THE DEVELOPMENT OF MOVEMENT COMPETENCY, STRENGTH, AND POWER IN YOUNG MALE ATHLETES

Ian James Dobbs

MSc, CSCS*D

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Director of Studies: Dr. Rhodri S. Lloyd

Supervisors: Dr. Jon L. Oliver and Isabel S. Moore

Abstract

Natural growth and maturation have been demonstrated to influence movement competency, strength, and power performance in males. However, little is known with regards to how maturational status influences these athletic qualities follow short- and long-term training responsiveness. Most screening tools for assessing movement competency in youth are extensive and require analysis of multiple movements which tends to be impractical for strength and conditioning coaches. Analysis of a single multi-joint movement pattern such as the back-squat is likely a more impactful and practical method to assess movement competency in youth. Previous research on strength and power performance in youth often assess singular external measures such as one repetition max (1RM) or jump height. Little data exists regarding the strength and power kinetics in youth athletes and how they alter through growth and maturation. Reporting changes to force-time data from performance tests which assess a wide range of kinetic variables can help develop a greater understanding of maturation’s role in training. Therefore, the aim of this thesis was to investigate the interaction between natural growth and maturation with short- and long-term adaptations to movement competency and strength and power kinetics in youth male athletes.

Study 1 examined the effects of a 4-week neuromuscular training program on movement competency in pre- and post- peak height velocity (PHV) males using the back-squat assessment (BSA). Significant within-group improvements in movement competency were made by both the pre- (5.0 to 3.0, *ES* = 0.48) and post-PHV (2.0 to 1.0, *ES* = 0.58) cohorts. Additionally, intra-rater reliability was tested by rating BSA total score across three separate sessions. Intra-class correlations (ICC) revealed very strong agreement for BSA total score in pre- (ICC ≥ 0.81) and post-PHV (ICC ≥ 0.97) groups across all sessions, but systematic bias was evident in the pre-PHV group for sessions 1 to 2. *Study 2* examined the maturational differences between pre-, circa-, and post-PHV male athletes in movement competency, isometric strength, and dynamic jump power. Increased maturity led to significant, moderate to large increases in allometrically scaled peak force (PF_{allo}) in the isometric and dynamic tests but only a small increase in BSA total score. Trends from the kinetic force-time variables indicate the largest differences in strength and power likely occur around the adolescent growth spurt. *Study 3* investigated the training response of a 12-week neuromuscular training program on isometric and dynamic kinetic force-time variables in pre- and post-PHV males. There were significant increases in isometric peak force and peak rate of force development by the post-PHV group, while the pre-PHV group improved in the concentric force-time variables within the dynamic jump tests. Findings indicate that responsiveness to short-term training differs between males of different maturity groups for isometric strength and dynamic power tests. *Study 4* investigated how a twice- and once-weekly training frequency during a 6-month combined training intervention affects movement competency, strength, and power in male athletes. A twice-weekly training frequency resulted in superior gains to movement competency, isometric strength, and concentric jump performance over once-weekly training. The overall findings of this thesis highlight that training responsiveness to short- and long-term interventions varies across stages of maturation but significant improvements in movement competency and force-generating abilities for isometric strength and dynamic jump performance are modifiable at all developmental stages.

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Peer-reviewed journal articles:

1. **Dobbs IJ**, Oliver JL, Wong MA, Moore IS, Myer GD, Lloyd RS. Effects of a 4-Week Neuromuscular Training Program on Movement Competency During the Back-Squat Assessment in Pre- and Post- Peak Height Velocity Male Athletes. *Journal of Strength and Conditioning Research* 2019 (published ahead of print).
2. **Dobbs IJ**, Oliver JL, Wong MA, Moore IS, Lloyd RS. Effects of a 12-Week Training Program on Isometric and Dynamic Force-Time Characteristics in Pre- and Post-Peak Height Velocity Cricketers. *Journal of Strength and Conditioning Research* 34(3): 653-662, 2020.
3. **Dobbs IJ**, Oliver JL, Wong MA, Moore IS, Lloyd RS. Movement Competency and Measures of Isometric and Dynamic Strength and Power in Boys of Different Maturity Status. *Scandinavian Journal of Medicine and Science in Sports*. 2020 (in press)

Journal articles under-review:

1. **Dobbs IJ**, Oliver JL, Wong MA, Moore IS, Lloyd RS. The Effects of Training Frequency During A 6-Month Neuromuscular Training Intervention on Movement Competency, Strength, and Power Adaptations in Youth Males. *Medicine & Science in Sports and Exercise*. 2020 (under review)

Platform presentations:

1. The effects of a 12-week training program on strength in male youth cricketers. *National Strength and Conditioning Association (NSCA) Annual Conference, Washington, D.C. July 2019.*

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2. **Dobbs IJ**, Wong MA, Lloyd RS. The effects of a 12-week training program on isometric and dynamic performance tests in young male athletes. *Southwest American College of Sports Medicine,* Costa Mesa, CA. September 2019.
3. **Dobbs IJ**, Wong MA, Moore IS, Oliver JL, Lloyd RS. The influence of maturity status on force-time characteristics during the isometric mid-thigh pull in young male cricketers. *National Strength and Conditioning Association (NSCA) Annual Conference*, Washington D.C. July 2019.
4. Wong MA, **Dobbs IJ**, Moore IS, Oliver JL, Lloyd RS. The effects of drop jump movement competency following 4-weeks of neuromuscular training in pre-and post-peak height velocity male cricketers. *National Strength and Conditioning Association (NSCA) Annual Conference*, Washington D.C. July 2019.

5. **Dobbs IJ**, Wong MA, Moore IS, Oliver JL, Lloyd RS. Back squat assessment in pre- and post- peak height velocity male cricketers following 4-weeks of neuromuscular training. *National Strength and Conditioning Association (NSCA) Annual Conference*, Indianapolis, IN. July 2018.
6. Wong MA, **Dobbs IJ**, Moore IS, Oliver JL, Lloyd, RS. Changes in drop jump performance following 4-weeks of neuromuscular training in pre- and post- peak height velocity male cricketers. *National Strength and Conditioning Association (NSCA) Annual Conference*, Indianapolis, IN. July 2018.

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CHAPTER 1 - INTRODUCTION

1.1 OVERVIEW

The development of movement competency, strength, and power has been advocated by numerous long-term athletic development models for young athletes competing in sport (176, 177). Growth and maturation drive the underpinning mechanisms which naturally develop these athletic qualities throughout childhood and adolescence. However, movement competency, strength, and power can also be modified through targeted training programmes in youth of all stages of maturity. Despite the trainability of these athletic qualities in youth populations, the development of movement competency, strength, and power in children and adolescents following short- and long-term training interventions is unclear. Establishing a better understanding of the interaction between natural growth, maturation and training-induced adaptations in performance could lead to more targeted and individualized training programmes for young male athletes. Thus, the current thesis will investigate how the development of these athletic qualities are influenced over short and long-term training interventions using reliable and validated test measures.

1.1.1 Assessing movement competency, strength and power in young males

Assessing movement competency can identify functional deficits and technical flaws in fundamental movement patterns (230). The current paediatric literature has used functional movement tests that are relatively easy to use and assess competency across a broad range of movements, in children and adolescents (49, 50, 265). However, strength and conditioning practitioners working with large groups of young athletes may find current movement screens that assess multiple movement patterns to be impractical. Therefore, simplified movement screens have been proposed within the paediatric literature as a more time-efficient and less-labour intensive method for coaches to assess movement competency in youth (163, 164). Recently, the back-squat assessment (BSA) was developed as a screening tool for movement competency using real-time assessment in addition to two-dimensional video analysis (230). While the BSA may be more practical to use, the reliability of this screening tool has not been tested in young athletes of different stages of maturity.

1.1.2 The influence of maturity status on measures of movement competency, strength and power in young males

Children and adolescents are capable of making significant improvements in movement competency, muscle strength, and muscle power following training that can exceed changes resulting solely from growth and maturation (12, 13, 87). However, the majority of training interventions have typically only reported the chronological age of their participants, without providing any data for biological maturity. Of the available data comparing youth of different maturity status, it appears that the training responsiveness of children and adolescents is somewhat sensitive to the mode of training (180, 188, 210, 245). Seemingly, the most worthwhile changes in movement competency appear to occur when children are introduced to neuromuscular training prior to puberty (188, 228, 249). While greater changes in absolute measures of strength and power are expected during adolescence due to the heightened anabolic internal environment associated with adolescence, children can still make worthwhile adaptations in strength and power, albeit with a greater reliance on neural adaptations as opposed to the structural adaptions expected as a result of the adolescent growth spurt (11, 39, 214). The literature has reported that natural growth and maturation typically enhances strength and power increases in adolescents following resistance training, a recent review reported that children and adolescents make similar gains in strength relative to body weight (242). This notion warrants investigation into comparing how youth athletes of different maturity stages respond to similar modes of training. Similarly, changes to movement competency, strength, and power in youth of different maturity status would provide novel information to the literature into how maturation influences training-induced adaptations to these athletic qualities.

1.1.3 The short- and long-term effects of neuromuscular training on movement competency, strength and power in young males

While short-term training facilitates different magnitudes and rates of change in children and adolescents, further research is warranted since comparative training studies often do not directly report maturity status. Literature has shown that the mean duration of neuromuscular training interventions within the paediatric literature is ~10 weeks (134, 172, 242). However, a limited number of studies have examined the responsiveness of different maturity groups to training to strength, power, and movement competency parameters. A plethora of research has reported that youth of all stages of maturity can experience positive adaptations to movement competency, strength, and power following short-term (< 23 weeks) resistance and plyometric training (12, 13, 219, 221, 242). However, responsiveness to training is reportedly sensitive to maturity status with circa- and post-PHV males experiencing greater and quicker strength adaptations than pre-PHV males (219). Alternatively, short-term resistance training in children appears to effectively improve motor performance to a greater degree in children than adolescents which highlights the sensitivity for neural adaptations (12, 242).

Training parameters such as sets, repetitions, and periodisation of training within long-term interventions in youth are not consistently reported which makes it difficult to determine which training variables influenced gains in muscular strength and power. Additionally, due to the duration of long-term interventions it is difficult to differentiate between training-induced adaptations or changes as a result of growth and maturation alone or whether it is an interaction between both. Additionally, there is a lack of literature surrounding the influence of weekly training frequency in youth athletes. Previous literature investigating the role of training frequency in youth has primarily used short term training interventions and has not compared the effects in more than one maturational group (69, 91). Therefore, there is a gap in the literature for long-term training studies which accounts for natural growth and maturation by reporting biological maturity status as well as investigating the effects of weekly training frequency in different maturational groups.

Measuring maximal strength and power is of interest to practitioners due to its relationship with athletic performance within youth populations (19, 155, 257, 316). However, there is a paucity of research that has examined the kinetic variables that underpin strength and power performance in children and adolescents. The majority of studies examining strength and power in youth populations have relied solely on performance outcome measures (e.g. jump height) that fail to provide insight into the amount and sequencing of force production (16, 64, 112, 193). Ideally, the assessment of strength and power should comprise a battery of tests that use force plate technology to better understand the kinetic profiles of young athletes. Acceptable reliability in the isometric mid-thigh pull (IMTP), squat jump (SJ), and counter movement jump (CMJ) have been previously reported in the current literature (181-183, 216). There is currently no study which provides force-time data on maximal force and rate of force producing capabilities in a large cohort of male athletes of varying stages of maturity. Such data could potentially identify the most sensitive periods of time when youth experience natural changes in strength and power. In addition to the limited kinetic data available, it appears that paediatric research has yet to examine the changes to the force-time variables that underpin strength and power, which could be used to better target and individualise training interventions. Obtaining force-time data during strength and power tests will also identify how maturity-induced changes in performance (e.g. jump height) are driven by specific alterations in kinetic variables during various phases of a given movement.

1.2 AIMS AND OBJECTIVES

Aims:

1. Understand the effects of age and maturity status on movement competency, strength and power in young male athletes.
2. Examine the interaction of growth, maturation and training on the development of movement competency, strength and power in youth following exposure to neuromuscular training interventions.

Objectives:

1. Determine the intra-rater reliability of the Back-Squat Assessment (BSA) movement competency screen using 2D video analysis.
2. Determine the effects of a 4-week neuromuscular training intervention on movement competency in young males of different maturity status.
3. Examine the effects of age and maturation on measures of movement competency, strength and power in a large cross-sectional sample of young male athletes of different maturity status.
4. Evaluate the effects of a 12-week neuromuscular training intervention on measures of movement competency, strength and power in young males of different maturity status.
5. Determine the chronic effects of a 6-month intervention and a twice- *versus* once-weekly training prescription on measures of movement competency, strength and power in a cohort of young males.

1.3 ORIGINALITY, SIGNIFICANCE, AND RIGOUR

1.3.1 Originality

Originality relates to the extent to which research introduces a new way of thinking and provides a distinctive and transformative development to previous literature. Existing research examining the development of movement competency, strength, and power in child and adolescent populations has largely relied upon grouping participants according to age, without reporting maturity status. Thus, the interaction between growth, maturation and training remains unclear. The current thesis displays three training interventions of short, moderate, and long-term durations which examine the effects of training on more than one maturity group. Additionally, there is an over-reliance in the paediatric training literature on outcome measures being performance-oriented (e.g. jump height, maximal load lifted), with very few studies reporting the underlying kinetic variables that underpin strength and power performance in multiple tests across the force-velocity curve. This body of work enhances the understanding of the role maturation and training play in the development of movement competency, strength and power in both young athletes. Thus, the combined works are deemed novel and original, owing to the fact they provide a more in-depth analysis of underpinning adaptations in strength and power in response to training interventions of different durations, in male youth of varying maturity status. Additionally, it should be noted that the interventions presented in this thesis were conducted as part of a National Governing Body’s long-term athletic development pathway and throughout the interventions, collected data were used to inform training prescription for each individual. Therefore, the findings from this series of applied studies represent “real-world” practice.

1.3.2 Significance

Significance relates to the extent that research has exerted on an academic field or applied practice. Several empirical studies from this thesis have been published or are in review in peer-reviewed research journals, highlighting the quality of the research. Specifically, *study 1* determined that movement competency can be significantly improved in pre- and post-PHV males following 4-weeks of neuromuscular training and has reported acceptable intra-rater reliability for the BSA. *Study 2* provided a cross-sectional analysis of how advanced growth and maturation increases movement competency, strength, and power in a sample of 206 male youth athletes. This study provided novel force-time data in a range of strength and power tests in youth athletes, and these data could be used for the purposes of benchmarking. Findings from *study 3* reported the maturational differences in response to a 12-week neuromuscular training intervention between pre- and post-PHV athletes. The data showed that post-PHV males made significantly larger gains in absolute isometric strength while the pre-PHV cohort improved in concentric jump qualities in the SJ and CMJ compared to the post-PHV cohort. This is significant data for the paediatric literature that can be used to help frame future research questions related to changes in strength and power in youth populations. *Study 4* incorporated the effects of a twice- *versus* once-weekly training frequency over a 6-month training period; highlighting that twice-weekly training results in superior gains in movement competency, isometric strength and jump performance compared to once-weekly training. These findings can assist strength and conditioning practitioners with training prescription and potentially influence talent development pathways in order to optimize training adaptations in youth populations. Collectively, the outcomes of these studies provide novel data to the fields of paediatric exercise science and strength and conditioning and cumulatively have the potential to make a significant impact on applied practice.

1.3.3 Rigor

Rigor refers to the clear articulation of the purpose of the research, the appropriateness of the research design, intricacy of selected methodologies, and the strength of evidence presented. The current thesis presents a series of logical and interrelated studies that contain logical research questions that address the objectives and aims listed in *section 1.2*. The notable strengths for the respective research designs include 2D video analysis to enable the retrospective establishment of intra-rater reliability for the BSA, application of prediction error rates in maturity status offset equations, advanced analysis of robust and validated strength and power testing of force-time variables for each tests and appropriate statistical analyses that enable correct interpretation of the data in all the empirical studies. It should also be noted that the rigorous scientific protocols used within the thesis were implemented within the boundaries of a "real-world" long-term athletic development pathway.

1.4 THESIS ORGANISATION

The focus of the thesis is to investigate how the development of movement competency, strength, and power interacts with natural growth and maturation. *Figure 1.1* provides a schematic visual of the thesis organization.

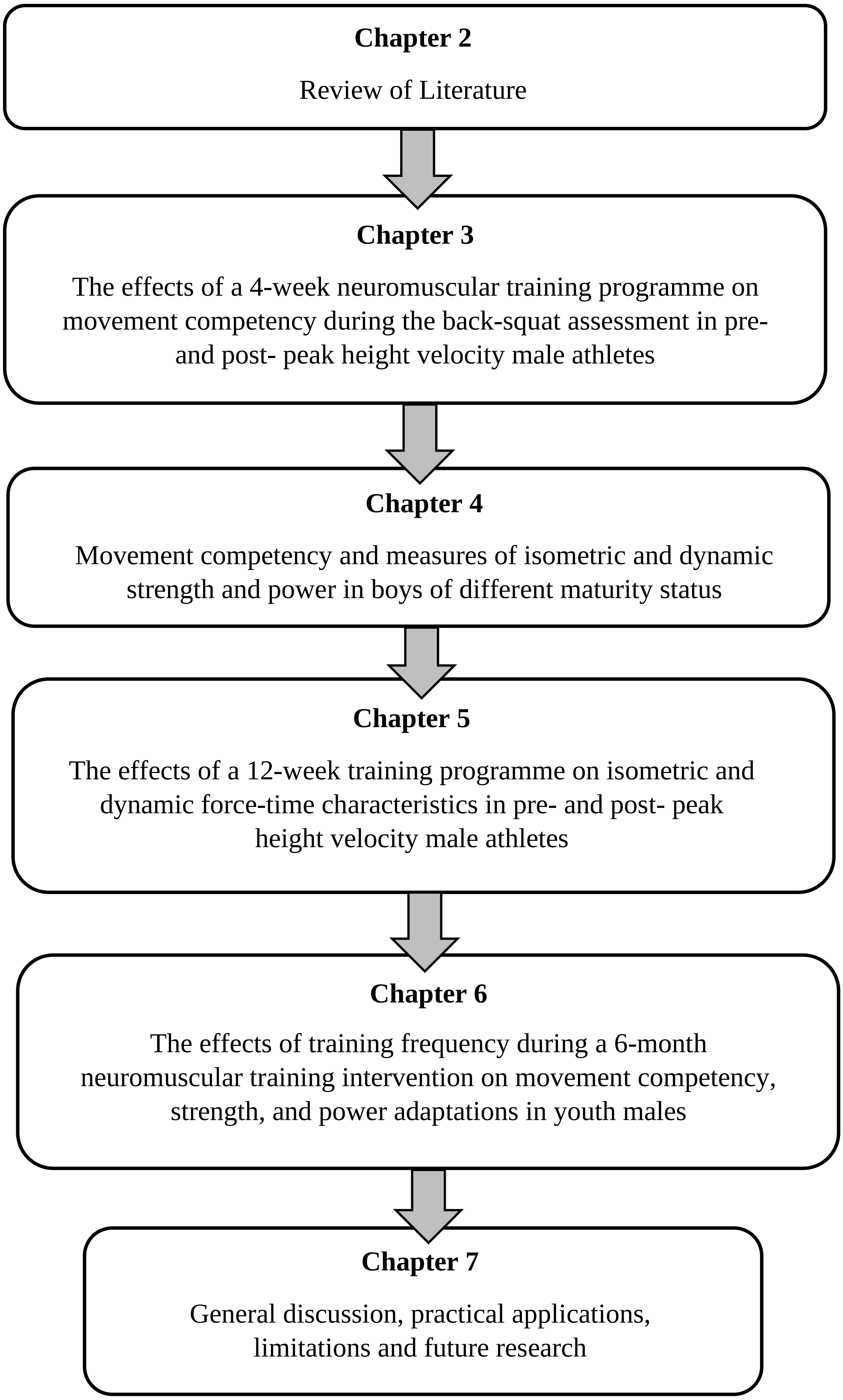

Figure 1.1 Schematic of the organisation of the thesis

Chapter 2 provides a review and critical analysis of the current paediatric literature surrounding a range of topics related to the thesis, including: natural growth and maturation of the neuromuscular system, the relationships between maturation, movement competency, and strength and power, and the effects of short- and long-term neuromuscular training on various athletic qualities. **Chapter 3** established the intra-rater reliability of the back-squat assessment tool, which would be used in the remaining studies of the thesis. In addition, the study examined the effects of a short-term, 4-week neuromuscular training intervention on back squat movement competency in pre- and post-PHV male athletes. **Chapter 4** employed a cross-sectional analysis to investigate the differences between movement competency and force-time characteristics during isometric strength and dynamic jump testing in a large sample of pre-, circa-, and post-PHV males. **Chapter 5** investigated the effects of a 12-week neuromuscular training programme induces adaptations to force-time variables in the IMTP, SJ, and CMJ in pre-, and post-PHV males. This study examined how maturation influences the magnitude of changes within different kinetic variables during the IMTP, SJ, and CMJ. **Chapter 6** employed a 6-month training intervention to determine the effectiveness of twice-*versus* once-weekly training frequency in young athletes. This study analysed how employing a twice-weekly training frequency can significantly influence adaptations over once-weekly training for force-time variables in the IMTP, SJ, and CMJ with maturity status included as a covariate in the statistical analysis to account for the effects of maturity on training response. **Chapter 7** provides an overall discussion of the thesis, revisiting the aims of the thesis in the context of the conducted empirical work. Furthermore, the chapter also provides an overview of areas for future research.

2.1 GROWTH AND MATURATION

2.1.1 Defining growth and maturation

For the purposes of the thesis, *growth* is defined as an increase in body size while *maturation* refers to the progression towards the adult state (21, 194). Changes often appear at the structural level which brings about changes in skeletal, contractile and connective tissue and the appearance of secondary sex characteristics (194). *Development* refers to a period of change in which differentiation of tissues occurs. There is inter-individual variation between the timing, tempo and magnitude maturation in all tissues, organs, and systems in youth (198). *Timing* is defined as the onset of specific maturation events, *tempo* refers to the rate of progression throughout the maturation process, while *magnitude* refers to the size or extent of maturational. Development is broader than growth and maturation and can refer to both biological and behavioural changes (187). *Chronological age* is the age measured at a single time point from the date of birth. While chronological age is easily assessed, there is no consideration for the timing and tempo for which individuals mature, grow, and develop. Children of the same chronological age are likely to vary considerably in biological maturity, with some individuals maturing earlier or later than their peers. Maturational assessment can be used to classify individuals as ahead of (early maturer), on time with (average maturer), or behind (late maturer) their chronological age group (194). More mature individuals are likely taller and heavier on average than their peers, affording them an advantage during training and competition; however, with time, these maturity-associated discrepancies in physical performance between early and later maturers often diminishes as youth reach a fully mature state.

2.1.1.1 Sex differences

The occurrence and process of sexual and somatic maturation differs between sexes during childhood and adolescence. During pre-puberty there are few differences between sexes, however, increases in circulating hormones at the onset of puberty initiates biological changes between the two sexes (194, 280). Generally, females mature earlier than males, with puberty occurring around the age of 12 in girls and 14 in boys (20, 194). Females experience the development of breasts, pubic hair, and the onset of menarche, while the development of the penis, tests, and pubic hair is observed in males (21). Similarly, differences in body composition accompany both females and males during this stage of development. During maturation, boys will experience significant increases in fat-free mass (FFM), arm and shoulder girth, along with decreases in fat mass (FM). Meanwhile, girls experience natural increases in body fat percentage and hip breadth in comparison to boys in preparation for childbearing in adulthood. On average the adolescent growth spurt increases stature at a rate of 8 cm/year in females and 10 cm/year in males (187). While the growth spurt typically occurs later in boys, it is generally longer than a female growth spurt and reaches a greater peak, which results in a taller eventual average height in males compared to females. About 50% of adult body weight is gained during adolescence and this rapid increase in body mass also accompanies puberty with an average increase of 9 kg/year in males and 8.3 kg/year in females (266, 293, 295). This period is referred to as peak weight velocity (PWV) and has been reported to occur between 6-12 months after the adolescent growth spurt in both males and females (17, 187, 194, 266). *Figure 2.1* shows the rates of growth for body mass and stature typically seen in males and females. While the effects of puberty differs between sexes with respect to the timing, tempo, and magnitude of changes of anthropometric measures, these rapid changes in body mass and stature are typically aligned with strength and power gains (118, 143, 173, 257).

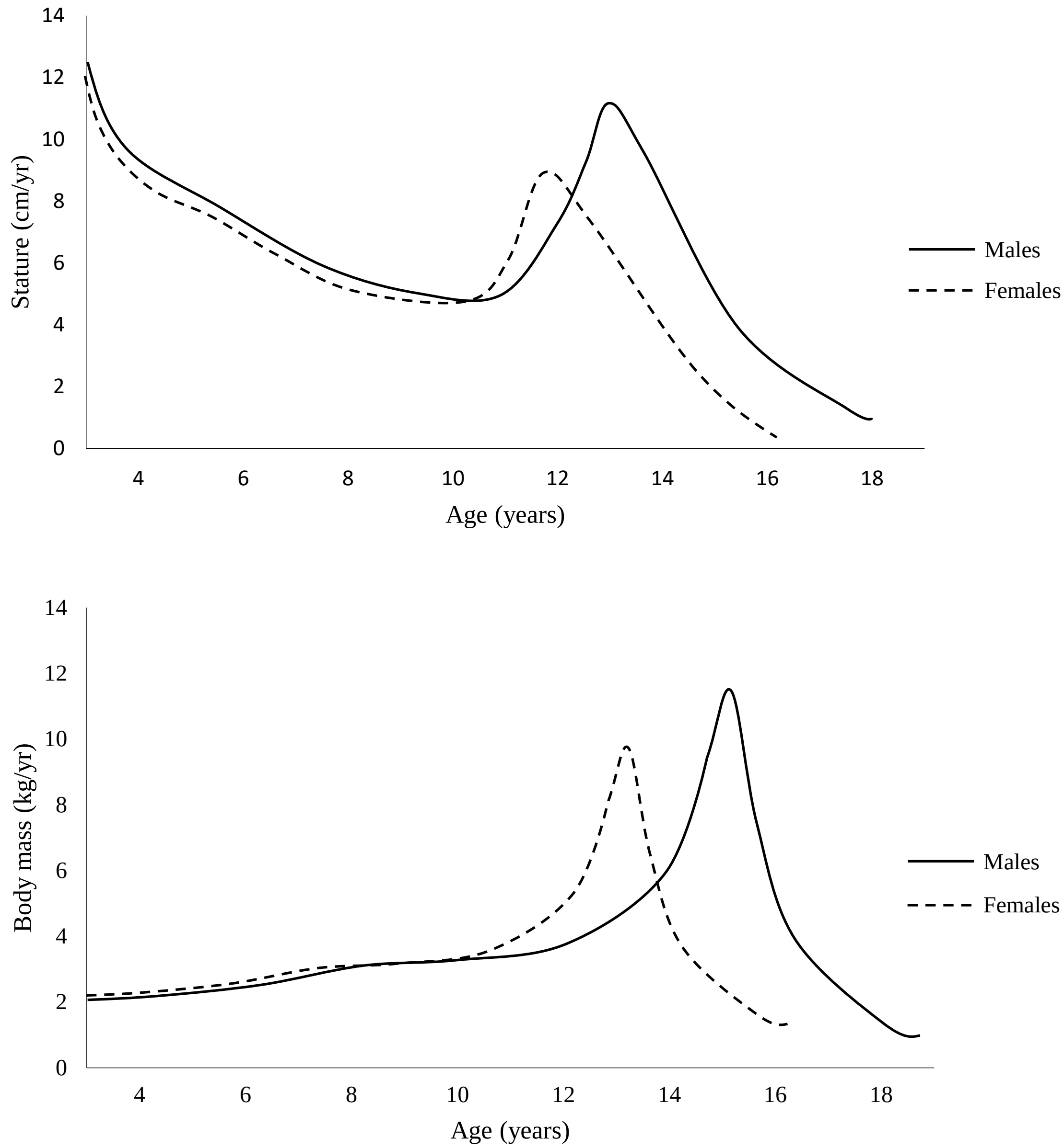

Figure 2.1 Growth rates for stature and body mass for the typical male and female. Adapted from Tanner et al. (293, 294, 296).

2.1.2 Methods of assessment

It is critical to understand biological maturation in youth in order to distinguish whether maturation or exposure to regular training is responsible for changes in physical performance. Full maturation results in a fully ossified skeletal system, fully functioning reproductive organs, and attaining final adult height (194, 200). Several methods for assessing maturation exist, all of which yield different results based on different interpretations of the biological systems. The most common indicators of maturation which are typically assessed are the *skeletal, sexual, and somatic* biological systems. Despite the measurement of these biological systems varying considerably, the correlations between these indicators are typically moderate to high, and are therefore considered to be valid estimations of biological maturity (295).

2.1.2.1 Skeletal maturity

Skeletal age is generally recognized as the best indicator of maturity status (1). All children begin with a skeleton of cartilage before progressing to fully ossified bones within the adult axial skeleton (1, 150). In tubular bones, fusion between epiphyses and the corresponding diaphysis marks full maturity; as a result, assessment of skeletal maturity is measured through skeletal age, requiring radiographs depicting initial ossification of bones within the hand and wrist (195). The *Greulich-Pyle, Tanner-Whitehouse, and Fels methods* are the most commonly used methods for assessing skeletal maturation (195). In the *Greulich-Pyle method*, skeletal maturity of an individual is determined through comparing hand-wrist radiographs with that of standardized plates within a chronological age-group (195, 200). The *Greulich-Pyle* method is based on the premise that bone tissue matures uniformly throughout the body (195, 199, 200). Therefore, this method does not account for individual rates of development in other bones which limits accurate determination of skeletal age (180). The

Tanner-Whitehouse methods assess the stages from initial ossification within twenty bones from the hand and wrist through a points system. However, the most recent version of the Tanner-Whitehouse method is the *Tanner-Whitehouse III* which only assesses scores within the RUS (radius, ulna, short bones) and CARP (seven carpal bones) scales. The original *Tanner-Whitehouse method* was based on a sample of 3,000 healthy British children, whereas, the *Tanner-Whitehouse III* (TW3) method includes reference values from British, Belgian, Italian, Spanish, Argentinean, American, and Japanese children (21). A drawback to the TW3 method is the complexity and time-consuming process for analysing radiographs. Additionally, the requirement for individuals trained to analyse radiographs along with accessibility to equipment makes the TW3 method impractical in youth training studies. Finally, the *Fels method* identifies 85 grade maturity indicators within bones of the hand and wrist as well as 13 measured ratios of diaphyseal and epiphyseal diameters (261).

The overall drawbacks for assessing skeletal maturity in all three methods are over/underestimating maturity status, cost, availability, time, specialist equipment, trained assessors, as well as deliberate exposure to radiation during testing. An issue with the *Greulich-Pyle* method is that this method is susceptible to over- or under-estimating maturation based on unequal bone growth throughout the body (194). Similarly, the *Greulich-Pyle* method compares radiographs to individuals of the same chronological age, however, skeletal maturation and chronological age have been reported to vary (195). A benefit of the *Tanner-Whitehouse* method is that this method contains a large sample size of children and therefore is likely to provide a statistically reliable and valid measure of skeletal maturity. However, one drawback to the TW3 method is the complexity and time-consuming process for analysing radiographs. Additionally, the requirement for individuals trained to analyse radiographs along with accessibility to equipment makes the TW3 method impractical in youth training studies. One benefit of the *Fels method* is that it uses specific software that provides skeletal age along with a calculated standard error of estimate. However, the *Fels method* is also complex and time consuming which limits the benefit of consistent long-term tracking of biological maturation in children adolescents. Collectively, the three methods for assessing skeletal age are considered the gold standard for determining biological maturity in youth despite the number of issues required for testing. Therefore, more practical and non-invasive assessments are typically used when assessing maturity status in youth.

Overall, the main advantage being that measuring skeletal maturity reflects the maturation of an important biological system by providing an estimated skeletal age (years) that can be compared with chronological age to determine if an individual is early, on-time, or late maturing (21). In addition, radiography gives precise and reasonably reliable measurements of the hand and wrist (196). However, limitations for measuring skeletal maturity include cost, access to a licensed radiographer, and exposure to low-level radiation. Skeletal age is often not accessible for most practitioners and researchers, thereby limiting its use in short- and long-term training studies in youth.

2.1.2.2 Sexual maturity

Sexual maturation refers to the process of the reproductive system reaching full maturity (21). Maturation of the reproductive system begins as an embryo and develops into early adulthood. Puberty is an important transitional period in sexual maturity because it brings about accelerated growth and the development of secondary sex characteristics. Measuring sexual age in males is typically based on assessment of the genitals and pubic hair. Perhaps the most commonly used method for measuring sexual maturation has been outlined by

Tanner et al. (293), which assess the development of secondary sex characteristics based on a 5 stage scale. Ratings for these stages requires individual inspection during clinical examination from a paediatrician. However, certain limitations exist with Tanner criteria for the assessment of sexual maturation: *firstly*, this method does not differentiate children and adolescents within stages, and therefore a child entering one stage would be classified in the same stage as a child nearing the end of that stage in development; *secondly*, there is no insight given with regards to the tempo of maturation and therefore it is more difficult to compare children within the same chronological age; *finally*, the Tanner stage criteria is limited only to adolescents and cannot be used within pre-pubertal children or young adults.

Another clinically used method for measuring sexual maturity in boys is testicular volume (247, 318). However, this method also requires experienced medical physicians to observe the genitals or self-assessment from a child to compare their sexual characteristics to those of reference drawings or photographs. Typically, during self-assessment boys tend to overestimate their sexual development stage, while girls generally underestimate (171). Assessing maturity through secondary sex characteristics reflects an accurate estimation of the developing reproductive system and hormonal profile (21, 194). However, measuring secondary sex characteristics is limited to the onset of puberty; making assessments of pre-pubertal children less feasible. The inability to provide insight into the timing and tempo of maturation makes this method less reliable for long-term tracking in children and adolescents. Additionally, the methods for assessing sexual maturity require access to a clinical setting. Therefore, only trained and experienced physicians are qualified to assess sexual maturation due to the sensitive and invasive nature of these methods. Similar to limitations with measuring skeletal age, assessing sexual maturity status is an invasive approach and needs to be performed by appropriately qualified clinicians. Thus, sexual age is likely impractical to be used as a means to inform exercise prescription in youth.

2.1.2.3 Somatic maturity

Somatic age estimates maturity status by measuring the degree of growth in overall stature and other specific dimensions of the body (180). The accurate assessment of somatic maturity requires consistent longitudinal recordings of chronological age, stature, and body mass from late childhood through adolescence (21). Longitudinal data displays non-linear increases in somatic measurements, with periods of rapid and plateaued rates of growth (287). Stature is often assessed and used to predict the beginning of the adolescent growth spurt and the period of maximal growth in height, termed peak height velocity (PHV). Genetic and environmental factors appear to affect the timing and tempo of the maturational process in males (21). Adequate nutrition provides the largest variation in maturation, with chronic malnutrition reportedly resulting in later stages of PHV and delayed skeletal maturity (21). However, assessment of somatic maturity can be used to identify periods of accelerated growth, peak-height velocity, and to predict full adult stature. Additionally, measuring somatic age is less invasive than assessing skeletal and sexual maturity, which makes it a more viable method of assessing maturity status for practitioners.

2.1.2.3.1 Growth Rates

The process of human growth results from the endocrine system stimulating skeletal maturation (177, 180). Longitudinal growth rates are measured by repeated assessments of breadths, widths, and lengths of specific body landmarks in the body. Measuring standing height over a period of time is the most practical option for assessing growth and allows practitioners to analyse growth curves and rate of change over time. Lloyd et al. (180) has suggested that measurements every three months allows for a consistent time in which to monitor basic somatic measurements and detect meaningful changes in height. The most rapid period of growth reflects age at peak-height velocity (PHV) and is believed to occur during the adolescent growth spurt (287). In males, it has been reported that initiation of the adolescent growth spurt begins around 10.3 – 12.1 years of age (21) and PHV typically occurs during 14 years of age (177, 180). Growth rates are highly individualized and are affected by the interaction of factors such as ethnicity, nutrition, and environment. Additionally, the initiation of sexual maturation and changes in endocrine function promote the marked increases in body mass as well as stature. Peak weight velocity (PWV) represents the greatest rate of change in body mass and typically occurs 12-14 months after PHV (64) in males. However, PWV is not typically used to measure rate of growth because body mass is more susceptible to influence from environmental factors and training, whereas PHV is genetically pre-determined.

