GROWTH AND MATURATION IN ELITE YOUTH SOCCER PLAYERS

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Abstract

Soccer is the world's most popular sport, with individuals of different standards and ages competing. The identification and development of youth soccer players with the potential to reach professional status has come more into focus over recent decades. Maturity presents a compelling paradox for young soccer players. During adolescence, individuals mature at different rates; the timing and tempo of specific maturational events can vary significantly with some individuals entering puberty well in advance or delay of their same age peers. Additionally, both physical performance parameters and match running metrics can fluctuate during this period. The aim of this thesis was to investigate longitudinally the consequences of biological maturity on various physical performance parameters and match running metrics amongst a total of 84 elite youth soccer players aged 11.3 – 18.0 years of age.

Initially, two common non-invasive methods for assessing maturity status, and a simple age-based strategy were compared to determine the accuracy in differentiating youths of varying maturity status. Longitudinal research was conducted over the course of five consecutive years, on a total of 28 elite youth soccer players. The study demonstrated the utility of the percentage height window determined using the Khamis-Roche equation, with maturity status estimated through this method showing a statistically significant improvement over chance ($\chi^2 = 19.17$), whereas Mirwald maturity offset method did not ($\chi^2 = 1.09$).

Having established the most reliable and valid method for determining maturation status in elite academy soccer players, the main and interactive effects of biological maturity and relative age upon physical performance metrics (5 m and 20 m sprint, change of direction, countermovement jump height and reactive strength index) were investigated for one competitive playing season. Maturation was associated with performance on all but one of the physical fitness tests, reactive strength index (5 m – $p < 0.01$; 20 m – $p < 0.01$; change of direction – $p < 0.01$; countermovement jump – $p < 0.01$ and reactive strength index – $p > 0.05$). In contrast, relative age only served as a significant predictor of fitness on the countermovement jump (5 m – $p > 0.05$; 20 m – $p > 0.05$; change of direction - $p > 0.05$; countermovement jump – $p < 0.05$ and reactive strength index – $p > 0.05$). The interaction between these two constructs was also tests, however showed no statistical significance.

Having found that maturation effects training data, the extent to which variance in biological maturation also contributed to in-match running performance (total distance covered, distance at high speed, distance at very high speed, maximum speed and the number of accelerations made from zone 4 to zone 6) across age groups (U14s, $n = 21$, U15/16s, $n = 16$) over one competitive playing season was examined. There was a suggestion that maturation does have an impact on high speed match running metrics within the U14 age group ($p < 0.05$), however some of this variance may be attributed to the same individuals under / over performing consistently in matches on the match running metrics. Furthermore, within the U15/16s age group, the influence of maturation on match running metrics appeared to have less of an impact.

Finally, to better understand the associations between biological maturation and fitness performance, Chapter 7 aimed to identify the overall dynamics of fitness performance relative to the timing of the adolescent growth spurt in 30 elite youth soccer players measured for six consecutive years. Measured velocities for fitness performance metrics did not express themselves at the same time relative to age at peak height velocity; however, these fitness metrics reached a peak around the time of maximal growth in height (12 months pre- to 12 months post-peak height velocity), with peaks in performance occurring for 5 m ~ 24 months pre and 12 months pre-peak height velocity; 20 m ~ 18 months pre-peak height velocity; COD ~ 12 months pre-peak height velocity, at moment of peak height velocity and 6 months post-peak height velocity; countermovement jump ~ 6 months pre-peak height velocity and RSI at moment of peak height velocity, respectively. In all the physical performance metrics measured, physical performance continued to show improvements following peak height velocity.

The overall findings of this thesis have demonstrated the effects of maturity status on match running and fitness performance in elite youth male soccer players. Being able to correctly identify the interval of the adolescent growth spurt is of use to practitioners working in this area. During adolescence, maturity had a positive influence on high speed match running, and on tests of short and long sprint time, change of direction and explosive leg power.

Publications Derived from this Thesis

Parr, J., Winwood, K., Hodson-Tole, E., Deconinck, F. J. A., Parry, L., Hill, J. P., Malina, R. M. & Cumming, S. P. 2020. Predicting the Pubertal Growth Spurt in Elite Youth Soccer Players: Evaluation of Methods. Annals of Human Biology (Special Edition). This publication forms Chapter 4.

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Parr, J., Winwood, K., Hodson-Tole, E., Deconinck, F. J. A., Hill, J. P. & Cumming, S. P. 2021. Maturity Associated Differences in Match Running Performance in Elite Male Youth Soccer Players. International Journal of Sports Physiology and Performance. This publication forms Chapter 6.

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List of Abbreviations

Abbreviation	Meaning
4G	4th Generation.
505	Change Of Direction.
ABC	Assessment Battery for Children.
Acc	Accelerations.
AIC	Akaike Information Criterion.
BA	Biological Age.
Bio-banded	Competition With Teams Grouped By The Level Of Maturation.
CA	Chronological Age.
CI	Confidence Interval.
CMJ	Countermovement Jump.
COD	Change of Direction.
CT	Contact Time.
DJ	Drop Jump.
EPL	English Premier League.
EPPP	Elite Player Performance Plan.
FT	Flight Time.
GP	Greulich Pyle.
GPS	Global Positioning System.
HSR	High Speed Running.
IQR	Interquartile Range.
KR	Khamis Roche.
MAD	Median Absolute Deviation.
Max.S	Maximum Speed.
MO	Maturity Offset.
MPS	Mid-Parental Stature.
MS	Maturity Status.
PAH	Percentage Adult Height.
PHV	Peak Height Velocity.
PPAH	Percentage Of Predicted Adult Height.
PWV	Peak Weight Velocity.
RA	Relative Age
RAE	Relative Age Effect.
RPE	Rating Of Percieved Exertion.
RSI	Reactive Strength Index.
RUS	Radius, Ulna and Short Bones.
SA	Skeletal Age.
SITAR	Super Imposition By Translation And Rotation.
SSC	Stretch-Shortening Cycle.
TW	Tanner-Whitehouse.
U	Under.
UK	United Kingdom.
US	United States.
VHSR	Very High Speed Running.
VO_2peak	Peak Oxygen Consumption.
Z4	Zone 4.
Z6	Zone 6.

List of Symbols and Units

Symbol / unit	Meaning
~	Approximately Equal To.
%	Percentage.
<	Less Than.
=	Equal To.
>	More Than.
±	Plus Or Minus.
≤	Equal to And Less Than.
≥	Equal to And More Than.
C_1	Age Dependent Intercept Coefficient.
C_2	Age Dependent Height Coefficient.
C_3	Age Dependent Weight Coefficient.
C_4	Age Dependent Mid-Parental Stature Coefficient.
cm	Centimetre.
F	F-Ratio.
h	Hour.
H	Height at Time of Observation.
Hz	Hertz.
ICC	Interclass Correlation.
kg	Kilogram.
km	Kilometre.
l.min	Litres Per Minute.
m	Metres.
min	Minute.
MAD	Median Absolute Deviation.
Nm	Newton Metre.
n	Number.
p	Probability Value.
p	Significance Value.
R^2	Correlation.
s	Second.
SD	Standard Deviation.
SE	Standard Error.
W	Weight at Time of Observation.
yr	Year.
Δ	Difference Between Two Points.
κ	Cohen’s Kappa Coefficient.
χ^2	Chi-Square.

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“The biggest risk was that we had erred in our assessment of a particular boy and could have used his slot to work with a more talented youngster. We had to wait a little longer to see the real potential in some boys, because not everyone’s physique develops at the same *rate.” – Sir Alex Ferguson, on talent identification at Manchester United.*

Ferguson (2015).

Chapter 1

1. General Introduction

Chapter 1

1.1. Research Overview and Context

Soccer is the most popular sport in the world, played in every nation around the globe (Reilly and Williams, 2003). Approximately 265 million players and 5 million referees and officials participate worldwide, representing approximately 4% of the world's population (Sarmento et al., 2018). According to the Football Association (FA), almost one in five adults (8.2 million) in the UK now play some form of soccer (TheFA.com, 2015), and approximately 2.5 million youth players aged 5 – 15 years compete either recreationally or are registered to a club or academy (SportEngland.org, 2016, FIFA.com, 2007). Approximately, 12,000 of these players are selected to play in an academy at a professional club, highlighting the demand and scale of talent identification within soccer. As a sport, soccer encompasses technical, tactical and physical elements, making the game unpredictable, multifaceted and unpredictable, and therefore interesting to audiences around the globe.

