitude of the volume and intensity of RT, PT and ST as an athlete grows and matures.

10.4 Limitations

This research has a number of limitations that could be addressed by researchers in the future:

- In the meta-analyses, a lack of uniformity in how training programmes were prescribed could contribute to high heterogeneity and, therefore, the accuracy of the results. Related to this, the composition of training in the RT and PT analyses could not be established.
- In addition to the above, in each meta-analysis, the training type of interest was usually carried out alongside complementary training which could also affect the result. This means that an isolation of the effect of a particular type of training is not possible.
- In the meta-analyses, because so few researchers have measured biological maturity status, the classifications used to account for biological maturity are related to chronological age and so can account for only some of the developmental diversity that is seen across groups.
- There are very few studies which outline the effects of ST in Pre-PHV athletes meaning knowledge in this area is currently scarce.
- Though it was hoped that each intervention study would include Pre-, Mid- and Post-PHV groups, this proved impossible to achieve.
- Across the intervention studies, the training and control groups posssed relatively low numbers of participants, potentially limiting the findings' applicability to a wider population.
- Due to difficulties in logistics and participant recruitment, the randomisation of participants to training and control groups was generally not performed.

- Though the utilised measure of biological maturity status is commonly used in youth sport, it underestimates age at PHV at younger ages and overestimates it at older ages.
- Though the performance measures utilised in the interventions showed clear differences between groups, they do not necessarily explain the underlying mechanisms meaning more research is required.
- In the ST intervention, the groups that performed 2 ST sessions per week only received supervision for one of those training sessions meaning the quality of the unsupervised sessions may have been limited.

10.5 Future directions

The underpinning factors of variable trainability have been discussed extensively throughout the preceding chapters and it seems that a natural progression of this work would be to investigate the nature and the development of the mechanisms that determine the described adaptations. Such research would be enhanced by an evaluation of adaptations in a cohort of male youth athletes over an extensive period of time, contrasting with the relatively short-term interventions undertaken in the different groups in the current work. However, there are a number of other issues that could be addressed by researchers in the future. For example, in the current work, it was anticipated that each intervention study would include groups of pre-, mid- and post-PHV athletes. This would have represented an unprecedented basis for comparison in a controlled study but due to difficulties in participant recruitment and attrition, such a design was not possible on this occasion. A further development of the research designs of the interventions in this study would be to expose the different experimental groups to different volumes of training to gauge if this could be a factor in the type and magnitude of the observed adaptation. This was achieved to an extent in the ST intervention but involved some unsupervised training and it would be interesting to observe the results of a similar design in relation to PT and RT programmes. In respect of this, there is variety of different programming parameters that could be manipulated ranging from training volume and intensity to frequency and the duration of the overall stimulus. This work has initiated work in this are but it could be built upon if researchers adopt these recommendations for future work.

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