2.1.2.3.2 Predicting age at PHV

Predictive equations for estimating years from PHV at a single period of time have been proposed as an alternate method to collecting longitudinal data in children and adolescents (215, 218). With acknowledgement to the different growth rates existing between the long bones in the legs and short bones within the trunk during maturation, Mirwald and colleagues (215) developed sex-specific regression equations (equation 1) to estimate an individual’s age (in years) from PHV, using chronological age, body mass, standing height, and seated height. The predictive equations provide a maturity offset value which can be summed alongside chronological age to predict age at PHV (215). The benefit of the repeated collection of anthropometric measurements over a long period of time would enable analysis of growth curves and provide information on the timing and tempo of an individual’s maturity status relative to the predicted onset of puberty (215, 281). Therefore, using the predictive equations by Mirwald et al. (215) to measure biological maturity in youth is beneficial for both practitioners and researchers due to the practicality of longitudinal assessments, non-invasiveness of measurements, and ability to distinguish children and adolescents at different stages of maturity.

Moore et al. (218) proposed an updated prediction model (equation 2) for predicting years from PHV without measuring sitting height. While this approach allows practitioners for a less complex calculation and a more time-efficient alternative for assessing maturity offset, it does not show improved accuracy. However, the validity of these prediction models have been questioned previously using samples from longitudinal studies (108, 160, 197, 199). Specifically, both equations were reported to be more applicable in average maturing boys than early or late maturing boys (197, 199). Both predictive models also appear to be influenced by chronological age and actual maturity status, with predictive age at PHV increasing linearly when measuring children during an older or more mature state (197). Due to the standard error of estimates for the predictive equation of both Moore (218) (± 0.542) and Mirwald (215) (SEE = ± 0.592 years) (215), caution is warranted when interpreting data (180); especially as the accuracy of the prediction models reduces the further away an individual is from PHV. However, by applying the error in these equations, between maturity-group comparisons can be made with more confidence. Specifically, by withdrawing individuals that have predicted maturity offsets within ± 0.5 years of the next PHV grouping threshold ensures that individuals are not erroneously placed in the wrong maturity group when assessing maturational status (72, 250). Additionally, it was noted that estimation of PHV becomes less accurate ± 2 years from PHV (180, 215) with the prediction equations proving most accurate at identifying youths who are at the point of PHV.

Equation 1. Mirwald et al. 2002 model

Maturity offset = - [9.236 + 0.0002708* Leg Length and Sitting Height interaction] – [0.001663*Age and Leg Length interaction] + [0.007216*Age and Sitting Height interaction] + [0.02292*Wight by Height ratio]

Equation 2. Moore et al. 2002 model

Maturity offset = -7.999994 + [0.0036124 x (age x height)]

Certain limitations exist for predicting PHV as a measure of biological maturity. Notably, PHV can only be identified retrospectively after a peak has already been identified, thus, it would be difficult to ascertain when a child is beginning the adolescent growth spurt.

2.1.2.3.3 Predicting adult stature

The prediction of adult stature is an alternative method of assessing somatic maturity by estimating the percentage of adult height attained by a youth athlete. Percentage of full maturational height at a given age is positively related to skeletal maturity during childhood (194, 195) and to sexual, skeletal and somatic maturity during adolescence (20, 261). Predictive models often require anthropometric measurements from the individual child in addition to both the mother and father's height in order to estimate final adult stature. Koo et al. (156) provides the most basic method for predicting final adult height by calculating mid-parental height and adding or subtracting 6.5 cm for boys and girls, respectively, based on the average difference in height between sexes (156). Khamis and Roche (150) developed a regression equation that includes child stature and weight to predict adult height. Within this method, the measurement error appears to be greater when individuals are within the 90th

percentile range (5.5 cm to 7.3 cm) than in the normal 50^{th} percentile (2.4 to 2.8 cm). Similarly, the Khamis and Roche method is only applicable for predicting adult height in Caucasian American children. The Beunen et al. (20) model uses chronological age, standing height, sitting height, in addition to skinfold measurements in the subscapular and triceps. However, this method was shown to have non-significant or low levels of correlation for estimating height while using chronological age and skeletal age. Similarly, the sample contained a large sample of girls aged 6-16 and therefore is likely not applicable within a male cohort. Cole and Wright developed a chart that predicts adult height (45) by comparing a child's current height and adjusts for regression of the mean. A benefit of the Cole and Wright chart is that it is designed to be easily read by parents and children. However, the authors cautioned using the chart as a clinical tool since it cannot account for possible abnormal growth and can overestimate the age-prediction during periods of rapid height velocity. Finally, Sherar et al. (281) used previously published retrospective data to create a regression equation for estimating height left to grow. Height left to grow was calculated using years from PHV in addition to maturity-specific velocity curves. Consequently, height left to grow can then be added to current height of the child to predict eventual adult height (280, 281). 95% confidence intervals revealed a measurement error of ± 5.35 cm in males and ± 6.81 cm in females for the Sherar method (281).

Limitations exist within each method as predicting adult stature does not provide any information with regards to the timing and tempo of maturation. Combined, the models for predicting adult stature typically possess standard errors of 3-6 cm but becomes more accurate with increasing chronological age. Additionally, measurement variability and overestimations of parental heights also appear to influence predictions within each method (25). While predicting adult height is not an indicator of growth velocity, it can be used to indicate whether a youngster is progressing through the adolescent growth spurt since PHV occurs around 88-92% of adult stature (45, 281). Similarly, equations for predicting adult height has been used as a maturational strategy for bio-banding to group athletes into maturational categories (58).

2.2 NATURAL DEVELOPMENT OF MOVEMENT COMPETENCY, STRENGTH & POWER

2.2.1 Natural development of movement competency

Currently, there is inconsistency regarding the terminology for assessing movement competency in youth, with previous studies using terms such as "movement proficiency" (190, 217), "motor skills" (28, 248), "motor competence" (167, 168, 230), and "motor performance" (12). While differences between the aforementioned terms may seem subtle, inconsistency in the literature inherently leads to confusion and less clarity for practitioners who aim to assess the quality of movement of their youth athletes. Therefore, in an effort to strengthen the understanding of movement and tests of competency in youth athletes, the term 'movement competency' will be used throughout this thesis and is defined as "the quality of performing a goal-directed movement pattern" (190).

Greater movement competency in youth is related to increased physical activity, participation in sport, and athletic success (140, 170). Natural development of movement competency is individualized and is affected by a myriad of environmental, genetic, physical and maturational factors (28, 86, 228). It is important to note that movement competency does not occur in children solely as a result of natural development, but rather it is an ongoing process that is learned through appropriate coaching and opportunities for movement (140). Seefeldt et al. (279) argued that individuals may encounter "proficiency barriers" when trying to learn motor skills if fundamental motor patterns were not acquired during pre-adolescence. Therefore, introducing and promoting the mastery of fundamental motor skills in children appears to be a pivotal period for acquiring greater movement competency (131). During childhood, the brain has high ‘plasticity’ as neurons undergo maturation and synaptic pruning takes place (114, 227). The brain’s neuroplastic mechanisms have been suggested to underpin the acquisition and retention of motor skill learning (60). Following puberty, further maturation of the corticomotor cortex results in myelination of motor neurons and synaptic pruning (189, 227, 283, 310) which affects the ability to modify motor competence (228). It has been previously demonstrated that training induced adaptations during learning of a new task are diminished with advancing age (264). However, it should be noted that motor competency can still be improved during the entire lifespan, but is best retained if introduced during pre-adolescence (84).

Developmental progress in movement competency during early childhood appears to be largely reflected by neuromuscular maturation (143). Recently, a study investigating the contribution of biological maturity to variance in motor competency in children ages 3-6 revealed that skeletal maturation only accounted for a relatively small (6.1%) percentage of variance (109). The relationship between skeletal age and motor performance was reported to be generally similar in boys ages 7-10 and 11-14 (110, 111). A similar study by Katzmarzyk et al. (143) found that skeletal age explained 7-14% of the variance in motor competency for boys aged 7-12. Despite the explained variance being relatively low, it was suggested that skeletal age alone has a negligible influence on motor competency in young children. During puberty, a greater hormonal profile and maturation of the neuromuscular system improves the neural contributions to muscular contraction patterns in the lower body (161, 174). While it has been suggested that these maturational changes lead to improved motor competency, a recent study by Pichardo et al. (245) indicates that relative strength has more influence on motor competency than maturity.

2.2.2 Natural development of strength and power

Muscular strength refers to the maximum force producing ability by a muscle or muscle group (155). Maximum muscular strength underpins most athletic skills seen in sports such as jumping and sprinting (289). A meta-analysis by Moran et al. concluded that strength in boys is sensitive to maturity status (219), with advanced maturation of children and adolescents leading to physiological changes that enhance force expression for strength and power activities (13, 105, 119, 187, 219, 222). The natural development of strength has been reported to increase linearly from childhood until the adolescent growth spurt which causes rapid physical development within the body. However, increases in strength are mainly due to maturation (222) which underpins physical growth and previous longitudinal studies (17, 18, 34) have reported that strength still increases when stature and mass are factored out. Findings from the Saskatchewan Child Growth and Development Study (34) reported that strength significantly increases incrementally from the ages 10-16 in boys, with the greatest increases observed around 1 year after PHV. Additionally, the Leuven Growth Study (18) also reported that after the adolescent growth spurt there appears to be a marked acceleration in strength throughout the teenage period until adulthood (17, 18). With regards to maturation, both longitudinal studies reported that physical strength tends to be greater for early maturers than late maturers during adolescence, respectively (18, 34).

Growth-related strength increases in children are reported to be small (88), and are largely due to neuromuscular adaptations (13). As such, strength increases are relatively limited in children prior to PHV because pre-adolescents are not conducive to increasing muscular hypertrophy. Anabolic hormone concentrations are low in children prior to puberty, inhibiting the potential for structural changes to muscle architecture (187). Following puberty there are substantial increases in the endocrine hormonal profile which are reflected through increases in a wide range of physical characteristics such as muscle size and body mass. Morphological adaptations from puberty include increases in body mass, muscle fibre size, angle of muscle pennation, and tendon stiffness (219, 250). As such, these physical growth and maturational changes facilitate an increased ability for force production and measures of muscle strength (302). Neural adaptations also accompany maturation as adolescents are capable of greater motor unit recruitment and firing frequencies than children (10, 12, 13, 308). Greater recruitment of higher-threshold motor units increases absolute force production as well as the rate of force production (RFD) which is parament to power (79, 80). Additionally, there is evidence for an ‘age effect’, which suggests that adolescent are simply stronger than younger counterparts despite being of similar size (312), with the ‘age-effect’ related to the neural adaptations gained during maturation.

Lower body power has often been used to differentiate between young athletes within talent identification and sporting selection programmes (66, 68). Muscular power refers to the combination of force and velocity, which is displayed during ‘explosive’ movements such as plyometrics and sprinting (119, 128, 135). However, maximal power output is influenced by a variety of neuromuscular factors such as muscle fibre composition, cross-sectional area, pennation angle, and motor unit recruitment (55). Power output appears to increase with advanced maturity and has been reported to be a key determinant in jumping, sprinting, and sport performance between children and adolescents (119, 220, 221). These movements are performed with the utilization of the stretch-shortening cycle (SSC), which is a muscle action that generates force through eccentric lengthening and a subsequent concentric shortening to increase lower body power (251). Considering that the SSC is a key determinant of power, paediatric literature often measures lower body power through various jumping tests that utilize both slow and fast SSC muscle actions (181, 183, 188, 214, 236, 249). Slow and fast SSC movements are determined through ground contact times; lower than 250 ms are categorized as fast and above 250 ms are slow (251). Slow SSC movements allow for greater force production because of increased time, meanwhile fast SSC actions utilize elastic energy and a stretch reflex to produce faster movement speeds.

Natural improvements in SSC function increases non-linearly with age, but significant adaptations to physical and neuromuscular properties are seen follow the PHV (251). Children are reported to produce less absolute power in comparison to adolescents, however, improvements in muscular power will occur in spurts throughout maturation (66, 67, 308). Previous research indicates that there are periods of rapid development in muscular power between ages 5 and 10 (28), likely due to age-related improvements in neuromuscular coordination (187). A secondary spurt for muscular power has also been reported for males in accordance with the onset of puberty (105). The onset of puberty (PHV) occurs around the age of 14 in males (194); however, natural improvements in muscular power appear to coincide with PWV as opposed to PHV (221). The period of PWV includes increases in muscle CSA, as well as alterations to muscle architecture, potentially explaining the rapid gains in muscular power observed during this stage of maturation.

2.2.2.1 Mechanisms of force production

Natural growth and development leads to improved neuromuscular function, increased muscle size, and other physiological changes which result in muscular strength gains (187). Different tissues and systems in the body have different growth curves during the maturation process in children (276). The neural growth curve outlined by Scammon et al. (276) characterizes maturation of the central nervous system and demonstrates that over 90% of neural growth is attained before age 7. Accompanying puberty are accelerated periods of growth in body mass and stature which contribute to increased force production (142, 212, 302). Additionally, greater force production due to increased body mass has a greater influence on sporting performance in youth athletes around the time of PHV and PWV (100, 118, 119, 198, 225). Cumulatively, the improvements within neural, hormonal, and physical factors following natural growth and maturation are key factors which allow adolescents to produce greater absolute amounts of force compared to children (64, 105, 250, 302, 308).

2.2.2.2 Structural

As children reach puberty, secondary sex characteristics and morphological changes begin to emerge within the body due to increased anabolic hormones circulating such as testosterone, growth hormone, and insulin-like growth factor circulating within the body (21, 180, 194, 262, 287, 295). Also, maturation of skeletal tissue results in rapid but non-linear increases in stature and body mass. An increase in stature introduces a mechanical advantage in conjunction with skeletal growth (64). De Ste Croix et al. (64) suggested that an increase in the length of long bones aids muscles limbs in producing force due to greater muscle moment-arm lengths. While body mass is a determinant of force production, absolute-body mass can be misleading and therefore fat-free mass (FFM) or muscle cross sectional area (CSA) are more commonly used to determine muscle strength and power (302). FFM typically increases during childhood and puberty, suggesting that a greater proportion of muscle mass throughout the body. Therefore, increased muscle mass in the upper and lower extremities contributes to a greater potential force production.

Increased circulation of anabolic hormones contributes to maturity-related changes in muscle architecture (166, 250). Radnor et al. (250) reported that advancing maturity increases muscle thickness, pennation angle, and fascicle length in the gastrocnemius and vastus lateralis muscle groups. Previous studies have noted similar findings in school aged boys and reported that the growth and maturational changes to muscle architecture contributes to producing explosive-type movements (182, 302, 309). Muscle size CSA is positively related to muscular force production by a muscle, suggesting that greater hypertrophy within a muscle increases the potential of force which can be produced (302, 311). Muscle CSA dictates the maximum amount of force that a muscle can produce and generally increases with age. While muscle CSA increases following puberty, De Ste Croix (64) stated that strength can vary independent of muscle size within prepubertal children. However, a later study by Tonson (302) concluded that maximal isometric force production was proportional to muscle volume, regardless of age.

2.2.2.3 Neural

Gains in muscle force during childhood have been reported to be driven primarily by the development of neural factors (126, 180, 308). Following puberty, greater force production from adolescents is reflected through neural mechanisms associated with hormonal and morphological changes (302). Similarly, myelination of muscle nerves are incomplete until sexual maturation is reached and subsequently effects force production (139, 312). In addition to more lean muscle mass, a greater amount of fast-twitch fibres are found within adolescent skeletal muscles in comparison to children (17, 64, 194). Motor-unit recruitment and increased firing frequency from these fibres allow a greater amount of absolute force which can be produced during measures of strength (16, 308). Additionally, neural contributions also increase during maturation in maximal jumping and SSC type activities

(184, 185). Compared to children, adolescents utilize pre-activation, have shorter stretch reflex latencies and less co-contraction during plyometric activities than children (183). These adapted neuromuscular mechanisms from maturation result in greater leg stiffness and vertical peak power (158). Interestingly, Quatman et al. (248) provided evidence for the male ‘neuromuscular spurt’, in which pubertal males experienced increases in vertical jump power and eccentric strength during maturation.

2.2.3 Natural development of the F-V curve

The force-velocity (F-V) curve represents the inverse relationship between the amount of force a muscle can generate and the velocity at which it contracts (122). Greater forces have lower velocities, whereas, high velocity movements typically result in less force production. Maximal strength is typically expressed on the force part of the spectrum and is often measured during a maximal isometric or slow velocity contraction. Alternatively, maximal power requires higher velocity contractions and is therefore considered to be more related to the velocity spectrum. However, it should be noted that both strength and power are expressed along all regions of the F-V curve. Previous literature indicates that maturation of the neuromuscular system influences the F-V relationship, allowing adolescents to produce greater levels of force and at faster velocities than children, thus shifting their respective F-V curves up and to the right (64). During isokinetic testing, children were unable to attain the same levels of peak torque as teenagers (63). It has been suggested that a reduced neural drive and lower hormone levels limit children to slower and less forceful muscle actions (63, 64, 80, 257). A lower neural drive suggests that children are unable to recruit a greater amount of high-level motor units, which inherently limits their ability to produce maximal force and rates of force development during muscle actions.

Following puberty, rapid increases in strength arise due to the physiological changes associated with growth and maturation. Ramos et al. reported that increased testosterone in boys preceded gains in overall muscle strength as well as increased peak torque (257), which indicates that increases in a male hormonal profile lead to morphological changes within the body. The morphological changes following maturation also influence the F-V curve through muscle growth and fibre type composition changes at the onset of puberty in males which allows faster and more forceful muscular contractions (302). These morphological changes allow for greater maximal force producing abilities within a maturing individual. Similarly, a combination of greater muscle CSA (142) and a faster shortening velocity of myofibrils also positively influences velocity-dependent muscle actions related to power such as the SSC (251). Shortening velocity is related to the length of myofibrils and the amount of available fast-twitch-fibre in the active muscle (277). Thus, the rate at which force can be produced increases within the muscle which inherently improves absolute muscle power. Growth related outcomes such as increased leg length and muscle mass also contribute to force production during high-velocity movements such as the vertical jump (32). Therefore, natural development of the morphological and neural systems via growth and maturation promotes a higher degree of maximal force and maximal velocity capabilities within the muscle.

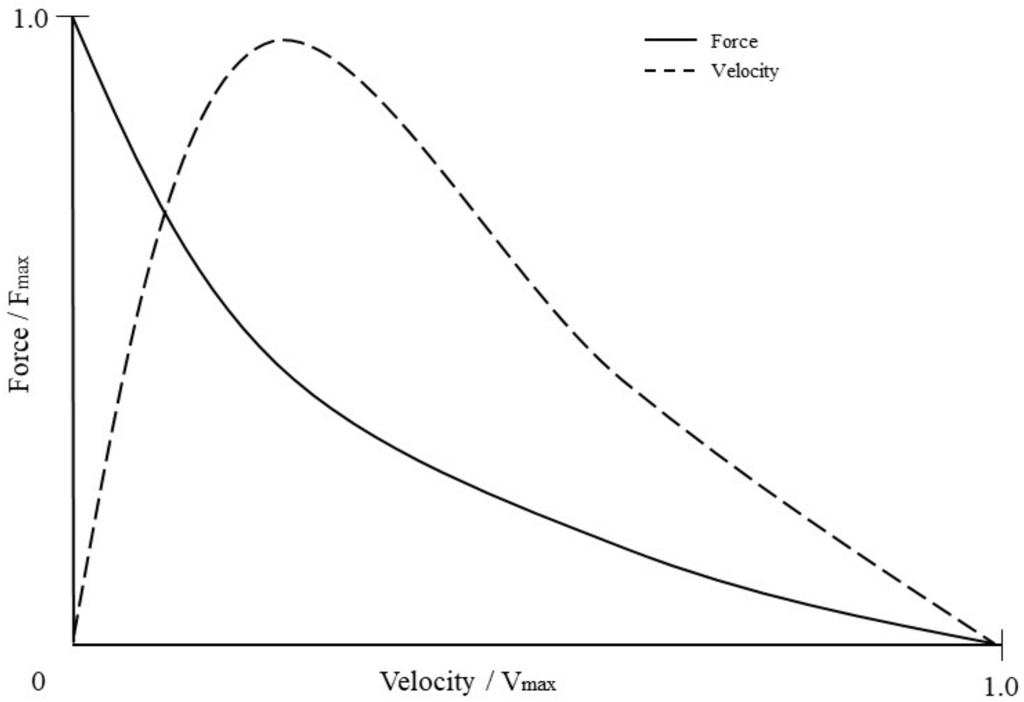

Figure 2.2 The force-velocity relationships for concentric contractions in skeletal muscle. Force and velocity are normalized to the maximum isometric force (F_{max}) and maximum velocity of shortening (V_{max}).

2.3 TESTING MOVEMENT COMPETENCY, STRENGTH & POWER IN YOUTH

Performance across a range of fitness tests are administered in order to establish baseline levels of fitness, as well as determining the effectiveness of a given training programme. The frequency of testing may be required more frequently due to the rapid changes in performance which accompany maturation from childhood to adolescence (180). Due to performance differences between maturational groups, the interpretation of data based on chronological age groups between youth athletes has been discouraged (301). Alternatively, performances tests in youth athletes should be based on maturity status alone and the use of z-scores according to rolling averages have been suggested by Till et al. (301). Cross-sectional analyses of performance tests in a large cohort provide valuable insight into the interaction between maturation and changes in movement competency, strength, and power. To accurately measure these qualities in male youth athletes, several valid and reliable tests which examine different force-velocity relationships must be administered (*Figure 2.2)*.

2.3.1 Assessing movement competency

Movement competency requires the demonstration of sufficient goal-directed motor patterns within different fundamental motor skills (FMS) (103). Similarly, movement competency is the primary underlying mechanism for promoting health-related physical fitness and sports participation in children (140, 170, 260, 285). While high levels of movement competency are associated with higher levels of sporting performance (245), it is important to understand that movement competency can be modified through biological maturational processes and training which allows for the development of difference locomotive skills. Therefore, assessing movement competency in youth is critically important for both researchers and coaching practitioners.

Proficient movement competency is considered an essential aspect of sporting performance in youth due to neuromuscular processes which underpin movement such as motor unit coordination, firing and recruitment (12). Additionally, numerous governing bodies have identified technical movement competency as paramount to all LTAD programmes (10, 88, 176) and suggest that movement competency likely has a positive transfer to displays of strength and power (12, 105). Therefore, the assessment of technical movement competency should arguably precede strength and power testing. Assessing movement competency in youth allows practitioners to identify functional deficits and technical flaws in fundamental movement patterns (230). Different movement competency tests exist with regards to children and adolescents (31, 49, 50, 304) as well as athletes with lower training age (265). The strengths of such tests are that they identify individuals with motor deficiencies across a broad maturity range, as well as assessing various running, jumping, and balance movements. Similarly, these tests are relatively easy to use and are often conducted in physical educational settings. However, assessment for the large amount of movement items within these tests are not time efficient for large groups and require multiple raters.

Of interest to strength and conditioning practitioners are movement competency tests that are both time efficient and allow for easy detection of deficient motor patterns. Movement competency has been previously assessed in the drop jump to screen for injury-risk factors during landing (70, 238) as well as in the functional movement screen (FMS™) for upper and lower body movements (237). While movement competency tests such as the FMS™ offer a practical and cost-effective method for assessing movement competency, its examination of seven different exercises is time-consuming. Contrastingly, movement competency tests for the drop jump require video analysis and can only be scored retrospectively (70, 238).

A widely used movement screen is the Test of Gross Motor Development-2 (TGMD-2) (305) which evaluates motor skill performance in children ages 3-10. The TGMD-2 examines 12 functional motor skills using a criterion-based assessment to qualitatively evaluate motor performance. However, one limitation to the TGMD-2 is the time required to demonstrate, communicate and evaluate all twelve movements. A movement screen designed to assess athletic ability and movement efficiency during gym-based exercises was developed by McKeown and colleagues (205). The Athletic Ability Assessment (AAA) screen is a reliable test which assesses a total of 9 movements which expose common deficiencies in foundational movements within the trunk and lower body. However, the AAA screen was created for athletes that regularly train and perform competitively in sports. Therefore, the AAA screen may be inappropriate for athletes with a zero to low training age who are likely to score poorly on the AAA. Since most youth athletes have a low training age, a more appropriate movement screen may be the Athlete Introductory Movement Screen (AIMS-4) (265) which assesses 4 separate movements scored on a 3 point grading scale. Several limitations within these movement screens exist with regards to their practicality for strength and conditioning professionals. One issue with assessing multiple movements within a movement screen is that they can be labour intensive when using only a single rater. Assessing multiple movements within a large group of athletes can prove difficult and inhibit the quality of screening for movement. Additionally, some movement screens require further screening in order to identify the causes of a faulty movement pattern. A second issue is that there is a lack of evidence supporting these movement screen's abilities to longitudinally predict injury. While acknowledging the potential benefits of screening multiple movement patterns, it may be more practical for professionals to focus on one fundamental movement pattern.

Single movement screens have been proposed within youth literature that are less labour intensive for raters and may be more practical for strength and conditioning coaches. Of note, a forward lunge (164) and bilateral bodyweight back-squat screen (163) have been developed to assess movement competency and identify any potential movement patterns which may contribute to injury. The biomechanical requirements for the lunge and bodyweight squat are used to assess neuromuscular control, strength, stability, and mobility throughout the body. Similarly, they can highlight compensational movement strategies that individuals use in order to complete a faulty movement. However, one potential issue with the bodyweight squat is that it does not necessarily replicate a squat that athletes perform in a gym-setting. Individuals performing a resisted bilateral squat typically utilize a barbell which causes retraction of the shoulders in order to support the weight while maintaining a more upright torso (167). Therefore, it may be more appropriate to utilize a back squat movement screen which considers this slight difference within the squat. Similarly, a major limitation of the bodyweight squat (163) and forward lunge (164) tests are that they are not sensitive enough to detect meaningful changes in movement competency because scoring is performed across a narrower scale. Thus, it would be difficult to use these tests in research and a larger range of possible scores would offer a more detailed level of analysis for changes in movement competency. While criteria for optimal and non-optimal movement patterns for the respective movements are thoroughly outlined, scoring provided by the authors makes assessing changes in movement competency over a period of time less clear. Therefore, movement competency tests which score and clearly outline movement criteria would provide a more objective assessment of movement competency.

The back-squat assessment (BSA) was recently developed by Myer and colleagues (230) as a dynamic screening tool for movement competency using real-time assessment in addition to two-dimensional video analysis. The BSA requires individuals to perform 10 continuous repetitions of bodyweight squats with a wooden dowel on their back. During the BSA, individuals are assessed on ten different criteria which highlight the movement patterns and positioning of upper and lower body extremities during the squat. Participants are scored if a deficient movement pattern or position is observed with higher scores indicating less optimal squat movement competency and lower scores being indicative of more favourable squat competency. Due to the BSA being scored on a ten-point scaled, this larger range of scoring allows for a more granular level of analysis in comparison to previous tests which score on a smaller scale (163, 164). Thus, the BSA can potentially detect changes in movement competency in youth offers a practical method for assessing competency in youth. However, prior to this thesis the reliability of the BSA for screening youth athletes was unclear. Therefore, reliability of the BSA for measuring movement competency in youth athletes of different maturity status must first be established before it can be used confidently to detect meaningful changes in movement competency in youth following training interventions.

2.3.2 Assessing performance across the force-velocity curve

Performance tests which require the production of maximal force or maximal velocity indicates an individual's F-V relationship. Performance tests for maximal muscle strength require heavy external resistances in order to produce maximum force. However, a more accurate way of measuring maximal strength and absolute force-production can be assessed during isometric tests (216, 222, 300). Unlike maximal force production during isometric muscle actions, testing for maximal velocity can never be achieved due to some form of resistance always being present in the body. Therefore, measuring muscular power requires high velocity movements such as the vertical jump or squat jump are commonly used since these tests require resistance only in the form of body mass (115, 128, 225). It should be noted that the relationship between high levels of force production (strength) and the ability to produce force quickly (power) are related (9, 75, 122, 208). Strength is considered to be a foundational element of power because stronger individuals are able to generate greater forces more quickly than weak individuals (122, 146, 297, 316). While strong correlations between strength and power exist in youth (316) it is critical to conduct different performance tests in order to identify how these qualities interact with growth and maturation. Owing to the F-V curve, different performance tests typically include both high levels of force and velocity, but trend towards either end of the spectrum (*Figure 2.3*). Therefore, tests which assess performance within the middle areas of the F-V curve are also as significant to testing maximal force or velocity performance.

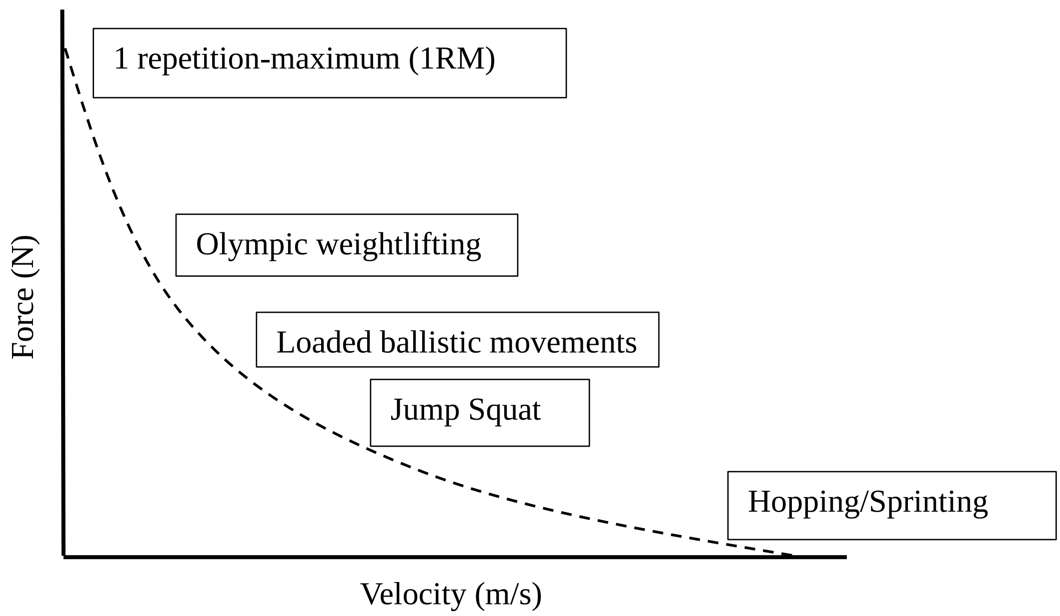

Figure 2.3. Performance tests associated along the force-velocity curve. Adapted from Kawamori and Haff (144).

2.3.2.1 Maximal strength

Assessing maximal strength is of interest to practitioners and researchers due to its relationship with athletic performance (27, 59, 145, 155, 222, 297, 316). Testing for maximal muscle strength in youth has been traditionally investigated through isokinetic testing (63, 257) as well as lifting heavy external resistance and testing for 1RM loads (133, 146). However, testing for maximal strength using these methods may be challenging for individuals with a low training age and requires appropriate levels of technical competency prior to being used with young athletes. Another option is to use multiple repetition testing; however, using multiple RM's to test strength become less valid as they go further away from a 1RM. Also, another limitation is the accumulated fatigue of high RM protocols which may pose as an injury-risk to athletes with relatively low training ages. The isometric mid-thigh pull (IMTP) test offers a safer alternative form of strength testing and is used to measure maximal force production throughout the whole body (46, 65, 123, 125). The IMTP test is quantified through ground reaction forces while standing on a force platform and pulling on an immovable bar (300). Testing for maximal strength using IMTP test requires no prior training age and little instruction to perform correctly. As such, the IMTP test is likely the most suitable method for assessing strength in youth athletes of different maturational groups (30, 222). The ability to produce maximal force within the IMTP appears to be optimal when setting up with an upright torso position while having a knee-joint angle of ~125º and a hip angle of ~140º (8, 46). Collectively, these joint angles take advantage of the length-tension relationship within the muscles that allow for maximal force production due to optimal overlap of the actin and filaments within the sarcomere (8, 55). Finally, the IMTP provides a greater amount of information than maximal repetition testing by reporting multiple force-time variables. The reporting of force-time variables enhances the information surrounding measures of strength by evaluating the mechanical variables which underpin maximal force production and the ability to produce force quickly.

The IMTP appears to be reliable for measuring peak force values in youth athletes (74, 76, 216). Alternative testing methods such as an IMTP dynamometer have also been investigated but were reported to underestimate peak force (300). Similarly, collecting kinetic IMTP variables has increased measurement error when deviating from a hip joint angle of 145º during the IMTP (77). Dos'Santos et al. (76) reported acceptable levels of within- (ICC = 0.84-0.98, CV = 4.05-10.0%) and between- (ICC = 0.86-0.96, CV = 3.76-7.87%) session reliability for peak force and peak force at 30-250 ms. However, the participants in the study had previous training experience and a reported chronological age of 16.7 years, suggesting maturation was in the late adolescent stage. The only study comparing reliability of force-time variables between children and adolescents has been in young female gymnasts (216). Moeskops et al. (216) reported large within-session measurement errors for the IMTP in pre- and post- PHV athletes with relatively large coefficients of variation for peak RFD (pRFD) (CV = 22.0 – 36.5%), time to PF (TPF) (CV = 41.0 – 44.4%), and time to pRFD (CV = 47.6 – 81.0%) (216). Less consistent values were displayed between-sessions with both groups displaying higher CV's for pRFD, TPF, and time to pRFD. More mature athletes were reported to display greater reliability between sessions for absolute and relative peak force (CV $\leq$ 7.3, ICC $\geq$ 0.81) than the pre-PHV athletes (CV $\leq$ 10.2, ICC $\geq$ 0.71). Similarly, the CV's for PF at time epochs of 50-, 90-, 150-, 200-, and 250-ms were between 19-37% for the pre- and 5-24% in the post-PHV group. Therefore, it appears that there is an acceptable degree of reliability for all force-time variables within the IMTP in children or individuals with low training age.

2.3.2.2 Strength-speed

The strength-speed zone lies below and to the right of maximal strength in the F-V curve and requires producing high levels of force within a limited time frame (234). As a result the force-velocity relationship within this zone is primarily force dominant and can only be expressed under loaded conditions (234). Therefore, exercises or movements which have moderate to high loads (80-90% of 1RM) while also achieving faster movement velocities than that of maximal strength tests are classified within the strength-speed zone of the F-V curve (47, 122, 223, 234). Olympic weightlifting and their derivatives require both high-force and high-velocity which could maximize power output along the strength-speed portions of the F-V curve (122). The power clean and snatch variations incorporate multi-joint movements that are expressed at high velocities under near maximal loads (203, 223) and has been suggested to be specific to sports which require expression of high power output under loaded conditions (4, 5, 234). Alternatively, traditional strength building exercises such as the back squat, deadlift or bench press have also been used to train within the strength-speed portion of the F-V curve (57, 286, 292). However, these strength exercises are generally performed at a lower velocity than weightlifting movements which may result in lower power output (137, 203). It should be noted that although movement velocity is compromised at higher loads, the intent to produce maximal velocity should still be performed in order to generate maximal power output.