Individuals of different standards and ages compete in soccer, from amateur through to professional level standard and from junior age level (e.g., Under 8's) through to senior and even masters level of play, for both male and females. The differences in both playing standards and age groups place different impacts on the physical demands to players during a competitive match. Recently, Barnes et al. (2014) described the changes in the demands of the game (soccer) over recent years, detailing how it has become much faster and more intense. They examined soccer performance across seven seasons (2006-07 – 2012-13) in the English Premier League (making 14,700 match performance observations). They found an increase in high intensity running actions by approximately 30% (1,151 vs 890 m), an increase in sprint distance by approximately 35% (350 vs 232 m). Amongst senior male professional players, the usual distance an outfield player covered varies between 10,000 – 12,000 m in a competitive match, depending on the position being played (Mohr et al., 2003). The distances that are covered in a game are distinguished by constant changes in exercise type and intensity – for example, jogging, sprinting and jumping (Stolen et al., 2005). Although frequent periods of matches are being competed at lower intensities, it is usually high energy, explosive actions, such as making a tackle or attempting a shot that are believed to be instrumental, and decide the outcome of competitive matches (Faude et al., 2012).

At the youth level, a systematic review by Vieira et al. (2019) highlighted that as individuals become older, running profiles for actual playing time (parameters such as maximum speed, total distance covered and high speed running) became greater than their younger counterparts. For example, Goto et al. (2015) highlighted that the U15s covered greater total distance (6,700 m covered within an hour) compared to the U11s (5,700 m covered with an hour). Additionally, the U15s also covered greater distances at higher speeds (> 6.0 $m \cdot s^{-1}$ [21.6 $km \cdot h^{-1}$]) than the U11 squad (164 $m \cdot s^{-1}$, 29.0 $m \cdot s^{-1}$, respectively). These increases in match running profiles, performed by the older players, could be attributed to the enhanced physical characteristics (strength, speed and power) of youth soccer players (Vieira et al., 2019), and in turn, these physical characteristics interact with the technical, tactical and psychological elements of match play (Sarmento et al., 2018).

The benefits that are associated with advanced maturation and the influence it has on performance have previously been reported (Baxter-Jones et al., 2002, Goto et al., 2019), however, the inclusion and implementation of this growth and maturity information into training protocols is somewhat inadequate (Bailey et al., 2010). Variances in performance have been attributed to differences in maturity status and also to time of birth in selection year (an effect commonly referred to as the relative age effect). The work in this thesis looks into how growth and maturation can have an effect on training and match performance, the understanding of this can be applied to training and development of youth soccer players in the elite academy setting. This thesis concludes with examples of how this be implemented.

1.2. Relevance of the Research

In 2011, the English Premier League introduced the elite player performance plan (EPPP) with the long term strategy of developing and producing more and better home-grown players (EPPP, 2020). The EPPP recognised the benefit of youth development for sporting success and financial gains for sporting organisations (Bullough and Jordan, 2017), and has implemented various ongoing projects such as benchmarking for fitness testing and growth and maturation screening, in all academies with category statuses. The EPPP emphasises the importance of the evolving physical fitness demands to compete at the highest level in soccer.

The work in this thesis is conducted in an EPL academy where the EPPP is implemented and many of the ideas and hypotheses tested come directly from results gathered through EPPP testing of elite youth soccer players. Data collected for use within this thesis was taken in accordance with the EPPP guidelines and all physical performance tests used are aimed at identifying elite players and their development. All of the analysis conducted in this thesis will help to take the EPPP forward, and the results will be of use to those working in an elite academy setting.

1.2.1. Research Context from a Researcher-Practitioner Perspective

Jones et al. (2019) defined a researcher-practitioner as an individual that usually spends approximately 30 % of the their time as a practitioner (for example, day-to-day activities, providing support to athletes and / or coaches and planning training / athletic development sessions) and around 70 % of their time as a researcher (e.g. creating research questions, collecting, analysing and interrogating data and developing feedback mechanism which will feed into communication lines between multidisciplinary departments).

In contrast to the research by Jones et al. (2019) who suggested that a research-practitioner typically spends 70 % of their time in research and 30 % in practice, the author typically spends approximately 70 % of their time as a practitioner and 30 % as a researcher in their day-to-day activities. Currently, the author spends their time in both practice (the soccer club) and research (university) environments, benefiting from available participant data (anthropological and performance data). These two roles are also linked through the impact of growth and maturation on performance that is the driver of the research.

Practitioner duties:

- Providing support to athletes and coaches
    - Being able to adequately improve athletic performance, implementing injury prevention programmes, optimise return to training / play;
    - Provide coaches with vital information / data on the athletes to allow informed decisions to be made.
- Athletic development programme planning
    - Planning is a vital role to the current authors job, working across a broad spectrum of age groups (U12 to U23s), the needs and requirements for each athlete (and age group), vary significantly and requires careful consideration.
    - Training session planning (around match programme and player physical progression) is a key part to the authors job role. This involves:
        - On-field (pitch based running session – taking into consideration match days (for example - matchday – 1 / matchday – 2);

        - Targeted gym work for both player specific and development specific requirements (different components are being performed – strength:speed / speed:strength / upper body and core, along with preparatory movements / primers and isometrics).
- Data collection
    - Collection of GPS data allows for objective data to be viewed and discussed both with athletes and coaches;
    - Regular collection of EPPP testing metrics (running speed, COD, lower limb explosive strength), allowing for data visualisation and longitudinal monitoring of performance indicators;
    - Frequent collection of anthropometric measurements.

Researcher duties:

- Creating research questions, analysing and interrogating data
    - Following in-depth conversations and ideas between academics and the club, discussions follow in order to drive the research and its practises to best collect / analyse / interrogate data.
- Writing up research and sharing with wider audiences
    - Research questions that have been identified are written up and submitted for publication, this allows broader audiences to view and be able to implement and / or adapt their practices following the results from the current author's research.
- Embedding learnings into the practical environment
    - Findings from the current authors research are also implemented in the current club, for example, the findings of Chapter 4 have recently been implemented into the collection and analysis of the growth and maturity data within the current club.

1.3. Research Rationale and Aims

Despite the vast amount of literature on the influence of maturity on physical fitness performance, there is still a scarcity of research pertaining to the relative age effect and the overall physical development of youth soccer players. Previously, physical development models have been criticised for this shortage of evidence (Ford et al., 2011), but realistically, this may be a consequence of the practical environment in the real-world of youth athletic development. Practitioners could be constrained for time, support staff, and possibly may even lack equipment required for such research.

Therefore, the primary aim of the current research was to determine the consequences of growth and maturation on various physical and match running metrics.

The objectives of the current research are four-fold.

1. To explore the sensitivity and accuracy of commonly-used, non-invasive methods for the prediction of maturational status and forecast of PHV amongst elite academy soccer players that have been tracked longitudinally over five consecutive playing seasons (2013 – 2017).
2. The main and interactive effects of biological maturity and relative age will be investigated within a cross-sectional study aimed at exploring the effects on fitness performance amongst 84 elite youth soccer players aged between 11.3 – 16.2 years of age. Physical fitness will be assessed in four areas: sprinting performance; change of direction; countermovement jump; and reactive strength index. The maturity status of the participants will be determined using percentage of predicted adult height at observation (Khamis and Roche, 1994).
3. Maturity associated differences in match running metrics amongst elite youth soccer players will be investigated within a cross-sectional study design. Sixty-one participants will be monitored over the course of one competitive playing season (2018-19). A global positioning system (GPS) will be used in matches. A series of multilevel models will be used to examine the predictive associations of biological maturation upon match running metrics.
4. Changes and development of performance indicators relative to the timing of maximal growth in height (PHV) and weight (PWV) in a sample of 30 elite male soccer players will be longitudinally investigated across six consecutive years. Anthropometric characteristics will be collected bi-monthly, and five performance tests will be measured every three months for the duration of the research. A series of performance velocity curves will be employed to examine the changes in performance over time.

   The research techniques, strategies and purposes are also summarised in Table 1-1, including details of the research aims, number of participants, the research design and the data collected.

Table 1-1. Overview of thesis research studies.

Research Title	Research Aim	Participants	Research Design	Data Collected
Chapter 4: Predicting the Pubertal Growth Spurt in Elite Youth Soccer Players: Evaluation of Methods.	Three methods for estimating the interval of the pubertal growth spurt were compared relative to observed age at PHV: an estimate of 13.8 ± 1.0 year - generic age at PHV; predicted age at PHV based on the maturity offset equation, predicted age at PHV ± 1.0 year; and a window of PHV based on a PPAH at the time of observation between 85% – 96%.	28 adolescent males from a professional soccer academy.	Longitudinal.	Anthropometric measures were collected across five consecutive playing seasons.
Chapter 5: The Main and Interactive Effects of Biological Maturity and Relative Age on Physical Performance in Elite Youth Soccer Players	To investigate the main and interactive effects of maturation and relative age upon fitness parameters; 5 m, 20 m, change of direction, countermovement jump and reactive strength index in elite youth soccer players.	84 male participants aged between 11.3 - 16.2 years from a professional soccer academy in the English Premier League.	Cross-Sectional.	Height, sitting height (cm), and weight (kg) were measured every two months throughout the competitive playing season. 5 m and 20 m split times, change of direction (505), CMJ and RSI.
Chapter 6: Maturity Associated Differences in Match Running Metrics in Elite Youth Soccer Players	To investigate maturity status, measured using PPAH, and playing position associated variance in match running metrics (total distance, distance covered at HSR, distance covered at VHSR, maximum speed and a count of accelerations from zone 4 to zone 6) of elite academy male soccer players across the course of one playing season.	37 elite male youth soccer participants from an English professional soccer academy.	Cross-Sectional.	Five match running metrics were collected from the GPS data: total distance covered at all speeds; distance covered at HSR; distance covered at VHSR; accelerations from zone 4 to zone 6 and maximum speed.