2.3.2.3 Speed-strength

The speed-strength portion of the F-V curve requires producing maximal movement-velocity against relatively low loads (122, 286). Force production is low within this area of the curve due to higher movement velocities which limits the time in which force can be produced (55). Ballistic movements such as the vertical jump, squat jump and sprint are typically used to train or assess the speed-strength area of the F-V curve. Ballistic movements are high-velocity muscular contractions that rapidly generate force production throughout an entire range of motion (56, 57, 235). Despite lower loads being used during ballistic exercises (0-

30% 1RM), the greater velocity displayed during these movements are generally more sport specific and may prompt performance changes than heavy resistance training alone (52, 53, 56, 57). However, it should be noted that performance in ballistic exercises such as the jump squat favours stronger individuals (53, 54, 56). This is due to stronger individuals having greater rates of force production and expressions of power when compared to weaker individuals. With regards to youth athletes, adolescents are likely to display greater power output within loaded and unloaded squat jumps than children due to changes associated with growth and maturation (61, 308). When assessing peak power output at different intensities in the squat jump, Dayne et al. (61) reported that adolescents displayed the greatest peak power at body weight compared to 20, 40, 60, and 80% of squat 1RM. Therefore, it appears that the use of body weight or lower loads are likely more valid when assessing ballistic performance in children. As such, the use of a squat jump test to test the speed-strength qualities of youth athletes would be an appropriate measure of lower body power.

2.3.2.4 Explosive strength

The maximal strength of a muscle underpins explosive force production (37). However, the relationship between maximal and explosive force production are not perfectly related (75) and it appears that other variables influence explosive strength (9, 135). Explosive strength requires individuals to produce high levels of force as quickly as possible and evaluates rate of force production (RFD) (26, 144, 145). Since most sporting movements occur at < 250ms, measuring explosive force production is a valid way to measure athletic performance (9, 37). Explosive force production has been measured through isometric maximal strength tests (9), but more commonly during dynamic lower body power tests (115), especially in youth population. The RFD produced during the initial 250 ms is commonly associated with measures of lower body muscle power during the countermovement jump (CMJ) and squat jump (SJ) tests (75, 297).

The SJ and CMJ tests are commonly used to measure lower body muscle power in paediatric populations. However, vertical jump data is commonly recorded using portable equipment such as contact mats which provide only a limited number of variables beyond jump height. While portable field-based jump tests are more practical, the use of force platforms which collect kinetic data can provide more insight into the mechanical variables which underpin jump performance. Research consistently shows greater measurement error is evident in children compared to adolescents (113, 181, 213). For example, Gillen et al. (113) reported lower reliability from children aged 6-9 years when compared to adolescents (12-15 years) for measuring vertical jump height, while Meylan et al. (113) reported that less mature athletes display larger variation in kinetic and kinematic variables during the eccentric phase of vertical jumps, but not the concentric phase in comparison to older athletes. This greater movement variability by pre-adolescents within the CMJ is likely due to an immature neuromuscular system (113, 213). Lloyd et al. also reported lower reliability for measuring CMJ jump height (CV ≤ 14.48%) compared to SJ jump height (CV ≤ 8.64) in youth male athletes (181). Therefore, the lack of an eccentric phase during the SJ tests appears to improve the reliability of kinetic and kinematic jump measures in male youth athletes. Previous research indicates that a 90º knee-angle and a self-preferred squat depth does not affect SJ height in post-PHV males (243). However, greater measurement error was observed in SJ force, power, and jump height when a standardized 90º knee angle is administered as opposed to a self-selected depth during the SJ test (243). The knee-angles during self-selected depth were typically larger (> 90º) prior to jumping, but the resulting jumps produced more consistent and reliable outputs of maximal jump height, force, and power than a standardized depth.

2.3.2.5 Reactive strength

Recently, explosive strength has also been evaluated using a modified reactive strength index (RSI_{mod}) during vertical jump tests (151). Reactive strength is the ability to quickly switch from an eccentric to concentric muscle action during SSC activities typically seen during rebound activities such as hopping and sprinting (128, 270, 272). Force production during a sprint or jump is enhanced when there is a rapid lengthening of muscle prior to a concentric muscle contraction (136). Similarly, the amount of time spent during the eccentric and concentric portions of the countermovement is an essential component of jump performance (165). It appears that SSC performance within different hopping and jumping tasks increases non-linearly with age (169, 182), yet the effect of maturation on the underlying neuromuscular mechanisms dictating SSC and rebound type jumps is unclear (251). Previous studies have also reported that children and adolescents typically utilize different strategies when performing both slow and rapid SSC type movements (72, 181, 184, 270). Therefore, measuring the force-time characteristics within different jumping tasks in youth of different maturational status can expand the understanding of reactive-strength capabilities and maturation. The RSI_{mod} is calculated by dividing time to take-off (TTT) by jump height, thus providing force-time characteristics during a vertical jump by measuring the quantity of vertical ground reaction forces as well as the time taken to apply force into the ground prior to take-off. The use of RSI_{mod} has been shown to be valid and reliable measure of lower body explosiveness during vertical jumps (151, 288) and has been commonly used to evaluate lower body explosiveness. Although explosive force production is limited by time, a moderate correlation has been reported between reactive strength and maximal strength (r =

0.346) (75). Similarly, it was reported that athletes with greater reactive strength also produce greater RFD and force at time epochs > 200ms (9).

2.3.3 Ratio and allometric scaling

Assessments of physical performance tests are dependent on the body size effect. Normalization of performance tests by scaling of body mass have been used in previous literature (48, 201). Ratio scaling involves normalization of absolute force per kilogram of body mass through the presumption of a directly proportional relationship between increases in performance and body mass (48, 290). This assumes that doubling body mass would also double strength performance which is not the case. Thus, ratio scaling does not correctly account for proportionality and inherently favours peak force production in athletes with very low or very high body mass. For example, ratio scaling for absolute peak force output during an IMTP test will have a lesser effect on athletes with relatively lower body mass. Therefore, the effect of body mass tends to be over or underestimated as opposed to controlling for body mass' effect on force production (290). Jaric et al. (141) proposed an allometric scaling method based from the geometric similarity theory, which suggests that body measurements can be calculated based on the assumption that all human body shapes are similar, and only differ in size and length. Due to muscle CSA being directly related to force production, it was theorized that calculating muscle CSA would provide the most accurate scaling method for performance tests (201, 232). Since measures of area are two dimensional and volume is three-dimensional, muscle CSA could be estimated using body mass calculated to the power of two-thirds; therefore, the allometric normalization method divides absolute force from a performance tests by body mass in $kg^{0.67}$. Comfort et al. (48) reported that both ratio and allometric scaling methods are appropriate for normalizing power and strength data in different tests when the assumptions are met. However, limitations within the allometric scaling methods arise when comparing separate groups using fitted exponent (290).

2.4 TRAINING RESPONSIVENESS IN YOUTH

2.4.1 Introduction

Both children and adolescents are capable of making significant improvements in movement competency, muscle strength, and muscle power following training that surpass changes that result from growth and maturation alone (12, 13, 87). However, it appears that certain training modes should be prioritized with regards to maturational status. The most worthwhile changes in movement competency appear to occur when children are introduced to neuromuscular training prior to puberty (228). The ability to improve movement competency might diminish with advancing age and maturity since it is accepted that the brain's neuroplasticity reduces following puberty (60, 189, 227). Adolescents are more inclined to make larger adaptations in strength than children follow resistance training programmes primarily due to greater size and circulating hormones. Maximizing training responsiveness for power requires different training modes between children and adolescents (182, 188). Previous literature has indicated that pre-PHV athletes observe large lower body power adaptations following plyometric only training, whereas, circa- and post-PHV athletes respond more favourably to a combined strength and plyometric training programme (96, 97, 303, 315). Regardless, the different training modes appear to complement the physiological adaptations that occur with maturation for these specific training qualities.

A limitation of the current literature on training youth athletes is that the same training modes are typically administered to youth participants of different maturity groups and technical abilities (188, 245). While it has been established that developmentally appropriate strength and conditioning training can be administered to children and adolescents (176, 177, 228), previous training studies do not prescribe individualised and targeted training interventions for groups of different technical ability or maturity status. With acknowledgement to the natural development of movement competency, strength, and power during growth and maturation, it can be assumed that children and adolescents will likely require different exercise programming as well as different training modes to optimise adaptations (180) and therefore training prescription should reflect these needs.

2.4.2 Effects of neuromuscular training on motor competency

The greatest potential influence on motor competency appears to be the interaction of an individual with their environment. A recent review highlighted the significant role that environmental conditions have on both the structural and functional changes in white matter in children (104). Therefore, environments promoting the development of functional motor skills appear to be important in developing motor competency in young children. While maturation affects motor competency, a review by Myer et al. (228) reported that improving motor competence in youth can be achieved through the interaction between the individual and an environment which provides opportunities for learning a variety of motor skills. As such, school based interventions and opportunities for play allow for natural improvement of physical literacy and motor competence in youth of all maturational ages (86, 170, 190).

Training programmes that incorporate general and specific exercises that enhance overall health and skill-related physical fitness in youth has been termed “neuromuscular training”. While it is generally considered that children and adolescents have a genetically predetermined range of physical and motor competency potential, it is believed that well designed integrative neuromuscular exercise can maximize these qualities (228, 231).

Neuromuscular training has also been previously demonstrated to improve movement competency and subsequently reduce injury-risk in both children and adolescents (73, 87, 92, 101, 132, 229, 284). The improved motor competency from neuromuscular training appears to be greater than changes attributed to normal growth and maturation as well as improving overall physical literacy (86, 284). Pre-adolescent athletes that participate in progressed neuromuscular training programmes appear to benefit the most due to simultaneous adaptations in the neuromuscular system resulting in greater cognitive and muscular control (86, 87, 92).

Successful neuromuscular training programmes require instruction from qualified professionals that understand the interaction between physical training and normal growth and development (231). The focus of integrated neuromuscular training combines resistance training, core-focused training, as well plyometric and agility exercises (87, 217, 228, 229). The integration of these different exercises is believed to promote visual-motor, psychosocial, neuromuscular, and neurocognitive development (87, 168, 228). However, the neuromuscular training prescriptions and exercise progressions must be developmentally appropriate and accommodate the training age of young athletes. Developmentally appropriate training relates to the biological or somatic age of an individual as opposed to chronological age. Technical movement competency determines the simplicity or complexity of movements and exercises within a neuromuscular training programme. It is paramount that corrective feedback is given by coaches in order to develop and refine correct movement patterns (168). Over time, movements and exercises may be progressed once an individual displays competent movement. Therefore, it is believed that appropriate implementation and progression of neuromuscular training programmes strengthen the neural pathways and subsequently allows children to self-organize and display optimal movement patterns quickly (168, 231).

Numerous short-term interventions have reported improvements in motor competency in both children (42, 87) and adolescents (101, 138, 170, 236). While neuromuscular training is effective in youth across all ages, it has been highlighted induce greater gains in motor competency in pre-pubertal children (12, 92, 226, 228).

2.4.3 Effects of neuromuscular training on strength and power

The cornerstone of integrative neuromuscular training is incorporating a wide variety of general and specific training modes which enhances an athletes fundamental movement base (87, 190, 228). This has been previously demonstrated to improve overall movement competency and skill-related fitness within youth athletes of different maturity statuses (72, 73, 87). Since movement competency is associated with athletic performance, it is believed that implementing integrative neuromuscular training can enhance strength and power performance in children and adolescents while also reducing injury-risk (87, 92, 226, 229). While the effects of resistance training on improving strength has been well established (11, 13, 173), there are still voids in the literature with regards to the general effectiveness of implementing neuromuscular training for improving strength and power. The majority of the literature surrounding the effectiveness of neuromuscular training programmes on youth typically measure injury prevention despite the inclusion of heavy resistance training (6, 11, 39, 71, 98). Few studies have specifically measured strength outcomes during a neuromuscular training programme in children with contrasting findings. Faigenbaum et al. reported that children were able to significantly improve upper-body strength and lower-body power following 15 minutes of twice-weekly neuromuscular training (87), whereas, Chaouchi et al. reported that neuromuscular training did not improve 1-RM leg press strength in children after 8-weeks (39). The discrepancy in findings may be due to reported strength training within both studies using relatively low loads in the neuromuscular training programme. The only study that used progressive and relatively high resistance training loads in strength in children found significant increases in isometric strength following 12-weeks of neuromuscular training (72). Despite the effects of neuromuscular training improving strength in children being unclear, it is suggested that teaching and mastering fundamental resistance training movements during pre-adolescence is the most opportune time (226, 228).

While muscular strength gains in children are primarily driven by neural adaptations due to their limited hormonal profiles, developing correct movement mechanics can maximize muscular strength gains later in their natural development. Previous literature indicates the effects of neuromuscular training programmes has a profound effect on lower-body power performance in children (6, 39, 71, 214). The adaptations in children for improved jumping (6, 39, 71) and sprinting (87, 98, 138) are likely a result of the synergistic effect between short-term integrative neuromuscular training and maturation (121, 188, 251). The ability to produce more force and power increases as children begin to mature (80, 175, 257) and therefore training responsiveness to neuromuscular training is potentially greater in adolescents than in children (72, 319). The only study comparing the child-adolescent differences following neuromuscular training reported that adolescents generally had a greater response to training by improving in both strength and power indices (72). While there is a plethora of literature that has demonstrated that gains in absolute strength favour adolescent males over children after both resistance training only and combined training (97, 263, 303), it appears that similar gains in relative strength can still be made by children (242). However, there is a gap in the literature comparing children and adolescents for measures of strength following developmentally-appropriate training interventions. In the few training studies that have directly compared children and adolescents for measures of strength and power, the same neuromuscular training programme is often administered to all groups irrespective of individual needs, thereby contradicting existing long-term athletic development guidelines (69, 180, 188). Despite neuromuscular training effecting strength and power differently in youth athletes of different maturational stages, the inclusion of neuromuscular training is recommended in order to provide athletes with a well-rounded and dynamic programme to supplement athletic development (226, 284).

2.4.3.1 Synergistic adaptation and interactions between training and maturation

It is important to strategically prescribe age-related neuromuscular training with consideration to an athletes physical and cognitive development stage in order to optimize motor skill development (231). However, neuromuscular training is recommended to be introduced during late childhood (7-9 years) as opposed to early childhood (2-6 years) once certain cognitive and motor development thresholds have been reached (168). Late childhood has been identified as the ideal period for children to learn and execute basic-fundamental movements because they are more able to comprehend instructional feedback during exercises (168). Research strongly suggests that early exposure to neuromuscular training can successfully position children to progress more quickly through periods of skill acquisition and promote the development of efficient motor control due to the high degree of 'plasticity' in their brain (168, 228). Taking advantage of children's neural plasticity through training can facilitate advanced development of gross motor skills similar to that of adolescents and adults (14, 240). The brains cortico-motor plasticity enables children to better refine fundamental movements and become more adept to learning new motor skills prior to synaptic pruning of the brain during puberty (228, 231). Neuronal, axonal, and synaptic pruning at the onset of puberty are theorized to contribute to diminished learning of new motor skills in adolescents (114, 227). Therefore, exposure to neuromuscular training may limit the potential for adaptive motor learning in adolescents, however, motor competence is still modifiable (227, 228). Meaningful changes to motor competence are achieved in adolescents through natural growth and maturation as well as periodized resistance training programmes (132, 228). Therefore, training must be appropriately prescribed for adolescents with consideration to the rapid physical growth and hormonal changes being experienced after puberty. Adolescents are more capable of generating greater overall force and often experience large increases in muscular strength and power following neuromuscular training (168). Similarly, cognitive development in adolescents enables the use of more technical instructions and teaching of complex exercises which can progress to greater strength and power adaptations (167, 168).

2.4.4 Influence of different training prescriptions on training responsiveness

2.4.4.1 Volume

Different configurations of training volume result in different forms of physiological stress, which induce different responses to neural and physical adaptations. Training *volume* typically refers to the amount of sets and repetitions performed within an exercise training session. A review by Lesinski et al. (172) reported that multiple sets (3-5) per conventional resistance training exercises promoted the greatest gains in muscle strength in youth athletes compared to two or fewer. Various training studies have reported positive increases in strength and power following single set training exercises (69, 83, 193). However, these training studies did not compare single set versus multiple set training effects and therefore it is unlikely that lower exercise sets will elicit a sufficient or greater adaptation in youth athletes. Additionally, performing 6-8 repetitions per set from resistance training produced the largest effects on muscle strength (172), however, preadolescent children are likely to benefit from more repetitions per set (94, 242). Performing 3-4 sets and 9-12 repetitions of traditional resistance training were reported to have the greatest effect on increasing lower body power in youth athletes (172, 242). However, this is likely due to the untrained status of most individuals within youth training studies who are likely to experience improvements in power from general strength training. Youth athletes with higher training ages require a greater training volume in order to elicit increases in strength (116, 117). A meta-analysis by Lesinski et al. (172) reported that improving lower body power through plyometric training was most effective following 3-4 sets per exercise and 3-5 repetitions. Lower repetitions during plyometric training appears to be more effective in youth athletes (175, 182) because higher repetitions are likely to cause greater fatigue and reduced movement quality in jumps.

2.4.4.2 Intensity

Intensity during resistance training typically refers to the effort required to lift a load relative to a 1RM and there is an inverse relationship between training intensity and the number of quality repetitions that can be performed (124). A recent review (172) reported that youth athletes performing conventional RT at an intensity of 80-89% of 1RM resulted in more significant improvements (SD = 2.52) for muscle strength compared to lower intensities (30-69%). Peitz et al. (242) also recommended that a > 80% of 1RM training intensity was also the most effective method for improving strength in young athletes. However, the studies with higher-training intensities (≥ 80% of 1RM) which were included for statistical analyses in the Lesinski review reported only a chronological age of 14-17 years with no indication of biological maturity status (172). Therefore, it can be assumed that the recommended training intensity ≥ 80% of 1RM may be suitable for only circa- and post-PHV individuals and not pre-adolescent children. However, only a few training studies reportedly used the recommended training intensity (≥ 80% of 1RM) as most of the researchers and practitioners adopted a more cautious approach when training youth. Since most youth interventions are short-term, long-term interventions are likely needed in order to safely and effectively progress untrained children and adolescents to higher exercise intensities.

While heavy resistance training is safe and effective at improving strength in children (94), it is generally recommended that pre-adolescents perform resistance training under qualified supervision and should emphasize proper technique with higher repetition ranges (16, 88, 105, 176). This notion is supported by several studies that found increases in upper-body strength for untrained children when using a low-intensity high-repetition protocol for strength (90, 94). However, the training duration in these studies were low and therefore caution is warranted when only applying a low-intensity high-repetition protocol in children. Intensity can be increased for resistance training during and after PHV, however, athletes around PHV are at a greater risk to sustain an injury due to rapid changes in the body and therefore careful consideration must be given (212, 219). Various training intensities appear to elicit a positive response in adolescents as previous studies have reported increases in strength following low, moderate, and high training intensities relative to 1RM (3, 116, 129, 159, 303). Gonzalez-Badillo demonstrated that trained adolescents can improve maximal strength with high training intensities (> 90% of 1RM) in 10 weeks when adhering to a moderate training volume (116, 117). However, this protocol may not be optimal for improving strength in most youth athletes since the participants within the Gonzalez-Badillo studies (116, 117) were elite junior weightlifters with a training age > 3 years.

Plyometric training intensity can be modified through load and drop-jump height (242). Ferrete et al. (99) included loaded vertical jumps with a 3-kg weight within a combined training programme for pre-adolescent children and reported positive changes to CMJ height after 26-weeks. The only study to assess the effectiveness of loaded vs. unloaded plyometrics in pre-pubertal children found that loaded jumps (8% of body mass) was more effective at improving CMJ height and standing long jump distance. However, caution is warranted because although maturational status was calculated (197), the reported chronological age of the cohort were 13 years of age and were likely circa-PHV (233). A study investigating the effects of unloaded vs. loaded jumps in pubertal soccer players found that loaded jump training was more effective at improving horizontal and vertical jumps (267). The loaded jump group performed maximal intensity jumps throughout the 6-week programme with various loads ~ 0-15% of body mass used hand-held weights. Similar findings for increasing squat jump and countermovement jump height were observed in loaded plyometric training protocols using loads of 8% and up to 40% of body mass in adolescents (152, 154, 233). However, the 40% of body mass load was administered to elite U17 and U19 volleyball players and is likely not appropriate for younger athletes. While no recommendation has been provided for loaded jumps, it can be assumed that ~8-15% of body mass (154, 267) is an effective load for increasing jump ability in adolescents.

Matavulj et al. (202) assessed the effects of different drop jump heights at 50 and 100 cm as a measure of plyometric training intensity in adolescent boys. After 6-weeks, no differences in CMJ height was seen between the different training intensities. Interestingly, the plyometric programme lasted 15 minutes per day and consisted of only 3 sets of 10 drop jumps, with 3 minutes of rest between sets. It is possible that the similar responses between the different intensities may be due to an improper drop jump protocol which may not have been optimal due to the high repetitions. A recent study by Ramirez-Campillo et al. (252) found that generating an optimal drop-jump height for youth soccer players was a more effective method than a fixed drop-jump height for developing reactive-strength during plyometric training. In the study, optimal jump height was determined by participants performing drop jumps at 10, 20, 30, 40, and 50 cm at baseline and were assessed for maximal reactive strength at a given height. An optimal drop-jump height was individually given to participants throughout the plyometric training programme and this strategy appeared to improve CMJ height, RSI, and multiple bound performance as opposed to a fixed 30-cm drop-jump height. In relation to training intensity, it can be assumed that adaptations are dependent on the physical fitness and training status of an athlete. Paediatric literature has reported that children are better at sustaining high-intensity exercise (221, 258) and are able to recover more quickly during explosive plyometric training (253, 254). Therefore, children may be able to improve jump performance using loads greater than 3-kg (99) as long as a correct movement technique can be displayed and maintained during loaded plyometric exercises.

2.4.4.3 Rest

Rest refers to the intervals of time in between exercise sets and is typically dictated by the volume and intensity (172, 242). Long rest periods of 3-4 minutes between sets appears to be most effective for improving muscle strength and power following conventional RT in youth athletes (134, 172). Longer rest periods likely allow sufficient recovery and allow youth athletes to perform higher volumes and intensities during exercise. However, children and adolescents appear to recover relatively quickly between sets of resistance training and are more resistant to fatigue than older individuals (64, 93, 242). Comparatively, children appear to resist fatigue to a greater degree than adolescents during resistance training (23). However, these differences were observed during isokinetic dynamometer testing and therefore may not be applicable in traditional resistance training settings. Child-Adolescent differences for rest also appear within inter-set recovery during plyometric jump training with pre-adolescents appearing to recover more quickly than more mature individuals (253, 254). Ramirez-Campillo et al. (253) found that older players benefit more from longer rest intervals (>120 seconds), whereas, pre-PHV children displayed similar improvements using either 30 seconds or 120 seconds of inter-set recovery. Currently, there is only been one study which compares the effects of inter-day rest on CMJ performance in children and adolescents (256) and recommended that plyometric training is best applied on non-consecutive days for adolescents. However, more research is warranted on inter-day rest to determine how athletes of different maturity status respond to different training volumes.

2.4.4.4 Frequency

Training *frequency* refers to the number of RT sessions within one week and plays an important role for inducing desired training adaptations (69, 172). A training frequency of 2-3 days on non-consecutive days has been identified as optimal for increasing muscular hypertrophy, strength and power in youth athletes via RT (13, 242). A meta-analyses by Behringer et al. (13) reported a significant positive correlation between training frequency and increased muscular strength. Considering the low training age in most youth athletes, a training frequency of 2-3 days allows for sufficient rest and recovery to induce strength adaptations. Recently, a systematic-review by Lesinski et al. (172) reported no differences between a training frequency of two and three times per week for improving strength and power in youth athletes which suggests that a twice-weekly training frequency may be optimal and time-efficient for inducing strength and power adaptations. Studies directly comparing the effects of once- and twice-weekly training frequencies on physical performance measures of strength (69, 91) and power (193) have produced mixed results. An 8-week RT training programme by Faigenbaum et al. (91) reported that both one day and two day training frequencies improved strength in pre-pubescent children, but a significantly greater dose-response was observed from twice- weekly RT. In a separate study by DeRenne et al. (69), it was determined that a once- and twice- weekly training frequency produced similar strength adaptations in pubescent males during a 12-week in-season RT programme.

However, prior to this 12-week in season training programme both training groups participated in a 12-week pre-season RT training programme with three sessions per week. Cavaco et al. (36) also reported that a once and twice weekly training frequency did not affect squat 1RM strength and 15 meter sprint in 14 year old male soccer players. Caution may be warranted when interpreting these findings since the total sample size in both the DeRenne (n =21) and Cavaco (n =16) studies were low and may not be applicable to all youth athletes. Additionally, no biological maturity data were reported, which suggests that the training intervention was administered to participants irrespective of their stage of maturity. Due to the synergistic effect of training with growth and maturation, it is likely that the training induced adaptations from the intervention was more conducive to particular maturity groups than others.

A recent meta-analyses reported that twice-weekly training sessions are more effective than one for developing lower body power in children and adolescents (242). A limited number of training studies have directly compared different weekly training frequencies on jump performance in youth athletes. An earlier training study investigated the effects of two, three, and fives weekly training sessions per week and reported that five sessions was superior to two sessions in improving broad jump distance (306). Notably, insignificant differences were revealed between two versus three and three versus five weekly sessions. However, caution is warranted with the power-related results of this study because the main aims of the study were related to cardiorespiratory endurance in well-trained youth endurance athletes. Additionally, a training frequency of 5 days per week may not be desirable and is likely unrealistic and for most youth athletes. A more recent study investigated one versus twice-weekly plyometric training frequencies across 8 weeks in pre-pubertal soccer players and revealed no differences between training frequency for CMJ, SJ, and RSI in the drop-jump

(24). Interestingly, the weekly plyometric training volume (foot contacts) was equal in both groups which suggests there is no added benefit from performing two plyometric sessions per week and that a once-weekly plyometric training frequency may be optimal for improving athletic performance in children. Therefore, a lower training frequency of one day per week is likely more desirable in adolescents in order to maximize training response with minimal dose while avoiding non-functional overtraining or overreaching. Additionally, a more cautious approach to training frequency ensures for sufficient recovery time to induce training adaptations while also allowing for normal growth and maturation processes to occur. Cumulatively, the optimal frequency for improving power in most children may be one weekly session whereas adolescents will likely benefit from between 2-3 weekly sessions. It should also be mentioned that individuals with a greater training age and level of strength will likely warrant a greater frequency to induce power adaptations (299).

2.4.4.5 Duration

Youth training interventions have a mean duration of around 10 weeks for both traditional RT and plyometric training programmes according to recent systematic-reviews and meta-analyses (13, 134, 172, 242). The *duration* of a training programme, which typically refers to the length of an intervention in weeks, is a critical variable for all interventions. Consequently, training induced adaptations from short-term training interventions (< 24 weeks) were reported to peak between 9-12 weeks in both traditional resistance training (RT) and plyometric training. A review by Lesinski et al. (172) reported that the effects of training interventions >23 weeks elicit larger increases in muscle strength and power than short-term interventions. However, few studies have examined the effects of long-term training interventions in youth athletes on physical strength and power performance measures (99, 146-148, 274). Traditional strength training and plyometric training was reported to significantly improve sprint-times and countermovement jump (CMJ) height in pre-pubescent males following a 26-week training intervention (99). However, the authors reported that the only traditional resistance training exercises performed were ¼ squats and deep squats performed at body weight or body weight plus light resistance. The only load reported was for weighted vertical jumps where participants used a 3-kg weight throughout the 26-week programme. An earlier training study by DeRenne et al. (69) examined the effects of a 12-week pre-season strength training programme followed by a 12-week in-season maintenance programme in pubescent boys. Although the total duration of training was 24 weeks, progressive increases in volume and intensity were only applied in the first twelve weeks and no increases in weight, volume, or intensity were used during the in-season training protocol. Significant greater increases in bench press 1RM, leg press 1RM, and pull-up repetitions were reported following the first twelve weeks, meanwhile, only a significant increase in bench press 1RM was displayed by participants after the last twelve weeks but was lower than the changes observed during the first twelve weeks. These findings indicate that adolescents need a progressive increase in volume and intensity in order to continuously increase strength beyond 12-weeks.

Numerous two-year strength and plyometric training interventions reported significant positive effects in pre- and post- pubescent males on measures of lower body strength and power (146-148, 274). The authors reported that training load and intensity increased throughout the two-year programmes but correct movement technique was always the focus in training. However, several issues arise from these studies with regards to training adherence and maturity. Training adherence throughout the two years was not reported within the training groups and therefore it is unclear how much the adaptations within strength and power tests can be attributed to training. Secondly, there was no report of biological age and only chronological age was reported at baseline, one-year, and two-years. This complicates interpreting results since it is likely that improved performance can be attributed to both natural growth and maturation as well as training. Regardless, these training studies highlight the trainability of youth athletes of all maturational ages as for participating in long-term training programmes (146-148, 274). A gap in the literature regarding long-term training adaptations in youth pertains to measuring kinetic data that underpins strength and power performance. The strength and power adaptations from previous long-term interventions are measured using traditional tests that provide only external performance measures such as repetition-max (RM) or jump height (69, 99, 148, 274). Currently, no data exists on the effects of long-term training on strength and power performance via isometric and dynamic forms of testing.

2.4.5 Short-term training adaptations

Traditional resistance and plyometric training is likely to enhance strength and power performance in youth athletes beyond that which can be observed from natural growth and maturation (88, 94, 95, 206). Numerous short-term training studies have demonstrated positive changes to strength and power adaptations in youth athletes (71, 90, 94, 184, 193). However, there is variation between the adaptations experienced by youth athletes of different biological maturity status in response to training (212, 221). A recent meta-analysis by Moran et al. (219) indicated that strength adaptations are sensitive to maturity status, and that short-term resistance training benefits circa- and post-PHV males more than children. Previous meta-analyses (172, 242) and comparative training studies (72, 212, 272) have supported this claim and reported smaller effect sizes for absolute strength in pre-PHV males that undergo the same resistance training as older cohorts. It should be noted that pre-adolescent boys are able to significantly increase muscular strength but are undermined by a

limited hormonal profile which is not conducive for enhancing strengths to a similar degree as older boys (13, 88, 257). It is believed that because pre-adolescents have a limited ability to increase muscle size their strength adaptations from resistance training are primarily due to adaptations to neural mechanisms such as increased motor-unit recruitment (241). Interestingly, it has been reported that relative strength gains can be similar and larger to circa- and post-PHV cohorts when bodyweight is controlled for (22, 242).
Given that children depend on neural factors to display strength, it has been suggested that resistance training in children can be incorporated along neuromuscular training (12, 87, 90) to induce adaptations to jump performance and motor competency (72, 73, 188, 249). A meta-analyses by Behringer et al. (12) reported that short-term resistance training was more effective for improving motor performance in children than adolescents. Therefore, training gains from short-term training adaptations are primarily underpinned by neural adaptations. However, further research is warranted due to inconsistences in training studies comparing children and adolescents for estimating biological maturity or the report of only chronological age. There is also a gap in the youth literature for measuring how short-term resistance training affects adaptations to kinetic variables which underpin strength and power performance.

There is a heightened sensitivity to resistance training during and after PHV due to an increased hormonal profile and changes to muscle architecture which supports greater muscular strength and power adaptations to occur (10, 88, 250, 251). Therefore, the synergistic effect between advanced maturity and resistance training adaptations facilitate greater force production and rates of force production in circa- and post-PHV males which can be observed during tests of absolute strength and power (61, 212, 269, 272, 302). An increase in resistance training volume has been suggested to be beneficial for enhancing strength and power adaptations during and after PHV as long as correct technique can be maintained (219, 233, 282). Despite increased trainability in adolescents, an increase in training intensity and volume for adolescents with a low training is not advised and can result in a lower ceiling of adaptation (89, 179). Additionally, it is also important to consider that there is a higher susceptibility to overuse injuries if a rapid increase in volume of exercise is undertaken by males during PHV (82, 226, 228). Gabbett et al. (112) reported that maturity related differences exist between circa- and post-PHV elite junior rugby cohorts following a 10-week high intensity resistance training programme. Larger increases were reportedly displayed by the circa-PHV group for upper body muscle endurance while the post-PHV cohort had significantly larger increases in lower body muscular endurance. A training study by Meylan and colleagues (212) reported similar findings where a larger training effect was observed with advancing maturity for squat 1RM, maximal force, and maximal velocity.

Power adaptations following resistance training interventions have been demonstrated in previous systematic reviews (134, 242) and training studies (133, 159) to be effective in youth athletes of all maturational stages. However, adaptations to athletic performance have been reported to be greater when adolescents during and after PHV use combined resistance and plyometric training protocol (97, 159, 188, 303) as opposed to plyometric-only training (39, 206, 263). Interestingly, when plyometric-only training is administered there are greater adaptations to vertical jump height in pre-PHV and post-PHV cohorts in comparison to circa-PHV males (220, 221). One limitation to the current paediatric training literature is that classifications of maturation are commonly reported using chronological age. Also, the effectiveness of training studies is often explained by the principle of specificity and different moderator variables such as training frequency, intensity, and volume of exercise will influence training-induced adaptations. Therefore, variations in training protocols which have different variables is likely to induce different training adaptations in cohorts.

2.4.6 Long-term training adaptations

There are limited studies which have examined the effects of long-term training studies on adaptations to strength and power in youth athletes. A recent meta-analyses (172) determined that superior strength and power adaptations are observed in youth following training interventions ≥ 24 weeks. However, the weighted means of all studies revealed that a ≥ 24-week training period was similar to a 9-12 week training period for improving vertical jump height using conventional resistance training (172). However, caution is warranted interpreting these results due to the scarcity of literature for vertical jump performance following long-term training studies (99, 148). Unfortunately, several long-term youth training studies have included periods where training volume was reduced or maintained which is likely to hinder any gains in explosive strength and power (69, 275). A 1-year sport-specific training programme reportedly decreased sprint times and standing long-jump distance in 9-year old children (120). The authors reported that training intensity and volume increased throughout the intervention using RPE scales after sessions and duration of each training session, respectively. The specific exercises and use of loads beyond body weight were unreported and therefore it is unclear what type of training was performed within the pre-pubertal cohort. Several studies have utilized a two year training interventions on absolute measures of strength, vertical jump height and sprint speed in youth athletes (146-148, 274). Keiner et al. revealed that two cohorts of 9-10 and 11-12-year old boys did not improve SJ, CMJ, or DJ height from baseline to 1 year, but improved from 1-year to 2 years in those jump tests. It was suggested that this may be due to a focus on movement quality within the first year which resulted in low volume and intensity. This suggests that greater adaptations are likely to occur in children with at least a one-year training age.

Owing to the literature, one limitation within the adaptations from long-term training interventions is that resistance training parameters are not consistently reported. Thus, it is more difficult to determine how gains in muscular strength and power were influenced when training variables such as exercises, loads, volume, intensity were not reported. Another limitation is that none of the current long-term training studies in the literature have reported biological maturity data within their cohorts. Additionally, due to the duration of these training intervention it is difficult to differentiate between the magnitude of training responsiveness versus the adaptations resulting by natural growth and maturation alone. Further long-term research is needed in order to which accounts for the changes experienced during maturation.

CHAPTER 3 PRELUDE

Chapter 2 showed how proficient movement competency is an essential aspect of all LTAD programmes and likely underpins displays of strength and power (12, 105). Previous assessment tools for examining movement competency in youth are time consuming and require rating of multiple movement patterns (49, 50). Assessing competency in a single movement pattern such as the back-squat which encompasses strength, stability, and mobility is a more practical method for measuring movement competency for coaches. Previous literature has also suggested that neuromuscular training can successfully improve motor competency and appears to be more important to develop in young children before reaching the adolescent growth spurt (87, 92, 228). Therefore, the first study sought to determine how four weeks of neuromuscular training influences movement competency in the back-squat assessment (BSA) for pre- and post-PHV males while also determining the intra-rater reliability of the BSA.

CHAPTER 3 – The effects of a 4-week neuromuscular training programme on movement competency during the back-squat assessment in pre- and post- peak height velocity male athletes

3.1 INTRODUCTION

Movement competency reflects the proficiency displayed by an individual during goal-directed human movement (260). Greater movement competency in children is associated with athletic (87, 176) and health related benefits (153, 190). Increased movement competency during childhood also increases the likelihood of individuals accruing greater quantity of physical activity during adult life (268). Additionally, the magnitude of associations between motor competency and other fitness qualities such as muscle strength (219), sprint speed (210, 221), and lower body power (172, 221) appear to increase from childhood into adolescence (260).

During childhood, the neuromuscular system is highly plastic as evidenced by the malleability and strengthening of neural pathways (35, 114), and offers the greatest opportunity for motor skill acquisition (177, 227, 228). Consequently, leading international consensus advocates the use of neuromuscular training to help children improve their fundamental movement competency early in life (176). Neuromuscular training utilizes a range of training modes including resistance training, plyometrics, dynamic stability, core strength development, and speed and agility training to enhance movement skill competence, physical fitness, and to target movement limitations or deficits (228). While neuromuscular training improves muscle strength, muscular endurance, lower body power and cardiorespiratory fitness in youth populations (87), research has yet to examine its effects on quality of movement.

Numerous assessment tools are available to rate movement competency (138) and assess injury-risk (107, 259); however, some of these screens are time-consuming and equipment intensive. Similarly, some athletic training programmes may only choose to assess certain criteria within a given screening tool. Thus, practitioners often adopt abbreviated versions of movement screens, assessing proficiency in a smaller number of ‘key’ athletic movements (43). The squat movement is an example of a primal movement pattern in which youth athletes are required to display neuromuscular control, strength, stability and mobility throughout the body (177, 230). Literature also indicates that mastery of the squat and other fundamental movement skills may offer multiple long term physical and cognitive benefits (87, 146, 192, 236, 274).

The back squat assessment (BSA) is a novel screening tool that was developed to enable practitioners to assess competency in squatting (230). Consisting of a 10-point scoring criteria, the BSA serves as a practitioner tool to identify functional deficits in the squat pattern from which targeted training exercises can be introduced to enhance technique and movement quality (167). While the BSA can provide useful insights into movement competency of young athletes, to date no empirical data exists that has determined its validity as a screening tool or its sensitivity to detect meaningful changes in performance following neuromuscular training interventions. Therefore, the aim of this study was to 1) determine the intra-rater reliability of the BSA as a screening tool in pre- and post-peak height velocity (PHV) boys, and 2) determine the effects of a short-term, four-week neuromuscular training intervention on movement competency in the BSA.

3.2 METHODS

3.2.1 Experimental approach to the problem

Using a within-group approach, intra-rater reliability was determined by rating a pre-PHV and post-PHV group performing the BSA on separate occasions. The same videos were rated by the same rater on three separate occasions to assess reliability of total score and all individual rating criteria in both maturity groups. A between-groups design was used to determine the effects of a four-week neuromuscular training intervention on back squat movement competency. Participants were split into four groups; pre-PHV experimental group, pre-PHV control group, post-PHV experimental group, and post-PHV control group. The experimental groups completed four weeks of a twice-weekly neuromuscular training programme. All participants were screened in the BSA before and after four weeks.

3.2.2 Subjects

A total of 48 elite male youth cricketers between the ages of 10-17 volunteered to take part in the study and were recruited from a professional county cricket academy in the United Kingdom. Participants were separated by maturity offset with 26 pre-PHV and 22 post-PHV athletes. Subsequently, the maturity groups were randomly sub-divided into an experimental (EXP) and control (CON) group for the integrative neuromuscular training intervention (Table 3.1). None of the players reported injuries at the time of testing and all participated regularly in cricket training sessions but no formal strength and conditioning activities. Parental consent and participant assent were collected before the commencement of testing. Ethical approval was granted by the institutional research ethics committee in accordance with the declaration of Helsinki.

Table 3.1 Descriptive statistics (mean ± SD) for each group.

	Age (years)	Height (cm)	Mass (kg)	Maturity Offset (years)
Pre-PHV EXP (n=15)	11.2 ± 0.7	147.8 ± 5.6	39.8 ± 8.9	-2.2 ± 0.6
Pre-PHV CON (n=11)	11.6 ± 0.6	148.5 ± 6.8	42.2 ± 6.6	-2.0 ± 0.4
Post-PHV EXP (n=11)	15.4 ± 0.9	171.9 ± 8.4	64.4 ± 9.2	1.3 ± 1.3
Post-PHV CON (n=11)	14.5 ± 0.8	170.5 ± 11.9	61.6 ± 12.9	0.7 ± 1.1

3.2.3 Procedures

3.2.3.1 Anthropometrics

All participants were measured for standing height, sitting height, leg length, mass, and maturity offset during baseline testing. Standing and sitting height were measured using the nearest 0.1 cm with the use of a stadiometer (SECA, 321, Vogel & Halke, Hamburg, Germany). Participants sat on a 50 cm box with feet elevated off the ground when being measured for sitting height. Leg length was determined by subtracting sitting height from standing height. Body mass was measured to the nearest 0.1 kg on an electronic scale (SECA, 321, Vogel & Halke, Hamburg, Germany). These data were then entered into a sex-specific regression equation to calculate a maturity offset to estimate whether they were pre- or post-PHV (215). The cut-off for maturity status in the pre- PHV group was less than -1.00 years and greater than 1.00 years for the post-PHV group. Any participants with a maturity offset that fell between these cut-off ranges (i.e. -1.00 to +1.00) were removed from the final statistical analyses.

3.2.3.2 Back squat assessment

Prior to all testing sessions, participants performed a dynamic warm-up consisting of arm swings, bear crawls, high skips, high knees, side lunges, reverse lunges, single leg stick and land, and sprints. Each movement within the warm up was performed for a distance of 20 meters. Participants performed 5 sprints with increasing intensity at 50%, 75%, 90%, and twice at 100%, with 60 seconds rest between each run. During the BSA, participants were instructed to perform ten continuous squat repetitions in place with a wooden dowel on their back as per previously published guidelines (Myer et al., 2014). Participants were instructed to position their feet slightly wider than hip-width and to descend until thighs were parallel to the ground. Each participant completed the BSA twice, with one minute between each trial. Aside from the standardized script proposed by Myer and colleagues (230), no other verbal cues or advice were given to participants before or during the testing sessions. All ten repetitions were recorded at 30 f/s using two 2D high definition cameras (Apple iPad, California, USA) positioned at a height of 0.70 m and at a distance of 5 m from the center of the capture area in both frontal and sagittal planes. Scoring of BSA performance was conducted retrospectively using a 10-point criteria, with one point given for each technical fault (230). The 10-point criteria consisted of: head position, thoracic position, trunk position, hip position, frontal knee position, tibial progression angle, foot position, descent, depth, and ascent. During the scoring process, each of the 10 criteria were analyzed and a deficit was scored if present during two or more repetitions. Movement variation between repetitions indicates inefficient motor-unit coordination and is likely due to factors such as muscle weakness, strength asymmetry and joint instability (230, 278). Therefore, a deficit occurring twice or more highlights movement variability by the participant in the BSA (230). Deficits were tallied to provide a total score, with higher total scores indicative of poorer squat technique. The lowest total score for each participant was used for statistical analysis. To determine intra-rater reliability, the video footage taken at the start of the four-week intervention for both EXP training groups were viewed and scored on three separate occasions by the same rater. Scoring of the videos was separated by one month to reflect the length of time and potential associated noise of the subsequent short-term intervention. On each occasion, videos were viewed in a randomized sequence to avoid rater bias. The variables recorded for each participant were BSA total score and scoring of the individual criteria between scoring sessions 1-2 and sessions 2-3.

3.2.3.3 Neuromuscular training intervention

Following baseline testing, both EXP groups commenced the neuromuscular training intervention that required them to complete 1-hr training sessions, twice-weekly for four-weeks. All training sessions were led and supervised by a National Strength and Conditioning Association Certified Strength and Conditioning Specialist. The programme consisted of a 10-minute dynamic warm up that incorporated multiplanar movement, mobility, coordination, balance, plyometrics and running with the goal of raising body temperature and was similar to the warm up completed for the BSA protocol. Following the dynamic warm up, participants performed primary exercises focusing on muscular power, lower body strength, upper body strength, and core strength. The participants were familiarized with every exercise within the neuromuscular training programme and performed a warm up set prior to each exercise. Each training session aimed to develop the neuromuscular capabilities of multiple muscle groups through a combination of coordination, plyometrics, and resistance training. Volume increased incrementally as participants became more accustomed to the exercises. New exercises with similar movement patterns were introduced for both groups during week three to facilitate ongoing motor learning. Exercises included the use of body weight, barbells, dumbbells, resistance bands, and weighted plates (Table 3.2 and 3.3).

Despite differences in exercise selection, both pre- and post-PHV EXP groups followed a similar training regimen outline. Participants performed between 3-4 sets of 10-15 repetitions for each primary exercise as per published recommendations (176, 177). Due to the low training age of all the participants, higher repetitions were prescribed for practice as well as to provide opportunities for feedback. When appropriate, relevant feedback on the movement quality of each exercise was given to participants to promote kinaesthetic awareness and increase their understanding of correct technique. Instruction and technical correction of the squatting movement pattern were included in each session. Participants were encouraged to increase loads on an individual basis where exercise technique could be performed adequately for 10-15 repetitions. External load was increased where competency was retained throughout the set; however, if a participant displayed poor technique then the load was reduced.

Table 3.2 Neuromuscular training programme for pre-PHV group week 1-4.

	Session 1				Session 2			
Week	Exercise	Sets	Repetitions	Rest	Exercise	Sets	Repetitions	Rest
1	Single Leg Hops	3	10 each	90s	Box Jumps	3	5	90s
	Push Ups	3	10	90s	Face pulls w/ band	3	10	90s
	Body weight squat	3	15	90s	DB Goblet Squat	3	10	90s
	Side planks	3	30s each	90s	Planks	3	30s	90s
2	Single Leg Hops	3	10 each	90s	Box Jumps	4	5	90s
	Push Ups	3	10	90s	Standing Band Rows	4	10	90s
	Body Weight Squat	3	15	90s	DB Goblet Squat	4	10	90s
	Side Planks	3	30s each	90s	Planks	4	30s	90s
3	Split Jumps	3	10 each	90s	Broad Jumps	3	5	60-90s
	DB suitcase carries	3	15m each	90s	Back Squat	3	12	60-90s
	Squat w/ band	3	12	90s	Inverted Rows	3	10	60-90s
	Shoulder Taps	3	10 each	90s	Deadbugs	3	10 each	90s
4	Split Jumps	4	10 each	90s	Broad Jumps	4	5	90s
	Squat w/ band	4	12	90s	Back Squat	4	12	90s
	DB suitcase carries	4	15 m each	90s	Inverted Rows	4	10	90s
	Shoulder Taps	4	10 each	90s	Deadbugs	4	10 each	90s

Table 3.3 Neuromuscular training programme for post-PHV group week 1-4.

	Session 1				Session 2			
Week	Exercise	Sets	Repetitions	Rest	Exercise	Sets	Repetitions	Rest
1	Back Squat	3	10	90s	Bench Press	3	10	90s
	Standing Band Row	3	10	90s	DB Split Squats	3	10 each	90s
	Hurdle Jumps	3	10	90s	DB Rows	3	10 each	90s
	Shoulder Taps	3	10 each	90s	Paloff Press	3	15 each	90s
2	Back Squat	4	10	90s	Bench Press	4	10	90s
	Pull Ups	4	5 to 10	90s	DB Split Squats	4	10 each	90s
	Hurdle Jumps	4	10	90s	DB Rows	4	10 each	90s
	Shoulder Taps	4	10	90s	Paloff Press	4	15 each	90s
3	Back Squat	3	15	90s	Walking DB Lunges	3	10 each	90s
	Overhead Press	3	10	90s	Hip Thrusts	3	10	90s
	Split Jumps	3	10 each	90s	TRX Rows	3	12	90s
	Side Planks	3	30s each	90s	Weighted Bear Crawl Hold	3	30s	90s
4	Back Squat	4	12	90s	Walking DB Lunges	4	10 each	90s
	Overhead Press	4	10	90s	Hip Thrusts	4	10	90s
	Split Jumps	4	10 each	90s	TRX Rows	4	12	90s
	Side Planks	4	30s each	90s	Weighted Bear Crawl Hold	4	30s	90s

3.2.4 Statistical Analysis

To determine intra-rater reliability, baseline BSA data for both maturity groups were scored on three separate occasions, from which two-way mixed effects intraclass correlation coefficients (ICC) were determined to assess the rank order repeatability of BSA total score (assessment 1 vs 2 and 2 vs 3) (157). Thresholds for ICC values were classified as poor (< 0.50), moderate (0.50 to 0.75), good (0.75 to 0.90), and excellent (> 0.90). Cohen's kappa (κ) coefficient was used to determine the accuracy of scoring for each individual criterion within the BSA across all three assessments, with the strength of agreement classified as: >0.8, very good; 0.6-0.8, good; 0.4-0.6, moderate; 0.2-0.4, poor; <0.2, very poor (204). Descriptive statistics were calculated for all BSA variables for both pre- and post-training intervention data. The Shapiro-Wilk test was used to examine the distribution of BSA total score for each of the EXP and CON groups, which was determined to be non-parametric across all cohorts. As a result, median BSA total score was subsequently reported. Wilcoxon signed rank test was used to determine each group's training responsiveness and within-group differences for BSA total score. The Mann-Whitney U test was used to determine between-group differences for BSA total score. Effect size (*ES*) was calculated for post BSA total score between-groups using Microsoft Excel (v. 2016 Redmond, WA, USA) in order to interpret the magnitude of effects according to Cohen's *d* statistic, using the following threshold: <0.20 (trivial), 0.20-0.59 (small), 0.60-1.19 (moderate), and > 1.20 (large) (291). All descriptive data and statistical analyses were computed using SPSS (V.24 Chicago, IL, USA), with statistical significance for all tests set at an alpha level of $p < 0.05$.

3.3 RESULTS

3.3.1 Reliability

ICC for BSA total score revealed excellent agreement for both maturity groups across all sessions (*Table 3.4*). Cohen's kappa values showed greater variability in the pre-PHV group than the post-PHV group for the BSA individual criteria. Between sessions 1-2 in the pre-PHV group, trunk position had the lowest agreement (0.31). However, the three criteria with perfect agreement (1.00) were head position, foot position and depth. The remaining criterion had moderate to very good agreement in sessions 1-2. Between sessions 2-3, the lowest agreement for the pre-PHV group were in the foot position (0.42) and ascent (0.44) criteria, while all other criterion having good to perfect agreement. The post-PHV group displayed good to perfect agreement for all criteria across all sessions (*Table 3.5*).

Table 3.4 Intra-class correlation (95% confidence intervals) for BSA total score across all sessions.

	Session 1-2	Session 2-3
Pre-PHV	0.81 (0.68 – 0.96)	0.98 (0.96 – 1.00)
Post-PHV	0.97 (0.94 – 1.00)	0.97 (0.95 – 1.00)

Table 3.5 Kappa values for all criteria in the BSA across all sessions.

	Session	Head	Thor.	Trunk	Hip	Knee	Tibia	Foot	Desc.	Depth	Asc.
Pre-PHV	1-2	1.00	0.87	0.31	0.76	0.67	0.72	1.00	0.60	1.00	0.58
	2-3	1.00	0.73	0.87	1.00	0.82	0.87	0.42	0.71	0.86	0.44
Post-PHV	1-2	1.00	0.79	0.81	0.81	0.62	1.00	1.00	1.00	1.00	1.00
	1-3	1.00	0.79	1.00	0.81	1.00	1.00	1.00	0.82	0.79	1.00

3.3.2 Pre- to post-intervention total BSA score

No significant differences were observed in pre-testing BSA total score between the EXP and CON groups in either maturity cohorts (*Table 3.6*). The EXP post-PHV group had a large difference (*ES* = 0.69) in comparison to the CON group for BSA total score whereas the EXP pre-PHV group had a medium difference (*ES* = 0.43) compared to the CON group during post- testing. Wilcoxon signed rank test revealed large significant within-group differences ($p < 0.05$) in median BSA total score for the EXP pre-PHV cohort (5.0 to 3.0) and EXP post-PHV (2.0 to 1.0). No significant within-group differences ($p > 0.05$) were observed in the CON pre- or post-PHV cohort. Data showed a significant reduction in post-testing BSA total score for the EXP groups but not the CON groups ($p < 0.05$). Following the intervention, 67% of the participants in the EXP pre-PHV cohort decreased BSA total score, with only 13% recording a worse score. In comparison, 45% of the CON pre-PHV cohort reduced BSA total score with 36% recording a worse score. For the EXP post-PHV group, 91% of the participants reduced BSA total score, whereas, the CON post-PHV had only 9% reduce BSA total score and 73% recording no change, and 18% recording a worse total score.

Table 3.6 Median BSA total scores with interquartile ranges (25th to 75th percentiles) after 4-week training intervention.

	Pre BSA total score	Post BSA total score	Between group difference at post testing (ES)	Within group change at post testing (ES)
Pre-PHV exp	5.0 (3.0 to 5.0)	$3.0^{*\ \beta}$ (2.0 to 4.0)	$d = 0.43$	$d = 0.68$
Pre-PHV control	5.0 (4.0 to 5.0)	4.0 (3.0 to 6.0)		
Post-PHV exp	2.0 (2.0 to 4.0)	$1.0^{*\ \beta\ \theta}$ (1.0 to 2.0)	$d = 0.69$	$d = 0.82$
Post-PHV control	4.0 (3.0 to 5.0)	4.0 (2.0 to 5.0)		

* Significant difference from pre-testing to post-testing within-group ($p < 0.05$)
β Significant difference between EXP and CON group total score ($p < 0.05$)
θ Significant difference in post-BSA total score between EXP pre-PHV group ($p < 0.05$)

3.3.3 Pre- to post-intervention individual BSA criterion scores

Descriptive statistics for the sum of individual criterion deficits indicate which criteria contribute to the decrease of BSA total score in both the pre-PHV (*Figure 3.1*) and post-PHV (*Figure 3.2*) EXP groups. The greatest improvements within the pre-PHV cohort were observed in hip position (12.0 to 7.0), trunk position (11.0 to 6.0), and thoracic position (9.0 to 5.0). However, the criterion that increased for sum of deficits were head position (0.0 to

4.0) and depth (9.0 to 10.0). The greatest improvement in scores for the post-PHV group were hip position (7.0 to 0.0) and descent (6.0 to 1.0) with no increases in any criterion.

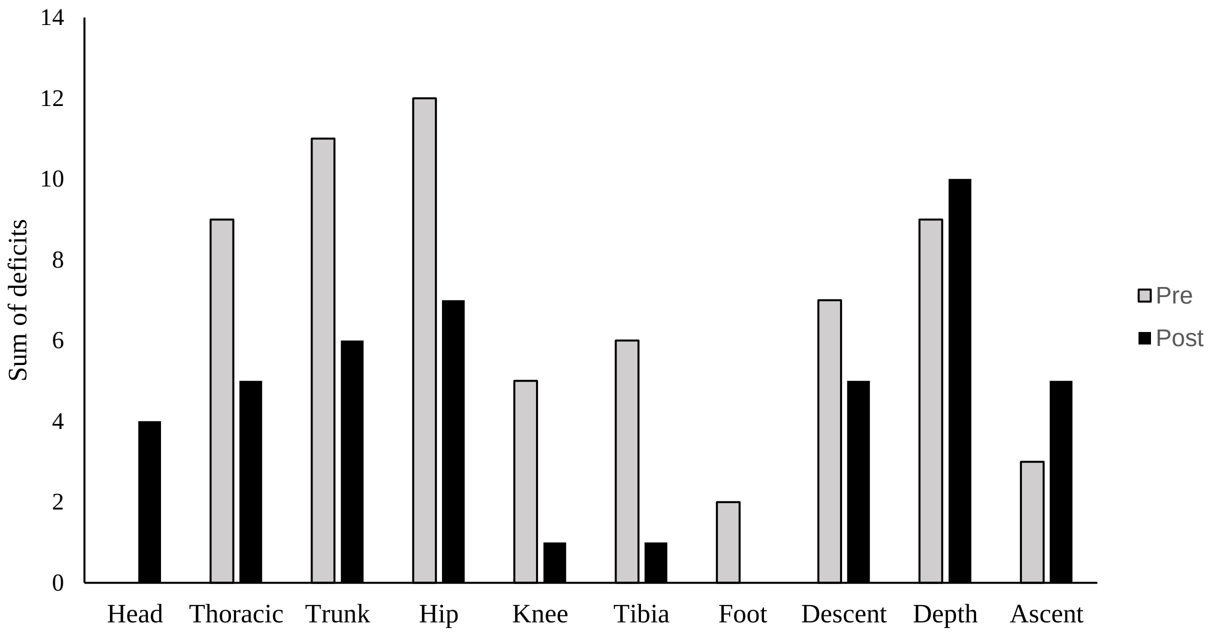

Figure 3.1 Sum of deficits observed for each individual criterion in the BSA for the pre-PHV group from pre to post testing.

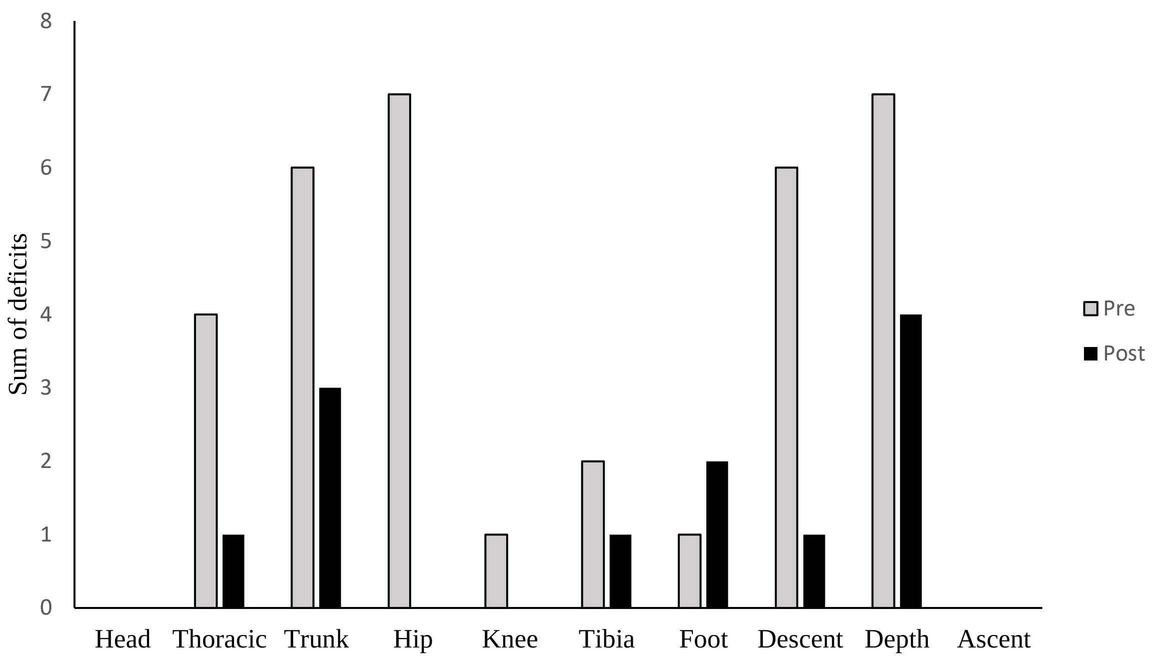

Figure 3.2 Sum of deficits observed for each individual criterion in the BSA for the post-PHV group from pre to post testing.

3.4 DISCUSSION

The current study has reported novel data on the intra-rater reliability of the BSA and the effects of a short-term neuromuscular training intervention on BSA competency in young male cricketers. Intra-rater reliability for BSA total score had very strong agreement across all testing sessions in both maturity groups; while ratings for the ten individual criteria were more reliable in the post-PHV group than the pre-PHV group. Additionally, BSA total score significantly improved within-group for both pre- and post-PHV experimental groups following the neuromuscular training intervention, which were significantly greater than any changes seen in the control groups. Hip position was the criteria with the greatest number of deficits at baseline, but also showed the greatest improvement in both maturity groups following training. Cumulatively, the findings of this study indicate that the BSA was a reliable screening tool for the individual rater when assessing movement competency in young male athletes and that improvements in movement competency can be achieved in four weeks.

Despite ICC levels for BSA total score being good and very good for both maturity groups, less agreement was observed for the individual criteria. Distinct differences in individual criteria were evident between the maturity groups, with kappa values ranging from poor to very good between sessions 1-2 and moderate to very good in sessions 2-3 for the pre-PHV group. This indicates that an additional familiarization session may be needed for raters when rating a pre-PHV cohort. Meanwhile, only one criterion from the post-PHV group had moderate agreement across all sessions, with all other criteria displaying good to very good agreement. The greater variance in kappa values indicate that there was more variability when rating the BSA performance in the pre-adolescent group. Previous research has noted that pre-adolescent children do not have fully mature sensorimotor function, which can affect neuromuscular and postural control during motor tasks (248). As a result, children show less stability during dynamic movements requiring posture and balance, which may explain why the pre-PHV group scored higher on the BSA than the post-PHV group. Despite the principal researcher rating the same trials on three occasions, having less stability during dynamic movements would contribute to more variability between repetitions, ultimately making the scoring process more challenging. It should also be noted that test-retest reliability of the BSA was not established prior to the intra-rater reliability for either maturity groups and therefore typical fluctuation within the BSA screen is unknown. Previous literature has demonstrated that movement variability is greater in pre-adolescence when compared to more mature youth athletes (186, 248, 259). Greater variance in performance by pre-adolescent children arises even in static tests such as the isometric mid-thigh pull (216). This tendency to display heightened movement variability by pre-PHV children may explain the lower agreement between sessions for some individual criteria within the BSA and underlines the potential need for a familiarization session by raters before scoring less mature young athletes.

Both EXP groups significantly improved BSA movement competency after the training intervention. A greater percentage of the EXP post-PHV group (91%) reduced BSA total score than the EXP pre-PHV group (67%) from baseline to post testing. However, the pre-PHV cohort had a greater reduction in BSA total score compared to the post-PHV group which may indicate a greater responsiveness to the training intervention. The greater reduction in BSA total score may also in part be due to the post-PHV group scoring lower at baseline and thus having less potential for improvement. It has been previously reported that exposing pre-PHV children to integrative neuromuscular training can have long lasting positive effects on movement competency due to the high ‘plasticity’ of their brains (87, 228, 229). Children that are regularly exposed to fundamental movements will likely enhance motor skill learning and the child is more likely to retain these skills throughout maturation (228). The findings of the current study would support the notion that neuromuscular training may be most effective with pre-adolescent children, which may help reduce the negative influence of the adolescent growth spurt.

A meta- analysis by Behringer et al. (2011) reported that pre-PHV athletes improved motor competency following resistance training significantly more when compared to post-PHV athletes (12). Yet, this gives no indication on the rate of motor skill development or the acute responsiveness to training in youth when exposed to neuromuscular training. Faigenbaum et al. (87) did report an improvement in movement competency in young children following an 8-week training intervention, however, there was no comparison with a post-PHV group. Similarly, there have been neuromuscular training interventions which have improved movement quality in solely post-PHV athletes after six-weeks (207, 236). While four-weeks was enough time to elicit an improvement in the current study, it appears that pre- and post-PHV athletes may differ in their responsiveness to neuromuscular training and the development of movement competency. Existing research has shown improvements in reactive strength index (RSI) and leg stiffness in youth athletes after four-weeks of training, albeit in plyometric performance (185). Cumulatively, it appears that four weeks may be the minimal amount of time to observe improvements in movement competency in youth athletes following a structured neuromuscular training programme.

There may be specific individual criteria which caused the improvement in BSA total score for both EXP groups. Both EXP groups displayed greater reductions in the sum of deficits for thoracic, trunk, and hip position following the training intervention. Basic training principles dictate that untrained individuals will see the greatest rate of improvement (38, 162, 180). Given that these criteria were the most failed at baseline, they also had the greatest potential for improvement and contributed to the reduced BSA post-testing scores. Hip position deficit was the most common occurrence in both EXP groups for baseline testing, which corroborates with a recent systematic review that reported youth cricketers having poor lumbo-pelvic-hip movement control as a result of asymmetries formed during cricket-specific tasks such as bowling (106). Following the intervention, the pre-PHV group recorded no deficit for foot position criteria, indicating the group had altered movement mechanics during the descent of a squat. A common error in foot position during the squat is raising the heels due to a lack of ankle joint mobility during dorsiflexion (230). However, keeping the entire foot in contact with ground during descent may inherently affect the descent, depth, and ascent criteria if inadequate dorsiflexion mobility still exists. At post testing the pre-PHV group increased the number of deficits observed in ascent by two and only reduced descent criteria by one. However, the post-PHV group decreased the descent criteria by five and had no change in ascent. Similarly, different outcomes for squat depth criteria were observed during post-testing, with the pre-PHV group increasing in the number of deficits observed after the intervention and the post-PHV group decreasing the occurrence by three. There may be multiple reasons for this, such as lack of mobility, lack of lower body strength, and/or lack of kinaesthetic awareness (167). The increase in the depth deficit occurring for the pre-PHV group during post testing may be due to natural movement variability and/or as per BSA guidelines, an absence of external load (230). This may inherently cause subjects to change their squat tempo by ascending and descending more quickly, which may have resulted in less kinaesthetic awareness for reaching squat depth during post testing.

The current study provides a novel contribution to the literature that shows improvements in BSA movement competency can be realized in young athletes following an acute neuromuscular training programme of just four weeks. A meta-analysis by Behringer et al. (12) did not report an optimal training dose-response for improving motor performance in youth, but did report the greatest results arrive from a combination of plyometric and resistance training (12). The results of the current study corroborate the Behringer (12) findings because both maturity groups improved motor competency when given neuromuscular training programmes containing plyometric, resistance, and balance training. However, the pre-PHV group had a greater response to the training intervention due to a larger change in total score from 5.0 to 3.0, whereas the post-PHV group only had a change score of 2.0 to 1.0. While the post-PHV group also significantly improved squat competency following the intervention, their lower responsiveness to the training programme indicates that maturity status and baseline may affect trainability and the rate of motor skill development in response to neuromuscular training.

One limitation of the current study is the short training period and the lack of information regarding the retention of back squat movement competency following training. While consistent neuromuscular training can have long lasting positive effects on movement competency (228), it is unclear how a longer and more chronic training dose would influence improvements in back squat competency for both maturity groups. Future studies could investigate the retention of movement competency in the BSA following a long-term neuromuscular training intervention. Another limitation is that the two cohorts received separate training programmes. However, the training programmes were designed with the maturity status and training age of the pre- and post-PHV cohorts in mind, thereby ascribing to existing long-term athletic development programming guidelines (180). *Finally*, the current study was that intra-rater reliability was only established and that inter-rater reliability remains unknown. However, from a practical perspective it is suggested that any rater involved in using the BSA to assess movement competency in young athletes should establish their own reliability prior to administering the screen.

3.5 PRACTICAL APPLICATIONS

The BSA is a time-efficient test to administer in pre- and post-PHV male athletes as means for measuring movement competency and can detect changes in competency following short-term training interventions. However, reliability of the BSA total score indicates that rating is less robust when scoring pre-PHV athletes and an additional familiarization trial is recommended for practitioners before scoring BSA performance in this population. Practitioners should be cognizant that competency in the BSA in both pre- and post-PHV males can be improved in as little as four weeks when exposed to a neuromuscular training intervention. However, a greater improvement in movement competency was seen in the pre-PHV group when compared to the post-PHV group, which indicates a heightened training responsiveness in less mature athletes. Data from the current study showed that hip and thoracic positions were the greatest deficits at baseline in both maturity groups, while also having the greatest reduction following the training intervention. Therefore, coaches working with youth athletes should provide cues that stabilize the hip and thoracic positions during training which can improve overall movement competency. While the current study examined the acute effects neuromuscular training, practitioners should take advantage of the heightened neural plasticity in pre-PHV athletes by using a combination of resistance, plyometric, and balance training as part of a holistic, long-term athletic development programme.

CHAPTER 4 PRELUDE

Chapter 3 provided empirical evidence that four weeks of neuromuscular training effectively improved movement competency in children and adolescents and showed the intra-rater reliability of the BSA tool. Previous literature has indicated that morphological and neuromuscular development as a result of natural growth and maturation typically drives increases movement competency, strength, and power (21, 64, 139, 143, 287, 308). However, these changes are likely non-linear and may be more sensitive to periods around PHV. Since maturation influences force producing capabilities, it is likely that the force-velocity relationship at different areas along the F-V spectrum also changes with natural growth and maturation. Unfortunately, previous literature comparing strength and power between youth of different maturational stages typically have not reported kinetic force-time variables. *Chapter 4* provided novel kinetic force-time variables in the IMTP, squat jump, and countermovement jump which vary across the F-V spectrum. Therefore, this study sought to examine the differences between pre-, circa-, and post-PHV males for squat movement competency, isometric strength, and dynamic jump power.

CHAPTER 4 - Movement competency and measures of isometric and dynamic strength and power in boys of different maturity status

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4.1 INTRODUCTION

Position statements on the long-term athletic development of youth highlight the importance of movement competency, strength, and power for young athletes competing in sport (176, 177). The natural development of such qualities has been reported to typically increase in a non-linear fashion with advancing growth and maturation (140, 222, 225, 302). Additionally, maturation has been purported to be a key determinant for improved overall athleticism in young males for many sports (178, 225, 239, 314). In the absence of physical training, the greatest improvements for strength and power arise during adolescence due to natural physical and physiological changes which lead to increased muscle mass and force producing capabilities (302, 308). As a result, boys that mature earlier than their age-group peers gain both a physical advantage in sport and are more likely to be selected in talent-identification processes over later maturing individuals (118). Therefore, an understanding of how movement competency, strength, and power interacts with natural growth and maturation is required in order to determine meaningful changes with developing athletes.

Studies comparing youth athletes commonly evaluate groups by chronological age which can be a limitation when interpreting athletic performance (51, 182, 221). Because the timing of growth and maturation is highly individualized, large discrepancies in size and strength can arise in youth within the same chronological age (51). As such, evaluating young athletes based on chronological age is likely to advantage mature children because of their size advantage during tests for movement competency as well as isometric and dynamic force production. Studies that examine developmental data by grouping athletes according to biological maturity provide more meaningful insights (215).

Movement competency reflects the proficiency displayed by an individual during goal-directed movements and this ability has been cited as an underlying determinant for athletic performance in youth athletes (140, 228). Previous literature comparing differences between children and adolescents report that more developed individuals generally display greater performance in movement competency, strength, and power tests (72, 73, 221, 302, 308). When comparing squat movement competency between untrained pre- and post-peak height velocity (PHV) males, Dobbs et al. (73) reported more mature boys had greater levels of movement competency than their less mature counterparts. Maturation enhances movement competency due to a more developed neuromuscular system which leads to greater kinaesthetic awareness during athletic movements (228). The onset of puberty also brings about increased physical size and muscle mass, which enable the greater absolute strength typically seen in adolescents (176, 302).

Isometric and dynamic testing in youth athletes provide insight into the natural development across the force-velocity (F-V) spectrum. Determining maximal strength requires an isometric contraction with maximal force with the absence of velocity. Literature on isometric force production has reported that more mature athletes tend to display greater absolute strength than younger athletes primarily due to increased size (80, 222, 302, 308). Allometric scaling provides a normalized methodological approach for performance tests (141) and has been previously used in measurements of full body strength for youth of different body size (30). Brownlee et al. (30)

reported significant increases in strength with maturity between pre-, mid-, and post-PHV youth soccer players, indicating that maturation likely improves force producing capabilities even when data are controlled for body mass. Despite increases in body mass, maturation appears to also improve movement speed and contraction velocity in male youth which contributes to greater power outputs (79, 80). Across different team sports, dynamic tests such as the 30 m sprints, countermovement jump (CMJ), and standing long jump have displayed that more mature individuals perform better than less mature individuals (51, 100, 118, 225). Yet, the kinetic strategy used to outperform less mature individuals is unknown.

Existing data investigating differences between pre- and post- PHV athletes often use field-based or laboratory-controlled tests which only provide absolute measures of strength and power. Data from field-based tests (e.g. 1RM or vertical jumps) are practical for coaches; however, they provide little insight into the mechanical variables which might explain increases in strength and power performance. Alternatively, laboratory-based isokinetic strength testing provides kinetic data, but generally has limited external validity with protocols limited to single-joint movements (79). Few studies have assessed force-time variables across multiple strength and power tests that span the force-velocity spectrum within youth populations. Such data could help determine specific force-time variables that drive athletic performance in youth populations at different stages of maturity and identify those variables that could be targeted synergistically with maturation to enhance athleticism more effectively.