Chapter 7: The Development of Athletic Performance during Stages of Rapid Growth through Adolescence.	To investigate the adolescent growth spurt in height and the overall development of five performance indicators over a six-year period relative to the period of the maximum growth in height in a group of elite male soccer players.	30 elite male youth soccer participants from an English professional soccer academy.	Longitudinal.	Height, sitting height (cm), and weight (kg) were measured every two months and 5 m and 20 m split times, change of direction, CMJ and RSI were measured every three months for six consecutive years.

Note: CMJ – Countermovement jump; GPS – Global positioning system; HSR – High speed running; PPAH – Percentage of Predicted Adult Height; RSI – Reactive strength index; VHSR – Very high-speed running.

An answer to each of the four above research avenues will help to provide a better understanding of the effects of the calculation of maturity and its impacts on boys within Elite academy settings. The information will be helpful to academics and practitioners in the field of performance linked to growth and maturation, particularly, but not restricted to, those involved with soccer.

Chapter 2

2. Review of the Current Literature

Chapter 2

2.1. Overview

This chapter gives the reader a generic overview of growth, maturation and an introduction to the development of the scientific research within sport, specifically within soccer. In addition, the chapter will highlight the reasons why there is a need for such research and finally the novel aims and objectives of the proposed studies for this PhD thesis.

2.2. Growth

Growth can be defined as changes (increases) in body size or the size attained at a specific anatomical site (Malina et al., 2004a). During the first two decades of human life, growth is the most significant biological activity (Malina et al., 2004a). Tissue growth occurs as an outcome of underlying cellular processes; increase in cell numbers (hyperplasia), caused by cell division, increase in cell size (hypertrophy), caused by an increase in functional units within the cell, and an increase in cellular substances (accretion), functioning to bind cells into complex networks. These processes are non-linear, for example, hypertrophy follows a non-linear pathway from childhood to adulthood (Malina et al., 2004a).

Growth anthropometric data can be measured reliably by skilled practitioners, following previously established protocols (Stratton and Oliver, 2014). Assessment of growth status involves the measurement of standing height, weight and possibly other dimensions such as seated height, breadths and circumferences. The uses for growth data can be broad, however, in paediatric literature it is most commonly described in reference to growth charts as shown in Figure 2-1.Throughout childhood and adolescence, there are rapid accelerations in stature in early childhood and around the adolescent growth spurt (~12 years in girls and ~14 years in boys, though this timing is highly individualised). However, around mid-childhood and towards the attainment of final adult stature, growth is much steadier and begins to plateau. The growth chart denoted in Figure 2-1 represents various percentiles during growth in boys; the expectation would be that a child would track along a percentile from the age of four years through to adulthood (Cole and Wright, 2011).

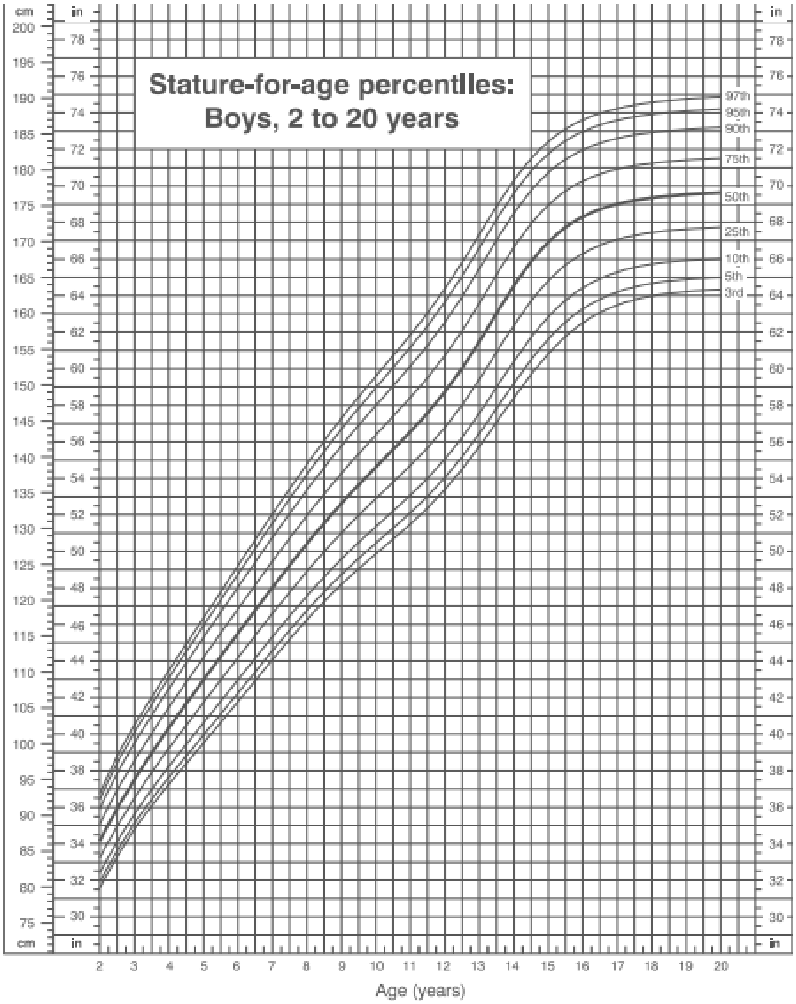


Figure 2-1. Individual growth chart for boys aged 2 – 20 years. Adapted from Centers for Disease Control and Prevention (2015).

The measurement of growth can be quantified using rate (tempo) and distance (timing). The rate of growth can be defined as by how quickly size is accumulating, whereas distance is the absolute size at any given point in time; it is an accrual of all the previous growth. Tanner (1990) highlighted that healthy children follow the same growth patterns and sequences, though the timing and tempo does vary from child to child.

Although, the timing and tempo varies considerably from child to child (Tanner, 1990, Malina et al., 2004a), the period of the most accelerated growth in height occurs during the first few years of childhood, shown in Figure 2-2. By approximately 4 – 5 years of age, the accelerated growth period decelerates from 20 $cm·yr^{-1}$ to approximately 5 – 7 $cm·yr^{-1}$ (Tanner, 1981). These growth rates remain steady; the child is getting taller at a constantly slower rate (between 5 – 7 $cm·yr^{-1}$). The growth rates reaches its lowest rate prior to the initiation of the adolescent spurt, approximately a year before peak height velocity (PHV) in boys, at which point, the velocity curve begins to accelerate (Malina et al., 2004a).

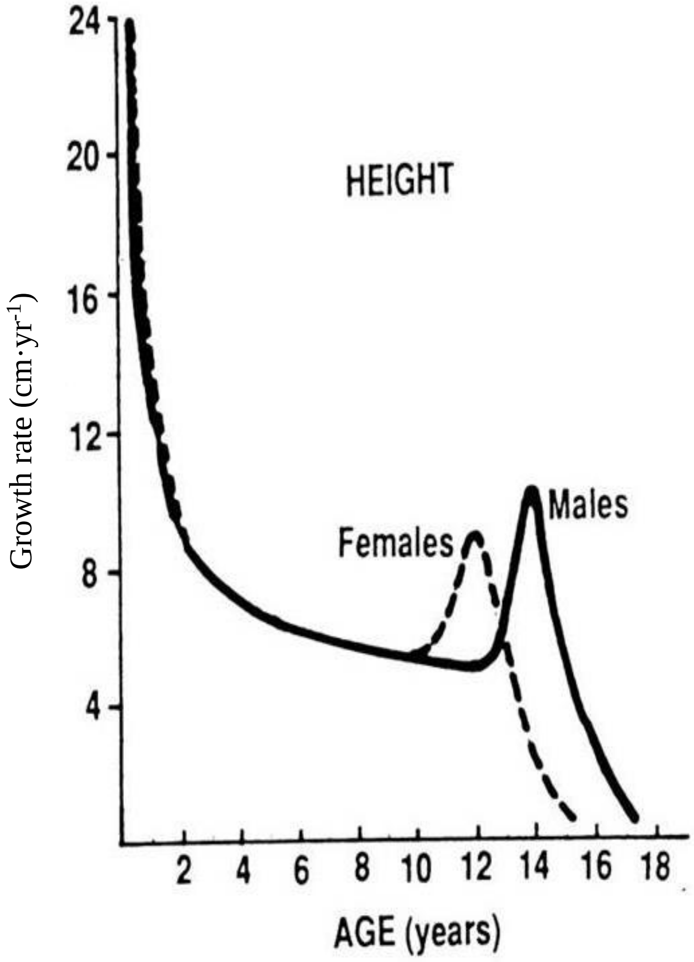


Figure 2-2. Typical individual velocity curves for height in males and females. Adapted from Tanner (1981).