Therefore, the main aim of the present study was to examine differences in movement competency and force-time variables with a range of strength and power tests both between and within cohorts of pre-, circa-, and post-PHV male athletes. A secondary aim was to determine the predictive ability of various force-time variables on squat jump (SJ) and countermovement jump (CMJ) height. It was hypothesized that movement competency, strength, and power would improve with advanced maturity; while jump height would be driven by kinetic variables related to absolute force production and velocity, regardless of maturity status.

4.2 MATERIALS & METHODS

4.2.1 Participants

Two-hundred and six young male cricketers aged 9-17 years at a first-class county cricket club academy in the United Kingdom agreed to participate in the study. No participants had previous experience with strength and conditioning training, screening, or testing prior to the study. Biological maturity status and anthropometric measures are displayed in *Table 4.1*. Players were grouped into discrete bands according to their stage of maturation based on their maturity offset (215) which was determined as number of years from peak height velocity (PHV) according to the following thresholds: pre- PHV= < -1.0; circa- PHV= -0.5 to 0.5; and post- PHV= > 1.0. Participants who recorded a maturity offset between -1 and -0.5 and 0.5 to 1.0 were subsequently removed from the data set to account for the ~6 month reported error in the regression equation (215); therefore, the final sample consisted of 206 players (n = 130 pre-PHV, n = 33 circa-PHV, and n = 43 post-PHV). No injuries were reported during testing and all participants were informed of the risks and benefits of taking part in the study. Parental consent and participant assent were obtained following ethical approval from the Cardiff Metropolitan University research ethics committee in accordance with the Declaration of Helsinki.

Table 4.1 Mean (± SD) values for descriptive details of each maturity groups anthropometric data.

	N	Standing height (cm)	Mass (kg)	Maturity offset (years from PHV)
Pre-PHV	130	148.02 ± 7.72	41.22 ± 7.98	-2.17 ± 0.65
Circa-PHV	33	164.12 ± 5.74*	55.48 ± 8.06*	-0.01 ± 0.36*
Post-PHV	43	175.94 ± 6.96**	70.15 ± 10.54**	1.92 ± 0.68**

* significantly greater than pre-PHV group ($p < 0.001$)
** significantly greater than circa-PHV group ($p < 0.001$)

4.2.2 Study design

This study used a cross-sectional design to determine differences in movement competency, isometric and dynamic strength and power in young male athletes. Participants were classified into one of three maturational groups; pre- PHV, circa- PHV, and post- PHV.

4.2.3 Procedures

4.2.3.1 Back squat assessment (BSA)

During the BSA, participants were instructed to perform ten continuous squat repetitions in place with a wooden dowel on their back as per previously published guidelines (230). All protocols were performed in the same manner as in Chapter 3 of the current thesis. During the scoring process, each of the 10 criteria were analysed and a deficit was scored if present during two or more repetitions. Total number of deficits are tallied to provide a total score, with higher total scores indicative of poorer squat technique. Acceptable intra-rater reliability has been previously reported for the BSA in youth athletes (73).

4.2.3.2 Isometric mid-thigh pull

The isometric mid-thigh pull (IMTP) test was performed on a custom built IMTP testing device using dual Kistler force plates sampling at a frequency of 1000 Hz (type 9287BA, Kistler Instruments AG, Winterthur, Switzerland). In line with previous research, participants were positioned where: feet were hip-width apart, the bar was positioned at mid-thigh, the torso was upright with a neutral spine, hand straps were wrapped around the bar at hip-width, and knee and hip angles were approximately 140° (8, 78). The customized IMTP rig allowed for incremental bar height adjustments of 1 cm to accommodate athletes of different leg length. Once in position, participants were instructed to remove slack from the bar without applying any force into the ground (8). Following familiarization, three maximal effort trials were recorded from each participant with a minimum of 90 seconds rest between each trial for recovery. Each trial was collected for eight seconds, which included a three second countdown and the participants pulling on the bar for five seconds. During the three second countdown, participants were instructed to remain still to optimize stabilization of body weight in order to identify the initiation of the pull. Trials were discounted if participants were unable to remain still or if a countermovement prior to the pull was displayed within the force tracing. All trials and data were analysed on a customized IMTP LabView programme. Force-time variables calculated from the customized software included: absolute peak force (PF_{abs}), allometric scaling ($N/kg^{0.67}$) of peak force (PF_{allo}) (141), time to peak force (tPF), peak rate of force development (PRFD), relative peak rate of force development ($PRFD_{rel}$), peak force at time periods of 0-50 ms (PF50), 0-90 ms (PF90), 0-150 ms (PF150), 0-200 ms (PF200), and 0-250 ms (PF250). Acceptable within- and between-session reliability has previously been reported for this IMTP protocol using young athletes (216).

4.2.3.3 Squat jump

The squat jump (SJ) test was recorded on an AMTI force plate with a sampling rate of 1000 Hz (Accupower, AMTI, Boston, MA, USA). All data were processed using a Butterworth filter. Participants were required to assume a squat position with 90° of knee flexion (243, 273) which was visually observed by the researcher. Once in the squat position, participants were instructed to remain still for three seconds, keep hands on hips, and to not perform a countermovement prior to jumping. Following familiarization, participants performed three maximal trials with 60 seconds rest between jumps. Trials were discounted and repeated if any of the following errors occurred: failure to remain still during countdown, hands were removed off hips, or a visible countermovement was observed from firstly watching the athlete and secondly analyzing the force trace. All trials and data were analyzed using a customized LabVIEW programme and the variables measured included: PF_{abs}, PF_{allo}, jump height, average RFD (RFD_{avg}), relative RFD_{avg}, peak velocity (PV), peak power (PP), relative peak power (PP_{rel}), impulse, PRFD, and time to peak rate of force development (tPRFD). Acceptable reliability has previously been reported for the SJ protocol using youth athletes (181).

4.2.3.4 Countermovement jump

Countermovement jumps (CMJ) were recorded using an AMTI force plate sampling at 1000 Hz (Accupower, AMTI, Boston, MA, USA). All data were processed using a Butterworth filter. In line with previous research, participants were instructed to perform maximal effort jumps with hands remaining on hips throughout to limit the influence of the upper body on jump performance (7). Participants were able to descend to a self-selected depth during the eccentric portion of the jump. The same verbal cues were given before each trial, *"jump as high as you can in 3, 2, 1, go"*. Three maximal effort trials were recorded per participant with a minimum of 60 seconds rest between trials. During the countdown participants remained still to optimize stabilization of body weight and establish a baseline prior to the jump. All trials and data were exported from the Accupower software (Accupower 3.0, Accupower solutions, Boston, MA, USA) and analyzed using a validated automated spreadsheet (40). The variables measured for CMJ analyses were; jump height, reactive strength index modified (RSI_{mod}), PF_{abs}, PF_{allo}, eccentric impulse (ECC_{imp}), duration of eccentric phase (ECC_{dur}), concentric impulse (CON_{imp}), duration of concentric phase (CON_{dur}), PP, PP_{rel}, eccentric power (ECC_{pow}), concentric power (CON_{pow}), and time to take off. Acceptable reliability has previously been reported for the CMJ protocol using youth athletes (213).

4.3.1 Statistical analyses

Descriptive statistics (means ± SD) were calculated for all performance variables for each group (*Table 4.1*). The Shapiro-Wilk test was used to examine normal distribution for all test variables and BSA total score was determined to be non-parametric across all cohorts. Therefore, a Kruskal-Wallis H test with Bonferroni post-hoc analysis was used to determine differences between groups and median BSA total score was subsequently reported. To ensure that ratio scaling had adequately controlled for the effect of body mass on force production, Pearson correlation coefficients (r) were calculated between PF_{rel} and body mass. Correlations between PF_{rel} and body mass was low for the SJ and CMJ tests ($r < 0.12$), suggesting that allometric ratio scaling had adequately controlled for the effect of size on force production. One-way analysis of variance (ANOVA) with Bonferroni post-hoc analysis was used to determine the differences between the three maturity groups for the IMTP, SJ, and CMJ variables. Homogeneity of variance was determined using Levene’s test for equality of variances, and where violated, Welch-ANOVA with a Games-Howell post-hoc was subsequently used. Effect sizes were calculated to interpret the magnitude of between-group effects according to Cohen’s *d* statistic, using the following thresholds: <0.20 (trivial), 0.20-0.59 (small), 0.60-1.19 (moderate), 1.20-1.69 (large), and >1.70 (very large) (44). Regression slopes describing the rate of change were calculated within each maturity group for PF_{abs} and PF_{allo} from the IMTP, SJ, and CMJ test performance with advancing maturity using Microsoft Excel (v. 2016, Redmond, Washington, USA). One-way ANCOVA were used to determine any significant between-group differences for the regression slopes of each test variable using PHV as a covariate. With data pooled across all participants multiple stepwise linear regressions were used to determine predictor variables for both CMJ and SJ height. The Durbin-Watson statistic was used to detect autocorrelation in residuals from the regression analyses and multicollinearity was determined using variation inflation factor (VIF) and tolerance diagnostics. All statistical analyses were computed using SPSS (V.24 Chicago, IL, USA), with statistical significance for all tests set at an alpha level of $p < 0.05$.

4.4 RESULTS

4.4.1 Back squat assessment

Analysis revealed a small difference for median BSA total scores between the post-PHV group (3.0) and the pre-PHV group (4.5) ($p < 0.001$, $d = 0.34$). No significant differences were observed between the circa-PHV group (3.5) and either the pre- or post-PHV groups.

4.4.2 Isometric mid-thigh pull

Results for all IMTP variables are displayed in *Table 4.2*. Analysis showed that PF_{abs}, PRFD, PF50, PF90, PF150, PF200, and PF250 all significantly increased with advancing maturity ($p < 0.001$). All absolute force values during the IMTP increased between each maturity group, and differences tended to be large from both pre- to circa-PHV and circa- to post-PHV, and very large differences between pre to post-PHV ($p < 0.05$). PRFD also significantly increased with maturity but with moderate effects between consecutive groups and a large effect from pre- to post-PHV ($p < 0.05$). PF_{allo} significantly increased between each group with moderate to large effect sizes. However, non-significant, trivial differences were reported between all maturity groups for both tPF and $PRFD_{rel}$ ($p > 0.05$).

Table 4.2 Group means (± SD) for IMTP kinetic force-time variables and effect-sizes (ES) with 95% confidence intervals (CI) for between-group differences.

	Pre-PHV	Circa-PHV	Post-PHV	Pre- vs. Circa- (*d*) (95% CI)	Circa- vs. Post- (*d*) (95% CI)	Pre- vs. Post- (*d*) (95% CI)
Absolute PF (N)	1216.70 ± 238.89	1766.99 ± 306.04	2244.77 ± 362.99	2.00** (1.71 – 2.59)	1.42** (0.91 – 1.88)	3.34** (3.19 – 4.20)
Allometric Scaled PF ($N/kg^{0.67}$)	102.16 ± 13.96	120.35 ± 17.59	131.98 ± 17.78	1.14** (0.83 – 1.62)	0.65* (0.20 – 1.10)	1.86** (1.58 – 2.36)
Time to PF (ms)	2820.16 ± 1137.16	2554.55 ± 948.88	2793.58 ± 1110.29	0.25 (-0.13 – 0.61)	0.23 (-0.21 – 0.67)	0.02 (-0.31 – 0.36)
Peak RFD ($N \cdot s^{-1}$)	4621.23 ± 1450.88	6624.94 ± 1956.78	7891.94 ± 2054.74	1.16** (0.87 – 1.67)	0.63** (0.18 – 1.07)	1.83** (1.60 – 2.39)
Relative Peak RFD ($N \cdot s^{-1}/kg$)	114.53 ± 38.11	119.58 ± 39.17	114.25 ± 33.80	0.13 (-0.24 – 0.50)	0.14 (-0.29 – 0.58)	0.00 (-0.33 – 0.34)
PF 50ms (N)	391.56 ± 89.06	550.66 ± 108.98	726.58 ± 153.77	1.59** (1.28 – 2.11)	1.32** (0.80 – 1.76)	2.66** (2.58 – 3.5)
PF 90ms (N)	444.11 ± 95.15	640.45 ± 123.58	833.42 ± 155.50	1.78** (1.49 – 2.35)	1.37** (0.86 – 1.82)	3.02** (2.91 – 3.88)
PF 150ms (N)	547.81 ± 127.03	815.59 ± 151.74	1034.79 ± 192.87	1.91** (1.58 – 2.44)	1.26** (0.75 – 1.71)	2.98** (2.81 – 3.77)
PF 200ms (N)	624.27 ± 146.48	961.61 ± 209.94	1178.00 ± 215.41	1.86** (1.64 – 2.51)	1.01** (0.54 – 1.47)	3.00** (2.81 – 3.77)
PF 250ms (N)	742.95 ± 193.13	1142.23 ± 241.90	1416.22 ± 257.85	1.82** (1.52 – 2.37)	1.09** (0.61 – 1.55)	2.95** (2.69 – 3.63)

* significant between-group differences ($p < 0.05$)
** significant between-group differences ($p < 0.001$)

4.4.3 Squat jump

Results for all SJ variables are displayed in *Table 4.3*. Analysis revealed that PF_{abs}, jump height, RFD_{avg}, PV, PP, PP_{rel}, impulse, PRFD, and tPRFD all significantly increased with advancing maturity ($p < 0.05$). Very large increases were revealed in PF_{abs} and PP with increasing maturity status ($p < 0.05$). There were moderate differences observed for jump height between the pre- (12.81 cm) to circa-PHV (15.45 cm) groups and the circa- to post-PHV (19.10 cm) groups; however, a very large difference was observed between the pre- to post-PHV group ($p < 0.05$, $d = 1.90$). Moderate differences were also revealed between the pre- to circa-PHV groups and circa- to post-PHV groups for PF_{allo}, RFD_{avg}, PV, relative power, impulse, PRFD, and tPRFD ($p < 0.05$). However, differences when comparing the pre- to post-PHV groups often became large or very large, with the exception of relative RFD_{avg}, PRFD and tPRFD which showed a significant and moderately difference ($p < 0.05$).

4.4.4 Countermovement jump

Results for all CMJ variables are displayed in *Table 4.4*. Analysis of CMJ variables revealed that PF_{abs}, jump height, RSI_{mod}, ECC_{imp}, CON_{imp}, peak landing force, PP, PP_{allo}, ECC_{pow}, and CON_{pow} all increased with advancing maturity status ($p < 0.05$). Large to very large differences were observed in PF_{abs}, ECC_{imp}, CON_{imp}, PP, ECC_{pow}, and CON_{pow} between the pre- to circa-PHV and pre- to post-PHV groups ($p < 0.05$). Also, large and very large differences were seen for ECC_{imp}, PP, ECC_{pow}, and CON_{pow} between the circa- to post-PHV groups ($p < 0.05$). Increases for jump height were revealed moderate differences between the pre- (17.45 cm) to circa- PHV (21.31 cm) and the circa- to post-PHV (25.43 cm) groups; however, there was a very large difference between the pre- to post- PHV ($p < 0.001$, $d = 2.03$) groups. Moderate differences were also observed for RSI_{mod} for all comparisons between the pre- (0.24), circa- (0.28) and post-PHV (0.32) groups. Moderate differences for PF_{allo} and PP_{rel} were observed between consecutive maturity groups; however, comparisons between pre- to post-PHV groups revealed large and very large differences ($p < 0.05$). Between-group differences for time to take off, ECC_{dur} and CON_{dur} were either trivial to small or non-significant.

Table 4.3 Group means (± SD) for SJ kinetic force-time variables and effect-sizes (ES) with 95% confidence intervals (CI) for between-group differences.

	Pre-PHV	Circa-PHV	Post-PHV	Pre- vs. Circa- (*d*) (95% CI)	Circa- vs. Post- (*d*) (95% CI)	Pre- vs. Post- (*d*) (95% CI)
Absolute PF (N)	842.64 ± 176.01	1184.62 ± 216.77	1530.87 ± 271.90	1.73** (1.41 – 2.26)	1.40** (0.89 – 1.86)	3.00** (2.85 – 3.81)
Allometric Scaled PF ($N/kg^{0.67}$)	71.57 ± 10.41	81.26 ± 10.31	91.04 ± 13.78	0.93** (0.54 – 1.31)	0.80** (0.33 – 1.23)	1.59** (1.32 – 2.08)
Jump height (cm)	12.81 ± 2.67	15.45 ± 3.76	19.10 ± 4.64	0.80** (0.51 – 1.28)	0.86** (0.39 – 1.30)	1.66** (1.51 – 2.28)
Average RFD ($N\cdot s^{-1}$)	1492.97 ± 713.15	2358.66 ± 845.68	3440.58 ± 1543.09	1.10** (0.77 – 1.55)	0.86** (0.37 – 1.28)	1.62** (1.55 – 2.33)
Relative Avg. RFD ($N\cdot kg^{-1}$)	35.44 ± 14.37	42.30 ± 13.66	49.56 ± 22.39	0.48** (0.10 – 0.86)	0.39 (0.07 – 0.82)	0.75* (0.49 – 1.18)
Peak Velocity ($m\cdot s^{-1}$)	1.97 ± 0.16	2.09 ± 0.22	2.30 ± 0.23	0.62** (0.31 – 1.07)	0.93** (0.46 – 1.38)	1.66** (1.43 – 2.20)
Peak Power (W)	1340.14 ± 274.51	1961.58 ± 371.74	2896.05 ± 567.01	1.90** (1.64 – 2.52)	1.94** (1.35 – 2.40)	3.49** (3.59 – 4.68)
Relative Power ($W\cdot kg^{-1}$)	32.71 ± 3.94	35.74 ± 6.26	41.41 ± 6.56	0.57* (0.29 – 1.05)	0.88** (0.42 – 1.33)	1.60** (1.43 – 2.20)
Impulse (Ns)	1.69 ± 0.23	1.89 ± 0.22	2.10 ± 0.25	0.88** (0.49 – 1.26)	0.89** (0.42 – 1.33)	1.70** (1.35 – 2.11)
Peak RFD ($N\cdot s^{-1}$)	4066.91 ± 1965.92	5641.72 ± 2147.30	7170.99 ± 3370.60	0.76** (0.40 – 1.16)	0.54* (0.08 – 0.96)	1.12** (0.92 – 1.64)
Relative Peak RFD ($(N)\cdot s^{-1}$)	10.18 ± 4.79	10.36 ± 3.80	10.52 ± 5.09	0.04 (-0.33 – 0.41)	0.03 (-0.40 – 0.47)	0.06 (- 0.26 – 0.40)
Time to Peak RFD (ms)	211.69 ± 121.08	153.12 ± 74.52	119.13 ± 60.85	0.58** (0.14 – 0.89)	0.49** (0.06 – 0.95)	0.96* (0.50 – 1.19)

* significant between-group differences ($p < 0.05$)
** significant between-group differences ($p < 0.001$)

Table 4.4 Group means (± SD) for CMJ kinetic force-time variables and effect-sizes (ES) with 95% confidence intervals (CI) for between-group differences.

	Pre-PHV	Circa-PHV	Post-PHV	Pre- vs. Circa- (*d*) (95% CI)	Circa- vs. Post- (*d*) (95% CI)	Pre- vs. Post- (*d*) (95% CI)
Absolute PF (N)	473.20 ± 122.27	723.58 ± 172.51	930.81 ± 212.01	1.67** (1.43 – 2.28)	1.07** (0.58 – 1.51)	3.01** (2.56 – 3.47)
Allometric Scaled PF ($N/kg^{0.67}$)	40.08 ± 8.93	49.05 ± 9.35	54.77 ± 12.01	0.98** (0.60 – 1.38)	0.53* (0.07 – 0.96)	1.38** (1.12 – 1.85)
Jump Height (cm)	17.45 ± 3.39	21.31 ± 5.23	25.43 ± 5.10	0.87** (0.61 – 1.39)	0.79** (0.34 – 1.25)	1.84** (1.64 – 2.42)
RSI modified (JH/time to take off)	24.40 ± 6.74	28.90 ± 7.66	32.92 ± 7.61	0.62** (0.27 – 1.02)	0.52* (0.08 – 0.97)	1.18** (0.86 – 1.57)
Eccentric Impulse (Ns)	36.01 ± 8.49	55.28 ± 9.76	73.85 ± 16.70	2.10** (1.75 – 2.63)	1.35** (0.82 – 1.78)	2.85** (2.87 – 3.83)
Concentric Impulse (Ns)	76.10 ± 15.67	114.43 ± 20.13	154.49 ± 26.20	2.12** (1.84 – 2.73)	1.71** (1.16 – 2.17)	3.63** (3.56 – 4.63)
Peak Power (W)	1414.04 ± 303.29	2208.77 ± 451.33	3152.05 ± 650.70	2.06** (1.88 – 2.78)	1.76** (1.12 – 2.13)	3.62** (3.55 – 4.63)
Relative Peak Power (W/kg)	34.94 ± 4.77	39.38 ± 5.83	45.03 ± 6.45	0.83** (0.50 – 1.27)	0.91** (0.44 – 1.36)	1.77** (1.52 – 2.30)
Eccentric Power (W)	-168.79 ± 41.52	-249.30 ± 56.83	-345.99 ± 91.80	1.61** (1.36 – 2.19)	1.26** (0.74 – 1.69)	2.48** (2.53 – 3.44)
Concentric Power (W)	759.25 ± 173.09	1193.44 ± 238.79	1675.19 ± 359.28	2.08** (1.84 – 2.74)	1.57** (1.03 – 2.02)	3.24** (3.33 – 4.37)

* significant between-group differences ($p < 0.05$)
** significant between-group differences ($p < 0.001$)

4.4.5 Regression analyses

Mean rates of change (+95% CI) for stature and body mass are displayed in *Figure 4.1.* Analyses revealed a significant difference between regression slopes for stature ($p < 0.05$), but not for body mass ($p > 0.05$). The greatest within-group variability for both stature and body mass were observed by the circa-PHV groups.

Mean rates of change for PF_{abs} and PF_{allo} in the IMTP, SJ and CMJ within each maturity group are displayed in *Figure 4.*2. The circa-PHV group were consistently experiencing the greatest rate of change in both PF_{abs} and PF_{allo} in each of the IMTP, SJ and CMJ; however, given the large variability in the circa-PHV group regression slope analyses revealed no significant differences between groups for rate of change for PF_{abs} and PF_{allo} in any protocol ($p > 0.05$). Of note, the slopes for IMTP PF_{abs} ($p = 0.069$), SJ PF_{abs} ($p = 0.063$) and SJ PF_{allo} ($p = 0.080$) were approaching significance.

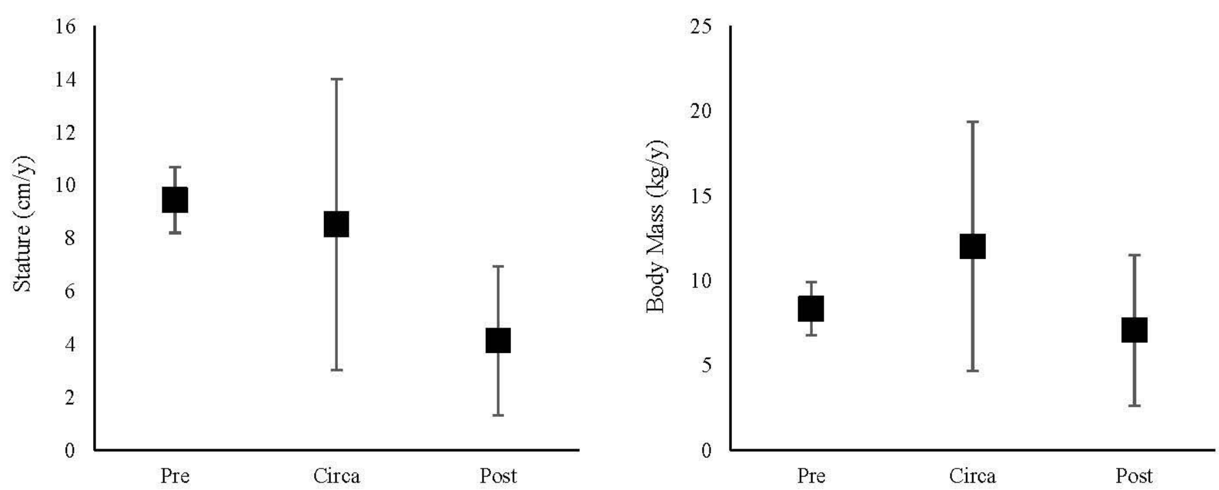

Figure 1. Mean rate of change and 95% CI for stature and body mass.

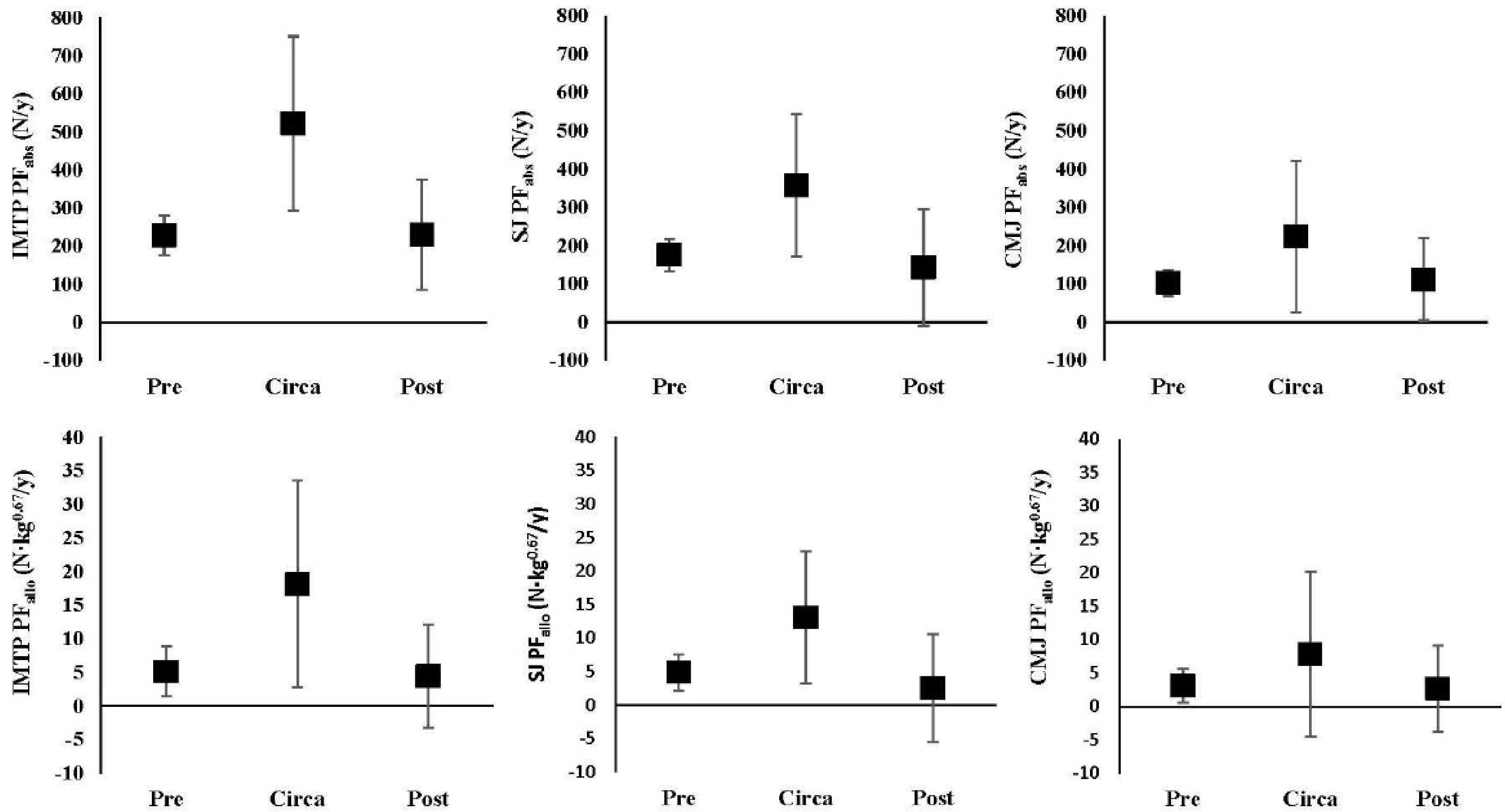

Figure 2. Mean rate of change and 95% CI for within-group scores for PF_{abs} and PF_{allo} in the IMTP, SJ, and CMJ tests.

Across all participants, multiple stepwise linear regression models significantly predicted 45% and 48% of variance in SJ height and CMJ jump height, respectively ($p < 0.05$). Regression analyses determined that IMTP PF_{allo} was the strongest predictor of SJ and CMJ jump height, explaining 34.8% and 41.3% of the total explained variance, respectively (*Table 4.5*). Maturity offset was the next greatest predictor of jump height within both regression models. BSA total score had a negative relationship for both SJ and CMJ jump height; however, BSA total score was only included in the final linear regression model for the SJ. For all stepwise multiple regression models, there was no evidence of multicollinearity (r <0.70), along with acceptable values for tolerance (>0.1) and VIF (<10).

Table 5. Stepwise multiple linear regression equations explaining the variables that significantly (p < 0.05) contributed to SJ and CMJ jump height for all maturity groups.

Dependent variable	Independent variables	Regression equation	Adjusted R^2 value
SJ jump height	Constant	10.08	
	IMTP PF_{allo}	0.05	0.348
	Maturity Offset	1.48	0.417
	IMTP $PRFD_{rel}$	0.04	0.430
	IMTP PRFD	0.0006	0.445
	BSA Total Score	-0.24	0.452
CMJ jump height	Constant	9.56	
	IMTP PF_{allo}	0.10	0.415
	Maturity Offset	1.87	0.458
	IMTP $PRFD_{rel}$	0.06	0.468
	IMTP PRFD	0.00	0.488

4.6 DISCUSSION

The main aim of the present study was to examine how movement competency, strength, and power differed between pre-, circa- and post-PHV male athletes with no prior experience of strength and conditioning. The post-PHV group displayed better overall movement competency in the BSA than the pre-PHV group, but not the circa-PHV group. IMTP data revealed PF_{abs}, and PF at all time epochs all significantly increased with advanced maturity with large to very large between group differences. Similar findings were observed in the SJ and CMJ test, where analysis of the force-time variables revealed more mature athletes were able to produce a greater amount of force (e.g. PF_{abs} and PF_{allo}). This was particularly evident for peak power in both the SJ and CMJ tests, where very large differences were displayed between consecutive maturity groups. RFD_{avg} and PRFD within the SJ also displayed very large increases with advancing maturity. Between-group differences can be partially explained by the different rates of change experienced within each group; the period of circa-PHV was associated with the largest rates of changes, although the high variability of change during this period meant that differences to other groups were not significant. Across all participants IMTP PF_{allo} was the strongest predictor of both SJ and CMJ height, suggesting the importance of absolute strength relative to allometrically scaled body weight for achieving a high jump height.

Analysis of the median BSA total scores revealed a small significant decrease in the number of technical deficiencies between the pre-PHV and post-PHV groups (4.5 to 3.0); however, there were no significant differences between consecutive maturity groups. These findings indicate that movement competency increases non-linearly across maturity groups; however, more sizeable changes may take longer to manifest following the adolescent growth spurt. This aligns with previous cognitive and motor skill development literature in youth which suggests that more meaningful movement competency improvements can be made prior to the adolescent growth spurt (140, 227, 228). Cumulatively, the data indicate that small improvements in movement competency appear to occur naturally as a result of growth and maturation. Since the participants in the current study had no formal training background, conceivably further improvements in their movement competency could be made by introducing a developmentally appropriate training programme.

Findings from the IMTP analyses revealed that advanced maturity improves not only maximal force production, but also the ability to produce force quickly. This notion is based on the large to very large effect size differences between maturity groups for PF_{abs} and PF at all time epochs (*d* >1.20) as well as the moderate differences observed for peak RFD (*d* = 0.63 to 1.16) between maturity groups. Interestingly, effect sizes were consistently greater for nearly all variables between pre- and circa-PHV groups compared to circa- to post-PHV. More mature athletes tend to have greater mass in comparison to children, which gives an advantage for absolute measures of strength; akin to those observed in the present study for PF_{abs}, PRFD, and PF at all time epochs. Previous literature comparing differences in force producing capabilities between children and adolescents noted that adolescents display a heightened neural drive, greater muscle size, and improved muscle activation patterns which aid in more notable increases in force production at this stage of development (79, 80, 166, 302). In the current study, differences for IMTP PF_{allo} revealed moderate effect sizes between the circa- vs. post-PHV (*d* = *0*.65) groups and a slightly larger but still moderate difference between the circa- vs. pre-PHV groups (*d* = 1.14). This would indicate that the rate of adaptation for force production is slightly greater during the pre-adolescent to pubertal period of maturation. However, regression analyses for rate of change with respect to maturity offset revealed a near-significant between-group difference in the regression slopes of the IMTP PF_{abs}. Similarly, the confidence intervals for mean rate of change demonstrated larger variations within the circa-PHV group compared to the pre- and post-PHV groups. Therefore, it should be acknowledged that while the period of rapid growth within the circa-PHV group likely resulted in greater absolute force production, the level of within-group variation affected maturational between-groups values for PF_{abs}.

The overall findings from the SJ test were that PF_{abs}, PF_{allo}, jump height, average RFD, peak velocity, and PP all increased significantly with advancing maturity status. Regression analyses in all maturity groups for PF_{abs} and PF_{allo} revealed non-significant differences in slopes, however, they were approaching significance ($p = 0.063$ and $p = 0.080$, respectively). Similar to IMTP PF_{abs}, the near-significant differences in slopes suggest that increased rates of adaptation for absolute and allometrically-scaled force production are likely a result of growth and maturation during the period around PHV. However, caution is warranted due to the larger confidence intervals observed in mean scores by the circa-PHV group, which inherently leads to greater between-group comparisons. Very large between-group differences were reported for PP between all groups. Meanwhile, moderate effect size differences were evident for peak velocity and PF_{allo} which suggests that increases in SJ PP during maturation are driven by greater force production and changes in velocity. In comparison to children, adolescent athletes have physiological advantages for producing high-velocity concentric force (80, 308). A review on muscle power by Van Praagh et al. (308) suggested that adolescents increase lower body velocity through longer limb length and faster muscle contractile properties, allowing for greater angular velocity around joints and quicker force production, respectively. This likely influenced the peak power scores for the circa- and post-PHV groups but did not increase absolute force production during the SJ. In conclusion, our results indicate that changes to peak power in the SJ as a result of maturation are driven from increases in velocity and force.

Overall findings from CMJ analysis were that PF_{abs}, jump height, ECC_{imp}, CON_{imp}, PP, PP_{rel}, ECC_{pow}, and CON_{pow} all increased with advanced maturity based off the moderate to very large between-group differences. Therefore, it appears that the onset of puberty also brings about slightly greater adaptations in CMJ kinetic variables for producing force quickly. Analysis of the force-time variables within the CMJ indicate that the post-PHV group had a moderately longer duration in the eccentric phase than both the circa- and pre-PHV groups ($d = 0.46$). Despite a longer eccentric phase, there were no differences between groups for duration in the concentric phase and time to take off, which indicates that the post-PHV group utilizes a longer eccentric phase during the SSC in order to produce greater force. The longer eccentric phase duration might indicate that the more mature group were more effective at relying on cross-bridge formation as the primary stretch-shortening cycle mechanism for CMJ performance, which is indicative of slow-SSC activities (183, 251, 302, 308). This explanation is supported by the significantly greater RSI_{mod} observed by the post-PHV group over both the pre- and circa-PHV cohorts despite having a greater time to take-off. Higher RSI_{mod} values typically reflect explosive jump performance and are characterized by greater absolute force, power, and velocity within the eccentric phase (165). Therefore, the data indicate that maturity improves the eccentric phase-specific qualities relevant to CMJ performance.

Between group differences in the IMTP, SJ, and CMJ tests appear to be driven by the variance in rates of change by the circa-PHV group. The regression slopes between the maturational groups were significantly different for stature but not body mass. The largest variance for rates of change was observed in the circa-PHV cohort and were much lower in the pre- and post-PHV groups. These differences within the circa-PHV group reflects the variable timing and tempo of maturation. Similarly, the significant differences in stature likely influenced force producing capabilities during the isometric and dynamic performance tests. This aligns with previous literature which indicates that morphological increases as a result of maturation increase strength and power (302, 308).

Stepwise linear regression models identified that IMTP PF_{allo} explained most of the variance in both the SJ (34.8%) and CMJ (41.3%) regression models, followed by a small predictive contribution from maturity status. This indicates that allometrically scaled force production during isometric actions appears to be an important variable of those measured for explosive vertical jump performance in young male athletes and should therefore be targeted within strength and conditioning programmes for young athletes. These findings are in accordance with previous paediatric literature that has advocated the development of a foundation of strength in order to significantly increase power (11). Both linear regression models also identified maturity status as predictors for SJ and CMJ jump height, suggesting that a more mature status will facilitate jumping higher. These findings reflect existing literature that that has shown advanced maturity being influential to both jump height and lower body power (51, 118, 182, 225, 251).

4.7 PERSPECTIVE

The overall findings indicate that natural growth and maturation induces positive adaptations to movement competency as well as isometric and dynamic strength and power. Squat movement competency improves with maturation, however, the current study did not control for behavioural factors such as physical activity levels which are also likely to enhance overall movement competency. Furthermore, it is unclear whether natural improvements to movement competency are noticeable towards the beginning or end stages of the adolescent growth spurt. Maturity resulted in significant improvements for PF_{abs} and PF_{allo} in the IMTP, SJ, and CMJ, suggesting that adaptations to force producing qualities accompany natural physical growth and development. However, it cannot be determined if greater adaptations occur during the pre- to circa-PHV period or the circa- to post-PHV period due to the large variation in rates of change from the circa-PHV group. Thus, it is difficult to identify when the greatest period of increased force production occurs. Linear regression analyses revealed that IMTP PF_{allo} positively influences jump height in both the SJ and CMJ. This finding highlights the importance of greater force production in relation to body mass for young athletes during lower body power movements. While natural growth improves force production, resistance training aimed at improving muscle strength levels can improve force producing capabilities in young athletes regardless of maturity status.

CHAPTER 5 PRELUDE

While *Chapter 4* identified how natural growth and maturation improves movement competency and kinetic data within isometric strength and dynamic jump tests, training responsiveness to these variables remain unknown. Limited data exists on the changes to kinetic force-time variables following training since previous studies typically assess strength and power performance in youth using external measures. Similarly, less is known about how maturation influences adaptations to various force-time variables and training responsiveness to neuromuscular training in children and adolescents. Previous training studies have delivered the same training programme to different groups irrespective of maturity status. It has been proposed that training exercises must be developmentally appropriate and therefore one training programme is likely not optimal for inducing desired adaptations in two or more groups of different maturity status. Intuitively, practitioners with an awareness and understanding of training youth athletes provide different training programmes with progressions and regressions for exercises to account for the different stages of maturity and technical abilities. Therefore, while similar movements (e.g. bilateral squatting, pushing and pulling) can be targeted across all programmes, it is prudent to use regressions and progressions of various exercises to further individualise the programmes. Also considering the maturational differences observed in *Chapter 4* for the tests along the F-V spectrum, it is likely that short-term neuromuscular training influences different adaptations to force-velocity-power variables in children and adolescents. This study sought to provide novel data by directly comparing the training-induced adaptations to isometric and dynamic kinetic variables in pre-and post-PHV males following a 12-week neuromuscular training programme.

CHAPTER 5 – The effects of a 12-week training programme on isometric and dynamic force-time characteristics in pre- and post- peak height velocity male athletes

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5.1 INTRODUCTION

When examining strength and power adaptations in response to training, it is important to assess neuromuscular function across a range of test protocols that target different regions of the force-velocity curve. Force-time data has commonly been analysed in isometric conditions, due to the ability to closely regulate optimal joint angles and body position (313), thereby minimizing the potential confounding influence of the length-tension relationship typically seen in more dynamic actions (e.g. countermovement jumps [CMJ]). Despite research supporting the use of isometric testing to assess neuromuscular function, one limitation is that it only assesses length-specific adaptations and arguably does not reflect force-producing capabilities at different joint angles and muscle lengths (102). Therefore, it is important to incorporate tests that assess dynamic movements with varying joint angles and muscle lengths alongside isometric tests (307). Consequently, force-time data is also typically assessed during a variation of a vertical jump protocol, such as the CMJ (209). Considering that relationships in force-time variables between isometric and dynamic muscle actions are weaker when lighter external loads are used during the dynamic action (224), it is evident that tests such as the isometric mid-thigh pull (IMTP), CMJ and squat jump (SJ) will test different regions of the force-velocity curve and thus different expressions of strength and power. Somewhat surprisingly, minimal evidence exists that has attempted to investigate the effects of neuromuscular training on isometric and dynamic force-time characteristics in youth, especially in a sample of varying maturity status.

Paediatric literature indicates that improving movement competency in children and adolescents can be achieved through neuromuscular training (228). Neuromuscular training is the inclusion of a wide range of training modes such as resistance training, plyometrics, balance, speed, and core strength with the goal of enhancing an athletes movement skill base (228). While pre-adolescence offers a more opportune time for developing movement competency due to the brain's neuroplasticity (228), it is important for all youth to refine and develop motor skills irrespective of their stage of development, due to the associated athletic and health related benefits (87, 190). Movement competency can be assessed through a range of fundamental movement patterns, but perhaps the most commonly assessed movement is the squat pattern (73, 167, 230). This particular movement is important due to squatting requiring numerous neuromuscular capabilities such as coordination, strength, stability, and mobility (146, 230). The back squat assessment (BSA) was developed by Myer *et al.* (230) with the goal of identifying technical deficits and rating the quality of the squatting movement pattern in young athletes using a 10-point scale. Recently, Dobbs *et al.* (73) established the BSA as a reliable tool for measuring and assessing movement competency in children and adolescents. In the same study, it was demonstrated that a four-week neuromuscular training programme could improve movement competency in the BSA in both pre- and post-peak height velocity (PHV) males (73). However, further investigation is warranted to determine how neuromuscular training can affect movement competency following a longer training intervention, inclusive of sequential training mesocycles, in children and adolescents.

Research has established that well supervised, developmentally-appropriate neuromuscular training is beneficial to sport performance as well as the overall long-term athletic development of youth (88, 172, 176, 177). Neuromuscular training in youth populations has not only been proven to elicit positive responses for motor competency (73, 87), but also for strength (146, 274) and power (221, 249). Despite a plethora of research supporting the trainability of both children and adolescents (146, 177), there are fewer studies comparing the effects of training on youth of different maturity status. Existing evidence suggests that more mature athletes have a greater response to strength training than immature athletes (212), with recent meta-analytical data showing that resistance training elicited greater strength adaptations in circa- and post-PHV boys after only 4 weeks of training compared to those who were pre-PHV (12, 13, 172, 219). Studies comparing different training modalities on pre- and post-PHV athletes indicate that training responsiveness may be influenced by maturity status, with pre-PHV boys commonly shown to respond favourably to plyometric training, whereas more mature athletes require a combination of plyometric and resistance training to induce specific performance adaptations (188, 221, 249).

One limitation with existing paediatric intervention studies is that strength and power attributes are often measured using field-based tests that solely assess performance outcomes such as sprint time (210, 246, 263, 315), vertical jump height (133, 206, 214, 263, 317) or one repetition maximum (1RM) strength (133, 146, 212, 274). While these tests can certainly indicate training effects, insights into the mechanical adaptations (e.g. force-time characteristics) that likely underpin strength and power performance typically go unreported. Some of the available data indicate that qualities such as rate of force development (RFD) is associated with explosive strength and plyometric performance (7, 130, 206), while concentric peak force is able to differentiate between weaker and stronger adolescent athletes (298). However, the manner in which these and other force-time variables are influenced by training in youths at different stages of maturation remains unclear. Another limitation in the existing literature is that the same training programmes are given to separate training groups of different maturational status. It has been demonstrated that children and adolescents respond more favourably to different training modes (184, 188, 245, 249) and should receive exercises which are developmentally appropriate.

Assessment of ground reaction forces during tests such as the IMTP, SJ or CMJ can provide insights into the force-time characteristics that influence explosive activities such as jump and sprint performance (7, 130, 210). Examining force-time characteristics in youth of different maturity status during commonly used strength and power tests would provide greater clarity on potential specific maturity-related adaptations that may result from exposure to neuromuscular training. Therefore, the aim of the present study was to examine the effects of a 12-week neuromuscular training intervention on movement competency and force-time characteristics in isometric and dynamic tests in youth male cricketers of different maturational status. Maturational status was determined through a validated equation (215) which predicts if males have yet to reach peak-height velocity (pre-PHV) or have already experienced peak height velocity (post-PHV). Owing to their respective stages of development, it was hypothesized that a) the pre-PHV cohort would experience greater improvements than the post-PHV group in BSA movement competency; and b) the post-PHV cohort would achieve greater improvements in force-time characteristics within the isometric and dynamic tests.

5.2 METHODS

5.2.1 Experimental Approach to the Problem

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

5.2.2 Subjects

Thirty-nine young male athletes (n = 24 pre-PHV, n = 14 post-PHV) aged 9-17 years at a sporting academy in the United Kingdom agreed to participate in the study. Participants were grouped according to maturity status and further sub-divided into an experimental (EXP) or control (CON) group (*Table 5.1*). Maturity status refers to the biological age of an individual and gives a clear indication as to the stage of development the individual is in (176-178, 215). Maturity status was determined by calculating maturity offset (215), which estimates a participants PHV. A PHV score < -1.0 yrs indicates an individual as pre-PHV and a score >1.0 yrs indicates post-PHV. The pre- and post-PHV EXP groups completed 12 weeks of twice-weekly, hour-long neuromuscular training sessions in addition to their regular sports training sessions. Conversely, the CON groups only participated in their sport-specific training with no exposure to neuromuscular training. Participants reported no injuries at baseline testing or during post-testing and were informed of the risks and benefits of taking part in the study. Prior to the 12-week training programme, both EXP groups received 4-weeks of general neuromuscular training but had no experience with strength and conditioning training previous to that. Parental consent and participant assent were obtained following ethical approval from the institutional research ethics committee.

Table 5.1 Mean (± SD) values for descriptive details of each maturity groups anthropometric data.

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

5.2.3 Procedures

5.2.3.1 Back-Squat Assessment

To assess the BSA, participants were instructed to perform ten continuous squat repetitions in place with a wooden dowel on their back as per previously published guidelines (230). Testing protocols were performed in the same manner as in the previous studies of the current thesis (chapters 3 and 4). Scoring of BSA performance was conducted retrospectively using a 10-point criteria, with one point given for each technical fault (230). The 10-point criteria consisted of: head position, thoracic position, trunk position, hip position, frontal knee position, tibial progression angle, foot position, descent, depth, and ascent. During the scoring process, each of the 10 criteria were analysed and a deficit was scored if present during two or more repetitions.

A deficit occurring twice or more highlights movement variability by the participant in the BSA and was counted as a deficit (230). Deficits were tallied to provide a total score, with higher total scores indicative of poorer squat technique. The lowest total score for each participant was used for statistical analysis at both baseline and post-testing. The variables recorded for each participant were BSA total score.

5.2.3.2 Isometric mid-thigh pull

The IMTP test was performed on a custom built IMTP testing device using dual Kistler force plates sampling at a frequency of 1000 Hz (type 9287BA, Kistler Instruments AG, Winterthur, Switzerland). All participants performed the testing protocol for the IMTP in the same manner as in chapter 4 of the current thesis. All trials and data were analysed on a customized IMTP LabView programme. Force-time variables calculated from the customized software included: absolute peak force (PF_{abs}), peak force relative to body weight (kg) (PF_{rel}) , time to peak force (tPF), peak rate of force development (PRFD), time to peak rate of force development (tPRFD), and peak force at time periods of 0-50 ms (PF50), 0-90 ms (PF90), 0-150 ms (PF150), 0-200 ms (PF200), and 0-250 ms (PF250). Acceptable within- and between-session reliability has previously been reported for this IMTP protocol using youth athletes (216).

5.2.3.3 Squat jump

The SJ test was recorded on an AMTI force plate with a sampling rate of 1000 Hz (Accupower, AMTI, Boston, MA, USA). Participants were required to assume a squat position with 90° of knee flexion (243, 273) which was visually observed by the researcher. Testing protocols for the SJ were performed in the same manner as in chapter 4 of the current thesis. All trials and data were analysed using a customized SJ LabVIEW programme and the SJ variables measured were: PF, jump height (JH), average RFD, peak velocity, peak power (PP), impulse, PRFD, and tPRFD. Acceptable reliability has previously been reported for the SJ protocol using youth athletes (181).

5.2.3.3 Countermovement jump

Countermovement jumps were recorded using an AMTI force plate sampling at 1000 Hz (Accupower, AMTI, Boston, MA, USA). In line with previous research, all participants were instructed to perform maximal effort jumps with hands remaining on hips throughout to limit the influence of the upper body on jump performance (7). Participants were able to descend to a self-selected depth during the eccentric portion of the jump (243). The testing protocol for the CMJ was performed in the same manner as in chapter 4 of the current thesis. All trials and data were exported from the Accupower software (Accupower 3.0, Accupower solutions, Boston, MA, USA) and analysed using a validated custom built automated CMJ spreadsheet (40). The variables measured for CMJ analyses were; jump height, time to take off, reactive strength index modified (RSI_{mod}), PF, eccentric impulse, duration of eccentric phase, concentric impulse, duration of concentric phase, peak landing force, peak power (PP), eccentric power, and concentric power. Acceptable reliability has previously been reported for the CMJ protocol using youth athletes (213).

5.2.4 Training programme

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

Table 5.2 Structure of 12-week training programme for pre-PHV EXP.

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

Table 5.3 Structure of 12-week training programme for post-PHV EXP.

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

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

5.2.5 Statistical analyses

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

5.3 RESULTS

At baseline, there were no anthropometric differences between the EXP and CON groups for both pre- and post-PHV cohorts (*Table 5.1*). The mean attendance rates across all training sessions for the pre-PHV EXP and post-PHV EXP groups were 77.1% and 75.7% respectively.

5.3.1 Back-Squat Assessment

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

5.3.2 Isometric mid-thigh pull

Mean changes in IMTP kinetic variables, including effect sizes, are displayed in *Table 5.4*. Data showed main effects for time, maturity and training for the following variables: PF_{abs}, PRFD, PF90, PF200, PF250 ($p < 0.05$). For PF_{abs}, PF200 and PF250, there were significant interactions in time x training, and time x group x maturity (all $p < 0.05$). The interactions are due to both CON groups showing no change in IMTP performance, while both EXP groups improved in nearly all force-time variables. At post testing, there were moderate significant differences between the pre-PHV EXP and CON groups for tPF and PRFD ($p < 0.05$). There was also a moderate significant difference between the post-PHV EXP and CON groups for PF_{abs} at baseline and a very large difference at post-testing ($p < 0.05$). Changes in PF_{abs} and PF_{rel} in the pre-PHV EXP group were small and non-significant; whereas PF_{abs} ($p < 0.05$, $d = 0.79$) had a moderate significant increase and PF_{rel} was non-significant in the post-PHV EXP group. The post-PHV EXP group had a very large significant within-group change in PRFD ($p < 0.05$, $d = 2.60$) and a moderate change in tPF ($p < 0.05$, $d = 1.00$). Both EXP groups showed moderate significant increases in PF90, PF150, PF200, and PF250 (*Figure 5.1 & 5.2*).

Table 5.4 Group means (± SD) for IMTP kinetic force-time variables and effect-sizes (ES) for within-group difference from baseline to post-testing.

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

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

$^{\alpha}$ significant between-group difference with CON group of same maturity status ($p < 0.05$).

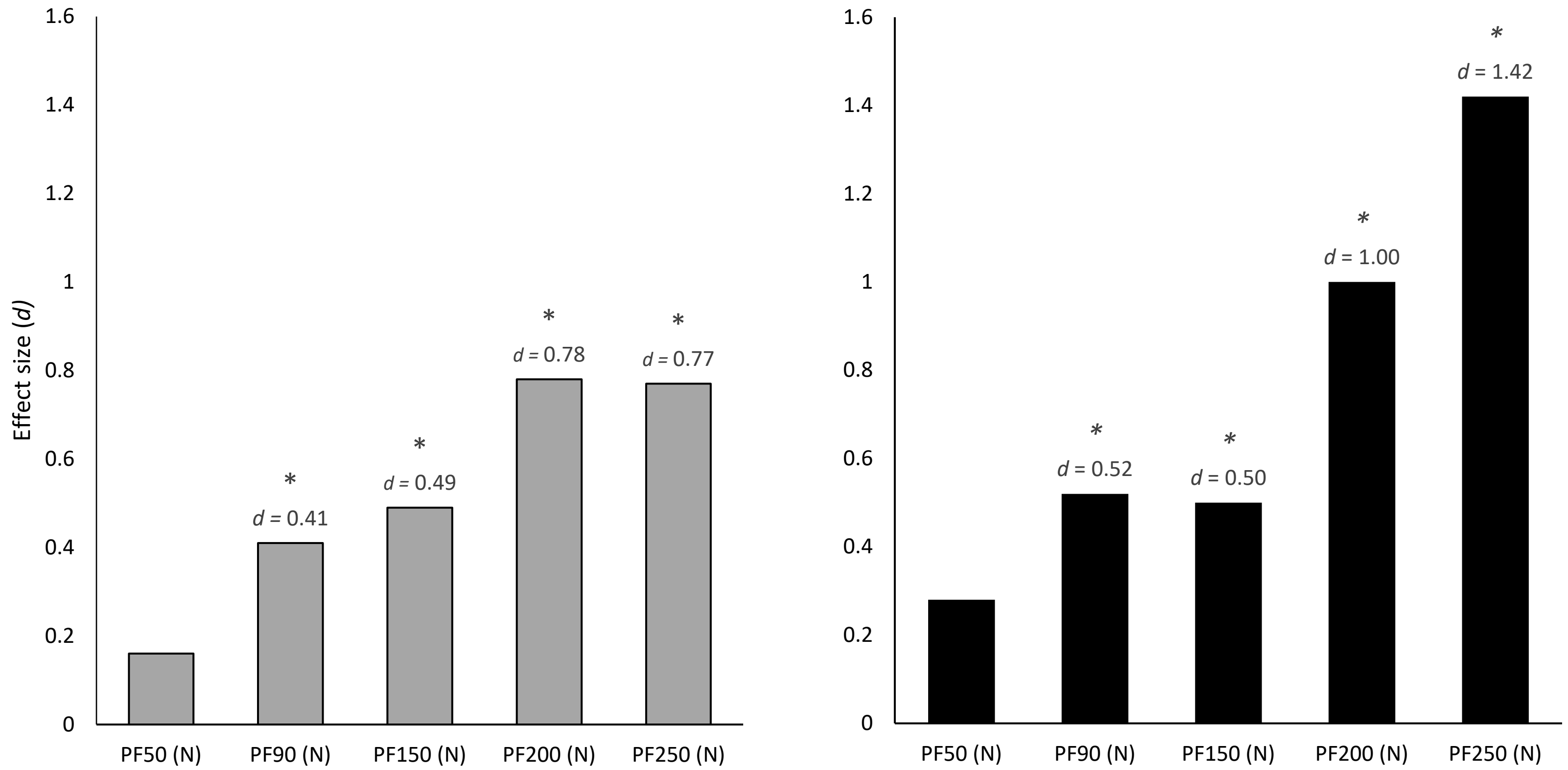


Figure 5.1 Effect sizes for pre- and post-PHV EXP within-group changes at PF for all time epochs for pre-PHV. * significant change from baseline to post-testing ($p < 0.05$).

5.3.3 Squat jump

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

5.3.4 Countermovement jump

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

Table 5.5 Group means (± SD) for CMJ kinetic force-time variables and effect-sizes (ES) for within-group difference from baseline to post-testing.

	Pre-PHV EXP			**Pre-PHV CON**			**Post-PHV EXP**			**Post-PHV CON**		
	Baseline	**Post**	**ES (*d*)**	**Baseline**	**Post**	**ES (*d*)**	**Baseline**	**Post**	**ES (*d*)**	**Baseline**	**Post**	**ES (*d*)**
Jump Height (m)	17.44 ± 4.23	18.79 ± 4.86	**0.32***	17.84 ± 3.09	17.14 ± 3.50	**0.22**	25.27 ± 6.09	29.72 ± 6.06	**0.73***	25.61 ± 8.26	26.72 ± 8.2	**0.13**
Time to take off (s)	0.56 ± 0.09	0.53 ± 0.09$^{\alpha}$	**0.33**	0.57 ± 0.06	0.63 ± 0.10	**0.68**	0.63 ± 0.06	0.62 ± 0.07	**0.15**	0.58 ± 0.09	0.63 ± 0.13	**0.43**
RSI modified (JH/time to take off)	0.23 ± 0.09	0.27 ± 0.09	**0.44***	0.24 ± 0.04	0.21 ± 0.05	**0.75**	0.32 ± 0.08	0.41 ± 0.07	**1.13***	0.35 ± 0.15	0.34 ± 0.12	**0.07**
Peak Force (N)	484.34 ± 182.64	540.03 ± 183.36	**0.30**	477. 32 ± 108.23	464.93 ± 160.68	**0.11**	874.13 ± 226.13	1022.89 ± 237.84$^{\alpha}$	**0.66***	840.60 ± 160.8	818.39 ± 155.71	**0.14**
Eccentric Impulse (Ns)	39.64 ± 11.30	41.42 ± 12.78	**0.16**	35.00 ± 7.46	36.10 ± 8.58	**0.15**	79.71 ± 19.22$^{\alpha}$	83.42 ± 22.35$^{\alpha}$	**0.19**	56.85 ± 16.41	60.28 ± 17.06	**0.21**
Duration of Eccentric Phase (s)	0.26 ± 0.05	0.27 ± 0.05$^{\alpha}$	**0.20**	0.28 ± 0.05	0.32 ± 0.06	**0.80**	0.34 ± 0.05	0.32 ± 0.07	**0.40**	0.34 ± 0.07	0.37 ± 0.10	**0.43**
Concentric Impulse (Ns)	79.78 ± 20.18	84.42 ± 20.63	**0.22**	76.20 ± 13.22	76.00 ± 11.37	**0.02**	157.00 ± 35.58	168.28 ± 35.80$^{\alpha}$	**0.32***	132.85 ± 34.69	140.42 ± 30.63	**0.22**
Duration of Concentric Phase (s)	0.30 ± 0.06	0.27 ± 0.04	**0.50***	0.28 ± 0.04	0.30 ± 0.06	**0.50**	0.29 ± 0.02	0.29 ± 0.05	**0.00**	0.24 ± 0.03	0.26 ± 0.03	**0.66**
Peak Landing Force (N)	1478.90 ± 469.17	1418.04 ± 556.88	**0.13**	1425.61 ± 200.20	1418.18 ± 340.86	**0.04**	2418.81 ± 763.43	2768.18 ± 930.55	**0.46***	2338.59 ± 386.17	2263.03 ± 371.26	**0.20**
Peak Power (W)	1449.81 ± 382.51	1575.54 ± 408.68	**0.33***	1365.05 ± 247.98	1416.35 ± 241.69	**0.20**	2997.89 ± 877.68	3335.51 ± 744.26	**0.38***	2806.29 ± 899.68	2875.25 ± 799.92	**0.08**
Eccentric Power (W)	-189.50 ± 52.55	-204.82 ± 63.75	**0.29**	-185.05 ± 41.68	-171.42 ± 48.42	**0.32**	-383.40 ± 90.21$^{\alpha}$	-402.27 ± 108.13$^{\alpha}$	**0.21**	-246.34 ± 48.21	-273.11 ± 59.00	**0.55**
Concentric Power (W)	764.57 ± 227.53	848.64 ± 197.89	**0.37***	711.20 ± 133.30	709.70 ± 136.70	**0.01**	1611.42 ± 411.75	1753.85 ± 507.17	**0.35***	1477.14 ± 472.58	1498.42 ± 379.23	**0.05**

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

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

5.4 DISCUSSION

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

The present study provides novel data regarding the effects of neuromuscular training on isometric force-time characteristics in pre-and post-PHV males. The IMTP is a valid and reliable assessment of maximal strength in young athletes (76, 216); however, the effects of neuromuscular training on isometric force-time variables during the IMTP have yet to be reported. In the present study, while within-group analysis revealed moderate improvements in peak force at all time points after 90 ms within both the pre- and post-PHV EXP groups, only the post-PHV EXP group significantly improved PF_{abs}, tPF, and PRFD following training. Yet, PF_{rel} was unchanged in the pre- and post-PHV EXP group. Effect sizes indicated that the post-PHV EXP also had greater increases in PF_{abs} and PF200 and PF250 during the IMTP than the pre-PHV EXP group, which were likely underpinned by the significant decrease in tPF as well as increased PRFD. Cumulatively, these findings suggest that the training intervention enhanced maximal absolute force producing capacities to a larger extent in the post-PHV EXP group compared to the less mature group, which is indicative of the child-adolescent differences in training responsiveness (172, 242). For example, Meylan et al. (212) compared estimated squat 1RM strength in pre- and post-PHV males and reported greater changes in maximum strength in the older cohort following an 8-week training intervention. Although the findings by Meylan and colleagues (212) were not based on kinetic data, the findings suggest that gains in absolute strength are generally greater in post-PHV athletes than in pre-PHV athletes following a short term training period. This notion is also supported by recent meta-analyses reporting smaller strength gains in pre-PHV males than post-PHV males following short-term resistance training programmes (172, 219). Resistance training in post-PHV males typically results in greater increases in muscle mass and strength, invariably due to their advanced hormonal profile (62). However, in a more recent meta-analysis, Peitz et al (242) reported that although absolute strength gains are smaller in pre-PHV cohorts, relative strength gains are comparable and can be even larger than older cohorts. This was observed in a study by Brownlee et al. (29) who found no difference in relative isometric strength in pre- and post-PHV soccer players following 8 weeks of training. In the current study the post-PHV EXP group increased relative strength to a slightly greater extent (0.50) than the pre-PHV group (0.10). However, when accounting for maturation there were no noticeable differences in relative force production between the training groups. Therefore, these results suggest that relative force production and relative gains in strength may not be dependent on maturation and are likely a result of the training intensities throughout the 12-week programme. Also, this could suggest that exposure to a longer training programme may enable larger gains in relative strength for both children and adolescents.

In terms of SJ performance, the pre-PHV EXP group displayed small, significant improvements in jump height; however, no other changes were evident for either of the EXP groups. Previous studies assessing SJ height between pre- and post-PHV males following short-term training interventions have found similar results (188, 249). In the present study, the pre-PHV cohort improved SJ performance following exposure to a combination of resistance and plyometric training. This trend was also observed by Radnor *et al.* (249), who reported a greater number of pre-PHV boys improved squat jump height in response to combined training than post-PHV boys. Of note, the post-PHV EXP group did not show improvements in any of the SJ force-time characteristics despite also being exposed to combined training. Similar results were observed by

Meylan et al. (211) who reported no change in SJ height in 12-14 year old youth soccer players following an 8-week plyometric training programme. Correct SJ performance requires a vertical jump in the absence of an eccentric phase contribution (307), however the current 12-week training programme appears to have failed at enhancing this ability. Considering the content of the training programme, which relied predominantly on dynamic (eccentric-concentric) and plyometric exercises as opposed to solely concentric exercises. It appears that the programme has thus elicited specific adaptations to the imposed training demands.

Both training groups made significant improvements in the CMJ for jump height and RSI_{mod}. However, the effect-sizes were greater in the post-PHV EXP group for both variables indicating the more mature group was more responsive to the training programme. Also, because time to take off was unchanged in both training groups, the increased RSI_{mod} was primarily due to an increased jump height. The results of this study slightly contradict a meta-analysis by Moran et a. (221) which stated that children make greater changes in CMJ performance than adolescents when experiencing similar training loads. This notion is also supported by Rumpf et al. (271) who reported that prepubertal athletes may have more pliable musculotendinous tissue which allows for more efficient energy storage during slow stretch-shortening cycles (SSC) such as the CMJ. However, in addition to plyometric training the post-PHV EXP group were exposed to larger loads and training intensities than the pre-PHV group during the 12-weeks which resulted in greater force-production capabilities. Therefore, the greater change in CMJ jump height by the post-PHV group is likely due to a larger force-related adaptation.

Maturational differences in kinetic force-time phase analysis of the CMJ have not previously been reported. The adaptations to concentric and eccentric variables within the CMJ appear to have been somewhat different in both maturity EXP groups. Specifically, while both maturity groups increased concentric power output, only the pre-PHV group significantly decreased the duration of concentric phase, indicating a greater ability to produce force during a relatively shorter amount of time. The post-PHV group had no changes to duration in the concentric or eccentric phases; however, they significantly increased PF_{abs}. The CMJ is governed by a slow SSC and with regards to youth athletes, appears to be utilized differently by pre- and post-PHV athletes (251, 271). A review of the SSC by Radnor *et al.* (251) indicated that adolescents have a greater RFD as a result of less agonist-antagonist co-contraction than pre-adolescents. In addition, more mature children have greater efficiency at recruiting high-threshold type II motor units, resulting in heightened explosive force production during SSC activities.

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

There are certain limitations within this study that should be considered when interpreting the results. *Firstly*, the low sample size in both the pre- and post-PHV cohorts indicate low statistical power, which may reduce the generalizability of the findings to wider populations of young athletes. *Secondly*, participants in both EXP groups failed to attend every training session, however, adherence was greater than the minimum threshold (> 14 training sessions) required to elicit increases in plyometric performance in youth athletes reported in a recent meta-analysis (221). *Thirdly*, the greater training load between the CON and EXP groups may be responsible for the improvements changes as opposed to the neuromuscular training itself. *Fourthly*, the pre- and post-PHV EXP groups received different training programmes which may have influenced the adaptations of each cohort. While the movement patterns and exercises programmed for each session were similar, it is also possible that different training variables between the pre- and post-PHV programmes such as load, volume, and intensity likely influenced the findings. *Finally*, the 12-week training programmes only provides insight into potential adaptations in response to short- to moderate-term training interventions. Meta-analytical data suggest that adaptations in strength and power are greater when training interventions are >23 weeks (172), and the interaction of maturity and training on isometric and dynamic force-time characteristics following longer-term interventions remains unclear. Despite these limitations, the current study makes an original and significant contribution to the literature, indicating the positive role neuromuscular training has on isometric and dynamic force-time characteristics in young males. Similarly, this study replicated the ‘real world’ nature of coaching by providing separate and developmentally appropriate training programmes which induced positive adaptations in both children and adolescents. Finally, the incorporation of the isometric and dynamic tests provides novel insight on the changes within different regions within the force-velocity curve for pre- and post-PHV males.

5.5 PRACTICAL APPLICATIONS

The findings of this study suggest that the kinetic variables which drive strength and power performance in male youth might be influenced by maturity status. The combination of plyometric and resistance training stimulated a greater increase in strength-related responses for the post-PHV boys as observed by improvements in PF_{abs} in both the IMTP and CMJ. Of note, the post-PHV group also increased CMJ peak landing force following training, which highlights the importance for additional training with athletes to land safely as a result of improved jump performance. Therefore, practitioners improving strength and power in youth athletes must still train for proper landing technique so that athletes can continue to land effectively and are not at a greater risk of injury as a result of their improved force production capabilities. Although no group significantly decreased BSA total score, both EXP groups lowered their scores suggesting maintained movement competency whilst increasing maximal force production qualities. Alternatively, the pre-PHV boys increased early force-producing capabilities (< 250 ms) in the IMTP and CMJ. Practitioners aiming to develop specific qualities in young male athletes should understand the nuances and different strength and power adaptations that are likely to occur depending on maturational status and consider these adaptations when programming. Given the short-term nature of this study, it should also be noted that these results may only be relative to this training period, and that longer interventions are required to have a greater understanding on the interaction between training and maturity status. Additionally, long-term interventions also allow for increases in training age which can result in a greater likelihood of experiencing larger training adaptations for youth athletes (299). However, though it appears that pre- and post-PHV boys may have different training responses, the implementation of a varied, developmentally appropriate, and periodized training programme should still be the primary goal of any long-term athletic development programme.

CHAPTER 6 PRELUDE

Chapter 5 examined the synergistic effect between maturation and developmentally appropriate training interventions influences the training-induced adaptations to isometric strength and dynamic jump power following separate short-term neuromuscular training programmes. However, it was suggested that a longer training intervention duration may be needed in order to experience greater adaptations in both children and adolescents. A recent meta-analysis (172) reported the largest training-induced adaptations in youth are typically observed in long-term training interventions ≥ 24 weeks. However, previous empirical data with training interventions ≥ 24 weeks have not provided biological maturity status of their participants and assessed strength and power changes using only external measures (99, 148, 274). Training frequency is another pivotal factor which influences movement competency, strength, and power adaptations in youth, however, limited data directly comparing different weekly training frequencies in youth exist (69, 91). Therefore, the final study investigated how long-term training interventions with a twice-weekly or once-weekly training prescription influenced the development of movement competency, strength, and power performance. This information can help strength and conditioning practitioners with training prescription to develop movement competency, maximal strength, and jump performance in youth athletes.

CHAPTER 6 – The effects of training frequency during a 6-month neuromuscular training intervention on movement competency, strength, and power adaptations in youth males

6.1 INTRODUCTION

Research has shown that resistance training can improve athletic performance and movement competency in young athletes (12, 177). The development of movement competency has been deemed a pivotal part of youth athletic development programmes by various organizations (176, 177) and research suggests that a positive relationship exists between movement competency and muscle strength in youth across all stages of maturity (12, 72, 217, 230). Thus, it can be assumed that greater movement proficiency is an underlying mechanism for effectively developing muscular strength and power in young athletes. Much like movement competency, the development of muscular strength and power in young athletes has been well documented in the literature in response to resistance training programmes (255, 303). While muscular strength is traditionally improved through heavy resistance training (94, 241), some studies have suggested that a combination of strength and plyometric training is most effective for improving indices of muscular power (72, 148, 274, 303). For example, Radnor et al. (2017) showed that a combined training programme, inclusive of both traditional strength training and plyometrics, resulted in significantly more individuals realizing meaningful changes in squat jump height, acceleration and maximal running velocity than either traditional strength training or plyometric training on their own. Additionally, recent evidence has demonstrated that combined training can effectively induce adaptations in isometric strength and jump performance in young athletes of mixed maturity status following a short-term training programmes (72, 97, 188).

Training induced adaptations are influenced by exercise variables such as training frequency and duration of the programme (177). The majority of existing paediatric literature examining the influence of training frequency has focused on the effects of once- *versus* twice-weekly training sessions on various measures of physical performance, with data showing somewhat equivocal findings (69, 85, 91, 172, 193). For example, an 8-week resistance training programme showed both once and twice-weekly training frequencies improved strength in 7-12 year old children, but a significantly greater response was observed from a twice-weekly training dosage (91). Similarly, recent meta-analyses have reported that engaging in resistance training on 2-3 non-consecutive days is optimal for increasing both strength and power in youth athletes (13, 242). Alternatively, strength changes were similar between once and twice-weekly, in-season maintenance strength training programmes in male pubescent baseball players (69); while no differences were observed in power-related performance measures in adolescent male soccer players following 6-week, once- or twice-weekly complex training interventions (193).

Certain limitations are evident within existing research that has examined the effects of various training frequencies in youth populations. *Firstly*, previous research has failed to examine the influence of maturity on training responsiveness to different frequencies of training. Biological maturity status has not been reported and previous studies have only compared frequency of training in a single chronological age group (69, 91). Similarly, comparative effects between age groups have not been conducted despite separate studies reporting significantly greater benefits from twice-weekly *versus* once-weekly training frequency in both children (91) and adolescents (69). Previous research has also reported that maturity status moderates the responsiveness to different training modes due to the different physiological profiles in children and adolescents at their respective stages of development (188, 272). While combined training interventions may be optimal in adolescents due to the neural and structural adaptations that accompany natural growth and maturation, children appear to be more responsive to plyometric training (176, 188, 210). Therefore, responsiveness to different weekly training frequencies is likely to be influenced by the type of training mode administered and may vary between children and adolescents. Consequently, limited evidence is available highlighting how maturation interacts with different weekly training frequencies and warrants future investigation.