Serial measurements in height can be converted into growth rates (cm·yr^{-1}) and then plotted against chronological age, as in (Figure 2-2). The growth curve can then be used to identify key events such as the onset of the growth spurt. The age at which maximum rate of growth during the adolescent spurt (growth speed is at its highest) occurs is termed age at PHV and is the most commonly used marker of somatic maturity. Usually, PHV occurs around the age of 14 years in European boys (Figure 2-2). However, this is individualised, and there can be considerable differences in timing and tempo, influenced by factors such as the environment and lifestyle (Malina et al., 2004a). During the early part of the adolescent spurt, girls tend to be taller and heavier than boys due to their earlier growth spurt; at this point boys are still gaining at a preadolescent rate of approximately 5 cm·yr^{-1}. This height advantage is soon lost as boys then undergo their adolescent growth spurt (Iuliano-Burns et al., 2001). In boys, the growth spurt typically starts later than in girls; however, it does last longer and is more intense. On average, girls are 13 cm shorter than boys as girls typically reach their final adult height earlier than boys. Girls stop growing in stature approximately 16 years of age, whereas boys continue growing for approximately a further two years.

The growth of stature has the most observable 'spurt', however other body tissues experience growth spurts similar to stature. Curves of systemic growth reported by Scammon (1930), identified post-natal growth rates that characteristically follow set patterns, described by four different curves of growth, as in Figure 2-3. The curves denote the growth of four different groups of body tissues, from birth to 20 years of age. The data shown in Figure 2-3 are relative, with the size attained at each structure expressed as a percentage of the total gain.

The general curve denotes the growth of the body as a whole (height, weight and external dimensions of the body). The growth pattern is S-shaped (sigmoidal) due to rapid growth that occurs through infancy and early childhood, steady and constant through mid-childhood, rapid growth through the adolescent growth spurt, and gradual eventual cessation following adolescence. Moreover, the final part of the curve continues into the twenties for the majority of dimensions.

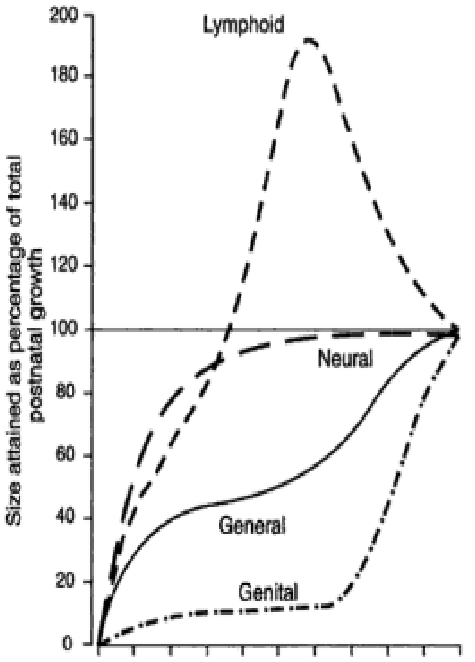


Figure 2-3. Scammon's curves of systemic growth and measurement of males throughout childhood. Growth of each structure is expressed as a percentage of total gains between birth and 20 years of age. Size at 20 years is equivalent to 100% on the y-axis. Adapted from (Scammon, 1930).

The neural curve involves the growth of the central nervous system, brain and associated structures, namely the eyes and parts of the skull. Malina et al. (2004a) identified that approximately 95% of the attainment in size between birth and 20 years is already attained by the age of seven years. Moreover, individuals do experience a slight spurt in neural tissues during the adolescent growth spurt (Figure 2-3). The genital curve defines the growth patterns of the primary and secondary sex characteristics. Genital tissues show minor growth during infancy, followed by a dormant period during most of childhood. This is then followed by rapid growth and maturation during the adolescent spurt (Figure 2-3). The lymphoid curve highlights the growth of the lymphoid glands, amongst others such as the appendix and tonsils. These tissues are involved with the development of immunological capacities. Throughout infancy and childhood, the lymphoid tissues undergo rapid growth, peaking around the ages of 11 – 13 years (Figure 2-3). Furthermore, the curves depicted by Scammon (1930) highlights the different growth rates between different areas and tissues of the body, and this is happening at different rates and times.

2.3. Maturation

One of the unique challenges that practitioners face when working with youth athletes is maturation. The concept of maturation is the process of progressing towards the adult (mature) state (Malina et al., 2004a). To some extent, maturation can be more difficult to define than growth, as this depends on the particular systems that are under study. Figure 2-3 highlights the shape of the growth curves for the lymphoid, neural, general and genital systems in boys during childhood. Characteristically, these growth curves are comparable between individuals, although, the exact chronological age at which different stages of maturity are reached, generally differs considerably (Malina et al., 2004a). Maturation varies amongst individuals of the same chronological age in timing (maturity status at a given age) and tempo (rate of change / maturity progress) between the different bodily systems. Maturation does not progress in accordance with chronological age, thus suggesting a variation or discrepancy between chronological and biological age; the level of biological maturity attained at a particular chronological age. Full biological maturation is only achieved when all tissues, organs and organ systems have been attained and are fully developed (Malina et al., 2004a). The phrase ‘maturity’ is used within the elite youth soccer setting (academies) and also within the literature; the expression refers to the maturational status that the athlete has currently reached in relation to their final adult status, i.e., their fully mature state (Malina et al., 2004a). Because of the interchangeability and variation of growth and maturity throughout childhood and adolescence, individuals will commonly be viewed as either ‘early, ‘on-time’ or ‘late’, reflecting that their maturity status is ahead of their chronological age, their maturity status is on-time with their chronological age or their maturity status is behind their chronological age, respectively (Lloyd et al., 2014). This is shown diagrammatically in Figure 2-4.

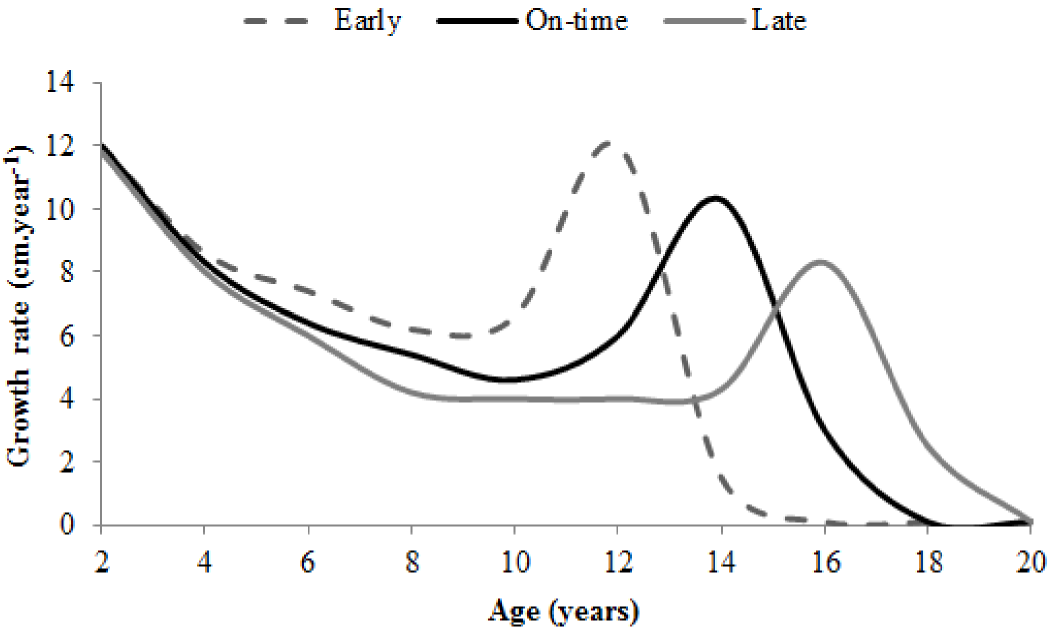


Figure 2-4. Changes in growth rates with chronological age for early, on-time and late maturing individuals. Based on hypothetical data.