Secondly, the current evidence base relies almost exclusively on performance outcome measures of athleticism (e.g. jump height, repetition maximum strength) and therefore the effects of different training frequencies on the kinetic variables underpinning such changes in physical performance remain unclear. Relying solely on performance measures can often mask alterations in movement signatures that occur as a result of neuromuscular training, while a better understanding of neuromuscular adaptations can help practitioners prescribe more individualized training programmes. It would appear that only one study has previously measured kinetic variables related to isometric strength and lower body power performance in young athletes at different stages of maturity, indicating that post-PHV boys experienced greater adaptations to force-time characteristics for isometric strength, whereas the pre-PHV cohort experienced greater concentric related power variables within the dynamic jump tests compared to the post-PHV group (72). However, this was only a 12-week study and some changes in kinetic variables may take longer to manifest, particularly in less mature individuals.

Finally, most studies have typically been short-term in nature (~6-12 weeks). Recent meta-analytical data indicated that greater strength and power adaptations are realised in young athletes when training programmes exceed >23 weeks in duration (172), with shorter term interventions likely failing to provide sufficient exposure to enable all youth to realise meaningful changes in function, particularly in less mature cohorts (185). Longer term training interventions have shown that physical qualities such as muscle strength (146), sprint speed (274), change-of-direction speed (147), high intensity intermittent endurance and motor skill competency (99) can be improved; however, these studies did not typically examine the effects of maturation on training responsiveness, relied solely on performance measures, and crucially did not examine the effects of different training frequencies on motor skill competency and strength and power adaptations (99, 146-148, 274).

In light of the limitations of the existing youth-based training intervention literature, it is deemed necessary to investigate the dose-response relationships of different training frequencies on adaptations in physical performance in young athletes following a long-term training intervention. Therefore, the aim of the current study was to investigate the effects of once-weekly *versus* twice-weekly training frequency on measures of movement competency, and strength and power kinetics in young athletes over the course of a 6-month neuromuscular training programme. It was hypothesized that a twice-weekly training frequency would induce larger improvements in all measures in comparison to the once-weekly training frequency.

6.2 METHODS

6.2.1 Participants

Ninety-five young male athletes aged 9-17 years at a sporting academy in the United Kingdom agreed to participate in the study. Individuals were assigned to either a twice-weekly training-group (G2x), a once-weekly training-group (G1x), or a control group (CON). Anthropometrics and biological maturity status for each group in *Table 6.1*. Maturity status was estimated using a previously published sex-specific regression equation (215). Written informed consent and assent were obtained from parents and participants respectively, following ethical approval from the university's institutional research ethics committee in accordance with the Declaration of Helsinki.

Table 6.1 Mean (± *sd*) anthropometric data and biological maturity status for each group at baseline.

	G2x (n=35)	G1x (n=36)	CON (n= 24)
Age (yrs)	11.9 ± 1.3	12.2 ± 1.3	11.7 ± 1.5
Stature (cm)	151.5 ± 9.1	152.5 ± 11.1	152.1 ± 13.3
Mass (kg)	43.6 ± 10.6	47.3 ± 10.9	45.1 ± 12.7
Maturity Status (yrs from PHV)	-1.6 ± 1.1	-1.4 ± 1.1	-1.7 ± 1.4

This study used a repeated-measures design to determine the effects of two different training frequencies on movement competency, and strength and power kinetics following 6-months of neuromuscular training in young male athletes. Testing at baseline and post-intervention consisted of participants completing the back squat assessment (BSA) and three trials of the isometric mid-thigh pull (IMTP), squat jump (SJ) and countermovement jump (CMJ) tests within a single test session. Prior to the intervention, no participants in either of the training groups had participated in a formalized strength and conditioning programme for at least five months. Testing was conducted one week before and immediately after the 6-month training programme. In order to be included in the final analyses, participants from the G2x and G1x groups had to attend a minimum of 75% of the total training sessions throughout the 6-month training programme. Participants that failed to attend the requisite number of training sessions, or did not complete all of the testing sessions, were removed from the final analyses.

6.2.2 Procedures

6.2.2.1 Back squat assessment

Participants were instructed to perform ten continuous squat repetitions in place with a wooden dowel on their back as per previously published guidelines for assessing the BSA (230). Each participant completed two trials of the BSA and aside from the standardized script proposed by Myer and colleagues (230), no other verbal cues or advice were given to participants before or during the testing sessions. All test procedures for the BSA were conducted in the same manner as in previous studies in the current thesis (chapters 3-5). The lowest BSA total score for each participant was used for statistical analysis at both baseline and post-testing (73).

6.2.2.2 Isometric mid-thigh pull

The IMTP test was performed on a custom built IMTP testing device using dual Kistler force plates sampling at a frequency of 1000 Hz (type 9287BA, Kistler Instruments AG, Winterthur, Switzerland). The customized IMTP rig allowed for incremental bar height adjustments of 1 cm to accommodate athletes of different leg length. Testing was conducted using the same procedures as in previous studies in the current thesis (chapters 4 and 5). All successful trials and data were analysed on a customized IMTP LabView programme. Force-time variables calculated from the customized software included: absolute peak force (PF_{abs}), peak force relative to body weight (kg) (PF_{rel}), peak force allometrically scaled to body weight ($kg^{0.67}$) (PF_{allo}), time to peak force (tPF), peak rate of force development (PRFD), and peak force at time periods of 0-50 ms (PF50), 0-90 ms (PF90), 0-150 ms (PF150), 0-200 ms (PF200), and 0-250 ms (PF250). The selection of these variables was based on findings from the cross-sectional analyses in Chapter 3. Acceptable within- and between-session reliability (CV ≤ 9.4%, ICC ≥ 0.87) has previously been reported for this IMTP protocol using youth athletes (216).

6.2.2.3 Squat jump and countermovement jump

Both the SJ and CMJ tests were recorded on an AMTI force plate with a sampling rate of 1000 Hz (Accupower, AMTI, Boston, MA, USA). Acceptable reliability for the SJ (CV ≤ 9% and ICC ≥ 0.85) (181) and CMJ (CV ≤ 9.4%, ICC ≥ 0.82) (213) have previously been reported for young males. Test procedures for the SJ and the CMJ were conducted in the same manner as in previous studies of the current thesis (chapters 4 and 5).

For the SJ, successful trials and data were analysed using a customized SJ LabVIEW programme and the SJ variables measured were: PF_{abs}, PF_{allo}, peak velocity, peak power (PP), relative peak power, impulse, PRFD, and peak rate of force development relative to body weight ($PRFD_{rel}$).

For the CMJ, all successful trials and data were exported from the Accupower software (Accupower 3.0, Accupower solutions, Boston, MA, USA) and analysed using a validated custom built automated CMJ spreadsheet (40). The variables measured for CMJ analyses were; PF_{abs}, PF_{allo} eccentric impulse, concentric impulse, peak power (PP), relative peak power, eccentric power, and concentric power. The selection of the SJ and CMJ variables was based on findings from the cross-sectional analyses in Chapter 3.

6.2.3 Training intervention

Following baseline testing, the G2x and G1x groups commenced their respective 6-month training interventions. An overview of the 6-month training intervention period is provided in *Figure 6.1*. All training sessions for the G2x and G1x groups were led and supervised by a National Strength and Conditioning Association Certified Strength and Conditioning Specialist. The G2x group received twice-weekly training sessions, which included a 45-minute field-based resistance training session and a 60-minute gym-based resistance training session. The G1x group only received the field-based training session. To satisfy the ≥75% adherence rate, participants from the G2x group needed to attend a minimum of 36 out of 48 total training sessions, while the G1x group were required to attend 18 of 24 total training sessions.

6.2.3.1 Field-based resistance training sessions

The G2x and G1x group completed the same field-based resistance training sessions once per week, which primarily consisted of plyometric and high-velocity, low-load resistance training exercises. The field-based resistance training sessions were the only training experienced by the G1x group. Participants were familiarized with each plyometric and resistance training exercise within the programme and were instructed on technical proficiency throughout the intervention. Forms of resistance included using body weight, resistance bands, medicine balls, kettlebells and dumbbells. Each training session consisted of a 10-minute dynamic warm up followed by ~15 minutes of ballistic and plyometric exercises and ~15 minutes of dynamic, multi-joint exercises aimed at developing muscular strength.

Periodised Plan 2018-2019

Week No.	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28
School Holidays										Christmas break																Easter			
Scheduled Testing	(red)																												(red)

Training Blocks		Block 1			Block 2		Block 3 (week 25: no training; weeks 26–27: continued)		
Mesocyles		1	2		3	4	5	6	
RT Mesocycle Theme		Movement Fundamentals			Strength		Explosive Strength / Power		
RT Block Goals		Introduction to fundamental athletic motor skill competencies. Teaching correct exercise technique and assessing movement deficits.		Christmas break	Large focus on developing strength base; increasing volume for upper and lower body multi-joint exercises. Gradually increase intensity by increasing load and decrease rep-ranges throughout the training block to continuously challenge participants. Develop core-strength through exercises challenging anti-rotation, -extension, and -flexion of the core.		Emphasis on increasing intensity through low-load high-velocity movements to develop power while maintaining technique. Power-based exercises prescribed such as loaded squat jumps and drop jumps. Maintenance of strength in multi-joint compound lifts with longer rest periods (> 3 minutes) following each set.		
Sets x Rep Ranges – RT Exercises		3 x 12-15	4 x 12-15		4 x 8-10	4 x 5-8	4 x 5	4 x 3-5	
Rest Periods		< 90 seconds			90 - 120 seconds		~ 2 minutes		
FBT Mesocycle Theme		Movement Fundamentals			Multi-directional Movements		High Velocity Movements		
FBT Block Goals		Introduce basic plyometric exercises and teach safe-landing technique. Game-based activities for change of direction (COD) and agility. Observe and assess particpants display of fundamental athletic motor skill competencies.		Christmas break	Recap on proper exercise technique from movements in previous training block. Further develop SSC ability by prescribing multidirectional drills. Perform similar upper, lower and core exercises prescribed in gym-based sessions using dumbbells, kettlebells, and medicine balls.		Continue to develop power through intoruducing more advanced plyometrics; single leg and continuous jumps. Perform high-velocity loaded movements such as; rotational-, vertical-, and overhead- medicine ball throws. Ongoing maintenance of multi-joint compound exercises.		
Sets x Rep Ranges – Plyometric Exercises		3 x 5	4 x 5		4 x 3-5		4 x 3-5		
Sets x Rep Ranges – RT Exercises		3 x 12-15	4 x 12-15		4 x 12-15		4 x 12-15		
Rest Period		< 90 seconds			90 - 120 seconds		~ 2 minutes		

Figure 6.1 Organisation of the 6-month training intervention for the gym-based resistance training (RT) and field-based training (FBT) sessions. Information regarding the volume, intensity, and rest periods are found in the block goals. Black squares denotes no training conducted during that week, blue squares indicate holidays, and red squares indicate the timing of the PRE and POST testing.

6.2.3.2 Gym-based training sessions

The gym-based resistance training sessions were completed once per week by only the G2x group. The foci of these sessions were to target movement competency and develop muscular strength using multi-joint exercises. Compared to the field-based training, the gym-based sessions consisted of higher-load and lower-velocity resistance training and utilized equipment such as barbells, dumbbells, and kettlebells. Following a 10-minute dynamic warm up, participants performed a variety of fundamental and multi-joint dynamic movements such as squatting, hinging, pushing, and pulling. Each workout incorporated at least two lower body and two upper body strength development exercises in addition to a core bracing stabilization exercise. Participants were familiarized with each exercise within the programme and performed at least one warm up set for each given exercise. Technical proficiency was of high priority during the gym-based sessions and field-based sessions and additional load was never increased at the expense of technical execution. If technique was not displayed to a satisfactory standard during a set and relevant cueing failed to remedy the technical error, participants ceased the set and were instructed to decrease load. When participants displayed optimal technique, they were instructed to increase load by ~5% the following week (2).

6.2.3.3 Periodized programme

The 6-month neuromuscular training programme was divided into 3 x 8-week training blocks for the G2x and G1x groups. For the gym- and field-based sessions, the first 4-week mesocycle was primarily a skill development phase aimed at developing movement technique and overall training experience. During the next 4-week block, sets and repetitions were increased in gym-based sessions providing participants displayed satisfactory competency in the exercises. The gym-based sessions primarily consisted of multi-joint dynamic exercises with relatively low load. The field-based sessions also included some multi-joint dynamic exercises, however the primary focus of these sessions were for high-velocity multi-joint plyometric movements and therefore, the prescribed volumes were lower. The focus of the second training block in the gym-based sessions was to build strength and participants were instructed to appropriately increase resistance for each exercise providing technical competency was maintained (2). For the field-based sessions, the focus was on developing stretch-shortening cycle (SSC) capabilities by prescribing bilateral multiple rebounding and multi-directional jumps. The final training block goal for gym-based sessions was to develop greater higher rates of force production, while maintaining strength levels. The focus of the field-based training sessions in the final block was to develop reactive-strength qualities through a combination of unilateral and bilateral plyometric exercises.

6.2.4 Statistical analyses

Normal distribution of data was assessed using the Shapiro-Wilk test. BSA total score for each group was deemed non-parametric; therefore, median scores were reported for the BSA and a Kruskal-Wallis H-test was used to observe between-group differences and multiple Wilcoxon signed-rank tests were used to determine within-group differences. When significance was observed, post hoc analyses for pairwise comparisons were conducted using a Bonferroni correction for multiple between- and within-group comparisons. Wilcoxon *r* effect sizes were subsequently reported. All variables within the IMTP, SJ, and CMJ tests were parametric; therefore, data were presented as means ± standard deviations (*sd*). A series of 2 x 3 (time x group) repeated measures analysis of covariance (ANCOVA) tests were conducted to determine within- and between-group effects, where "time" denotes PRE and POST intervention and "group" refers to the twice-weekly, once-weekly, or control cohorts. Maturity offset was included as the covariate to control for its influence on each dependent variable; therefore, adjusted means (M_{adj}) ± standard deviations are reported for each variable. Homogeneity of variances were determined using the Levene's Test and Greenhouse-Geisser adjustment was used when violated. To determine the magnitude of change between groups, a customized Microsoft Excel (2016, Redmond, WA, USA) spreadsheet was used to calculate the magnitude of training response in one group over another for all variables within the IMTP, SJ, and CMJ tests. The equation to calculate effect sizes for the magnitude of training effects of one group over another in all kinetic variables was reported according to Cohen's *d* statistic, using the following thresholds: <0.20 (trivial), 0.20-0.59 (small), 0.60-1.19 (moderate), 1.20-1.69 (large), and >1.70 (very large). Multiple stepwise linear regression models were used to determine predictors for significant mean changes in key dependent variables from the isometric strength and dynamic jump tests. The key dependent variables chosen for linear regression analyses were IMTP PF_{allo}, IMTP pRFD, SJ PF_{allo}, SJ pRFD, and CMJ peak power. These variables were chosen due to their significant group x time interaction effects from each test. Training frequency, maturity status, growth rate, and baseline fitness were chosen as independent variables in order to determine their influence on changes within the isometric and dynamic tests. Baseline fitness refers to the mean value at pretesting of the dependent variables and growth rate (cm/month) was calculated by subtracting stature (cm) at POST-testing stature from baseline stature (cm), then multiplying by 100. All statistical analyses were computed using SPSS (V.24 Chicago, IL, USA), with statistical significance for all tests set at an alpha level of $p < 0.05$.

6.3 RESULTS

At PRE testing there were no significant differences between groups for any of the IMTP, SJ, and CMJ variables ($p > 0.05$). At baseline and post-testing there were no differences between any groups for anthropometric and maturity status measures ($p > 0.05$). The mean adherence rate for the G2x group and G1x group was 82% and 84%, respectively.

6.3.1 BSA

BSA total score at PRE and POST testing are displayed in *Table 6.2*. The G2x group made a significant, moderate within-group improvement in median BSA total score from PRE to POST (4.0 to 2.0, $r = 0.68$), whereas, neither the G1x or CON groups had improved at POST testing ($p > 0.05$). The G2x group had a small and significantly lower median BSA total score (2.0) than the G1x group (4.0) ($r = 0.70$, $p < 0.05$) and CON group (4.0) ($r = 0.69$, $p < 0.05$) at POST-testing. There were no differences between the G1x and CON group at POST ($p > 0.05$).

Table 6.2 Median BSA total score with interquartile ranges (25^{th} to 75^{th} percentiles), between-group differences and within- group changes following the 6-month training intervention.

	G2x		G1x		CON	
	PRE	POST	PRE	POST	PRE	POST
BSA total score (25^{th} to 75^{th} %)	4.0 (2.0 to 6.0)	2.0 * $^{\beta\ \alpha}$ (1.0 to 3.0)	4.0 (3.0 to 5.75)	4.0 (3.25 to 5.0)	4.5 (4.0 to 6.0)	4.0 (4.0 to 5.0)

* significant within-group change ($p < 0.05$)
β significantly lower score than G1x group ($p < 0.05$)
α significantly lower score than CON group ($p < 0.05$)

6.3.2 IMTP

Data for all IMTP kinetic variables (M_{adj} ± *sd*) are displayed in *Table 6.3*. Significant time x group interactions were observed in PF_{abs}, PF_{allo}, and PRFD, with the G2x group experiencing moderate to large worthwhile training effects above the other groups ($p < 0.05$; $d = 0.78 - 1.00$; *Figure 6.2*). Differences in responses between G1x and CON groups were mostly small or trivial; however, the G1x experienced a significant training effect over the CON group for PF_{allo} ($p < 0.05$, $d = 0.52$). Results showed a main effect for time in PF_{abs} and PF_{allo} as well as significant within-group effects for the G2x and G1x groups (*Table 6.3*). There were no significant main effects for time or group or any interaction effects for PF50-250, with trivial differences for all between-group training response comparisons ($p > 0.05$).

6.3.3 Squat jump

Data for all SJ kinetic variables (M_{adj} ± *sd*) are displayed in *Table 6.4*. Results indicated main effects for time for most variables and a number of significant within-group effects were observed. Most variables also reported significant time x group interaction effects, with G2x often-experiencing greater training effects than those of the other groups (*Figure 6.2*). Comparisons between the G1x vs CON groups were nearly always trivial, apart from a small difference in peak velocity in favour of G1x. Conversely, G2x experienced moderate positive training effects above those of both G1x and CON for PF_{allo}, PRFD and $PRFD_{rel}$ ($d > 0.7$), and small positive effects for PF_{abs} ($d > 0.3$).

6.3.4 Countermovement jump

Data for all CMJ kinetic variables (M_{adj} ± *sd*) are displayed in *Table 6.4*. No time x group interactions were observed for any CMJ variables ($p < 0.05$). There was a main effect for time for concentric impulse, peak power, relative peak power, and concentric power ($p < 0.05$). Significant within-group improvements for concentric impulse and peak power were observed in the G2x and G1x group. Nearly all comparisons for the effect of training for CMJ variables were trivial ($d < 0.20$), with the exception of a small effect in favour of the G2x over the CON group for PF_{allo} ($d = 0.26$) and peak power ($d = 0.21$).

Table 6.3 Adjusted means ($M_{adj} \pm sd$) for all IMTP variables at each testing period along with *p*-values for main effects for time and time x group interactions.

	G2x		G1x		CON			
	PRE	POST	PRE	POST	PRE	POST	Time main effect	Time*Group interaction
PF_{abs} (N)	1290 ± 366	1488 ± 406*	1351 ± 344	1464 ± 361*	1396± 394	1427 ± 401	$p < 0.001$	$p < 0.001$
PF_{allo} ($N/kg^{0.67}$)	100.9 ± 16.8	112.7 ± 16.2*	102.3 ± 14.0	109.1 ± 15.4*	107.2 ± 15.6	106.3± 15.9	$p = 0.007$	$p = 0.025$
Time to PF (ms)	2818 ± 1391	2655 ± 943	2883± 1314	2946 ± 1180	2990 ± 1120	2694 ± 735	$p = 0.052$	$p = 0.63$
PRFD ($N·s^{-1}$)	4842 ± 1864	6169 ± 1527*	5447 ± 1791	5086 ± 1933	5312 ± 2060	4691 ± 2020*	$p = 0.73$	$p = 0.013$

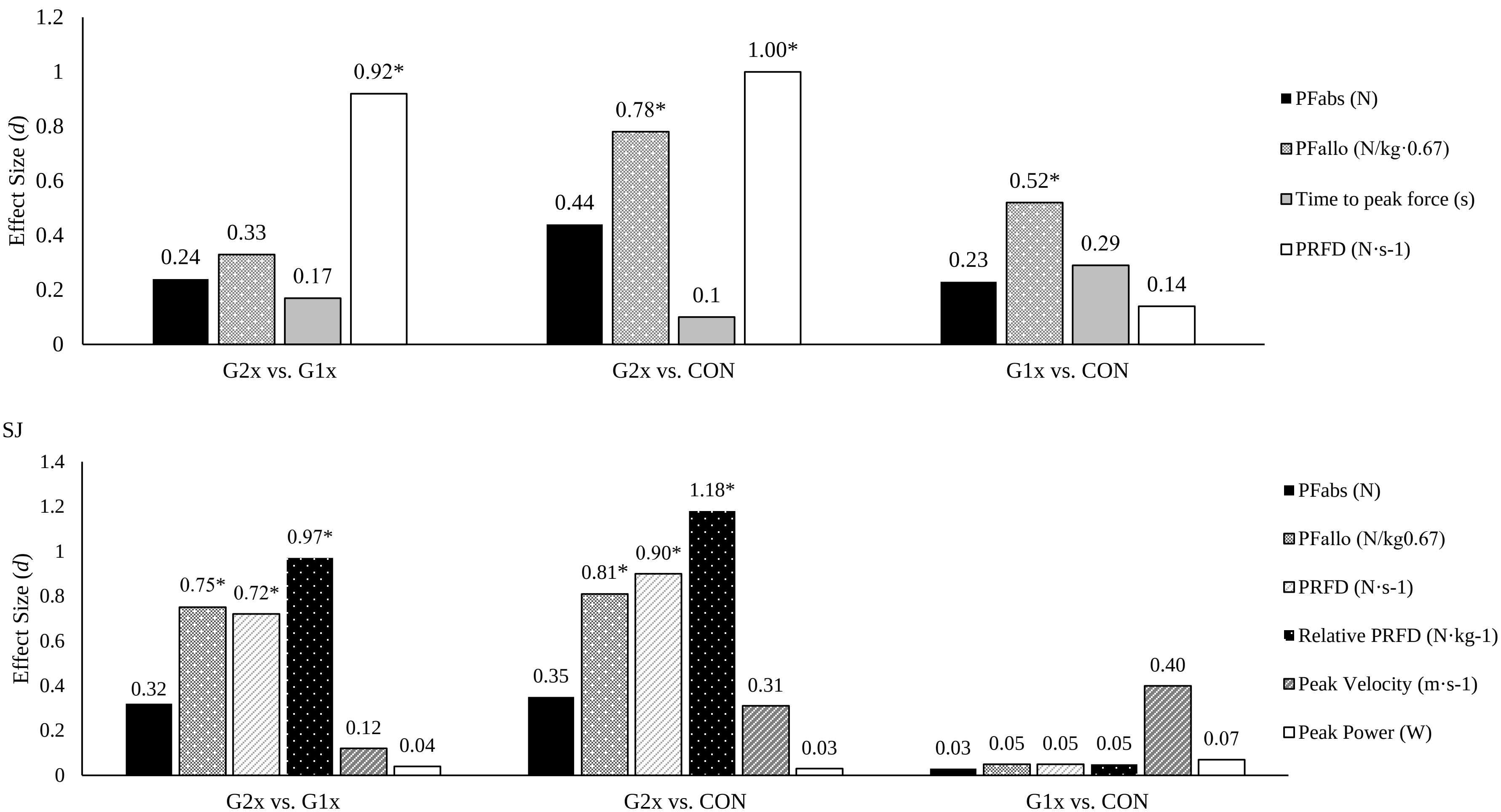
* significant within-group change from PRE to POST ($p < 0.05$)

Table 6.4 Adjusted means with SD for all SJ and CMJ variables at each testing period along with *p*-values for time main effects and the time x group interactions.

		G2x		G1x		CON			
		PRE	POST	PRE	POST	PRE	POST	Time main effect	Time*Group interaction
SJ	PF_{abs} (N)	894 ± 205	954 ± 258*	984 ± 261	968 ± 251	946 ± 289	921 ± 276	$p = 0.77$	$p = 0.014$
	PF_{allo} ($N/kg^{0.67}$)	69.3 ± 7.4	76.7 ± 12.0 *	73.7 ± 9.2	74.7 ± 10.3	70.8 ± 9.8	71.3 ± 9.9	$p = 0.19$	$p = 0.016$
	Peak Velocity ($m \cdot s^{-1}$)	1.9 ± 0.1	2.1 ± 0.3*	1.9 ± 0.2	2.1 ± 0.2*	2.0 ± 0.2	2.1 ± 0.2	$p < 0.001$	$p = 0.79$
	Peak Power (W)	1458 ± 397	1560 ± 401*	1545 ± 426	1665 ± 490 *	1599 ± 503	1687 ± 626*	$p < 0.001$	$p = 0.050$
	Relative Peak Power ($W \cdot kg^{-1}$)	32.3 ± 4.5	33.8 ± 5.0	32.8 ± 5.1	34.4 ± 4.9*	34.3 ± 5.5	34.5 ± 4.8	$p = 0.003$	$p = 0.35$
	Impulse (Ns)	1.7 ± 0.1	1.8 ± 0.3	1.6 ± 0.3	1.8 ± 0.2*	1.6 ± 0.2	1.9 ± 0.2*	$p = 0.005$	$p = 0.21$
	PRFD ($N \cdot s^{-1}$)	3837 ± 1948	5952 ± 3558*	4439 ± 2312	5019 ± 2528	3662 ± 1618	4137 ± 2248	$p = 0.007$	$p = 0.006$
	Relative PRFD ($N \cdot kg^{-1}$)	83.7 ± 36.3	137.0 ± 69.2 *	91.9 ± 38.2	108.8 ± 48.7	75.9 ± 24.5	91.3 ± 41.8	$p = 0.007$	$p = 0.034$
CMJ	PF_{abs} (N)	571 ± 196	565 ± 182	552 ± 178	568 ± 194	525 ± 213	552 ± 193	$p = 0.84$	$p = 0.44$
	PF_{allo} ($N/kg^{0.67}$)	44.8 ± 11.4	43.0 ± 10.8	41.9 ± 8.9	41.4 ± 9.2	39.7 ± 9.9	40.7 ± 8.4	$p = 0.84$	$p = 0.63$
	Eccentric Impulse (Ns)	41.2 ± 12.2	41.8 ± 12.0	41.5 ± 12.1	45.9 ± 13.4*	42.5 ± 13.5	47.7 ± 13.8*	$p = 0.09$	$p = 0.34$
	Concentric Impulse (Ns)	82.9 ± 21.7	90.9 ± 23.5*	87.8 ± 27.0	93.3 ± 29.8*	87.6 ± 28.6	96.6 ± 33.0*	$p < 0.001$	$p = 0.16$
	Peak Power (W)	1597 ± 439	1799 ± 439*	1630 ± 542	1752 ± 566*	1628 ± 596	1722 ± 687*	$p < 0.001$	$p = 0.06$
	Relative Peak Power ($W \cdot kg^{-1}$)	35.8 ± 5.5	37.1 ± 5.0	35.3 ± 6.1	36.5 ± 6.1	35.3 ± 5.5	36.8 ± 5.8	$p = 0.013$	$p = 0.23$
	Eccentric Power (W)	-183 ± 57	-192 ± 66	-191 ± 58	-216 ± 56*	-200 ± 71	-216 ± 74	$p = 0.19$	$p = 0.87$
	Concentric Power (W)	865 ± 272	911 ± 248	879 ± 303	930 ± 309*	876 ± 315	930 ± 358	$p = 0.005$	$p = 0.36$

* significant within-group change from PRE to POST ($p < 0.05$)

a) IMTP



* denotes significantly larger change observed by G2x group ($p < 0.05$).

Figure 6.2 Between-group effect sizes for training responsiveness in kinetic variables in the (a) IMTP and (b) SJ. Training frequency groups are presented as twice-weekly (G2x), once-weekly (G1x), and control (CON) groups.

6.3.5 Regression analyses

Results of the stepwise linear regression analyses are shown in *Table 6.5*. Training frequency and baseline fitness significantly contributed marginally to changes in IMTP PF_{allo}, IMTP PRFD, and SJ PF_{allo} regression models ($p < 0.05$), but not for SJ PRFD or CMJ peak power ($p > 0.05$). Training frequency appeared to be the most significant predictor of explained variance for SJ PF_{allo}. Baseline fitness appeared to be the most significant predictor of explained variance in the IMTP variables (~14–28%) followed by training frequency (~ 8–10%). No independent variables significantly contributed to the SJ PRFD or CMJ peak power regression models ($p > 0.05$).

Table 6.5 Standardized beta (β) and adjusted R^2 values from predictive variables in the IMTP, SJ, and CMJ stepwise linear regression models.

Dependent variable	Predictive variables	β	Adjusted R^2
IMTP PF_{allo}	Constant	65.175	
	Baseline fitness*	-0.539	0.141
	Training frequency*	-0.278	0.221
	Maturity Status	0.315	0.272
	Growth rate	0.107	0.276
IMTP PRFD	Constant	6278.214	
	Baseline fitness*	-0.651	0.282
	Training frequency*	-0.316	0.387
	Maturity Status	-0.267	0.432
	Growth rate	-0.021	0.426
SJ PF_{allo}	Constant	29.201	
	Baseline fitness*	-0.275	0.047
	Training frequency*	-0.286	0.122
	Maturity Status	0.073	0.116
	Growth rate	-0.022	0.106
SJ PRFD	Constant	9.839	
	Baseline fitness	0.094	-0.010
	Training frequency	0.190	0.007
	Maturity Status	-0.158	0.016
	Growth rate	-0.202	0.047
CMJ peak power	Constant	282.747	
	Baseline fitness	-0.286	-0.010
	Training frequency	0.095	-0.011
	Maturity Status	0.376	0.018
	Growth rate	0.094	0.016

* denotes the predictive variable(s) that significantly contributed to the explained variance in the predictive models. ($p < 0.05$)

6.4 DISCUSSION:

The main aim of this study was to compare the effects of different training frequencies on movement competency and strength and power kinetics in young athletes. Results indicated that a twice-weekly training frequency elicited superior adaptations in BSA movement competency, isometric strength and squat jump kinetics compared to once-weekly training over the course of a 6-month training programme. Intuitively, these findings suggest that the twice-weekly training programme was more effective at improving movement control and slower velocity force production, but not explosive force qualities. Significant interaction effects across the IMTP and SJ tests revealed that the G2x group consistently experienced larger worthwhile training effects above the G1x and CON groups. Comparisons for the training effects from the G1x and control group were often in favour of the G1x group, but nearly always trivial across all tests. Training frequency explained the greatest amount of variance in SJ PF_{allo} and PRFD, while baseline fitness explained the greatest variance in IMTP PF_{allo} and PRFD; however, in both instances these independent variables explained a small amount of variance (<28%). Maturity status did not significantly influence adaptations in any of the IMTP or SJ kinetics, which suggests that advanced growth and maturation did not appear to enhance the training responsiveness. Cumulatively, it can be suggested that a 6-month, twice weekly training regimen significantly improves movement competency, isometric strength and squat jump performance in youth athletes above once-weekly training, irrespective of maturity status.

The present study indicates that a 6-month, twice-weekly training frequency results in larger improvements in kinetic variables within isometric and dynamic jump tests than once-weekly training. Minimal data exist assessing the influence of resistance training frequency on measures of strength and power, but no studies have previously determined the effects of training frequency on strength and power kinetics. Of the available data, short-term studies have demonstrated that twice-weekly resistance training is effective in young athletes (85, 87, 94), while Faigenbaum et al. (91) reported that a once-weekly training regimen in children was reported to achieve ~67% of the gains in 1RM strength induced by a twice-weekly training programme. The current study has shown similar findings in that a twice-weekly training frequency greater improvements in IMTP and SJ kinetics compared to once-weekly training over a 6-month intervention period.

The G2x group displayed an improvement in BSA total score following the training intervention, whereas no changes were observed in the either the G1x or CON groups. While exercise technique was emphasized in all sessions for both training groups, it is likely that the additional session provided the G2x group with additional opportunities to enhance their movement competency (33). A previous meta-analysis reported that resistance training is an effect method for enhancing motor performance in children and adolescents when prescribing loads at least 50% of an individual 1RM (12). However, a ~50% (of 1RM) training intensity was also reported to be the “minimal threshold” for improving motor skills and that greater exercise intensities may be more conducive to enhancing motor competency (12). Since the G1x group only performed low-load resistance training during the field-based sessions, it is likely the “minimal threshold” was not met and may explain why BSA movement competency did not change. Therefore, the improved BSA movement competency by the G2x group can be partially attributed to the training effects of consistently performing resistance training at higher intensities while maintaining proper movement technique (33, 320). Similarly, improved movement competency has been affiliated with greater athletic performance (239, 244, 245), and therefore it is likely that improving squat movement competency transferred over to force producing abilities in the IMTP and SJ by the G2x group. Therefore, positive adaptations in isometric strength and dynamic jump performance by the G2x group may be associated with the improved squat movement competency.

While previous long-term training studies have used changes in 1RM as a measure of muscle strength (146, 274), the current study examined the effects of different training frequencies on kinetic variables underpinning changes in strength and power. Data from the IMTP revealed main effects for time for PF_{abs}, PF_{allo} and time to PF variables; however, of greater interest were the significant time x group interactions, which revealed the magnitude of training responsiveness differed between the different training groups. Significant interactions were observed in IMTP PF_{abs} and PF_{allo} which were due to the significant increases from both the G2x and G1x groups following the intervention ($p < 0.05$), while no changes were observed in the CON group. The significant increases in both PF_{abs} and PF_{allo} by both training groups indicate that twice- and once-weekly training frequencies successfully elicited increases in isometric force. The changes in PF_{allo} indicate that when normalized to 2/3 body mass, significant differences remained and thus points to ongoing neural development in the cohorts. Advanced motor unit recruitment and synchronisation has been previously reported to positively influence the production of maximal voluntary force in youth (64, 302), and these mechanisms are likely responsible for the improvements in the PF_{abs} and PF_{allo} evidenced by the G2x group over the 6-months.

There were small training effects in favor of the G2x over the G1x group (d = < 0.33) in most IMTP variables, with the only significant training effect observed in PRFD (d = 0.92). Similar findings were reported in a 12-week, twice-weekly training study where very large changes in IMTP PRFD were observed in post-PHV males (d = 2.60) and moderate changes in pre-PHV males (d = 0.64) (72). The increase in PRFD by the G2x group supports the use of combined training in youth which incorporates strength training and plyometric training methodologies, which reflects previous research that has shown combined resistance training is more effective than plyometric or strength training alone for improving force producing capabilities (99, 188, 249, 303). The current study further advocates the benefits of combined resistance training, especially when extended training periods (e.g. 6 months) and when training frequency is greater than once per week. Although speculative, an explanation for why PRFD improved to a much larger degree in the G2x cohort over the other groups may be due to training exposure across more regions of the force-velocity continuum (188). By an additional training exposure the G2x group likely enhanced greater force producing abilities which manifested in the IMTP. A greater training effect for PRFD but not PF_{abs} and PF_{allo} may be due to the twice-weekly training group having one strength-focused and one velocity-focused session each week. It is feasible to assume that the G2x group would have displayed significant training effects in PF_{abs} and PF_{allo} over the G1x group if exposed to two strength-focused gym-based training sessions instead of only one per week.