Depending on the biological system that is being considered, measures of maturity can vary significantly. Commonly used measures of maturity indicators include skeletal maturation, sexual maturation, and somatic maturation. It is important to grasp the difference between growth and maturity, which are used interchangeably, when defining the pathway from birth to adulthood. Growth can be defined as an increase in body size, or the size attained at a specific anatomical site which can be summed up, whereas maturation is a process that marks progress toward the adult (mature) state. This is important to bear in mind as work within this thesis regularly analyse player performance on a growth and maturity basis, and the two should not be confused. Likewise, the differences between chronological age (common, linear process) and growth and maturation (individual, non-linear processes) are important concepts for this work.

2.4. Methods of Assessments for Biological Maturation

As previously highlighted, particular bodily systems that are being considered, such as tissues, organs, and organ systems mature at different times and rates (Beunen et al., 2006). Commonly, systems that are used for the assessment of maturity status in youth athletes include skeletal, secondary sex characteristics (sexual) and somatic maturity (Beunen et al., 2006). Ultimately, the regulation of the timing of the growth spurt and sexual maturation are underpinned by the maturation of the nervous and endocrine system (Beunen et al., 2006). These methods of assessing maturity are discussed in more detail next.

2.4.1. Skeletal Maturation Methods

The maturation of the skeleton is widely accepted as the best indicator of maturity status (Acheson, 1966). As the development of the skeleton spans the whole of the growth period (from birth to approximately 20 years of age), skeletal maturation can be viewed as an ideal maturity indicator. Bone tissue accounts for approximately 98% of height and roughly 15 - 17% of body weight in individuals under the age of 50 years (Malina et al., 2004a). Skeletal age maturation is non-linear and differs between individuals, sex and races (Malina, 1969, Malina, 1970).

Commonly, skeletal age maturation can be assessed using a plain x-ray of the wrist and hand, and then compared to a reference sample (Greulich-Pyle, Fels or Tanner-Whitehouse), and is typically referred to as the gold standard for estimating maturity status (Malina et al., 2004a).

2.4.1.1. Greulich-Pyle Method

The Greulich-Pyle method (Pyle et al., 1971), based on the original work of (Todd, 1937), involves the matching an x-ray of the left hand-wrist to a series of standard x-ray plates that relate to specific chronological age. The comparison involves 28 bones being matched to reference radiographs in an atlas which contains radiographs of known child skeletal maturity at specific decimal ages. The closest match between the x-ray and reference radiograph would be selected as the equivalent bone age. Due to the inherent nature of subjectivity involved with this method, the Greulich-Pyle method does have large intra and inter observer variability (De Sanctis et al., 2014). However, amongst 406 children (276 males and 130 females), (Paxton et al., 2013) reported that the average bone age was 1.5 and 3.7 months less than chronological age for males and females, respectively. Additionally, the reference points within the atlas were established upon Caucasian Americans. Ethnicity has previously been shown to be one of the most important factors affecting bone age assessment (Mora et al., 2001) and therefore may not be applicable to individuals of various ethnicities (Malina et al., 2004a).

2.4.1.2. Fels Method

The Fels method (Roche et al., 1988), utilises ratios between linear measurements of long bones in the hand-wrist (carpals, ulna, radius, metacarpals and phalanges of the first, third and fifth digits), in addition to geometrical changes. Additionally, the ratio of the width of the epiphysis and metaphysis are estimated, and then converted into measures of skeletal age (Roche et al., 1988). The method was developed from 13,283 serial radiographs of boys (355) and girls (322) that were registered in the Fels longitudinal study.

2.4.1.3. Tanner-Whitehouse Method

The Tanner-Whitehouse method (Tanner et al., 1983) involves either matching the ossification of features of 13 bones (including the radius, ulna and phalanges) or corresponding structures from 20 individual bones to a series of written criteria, assigning each stage with a score, and then adding all the scores together to give a collective skeletal maturity score, and in turn, this can be converted to a skeletal age (Malina et al., 2004a). This original method was gathered from Caucasian British children. In a more recent version of the Tanner-Whitehouse method (TW3), (Tanner et al., 2001), European, South American, North American and Japanese youth references are used, which potentially avoids issues associated with ethnic variations.

All of the methods of assessing skeletal maturity use an x-ray of the left hand-wrist which is then compared to a set criterion (Malina et al., 2004a). However, the methods do differ within their measurement technique, and vary with the approach used to analyse the x-ray (Malina et al., 2004a).

Skeletal age is expressed relative to an individual’s chronological age. Therefore, a child with a chronological age of 11.5 years and a skeletal age of 12.8 years would be advanced in skeletal maturity status, this can also be represented as the difference between skeletal and chronological age (skeletal age – chronological age). Thus, using the same example, 12.8 – 11.5 years, the individual would be advanced in skeletal maturity status by 1.3 years over their chronological age.

2.4.2. Secondary Sex Characteristic Methods

The transition from childhood to adulthood is characterised by the development of secondary sexual characteristics e.g., breast development and the onset of menstruation, in girls, and the development of the penis and testes, in boys (Malina et al., 2004a). Moreover, the development of pubic hair can be assessed in both sexes (Stratton and Oliver, 2014).

The change and appearance of secondary sex characteristics is the first obvious sign of pubertal development, and can be used to measure biological maturation, however, they are only useful around the period of adolescence (Baxter-Jones et al., 2005). The genital curve illustrates the growth pattern of the primary and secondary sex characteristics (Figure 2-3). The curve highlights that the growth of the secondary sex characteristics does not occur until the onset of puberty, around 12 years of age. Normally, in boys, the commencement of puberty occurs between the ages of 9.0 – 13.5 years (Curtis, 2015).

Secondary sex characteristics are normally summarised into five stage scales. The most common method implemented for the assessment of pubic hair, breast and genital maturation was developed by Tanner (1962). Methods are sex specific and include the examination of genital development and pubic hair growth in adolescents, which are then compared to photographs and drawings of the stages of development known as the Tanner Stage (Figure 2-5).

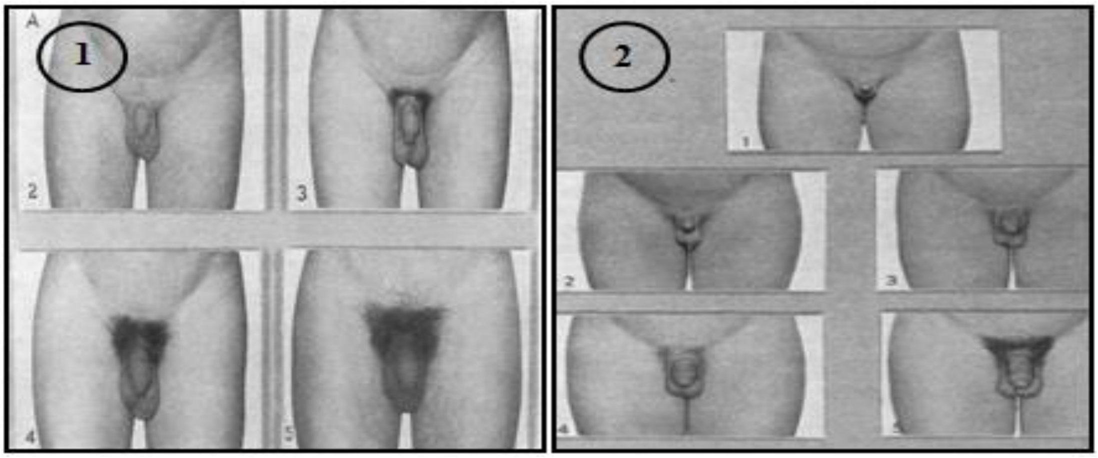


Figure 2-5. Illustrations of Tanner Stages. Photograph 1 – Standards for pubic hair ratings; Photograph 2 – Standards for genital ratings. Adapted from (Tanner, 1969).

The various stages of sexual maturity, described by Tanner (1962), have commonly been used to assess how sexually mature an individual is on a scale from stage 1 (pre-pubertal state of development, absence of each characteristic); stage 2 marks the initial enlargement of the genitals and appearance of pubic hair; stages 3 and 4 are somewhat more difficult to evaluate as they both encompass the continuous maturation of respective characteristics, and stage 5 marks the adult / mature state for all characteristics.

Due to the intrusiveness of the assessment, self-assessments are more frequently used (Bond et al., 2006), an approach that has previously been highlighted as being reliable (Leone and Comtois, 2007). Moreover, the criteria of sexual maturity indicates the stage of puberty at the point of observation, however, the moment at which the individual entered that stage or the duration they have been in that stage cannot be determined (Malina et al., 2004a, Tanner, 1962). Secondary sex characteristic development is a continuous process, and thus an individual who has just entered a stage (e.g., stage 2) of genital pubic hair development, and a different individual who is towards the end of that stage are rated the same, despite the second individual being more advanced in sexual maturation.

2.4.3. Somatic Maturity Methods

The assessment of somatic maturation refers to the degree of growth in overall stature. This non-linear process is interspersed with both periods of rapid growth and plateaus. The use of anthropometric measurements across the adolescent years would allow for determination of the growth spurts and can be used as an indicator for somatic maturity.

Manifested by progressive increases in body size, visually, somatic maturity can be the most obvious expression of a child’s biological maturity. However, it is important to note that the use of body dimensions as indicators of maturity status requires longitudinal data (Malina et al., 2004a, Faulkner, 1996). The components of somatic growth that are obtained take into consideration that the body growths distally to proximally, due to the different growth rates existing between the extremities and the trunk (Mirwald et al., 2002).

Moreover, the initiation of the adolescent growth spurt presents an increase in growth rates, in particular of height. There are two common methods that are used to estimate somatic maturity; age at peak height velocity and percentage of predicted adult height (PPAH) attained at the time of observation. The percentage attainment of final adult height during growth can be calculated if final adult size is available, and is a common estimate of somatic age in paediatric literature (Malina et al., 2004a), though clearly this can only be used as a post-factual tool.

2.5. Age at Peak Height Velocity

The highest growth rate in height is referred to as peak height velocity (PHV) and often, the chronological age at which this occurs, is termed age at peak height velocity. This is the focus of somatic age estimations. Age at PHV is the most commonly used estimate of somatic maturity in longitudinal studies of adolescents, and is the age at which maximum growth in height during adolescence occurs (Malina et al., 2004a). This is largely governed by genetic factors but can also be influenced by external factors such as nutritional status and the environment (Malina et al., 2004a).

The regular collection of height measurements approximately every three months allows for sufficient data to be obtained to plot growth velocity and distance curves (Figure 2-2). These curves can provide a way of comparing individual or group differences in growth (Lloyd et al., 2014, Malina et al., 2004a). This information can provide an estimate of age at PHV and give information pertaining to the growth spurt, such as velocity of growth in stature at PHV, and the amount of stature attained during the adolescent growth.

Previous research has suggested the initiation of the growth spurt occurs between 10 - 11 years in European boys, with PHV taking place around the age of 14 years, with the cessation of growth at approximately 18 years of age (Malina et al., 2004a). In this time, boys typically undergo growth rates in height of approximately 5 $cm.yr^{-1}$ at the time of initiation of the growth spurt, rising to approximately 10 $cm.yr^{-1}$ at PHV (Malina et al., 2004a). Longitudinal data is required in order to determine growth rates and the occurrence of PHV. This has its own problems as such, if a practitioner is presented with a youth athlete for the first time, growth rates won't be able to be calculated there would be no (reliable) historical data available.

2.5.1. Prediction of Age at Peak Height Velocity

The maturity offset equation developed by Mirwald et al. (2002) is a simple, non-invasive predictive method that employs cross-sectional data for the determination of somatic maturity status. Three longitudinal studies were used for reference data (Saskatchewan Paediatric Bone Mineral Accrual Study, Saskatchewan Growth and Development Study and the Leuven Longitudinal Twin Study). The first two studies listed were collected between 1991 – 1997 on children of Canadian ancestry and the final set of data consisted of 79 boys and 73 girls (aged 8 – 16 years), whereby serial anthropometric measurements were collected approximately one year apart. The three longitudinal studies were combined, and the sex-specific multiple regression equations were developed from the combined data. The predictive equation is a way of assessing the maturity offset of an individual, which determines the difference in growth rates between the lower limbs and the trunk; rapid growth of the long bones in the lower limbs characterises the initiation of the growth spurt, whilst growth of the short bones in the trunk occurs around the period of PHV (Malina et al., 2004a). Maturity offset is represented as a value (in years) that denotes how far away an individual is from their age at PHV. A negative value, e.g., -1.2, indicates a child who is pre-PHV, zero would indicate a child who is currently undergoing their PHV, and a positive value, e.g., + 1.2, indicates a child who is post-PHV. A predicted age at PHV that falls within ± 1.0 year of the mean would be classified as on- time (Sherar et al., 2005).

Sex-specific equations for boys (Equation 2-1) and for girls (Equation 2-2) were developed using independent, interaction and ratio variables. Single measures of anthropometric variables included: sex, chronological age, date of observation, height, sitting height and body weight. Moreover, to highlight the interactions between particular anthropometric variables and chronological age, interactions such as chronological age and height; chronological age and sitting height; chronological age and leg length; chronological age, weight, leg length and sitting height, were considered.

Boys’ Maturity Offset (years) =

$$
\begin{aligned}
&-9.326 + \left(0.0002708 \times (leg\ length \times sitting\ height)\right)\\
&+ \left(-0.001663 \times (age \times leg\ length)\right)\\
&\quad + \left(0.007216 \times (age \times sitting\ height)\right)\\
&\quad + \left(0.2292 \times (mass \times height\ ratio \times 100)\right)
\end{aligned}
$$

Here R = 0.94, R^2 = 0.89 and standard error of estimate = 0.59.

Equation 2-1.

Girls’ Maturity Offset (years) =

$$
\begin{aligned}
&-9.376 + \left(0.0001882 \times (leg\ length \times sitting\ height)\right)\\
&\qquad + \left(0.0022 \times (age \times leg\ length)\right)\\
&\quad + \left(0.005841 \times (age \times sitting\ height)\right)\\
&\quad - \left(0.002658 \times (age \times mass)\right)\\
&\quad + (0.07693 \times (mass \times height\ ratio \times 100)).
\end{aligned}
$$

Here R = 0.94, R^2 = 0.89 and standard error of estimate = 0.57.

Equation 2-2

The maturity offset value determined using the above equation can be converted into age at PHV by calculating the difference between chronological age and the maturity offset value (Mirwald et al., 2002). The maturity offset protocol is reported to have a standard error of approximately 7 months (0.56 – 0.59 years) for both boys and girls (Mirwald et al., 2002), which may be considered an acceptable standard error of estimate, and therefore, could provide a practical alternative to skeletal or sexual age. However, the maturity offset protocol has been examined and seems to only be consistent for individuals that are on-time in their maturity status and occurrence of the growth spurt period (12 – 15 years), (Cumming et al., 2014, Kozieł and Malina, 2018).

Although the maturity offset protocol is widely used, validation studies have highlighted several limitations in both predictive equations. A systematic bias in which there appears to be an overestimation of age of PHV in earlier maturing adolescents; boys 3 years post PHV (0.56 years) and an underestimation of age at PHV in later maturing adolescents; boys 3 years prior to PHV (-0.32 years), (Malina and Kozieł, 2014). This could prove to be a limitation in many youth athletes, who are typically early maturing. Additionally, when applying the maturity offset to population groups of varying ethnicities, caution must be taken as the protocol is based on individuals from European ancestry (Malina and Kozieł, 2014).

Alternatives of the Mirwald et al. (2002) maturity offset method have been developed to acknowledge some of the limitations that were associated with the protocol. Moore et al. (2015) simplified the original equations without a significant increase in the estimation of error (Equation 2-3 for boys and Equation 2-4 for girls). Additionally, an alternate equation was also provided for boys, Equation 2-5. The Moore et al. (2015) sex-specific regression equations do not involve the participants sitting height (increasing the practicality for practitioners). The Moore et al. (2015) equations focussed on the issues of overfitting and within-subject correlation. The revised equations enabled improved estimation of maturity offset and age at PHV in children that are growing by addressing issues of overfitting and within participant correlation.

Boys’ Maturity Offset (years) =

$$= -8.128741 + (0.0070346 \times (age \times sitting\ height)).$$

Equation 2-3.

Girls’ Maturity Offset (years) =

$$= -7.709133 + 0.0042232 \times (age \times stature)).$$

Equation 2-4.

Boys’ Maturity Offset (years) =

$$= -7.999994 + (0.0036124 \times (age \times stature)).$$

Equation 2-5.

Kozieł and Malina (2018) evaluated the new predictive equations using serial data from the Wroclaw Growth study, which involved 193 boys (aged 8 – 18 years) and 198 girls (aged 8 – 16 years). When predicated age at PHV was compared with observed age at PHV, the new maturity offset predictive equation (Moore et al., 2015) was highlighted to be useful for boys who were average maturing, and nearing the time of their PHV, however, this was not apparent for girls. When observed age at PHV (determined using Preece-Baines Model 1) were compared with both the new and original equations, predicted age at PHV were consistently later in earlier maturing youth and earlier in late maturing youth. The new offset equation does not substantially improve the measurement accuracy of the original equation, with a standard error of approximately 6.4 months (0.53 years) in girls and 6.2 - 6.5 months (0.52 – 0.54 years) in boys.

Furthermore, Fransen et al. (2018b) aimed to improve the prediction accuracy of age at PHV from anthropometric measurements by fitting nonlinear models and a maturity ratio (chronological age / age at PHV) to the original data derived from the Mirwald et al. (2002) research (Equation 2-6). The updated equation detailed the same variance as the original equation.

$$\begin{aligned}\text{Maturity ratio} = 6.99 &+ (0.116 \times CA) + (0.00145 \times CA^2) \\ &+ (0.00452 \times Body\ Mass) - (0.0000341 \times Body\ Mass^2) \\ &- (0.152 \times Stature) + (0.000933 \times Stature^2) \\ &- (0.00000166 \times Stature^3) + (0.0322 \times Leg\ Length) \\ &- (0.000269 \times Leg\ Length^2) - (0.000761 \times [Stature \times CA])\end{aligned}$$

Equation 2-6.