Positive changes to SJ performance by the G2x group over the cohorts may be also related to the relationship between isometric and dynamic force-time characteristics. A systematic review investigating this relationship reported that a significant correlation exists between SJ height and IMTP PF_{abs} (r = 0.40 – 0.87) and IMTP peak RFD (r = 0.48) (191). Although speculative, the authors suggested this relationship is likely contributed to similar knee angles often displayed at the beginning of both tests and concentric only muscle action required during the IMTP and SJ tests. In the current study, there were significant main effects for time across nearly all SJ kinetic variables which indicate that all groups improved in squat jump performance over the 6-month intervention. However, significant time x group interactions were also revealed for PF_{abs}, PF_{allo}, peak power, PRFD, and relative PRFD, with the G2x group showing moderate-to-larger increases in PF_{allo}, pRFD, and relative pRFD over both the G1x and CON groups. A previous 2-year training programme by Keiner et al. (148) in children reported no changes in SJ height after the first year of twice weekly training; however, significant increases in SJ height were then observed in the second year of the intervention. The authors hypothesized that the delayed adaptations in the first year were likely due to the low volume (10-15 repetitions) and intensity of training, along with the training sessions only lasting 20 minutes each and with no more than 4 exercises being performed within a session (148). Comparatively, gym-based training sessions in the current study had higher intensities, which likely provided enough of a stimulus for adaptations to be observed in the SJ within a shorter timeframe (i.e. 24 weeks). It is possible that the higher resistance training intensities within the gym-based sessions developed high-force and low-velocity qualities in the G2x group as opposed to the G1x group who were only exposed to low-force and high-velocity type training. Given the force-velocity relationship (54, 55), the higher intensities experienced by the G2x group in the gym-based sessions likely provided a greater overload to explosive concentric contractions, resulting in greater force production in the SJ.

Young athletes performing resistance training has been supported by previous meta-analyses as an effective method for improving CMJ performance (172, 242, 282). There were significant main effects for time for CMJ concentric impulse, peak power, relative peak power and concentric power which indicate that both twice- and once-weekly training programmes significantly improved CMJ performance. There were no time x group interactions ($p > 0.05$) and most comparisons of between-group training effects were trivial, with the exception of a small effect in PF_{allo} and peak power favouring the G2x over CON group. The lack of changes for kinetic variables within the CMJ in both the G2x and G1x group may be due to the principle of specificity. The plyometric element of the training programmes had a strong emphasis on developing rapid SSC capabilities and using higher-velocity exercises. However, the focus of the first two blocks of training were jumping and landing mechanics and slower SSC exercises. While the focus of the final block shifted to faster SSC exercises, the participants may have needed a longer exposure to fast-SSC activities to potentially realise greater adaptations in the CMJ. Similar findings were reported in a 28-week combined training programme where small to moderate increases in CMJ power were preceded by larger gains in movement competency and isometric strength (244). The authors highlighted that establishing a movement competency and strength foundation is required to subsequently develop power in youth athletes (11, 244). This possibly explains why in the current study there were trivial to small adaptations in CMJ kinetic variables but larger improvements in movement competency and force-time variables in the IMTP and SJ by the G2x group. Although speculative, greater adaptations to CMJ force-time variables may have been realized if the training duration were longer and if exercises targeting the slow SSC requirements of a CMJ were included.

Regression analyses showed that training frequency had a small significant contribution to changes in the IMTP PF_{allo}, IMTP PRFD, and SJ PF_{allo}. These findings further highlight the effectiveness of a twice-weekly training frequency over a once-weekly training for making significant improvements in maximal strength and jumping. Of note, baseline fitness was the largest contributor to regression models in IMTP PF_{allo} and IMTP PRFD which indicates that stronger individuals were more likely to experience greater adaptations from the training intervention, in particular in PRFD. One possible explanation is that some participants may have had a larger training age at PRE-testing despite participants reporting not engaging in any strength and conditioning training for at least a 5-month period prior to the study. A higher training age has been demonstrated to be an important factor for improving strength in youth athletes due to having greater development of the neuromuscular and morphological adaptations which enhances training response (299). Maturity status and growth rate did not significantly contribute to the regression models explaining performance changes in the IMTP, SJ, and CMJ variables. This aligns with previous literature which have demonstrated that maturity does not significantly influence peak force when ratio and allometric scaled (217, 245). Training frequency was not the primary predictor of IMTP performance but did explain the most amount of variance in the SJ regression models. Of note, only a small amount of variance was explained within the CMJ and SJ models which suggests that other factors contributed to changes in these performance variables beyond training frequency and baseline fitness. Although speculative, it may be that the coordination required when performing the SJ and CMJ tests improved by the G2x participants from baseline to POST testing. Despite improvements in the BSA, the enhanced movement competency in the G2x didn't necessarily translate to coordination in the dynamic jump tests.

There are certain limitations within the current study which warrant consideration. One limitation is that not all training sessions were gym-based which may have limited the ability to increase training load. A second limitation is that there were no clearly defined maturity groups with each group having a combination of pre-, circa- and post-PHV athletes. Therefore, it is less clear when examining maturational responses to long-term training despite the inclusion of maturity status and growth grate as covariates. Previous literature has indicated that pre-, circa-, and post- PHV athletes respond differently to combined training programmes due to the interaction between natural growth and maturation with adaptations to training (188, 249). Finally, the current study relied solely on kinetic data in the isometric and dynamic tests and the addition of kinematic data would have enabled a better understanding of specific joint loadings. As such, future youth training studies should investigate the maturation-specific long-term adaptations to kinetic and kinematic variables in the IMTP, SJ, and CMJ.

In conclusion, a twice-weekly training frequency resulted in young athletes experiencing superior gains in movement competency, isometric strength, and concentric jump performance when compared to a once-weekly frequency over a 6-month training intervention. Specifically, between-group comparisons of the IMTP and SJ data revealed that twice-weekly training led to significantly greater improvements in IMTP PRFD and SJ PF_{allo}, PRFD, and relative PRFD than training once per week after the 6-month intervention period. Tentatively, it appears that youth with a higher baseline level of strength may respond more favourably to a neuromuscular training programme.

CHAPTER 7 GENERAL DISCUSSION AND DIRECTIONS FOR FUTURE RESEARCH

7.1 Overall Summary

The purpose of the current thesis was to investigate how the development of movement competency, strength, and power is influenced by growth and maturation. The studies from the thesis highlighted the intra-rater reliability of a practical movement competency screen and recommended training prescriptions and training modes for applied practitioners working with youth athletes. The combined body of work furthers the knowledge surrounding maturity-related adaptations in response to training and provides novel data on adaptations in kinetic variables. The empirical studies showed that both pre- and post-PHV males improved movement competency and immature children experienced the greatest adaptations in concentric force-producing capabilities after short- and long-term interventions, whereas, adolescents experienced superior increases in maximal force production in the isometric and dynamic tests.

Findings from the training interventions in the current thesis revolve around the synergistic effect between both maturation and adaptations from training. By undertaking both the challenges of reporting scientific research as well as the duties of longitudinal coaching, the results of this thesis give greater insight into the implications for practitioners who work with youth athletes of different maturity status within authentic long-term athletic development pathways. Thus, a broad display of both scientific knowledge and rigour from the perspective of a coaching practitioner adds to the degree of novelty in the youth exercise science field.

7.2 Challenges Faced

The challenges of conducting applied research such as the reported training interventions in the current thesis extend beyond the scientific paradigm. *Firstly*, the challenge most consistently faced was providing good coaching whilst delivering developmentally appropriate training to youth athletes at different stages of maturity. Throughout each training study, the decision to prescribe different exercises between maturity groups as well as progressing or regressing exercises while not being "gold standard" for research design, did reflect the real-world demands of coaching young children. In fact, such an approach reflects the internationally accepted recommendations for exercise prescription with youth populations (15, 176, 177). However, the central theme of long-term athletic development is establishing a strong foundation of movement competency and providing safe and developmentally appropriate training programmes for youth athletes (176, 177). Therefore, the added challenge of always having individualised exercise prescription for each movement pattern during every session (while being cognizant of progressing volume and intensity to drive training adaptations) was a constant balance. Similarly, effective training with children and adolescents required different coaching cues and exercises in order to drive the desired adaptations for each training intervention (41, 81). Therefore, knowing how to communicate with both children and adolescents in order to develop movement competency, strength and power through neuromuscular training required both coaching experience and inter-personal skills (127, 149).

Secondly, another challenge was maintaining consistent communication with the parents and sport coaches of my participants along with Glamorgan Cricket and Cricket Wales. In retrospect, developing a strong relationship and line of communication with parents throughout my thesis was critical for both the longitudinal training interventions and data collection. Building a trust with not only the parents but also the child and adolescent participants was critical to every training intervention. The challenge of developing trust and respect from many parents combined with making training enjoyable for my participants are underappreciated facets of my thesis work and certainly enhanced adherence for every training intervention. Similarly, the trust from Cricket Wales and Glamorgan Cricket to train their youth groups required maintaining communication and transparency throughout all training interventions. Additionally, on occasion the sporting coaches were able to attend field-based and gym-based training sessions which gave me the opportunity to demonstrate my competency in coaching and answer any questions they had.

Finally, another difficult challenge from conducting the training interventions revolved around inconsistent attendance from participants during weekly training sessions or performance test days. The reason this was the largest challenge is because of the factors which are mostly out of the control of the principal researcher. All of the participants rely on parents or guardians as a means of transport to both testing and weekly training sessions; therefore, attendance from participants depended on cooperation and willingness from the parents. Despite the challenges of a large population of children involved in the project across multiple training centres, adherence rates for all groups were above 75% throughout the studies. In order to achieve this, it was paramount to have clear communication with parents and participants from both the training and control groups while also showing flexibility in my own personal schedule.

Many of the challenges faced during this thesis related to the "soft skills" of coaching, working with factors outside of logistical planning. These certainly highlight the challenges also faced by coaching practitioners in the field working with youth athletes while also displaying the difficulties of carrying out training studies. Thus, this thesis provides a broader perspective beyond research due to the practical nature of the work.

7.3 Aims and Objectives from the Thesis

The current thesis outlined a series of objectives in *Chapter 1* that were researched in the subsequent series of empirical studies (*Chapters 3-6*).

Objective 1: *Determine the intra-rater reliability of the Back-Squat Assessment (BSA) movement competency screen using 2D video analysis.*

- C*hapter 3* examined the intra-rater reliability of the BSA in young male athletes by rating movement competency in a pre- and post-PHV group across three separate sessions. Acceptable reliability was demonstrated for agreement in BSA total score across all sessions in pre-PHV (ICC $\geq$ 0.81) and post-PHV (ICC $\geq$ 0.97) groups. Additionally, analysis of kappa values (k) for the ten criteria in the BSA revealed less agreement for identifying deficits in the pre-PHV group (k $\geq$ 0.31) than the post-PHV group (k $\geq$ 0.62). While the BSA seems to be a reliable movement competency screening tool, it appears that pre-PHV children produce more movement variability and therefore additional familiarisation may be required when screening children in the BSA.

Objective 2: *Determine the effects of a 4-week neuromuscular training intervention on movement competency in young males of different maturity status.*

- In *chapter 3*, the BSA was used to monitor changes in movement competency in both pre- and post-PHV males following a four-week neuromuscular training intervention. The study demonstrated that significant within-group improvements ($p < 0.05$) in BSA total score were made by both the pre- (5.0 to 3.0, $ES = 0.68$) and post-PHV (5.0 to 3.0, $ES = 0.82$) groups. Consequently, it seems that both children and adolescents were sensitive to adaptations in movement competency after a short-term training intervention.

Objective 3: *Examine the effects of age and maturation on measures of movement competency, strength and power in a large cross-sectional sample of young males of different maturity status.*

- In *chapter 4*, cross-sectional analyses of a large sample of pre-, circa-, and post-PHV males was used to reflect the role of maturity status on movement competency, strength and power. Between-group analysis of BSA total score revealed that post-PHV males demonstrated more favourable squat competency than the pre-PHV cohort ($p < 0.001$, $d = 0.34$). However, no differences were observed between the circa-PHV group with either the pre- or post-PHV cohorts, which suggests that small increases in movement competency occur during maturation. Advanced maturation resulted in moderate to large increases in PF_{allo} in the IMTP, SJ, and CMJ ($p < 0.001$, $d = 0.53 – 1.83$) which aligns with the existing literature on the effects of natural growth and maturations on strength and power development. Interestingly, trends from the isometric and dynamic tests indicate that the largest adaptations to strength and power may occur around the adolescent growth spurt.

Objective 4: *Evaluate the effects of a 12-week neuromuscular training intervention on measures of movement competency, strength and power in young males of different maturity status.*

- The empirical study presented in *chapter 5* evaluated the trainability of strength and power in youth of different maturity status. Alterations in kinetic variables during IMTP, SJ and CMJ tests were reported in this study, which were a novel addition to the existing literature. Analysis revealed both the pre- and post-PHV groups made significant increases in IMTP PF_{abs}, PRFD, and peak force at time epochs 0-250ms ($p < 0.005$); however, superior increases were seen by the post-PHV group in all IMTP variables. Alternatively, the neuromuscular training increased concentric force qualities in favour of the pre-PHV cohort as demonstrated by increased squat jump height ($p < 0.05$, $d = 0.42$) and CMJ concentric power ($p < 0.05$, $d = 0.37$). Thus, the magnitude of changes in the kinetic variables that underpin strength and power performance are potentially influenced by biological maturity status in short-term neuromuscular training interventions.

Objective 5: *Determine the chronic effects of a 6-month intervention and a twice- versus once-weekly training prescription on measures of movement competency, strength and power in a cohort of young males.*

- Few studies in the existing literature have administered training interventions longer than 24 weeks, despite training responsiveness in youth reportedly being higher following longer-term training exposure. Additionally, there is a lack of research directly comparing the effects of different training frequencies in youth athletes. Therefore, *Chapter 6* investigated how training frequency influences changes in movement competency, strength, and power in young males of varying maturity status. The findings reported that twice-weekly training frequency resulted in superior training effects in movement competency ($p < 0.05$, $r = 0.70$) as well as superior gains in PF_{allo} and PRFD in the IMTP and SJ ($p < 0.05$, $d = 0.70$ -1.00) compared to a once-weekly frequency. The regression analyses reported that training frequency significantly contributed to the explained changes in IMTP and SJ variables ($p < 0.05$), albeit a small amount of explained variance. However, growth rate and maturity status did not appear to significantly influence adaptations to strength and power following the long-term training intervention which suggests that other factors are likely contributing to the degree of training responsiveness.

7.4 DIRECTIONS FOR FUTURE RESEARCH

The current thesis has contributed novel and significant data to the paediatric literature and have provided a greater breadth of understanding towards the interaction of natural growth, maturation, and training in young athletes. Using rigorous research designs, the empirical studies provided comparative data on the kinetic adaptations experienced by youth of different maturity status to short and longer-term training interventions. However, several questions remain unanswered and directions for research that warrant future investigations are listed below:

1. *Inter-rater reliability of the BSA in males of varying maturity stages*. While intra-rater reliability was established, acceptable inter-rater reliability of the BSA remains unknown, which would assist in the practical utility of the BSA by a group of practitioners. Additionally, reporting of inter-rater agreement for the BSA in youth of different maturity stages would highlight if greater movement variability was common amongst different raters when assessing pre-PHV males.

2. *The effects of neuromuscular training between pre-, circa-, and post-PHV males.* The empirical training studies in the current thesis compared training-induced adaptations between pre- and post-PHV athletes. While the cross-sectional analyses included a circa-PHV cohort and identified that this period of time resulted in large performance variability in comparison to the pre- and post-PHV cohorts, context-specific limitations in the talent development pathway in which these studies were completed made the addition of a circa-PHV impractical . While the literature highlights the confounding sensitivity of pubescent

males for developing movement competency, strength, and power, there is no research examining changes to force-time variables or how these characteristics adapt during rapid growth and maturation. While it is evident that maturation increases the development of these athletic qualities, future research can assess how training changes force production across a range of tests protocols across the F-V curve during periods of peak gains in stature and mass.

3. *The effects of training intensity following a long-term intervention between males of different maturity status.* The final study in the thesis administered a long-term training programme comparing the effects of a twice-weekly and once-weekly training frequency on gains in movement competency, strength, and power. However, optimal training intensities for inducing changes in strength, power, and movement competency is still unclear within the literature. Although recent reviews state that higher intensities lead to greater returns (172, 242), the comparative differences in response to training at different intensities is unknown in children and adolescents. Therefore, future research is warranted which compares adaptations in response to various training intensities between children and adolescents throughout a long-term training intervention.

CHAPTER 8 - REFERENCES

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Appendix 1 - PARTICIPANT INFORMATION SHEET

Project Title: Long-term athletic development of children who do and do not participate in strength and conditioning

Ethical Approval Code: TBC

Lead Researchers: Dr Jon Oliver (JOliver@cardiffmet.ac.uk)
Dr Rhodri Lloyd (RLloyd@cardiffmet.ac.uk)

Dear participant and parent/guardian,

You are being invited to take part in a research project with Cardiff Metropolitan University. Please read this information sheet carefully before deciding whether you/your child would like to participate.

Background
Strength and conditioning is becoming a popular form of physical training and involves a variety of exercises including resistance and weight training. However, children tend to take part in physical education and organised sports and not strength and conditioning. We want to examine the physical development of children who do take part in strength and conditioning and those who don't.

Aims of the research
This research aims to compare the long-term development of athletic abilities in children who do and do not participate in structured strength and conditioning programmes.

Why am I/why is my child being asked to volunteer
You are being asked to volunteer as you are aged between 11 and 18 years old and you take part in exercise at school and/or a sports club but you are not receiving any regular strength and conditioning coaching.

We also separately recruiting participants who are part of strength and conditioning academy. We will then compare the physical development of those who do and do not regularly take part in strength and conditioning.

What will happen if you decide to volunteer?
If you choose to participate you will have to take part in some fitness testing. As part of the testing we will measure your height, sitting height and weight. We'll also ask parents to tell us their height; this allows us to estimate how tall each child will be as an adult and how much more growing they have left. In terms of fitness testing we will ask you to do a sprint, an agility test, some jumps off both one and two legs, throwing a medicine ball, a balance test,

strength test and an endurance test (running backwards and forwards 20 m at increasing speeds).

We will continue to monitor your fitness at regular intervals over a number of years; up to a maximum of seven years or until you become 18 years old. We will test your fitness between one and three times per year, although you would only ever complete the endurance test once per year. If you do volunteer for the research you are free to withdraw at any time.

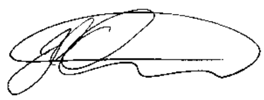
What are the risks of participating in the study?
The risks of participating in the study are minimal. You will be taking part in fitness tests, the risks of getting injured should be no higher than the risks of getting injured during your normal sports practice or during physical education lessons. All research staff that conduct fitness testing will hold a current DBS (police records check)

What are the benefits of participating in the study?
You will be given results and feedback regarding your fitness; this will help you understand how fit and healthy you are. Most importantly we will be able to show you how your fitness is changing over time. This information should help you set your own exercise and fitness goals.

What will happen to the information collected?
All data will be made anonymous and stored securely at the University for 10 years, after which it will be destroyed. Data will only be accessible to University researchers working on the project. Results of this project may be published but any data included will in no way be linked to any specific participant.

What next?
If you have any questions about the research then please do not hesitate to contact me. If you would like to participate in the study then the consent form needs to be signed by the parent/guardian and the assent form signed by the participant and returned to me.

Many thanks,



Dr Jon Oliver,

Reader in Applied Paediatric Exercise Science,

Cardiff Metropolitan University,

Tel: 029 2041 7276

e-mail: joliver@cardiffmet.ac.uk

Appendix 2 - PARENT CONSENT FORM

Project Title: Long-term athletic development of children who do and do not participate in strength and conditioning

Ethical Approval Code: TBC

Lead Researchers: Dr Jon Oliver (JOliver@cardiffmet.ac.uk)

Dr Rhodri Lloyd (RLloyd@cardiffmet.ac.uk)

I have fully read and understood the information sheet that has been provided to me. I have had the opportunity to ask any questions I may have and all the answers I have been provided with are satisfactory.

<u>**I understand that I am entitled to withdraw my child from the project at any time without any repercussions.**</u>

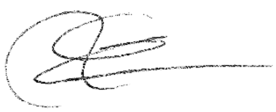
<u>I understand that:</u>

- ✓ My child has volunteered to participate in the study on their own accord, and that they are entitled to leave the study at any time should they wish to.
- ✓ To be eligible my child will have to confirm that they are not regularly taking part in strength and conditioning outside of their normal PE or sports club activities.
- ✓ My child will be required to take part in regular fitness testing sessions, up to three times per year for up to seven years.
- ✓ Data collected may be used in published research but it no way will my child be identified in any publications

Parent/guardian Name (print): Date:

Signed (parent/guardian):

Principle investigator’s name: Jon Oliver/Rhodri Lloyd



Signed (principle investigator):

To help with the research please also provide, if known, the height of both the biological mother and father of the child (either in meters of feet and inches). If you know your height simply enter below, otherwise parental height can be measured by one of the research team. Also, if known, please provide the birth weight of your child

Age ______________________ Date of Birth _________________________

Mothers Height____________________ Fathers Height________________________

Child Birth Weight (kg) __________________

Appendix 3 - PARTICIPANT (CHILD) ASSENT FORM

Project Title: Long-term athletic development of children who do and do not participate in strength and conditioning

Ethical Approval Code: TBC

Lead Researchers: Dr Jon Oliver (JOliver@cardiffmet.ac.uk)
Dr Rhodri Lloyd (RLloyd@cardiffmet.ac.uk)

I have fully read and understood the information sheet that has been provided to me. I have had the opportunity to ask any questions I may have and all the answers I have been provided with are satisfactory.

<u>**I understand that I am entitled to withdraw from the project at any time without any repercussions.**</u>

<u>I understand that:</u>

- ✓ I have agreed to join in the study.
- ✓ I can leave the study at any time. I just have to tell a member of the research team
- ✓ I will need to take part in fitness testing sessions up to three times per year for up to five years
- ✓ All information about me will be kept safely at the university for 10 years. The results of the study may be published in the future, however my name will not be mentioned anywhere.

Participants name (print): Date:

Signed (participant):

Principle investigator's name: Dr Jon Oliver and Dr Rhodri Lloyd

Signed (principle investigator):

Appendix 4 - Physical Activity Readiness Questionnaire (PAR-Q)			
Name of Participant: Please circle ‘YES’ or ‘NO’ to the following questions:			
1	Do you currently suffer from asthma or any breathing-related condition?	YES	NO
2	Have you ever consulted your doctor as a result of suffering from a heart-related condition?	YES	NO
3	Have you/do you suffer from any chest pains which may be aggravated by exercise?	YES	NO
4	Do you suffer from bouts of dizziness or from feeling faint?	YES	NO
5	Have you ever been told by a medical consultant that you suffer from a bone and/or joint condition which might be further aggravated by exercise?	YES	NO
6	Have you ever been diagnosed with high blood pressure?	YES	NO
7	Have you ever been diagnosed with diabetes?	YES	NO
8	Are you unaccustomed to regular vigorous exercise?	YES	NO
9	Is there a significant physical reason not mentioned above why you should not take part in the research project?	YES	NO
If you have circled ‘YES’ to any of the questions, please provide further details in the space below. Also, if there are any health and fitness related conditions that could affect your participation in the research which are not covered in questions 1-8, please provide further information below Should your situation change regarding any of the conditions mentioned above, please notify one of the researchers/member of staff/teacher as soon as possible.			

Signed (participant):	
Signed (parent/guardian):	
Signed (principal investigator):	
Date:	05/10/17

Appendix 5 - Approval for Cardiff Met use of video

<u>Approval for Cardiff Met use of video</u>

During the assessment day there will be use of video for some of the assessments, which will be property of Cardiff Metropolitan University, and may be use for subsequent research. Parental consent needs to be given to permit Cardiff Metropolitan University to use this video for their research purpose.

I (parent name):

Give permission for Cardiff Metropolitan University to use video recording during the assessment day of my child (child name):

Signed

Dated

Appendix 6 - ETHICS DOCUMENTATION

When undertaking a research or enterprise project, Cardiff Met staff and students are obliged to complete this form in order that the ethics implications of that project may be considered.

If the project requires ethics approval from an external agency (e,g., NHS), you will not need to seek additional ethics approval from Cardiff Met. You should however complete Part One of this form and attach a copy of your ethics application and letter(s) of approval in order that your School has a record of the project.

The document ***Guidelines for obtaining ethics approval*** will help you complete this form. It is available from the Cardiff Met website. The School or Unit in which you are based may also have produced some guidance documents, please consult your supervisor or School Ethics Coordinator.

Once you have completed the form, sign the declaration and forward to the appropriate person(s) in your School or Unit.

PLEASE NOTE:
Participant recruitment or data collection MUST NOT commence until ethics approval has been obtained.

PART ONE

Name of applicant:	Jon Oliver
Supervisor (if student project):	Click here to enter text.
School / Unit:	Sport
Student number (if applicable):	Click here to enter text.
Programme enrolled on (if applicable):	Click here to enter text.
Project Title:	Long-term athletic development of children who do and do not participate in strength and conditioning
Expected start date of data collection:	01/08/2016
Approximate duration of data collection:	5 years
Funding Body (if applicable):	Click here to enter text.
Other researcher(s) working on the project:	Dr Rhodri Lloyd, Dr Rob Meyers, John Radnor, Tom Matthews, Sylvia Moeskops, Steph Morris. Prof Avery Faigenbaum (New Jersey College). Prof John Cronin (Auckland University of Technology).
Will the study involve NHS patients or staff?	No
Will the study involve taking samples of human origin from participants?	No

Does your project fall entirely within one of the following categories:	
Paper based, involving only documents in the public domain	No
Laboratory based, not involving human participants or human tissue samples	No
Practice based not involving human participants (eg curatorial, practice audit)	No
Compulsory projects in professional practice (eg Initial Teacher Education)	No
A project for which external approval is required (e.g., NHS)	No
If you have answered YES to any of these questions, make this clear in the non-technical summary. No further information regarding your project is required. If you have answered NO to all of these questions, you must complete Part 2 of this form	

In no more than 150 words, give a non-technical summary of the project
Recent position statements on youth resistance training and long-term athletic development (Lloyd et al., 2014, Lloyd et al., in press) have suggested that it is beneficial for all children, and particularly those involved in sports to engage in strength and condition. The benefits can include improved health and wellbeing, reduced injury risk and improved athletic performance. However, very few studies have examined the long-term benefits of being involved in systematic strength and conditioning during childhood and adolescence. Similarly few studies have directly examined the influence of maturation on long-term training gains. Therefore, this study proposes to examine the wellbeing, injury risk and performance benefits of being involved in a long-term strength and conditioning programming during childhood and adolescence.

DECLARATION: **I confirm that this project conforms with the Cardiff Met Research Governance Framework**	
Signature of the applicant: 	Date: 28th June 2016
FOR STUDENT PROJECTS ONLY	
Name of supervisor:	Date:
Signature of supervisor:	

Research Ethics Committee use only	
Decision reached:	Project approved ☑ Project approved in principle ☐ Decision deferred ☐ Project not approved ☐ Project rejected ☐

Project reference number: 16/8/01S	
Name: Dr Brendan Cropley	Date: 24/08/2016
Signature: 	
Details of any conditions upon which approval is dependant: All individuals involved in data collection to have an up-to-date DBS stored on file	

PART TWO

A RESEARCH DESIGN	
A1 Will you be using an approved protocol in your project?	No
A2 If yes, please state the name and code of the approved protocol to be used[1]	
Click here to enter text.	
A3 Describe the research design to be used in your project	

The Youth Physical Development Centre at the Cardiff School of Sport has been set-up to offer local boys and girls the opportunity to join a strength and conditioning academy. The purpose of the academy will be to expose youth members to personalised strength and conditioning that will facilitate their athletic development; this includes improving their athletic performance, reducing their risk of injury when engaging in sport and improving their wellbeing.

Members will be recruited into the academy through contacts with local schools, clubs, academies and national governing bodies. Currently cohorts trained through the strength and conditioning academy include rugby boys from Llanishen High School, girls and boys from Llandaff rowing club and juniors from the tennis academy. The strength and conditioning academy will be open to children from 11 to 18 years old. Children (and their parents) will be offered the opportunity to purchase termly memberships to attend either one or two sessions per week. It is likely that some children will remain in the academy for many years while others will be more transient. In the recruitment of volunteer participants from the Centre membership it will be made clear (to both participants and their parents/guardians) that volunteering to take part in the research does not influence the training they receive when attending the Centre; all sessions will be designed to maximise individual development and fitness testing will be used to evaluate progression and inform prescription of all members (whether research participants or not).

The academy will regularly monitor and fitness test members to help evaluate programme effectiveness and inform future programme design. In this regards all members of the academy will be exposed to a range of monitoring processes and fitness assessment. Monitoring will be an ongoing process to track training loads and wellbeing. Fitness assessment will occur between three to six times per year depending on the training phase/programme. This application is requesting access to use that information to allow

[1] An Approved Protocol is one which has been approved by Cardiff Met to be used under supervision of designated members of staff; a list of approved protocols can be found on the Cardiff Met website here

data from the academy to be used for research purposes. To supplement the research a control group will be recruited from a local school and/or sports club, where children who are not part of the strength and conditioning academy will be longitudinally tested.

Monitoring

Members of the youth strength and conditioning academy will be asked to complete a training diary each time they train at our facility. Using google docs this system will ask members to record the exercises completed, the number of sets, reps and loads lifted. Participants will also be asked to highlight the number of other training and competition sessions completed since they last attended the academy (i.e. sessions completed outside of the academy). This will enable us to monitor training loads and volumes. In the same system members will also be asked to rate their wellbeing using a system similar to that developed by McLean et al (2010) and previously used in youth rugby players (Oliver et al., 2015). Members will provide a score from 0-5 on factors such as their mood, quality of sleep, soreness and fatigue. Athletes will also be asked to rate their enjoyment of each training session at the academy.

Anthropometric & Maturity Assessment

Members of the academy and the control group will be assessed for their standing height, sitting height and body mass following the International Standards for Anthropometric Assessment (ISAK). Maturity will be non-invasively estimated using two methods. Firstly, anthropometric measures will be entered into a predictive equation to determine how close a participant is to their peak height velocity (middle of the growth spurt) (Mirwald et al., 2002). Secondly, parental height will be captured and used to predict the participants adult height and their current %adult height (Khamis and Roche, 1994). Parents will have the option to have their height directly measured at the Centre or to recall their height and enter this onto a consent form.

Physical Fitness Measures

Members of the academy and the control group will be regularly assessed on a range of variables chosen to reflect athletic development; this will include measures associated with both sports performance and injury risk. The control group will be tested a minimum of once per academic year and a maximum of three times per year. The academy members will be tested between three to six times per year. However, the yo-yo intermittent endurance test will only be used once per year in both groups. The pattern used will mirror the testing schedule of the academy and will allow analyses to determine the effects of training over and above growth and maturation.

Tests will include
*^40 m sprint test
*^Agility sprint
*^Two-legged countermovement jump
*Single-leg countermovement jump (left and right leg)
*Two-legged horizontal jump
*Single-leg horizontal jump (left and right)
*^Drop jump from 30 cm
*Medicine ball throw
*Rotational medicine ball throw
*Y-balance test

*Plank hold test
*Yo-yo intermittent recovery test
Isometric-mid thigh pull
^1 rep max bench press

*All these tests, or slight variations of these tests, have previously been included in paediatric PhD research projects that have been approved by the Cardiff School of Sport Research Ethics Committee.

^All of these tests currently have applications to become approved protocols being considered by the research ethics committee. If successful future data collection will adhere to instructions in the approved protocols. General principles of protocols for two-legged vertical jumps will be applied to single-legged and horizontal jumps. Risk Assessments are included within the approved protocol applications

The isometric mid-thigh pull and 1 rep max bench press are measures of maximal strength. The bench press will only be used with academy participants (and not the control group). It has long been accepted that healthy children can safely engage in maximal strength testing providing appropriate procedures are followed (Faigenbaum et al., 2003), and national position statements (Faigenbaum et al., 2009 NSCA position statement, Lloyd et al., 2012 UKSCA position statement) and international consensus statements (Lloyd et al., 2014) have supported the use of maximal strength testing in children. Appropriate procedures include making sure participants are familiarised and able to maintain correct technical form while applying maximal effort; this is made easier by the use of low skill tasks such as the isometric mid-thigh pull and bench press. The isometric mid-thigh pull involves pulling maximally on an immovable bar while standing on a force platform, meaning there is no external load moved. During the bench press load starts at a known submaximal level and is gradually increased, an adult spotter is used to assist the participant should they fail to fully move a given load on their own.

Training Programme
Members of the youth strength and conditioning academy will receive personalised training programmes and coaching. Training programmes will be based on the participants technical abilities, training history, maturation, fitness and training goals, but with an overall aim of improving the physical fitness and reducing the risk of injury when engaging in sport. Training programmes will follow contemporary guidelines (e.g. Lesinski et al., 2015 BJSM) and models of youth physical development (Lloyd et al., 2012). Training will focus on resistance training; including the use of body weight, moving external loads and developing weightlifting abilities. Training will also include the use of movement skill, plyometric, speed and agility exercises.

Sample Size
The sample size for athletes in the youth strength and conditioning academy is not known. Currently n~60 youth athletes are trained through the academy. However, when the Youth Physical Development Centre is formally launched and there is a proactive recruitment drive it is expected that upto 150+ may be training in the academy each week. A control sample of n~200 will be recruited across an age range of 11-18 years old, the control will be recruited either from a local school and/or a local sports club where children are not engaging in strength and conditioning. Each year older participants will leave the study

once they reach 18 years of age and new participants will be recruited at the entry age (11 years old) ***Statistical Analyses*** Long-term, multi-level modelling will be used to compare the progress of children in the academy compared to controls. Confounding factors, including the effects of maturation, body size, baseline fitness and sex will be considered when examining development. Magnitude-based inferences will also be used to examine the magnitude and meaningfulness of changes over time, as well as providing a method to examine individual responsiveness across the cohort.

A4 Will the project involve deceptive or covert research?	No
A5 If yes, give a rationale for the use of deceptive or covert research	
Click here to enter text.	
A6 Will the project have security sensitive implications?	Choose an item.
A7 If yes, please explain what they are and the measures that are proposed to address them	
Click here to enter text.	

B PREVIOUS EXPERIENCE
B1 What previous experience of research involving human participants relevant to this project do you have?
As a Reader in Applied Paediatric Exercise Science I have extensive experience of research with youth populations. This includes publishing approximately 70 international peer review publications and supervising eight PhD students to completion. Dr Rhodri Lloyd and Dr Rob Meyers have extensive experience of research with athletic paediatric populations, including research that involves training interventions. John Radnor, Tom Mathews, Sylvia Moeskops and Steph Morris are all research active members of staff working towards PG and PhD qualifications and have experience of research with human participants from their UG and PG studies. Prof Avery Faigenbaum is an international lead in the field of youth strength and conditioning with the longest and most well established global reputation for research in youth strength and conditioning. Prof John Cronin has worked closely with other members of the research team (Jon Oliver, Rhodri Lloyd, Rob Meyers) in youth athlete research over the last eight years. This includes youth athlete development research at both Auckland University of Technology and the CSS.
B2 **Student project only** What previous experience of research involving human participants relevant to this project does your supervisor have?
Click here to enter text.

C POTENTIAL RISKS

C1 What potential risks do you foresee?
1) Safeguarding and welfare issues when working with minors 2) Potential injury from training and physical fitness testing 3) Feeling dizzy or faint during maximal strength testing
C2 How will you deal with the potential risks?
1) All researchers directly involved in data collection and coaching of children to have an up-to-date DBS. Similarly, all such persons shall be made familiar with the Cardiff Met Child Protection Policy and Procedure prior to any contact with children. 2) The risk of injury will be no more than that if children were engaging in normal physical activity, and likely less than during competitive sport and unsupervised play. A thorough warm-up will precede all training and testing to help avoid muscle strain. All participants will be familiarised with all test-procedures with sub-maximal efforts before progressing to maximal efforts. Progression to a maximal test effort will only be allowed where participants can execute a technically sound movement. 3) In line with the risk assessment for maximal strength testing, participants will be instructed to stop any effort if they experience a feeling of dizziness or light-headiness. Where this does occur participants will be withdrawn from testing, sat or lay down and monitored until they have recovered.

When submitting your application you **MUST** attach a copy of the following:

- All information sheets
- Consent/assent form(s)

An exemplar information sheet and participant consent form are available from the Research section of the Cardiff Met website.