However, Nevill and Burton (2018) described in a commentary that the maturity ratio was somewhat misleading and fundamentally flawed. The commentary highlighted that the maturity ratio equation contained the participant's chronological age in both sides (common to both the response and predictor variables) of the predictive equation, resulting in spuriously high R^2 values. Moreover, the authors highlight that the maturity ratio algorithm analyses repeated measures data (containing both between participant and within participant errors). Each participant has one age at PHV, however a series of repeated observations where predictor variables such as leg length are repeatedly recorded throughout their growth and are input as predictor variables. Therefore, it is noted that this analysis should have been carried out using a multilevel model approach which would take into account the nesting of the data (Nevill et al., 1998). Despite the commentary of the revised predictive equation being rebutted (Fransen et al., 2018a), accurate estimation of age at PHV in individuals that are either early or late maturing still remains a problem (Fransen et al., 2018b).

2.5.2. Percentage of Predicted Adult Height

Predicting the final adult height that an individual will attain is advantageous. Within the setting of talent identification, the first and obvious utility is to give a coach a view of the future. For positions such as goalkeeper, height is a desirable characteristic (in addition to capability and others). If the coach knows who will be taller of two similarly able young goalkeepers, this may aid his decision on selection. This is a rough and basic approach however and predicted adult heights can be used more intelligently to estimate maturity status of individuals, with their current stature expressing their progress towards their final adult stature. This helps coaches when analysing player performance as this can be offset against, or adjusted for, their current maturity status.

A child of the same chronological age that is closer to their final adult height than another child would be more advanced in their maturity status. However, knowing the potential for further growth of the child who has attained less of their predicted adult height may bring about an advantage and may mean this child has a greater potential for long term success. This approach can be used to differentiate between individuals that are early maturing (attained a greater percentage of their predicted adult height at a given chronological age) and those that are more inclined to being taller (their parents are tall). The current height of an individual, expressed as a percentage of their predicted adult height, can provide an alternate, non-invasive method of estimating somatic maturity status for individuals between the ages of 4 – 17 years of age (Cumming et al., 2017b, Khamis and Roche, 1994). Longitudinal data from 144 boys and 124 girls from the Fels Longitudinal Study (Khamis and Roche, 1994, Roche et al., 1983) were used to establish the method. Moreover, individuals with pathological conditions were omitted, and individuals that were of African American decent were excluded due to shortage of longstanding serial data existing for these ethnic groups (Khamis and Roche, 1994).

The accuracy of the Khamis and Roche (1994) prediction method at each chronological age interval is determined using median absolute deviation (MAD), (Table 2-1). The MAD highlights the median absolute differences between actual and predicted height. Adding or subtracting the MAD for corresponding chronological age and sex from predicted adult height, results in a range of values of which 50% of actual adult height lies. Median absolute error bounds of 90% specifies a range of which 90% of actual adult height lies for a given age and sex (Khamis and Roche, 1994). Moreover, the MAD is greatest around the expected point of PHV (13 – 14 years of age) and is tightest as individuals approach adulthood. This showcases the difficulty in assessing the maturity of individuals on a population basis and the particular challenge of estimating maturity at the point of PHV, which also happens to the point of most interest in most cases.

Table 2-1. Khamis-Roche median absolute error in boys aged 9.0 – 17.0 years. Adapted from Khamis and Roche (1994).

Chronological Age	50%	90%
9.0	2.0	5.2
9.5	2.1	5.2
10.0	2.2	5.2
10.5	2.3	5.3
11.0	2.4	5.5
11.5	2.4	5.8
12.0	2.5	6.2
12.5	2.5	6.7
13.0	2.6	7.1
13.5	2.7	7.3
14.0	2.8	7.2
14.5	2.7	6.7
15.0	2.3	5.8
15.5	1.8	4.5
16.0	1.3	3.6
16.5	0.8	2.6
17.0	0.8	1.9

The accuracy of parental heights needs to be implemented with caution. Commonly, these measures are self-reported or recalled, or in many instances, estimated. Although Himes and Roche (1982) detailed a high correlation (0.84 – 0.97), adults typically tend to overestimate when reporting height (Epstein et al., 1995, Bowman and DeLucia, 1992). Therefore, self-reported parental heights can be adjusted for overestimation using an equation formed from over one thousand measures and estimated heights of adults derived by Epstein et al. (1995).

The pattern of growth tends to be similar between sexes throughout the adolescent growth spurt; peak height velocity appears to occur between 85 – 96% of an individual’s predicted adult height, commonly around 91%, with a standard deviation of 2.5% in both sexes (Sanders et al., 2017). By using 91% of predicted adult height as a landmark (occurrence of PHV), individuals are able to be categorised into maturity classifications based on the attainment of their PPAH they have achieved (Cumming et al., 2017b). For example, individuals that had attained < 85%; ≥ 85 – 90%; 90 – 95% and ≥ 95% of adult height were respectively, pre-pubertal, early pubertal, mid pubertal and late pubertal (Cumming et al., 2017b). Furthermore, the utility of this method was recognised with a group of soccer players aged between 11.0 – 15.3 years of age. Pubic hair stages were correlated with four bands of PPAH at the time of observation (Cumming et al., 2017b, Figueiredo et al., 2009b). The majority of individuals with percentages of predicted adult height at time of observation < 85% and ≥ 85 – 90% were classified as pre-pubertal and early pubertal, respectively. Moreover, the majority of participants with percentages of 90 – 95% and ≥ 95% were mid-pubertal and late pubertal, respectively.

Estimated somatic maturity status can also be conveyed as a *z*–score using the Khamis-Roche method. Using the PPAH at the time of observation, and the half-yearly age and sex specific means and standard deviations derived from the Berkeley Guidance Study (Bayer and Bailey, 1959), can allow participants to be classified as either early, on-time or late in maturity status. This approach has been used in previous studies (Drenowatz et al., 2013, Cumming et al., 2009, Gillison et al., 2017). Individuals that have a *z*-score of between –1 and +1, are categorised as on–time in maturity status. If an individual has a *z*-score greater than +1, they are classified as early in maturity status. If an individual has a *z*-score below -1, they are classified as late in maturity status.

2.6. Assessment of Maturity Indicators

Despite the measures of skeletal, sexual and somatic maturation being different, in general, these indicators are positively associated with each other (Bielicki et al., 1984, Malina et al., 2004a). Moreover, the complexity of the association between these maturity indicators can be somewhat difficult to determine. Indicators of sexual and somatic maturity are restricted to the pubertal and adolescent period, and only skeletal maturity spans the entirety of the pre-pubertal and pubertal years (Malina et al., 2004a). Indicators of sexual and somatic maturity have been identified as being positively related through puberty. In earlier studies, correlations between sexual maturation and the timing of the growth spurt in stature have been shown to be moderate to high, implying that individuals who are early or late in sexual maturation are generally early or late in the timing of the growth spurt (Malina, 1978, Billewicz et al., 1981, Bielicki et al., 1984). Additionally, the development of secondary sex characteristics and PHV has been recognised as being associated to skeletal maturity. Marshall (1974) highlighted in the Harpenden Growth Study (70 girls and 100 boys) that skeletal maturity and the development of secondary sex characteristics and PHV are also related. For example, within this study, the average chronological age that boys achieved genital stage two was 11.5 years (± 1.1 year) with the average skeletal age being 11.5 years (± 1.2 years), a moderate-to-strong correlation of 0.63 was noted.

Regardless of being viewed as perhaps the best measure of biological maturity, skeletal age is rarely accessible to researchers due to financial and logistical limitations (Malina et al., 2004a). Similarly, sexual age has ethical and sensitivity considerations and is not normally suitable for researchers; therefore, the assessment of somatic maturation is largely used within the literature, in particular, studies involving large cohorts with a longitudinal design (Malina et al., 2004a).

2.7. The Relative Age Effect

Typically, the utilisation of chronological age-related cut-off criterion is implemented in order to place children into age groups for competition and training. These cut-offs, however, may lead to difficulties and unintentional biases related to inter-individual differences, commonly referred to as the relative age effect (RAE). Age groups are designed to ensure children are competing against those of similar maturity and skill levels (usually single-year age groups). However, within a single year age group, the relative age of an athlete could vary by up to 12 months, whereas differences in biological maturity can vary by up to as much as six years (Johnson, 2015), with those born at the start of the selection year competing against those born at the end of the selection year. It is important to note that biological maturity and relative age are not synonymous. Biological maturity and relative age are independent constructs that exist and operate independently of one another and are governed by separate factors such as genetics and environment.

The potential 12 month difference in relative age could provide an individual born at the start of the cut-off date with a 12 month advantage of further cognitive and physical development (Edgar and O'Donoghue, 2005). The independent nature of relative age and biological maturity can also be observed in the age at which their associated selection biases emerge and how they change with age. Whereas RAE can be observed from six years of age and remain consistent through late childhood and adolescence, maturity associated selection biases only emerge with the onset of puberty and tend to increase in magnitude with age and competitive level (Malina et al., 2004a). As RAE exist well in advance of puberty it is unlikely that these biases can be attributed to maturity associated differences in athleticism (i.e., speed, power, strength) which are not evident until approximately 11 – 12 years of age (Malina, 2003, Sherar et al., 2007). In contrast, younger individuals (less biologically mature) experience less amounts of playing time, coupled with greater amounts of failure (Cumming et al., 2018a). Rather, RAE is more likely to result from differences in playing experience, cognitive, emotional, behavioural, motor and social development; all of which are more likely to follow age than maturity (Figueiredo et al., 2019, Hill et al., 2019, Cumming et al., 2018a).

In sport, RAE has been reported in baseball, ice hockey, tennis and soccer (Thompson et al., 1991, Brustio et al., 2018, Mujika et al., 2009, Boucher and Mutimer, 1994, Edgar and O'Donoghue, 2005). The results of these studies highlight that there is a consistent RAE throughout junior and senior male athletes. Thompson et al. (1991) identified that the RAE was prevalent for 837 major league baseball players (Q1 = 29%; Q2 = 25%; Q3 = 23% and Q4 = 23%). Similarly, Boucher and Mutimer (1994) found a high correlation between the relative age of 951 elite A and AAA ice hockey team players (aged between 8 – 15 years) and their participation within the sport ($R = 0.71 – 0.99$). That is, more players were born in the earlier months of the selection year as opposed to the later months (Q1 = 37%; Q2 = 28%, Q3 = 23% and Q4 = 12%). However, in sports where characteristics such as physicality are not as essential i.e., gymnastics, Hancock et al. (2015) examined 921 female gymnasts and determined the complex nature of the RAE. When considering the < 15 age category, there was shift towards being born earlier in the year; Q1 = 26%; Q2 = 29%; Q3 = 24% and Q4 = 21%. However, when considering the > 15 age category, there was shift towards being born later in the year; Q1 = 18%; Q2 = 23%; Q3 = 25% and Q4 = 34%. It is important to note that in some sports, particularly sports such as gymnastics, being smaller in height can be beneficial, whereas other sports such as tennis, being taller in height can be advantageous.

Within soccer, biases in birth date distribution have been highlighted amongst both youth and professional teams (Armstrong and Van Mechelen, 2008). Additionally, as the standard of play increases, the magnitude of the effect also increases (Del Campo et al., 2010, Helsen et al., 2005). Helsen et al. (2005) investigated the birth date distributions across one season, 1999 – 2000, across ten European countries, examining the birth dates from players representing the national youth squads in international competitions, and birth dates from players representing professional and international squads. It was identified that there was an over-representation of national youth players (U15, U16, U17 and U18) that were born in the first quarter of the selection year (in this case, January to March). Significant effects were found in major European countries such as Belgium (Q1: 37%, Q4: 10%, $p < 0.01$), England (Q1: 37%, Q4: 9%, $p < 0.01$), France (Q1: 50%, Q4: 17%, $p < 0.01$) and Germany (Q1: 44%, Q4: 15%, $p < 0.01$). Moreover, significant effects were found for the U16 ($R = -0.90$, $p < 0.01$) and U18 ($R = -0.84$, $p < 0.01$) squads, with regression analysis identifying a strong relationship between birth month and number of participants. Relatively older players (players born towards the beginning of the cut-off for the selection year) can possess advantages such as increased size, weight, speed and strength (Malina et al., 2012a, Helsen et al., 2005). Especially in sports such as soccer where these attributes may be desirable, the chances of these players being selected and retained are increased (Hirose, 2009).

Moreover, Musch and Hay (1999) identified a strong RAE was present in professional soccer in Germany ($n = 355$, $R = -0.73$, $p < 0.01$), Japan ($n = 360$, $R = -0.87$, $p < 0.01$), Brazil ($n = 486$, $R = -0.53$, $p < 0.05$) and Australia ($n = 207$, $R = -0.76$, $p < 0.01$), concluding that the highest percentage of players were born in the first quarter of the selection year. A significantly greater proportion of male soccer players from youth to professional levels are born within the first quarter of the soccer selection year. Although the selection year has varied over time and across regions, the trend has been acknowledged across a range of competitive levels e.g., individuals participating in the 1990 World Cup, the 1989 (U17 and U20) World Championships (Barnsley et al., 1992), professional and youth Belgian players (Helsen et al., 1998), and senior semi-professional and amateur Belgian players (Vaeyens et al., 2005), among others. There has also been the suggestion that the RAE could be more apparent at higher levels of involvement in youth soccer (Mujika et al., 2009) and could also be a factor in playing position (Towlson et al., 2017). The RAE has both an immediate and long-term influence on participation in soccer.

2.8. The Impact of Growth and Maturity on Physical Performance

Talent identification has been recognised as the ability to identify individuals with the potential to become elite players (Reilly et al., 2000b). Moreover, the development of talented individuals is one of the primary aims of any academy (Carling et al., 2009). It has been recognised that any individuals that possess superior physical characteristics, such as strength, speed and power, and also, anthropometrical advantages such as greater stature and weight, stand a better chance of being selected for elite development programmes (Carling et al., 2012, Vaeyens et al., 2006). Moreover, superior physical performance and anthropometrical characteristics are commonly associated with those individuals considered to be early maturers (Malina et al., 2004a).

Previously, modified meta-analysis from 31 original studies and 11 review articles (cross-sectional and longitudinal studies were both included) were used to establish the concordance and discrepancies between chronological age periods (6 – 18 years) and characterise any rates of improvement in parameters such as running speed, muscular strength, power and aerobic endurance (Viru et al., 1998). The data within this study was analysed by using annual changes, whereby improvement rates were detected by the time of greatest inclination in the curve. The period between 7 – 9 years and 12 – 16 years of age were identified as critical periods for the improvement of motor abilities in boys, Figure 2-6. Increased rates of sprint speed and explosive strength characterise the first period of accelerated improvement, whilst aerobic endurance characterises the second period of improvement. Typically, two years following improvements in aerobic endurance, boys were seen to experience accelerated improvements in strength and power.

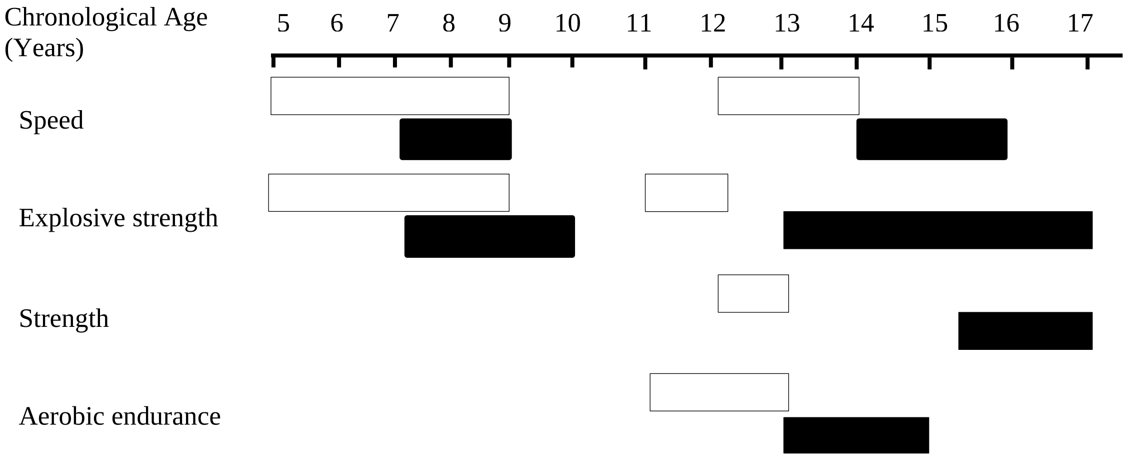


Figure 2-6. Periods of accelerated improvements of motor abilities in boys (black boxes) and girls (white boxes). Adapted from Viru et al. (1998).

2.8.1. Longitudinal Studies into the Development of Physical Performance

Longitudinal studies follow a set of participants over a period of time and involve repeated measurements / observations on the same individual at specific time intervals. This kind of research can be useful for identifying trends that occur as a result of the ageing process, providing information not only on the status but also on change over time (individuals are measured at specific intervals over time, change and rate (e.g., $kg \cdot yr^{-1}$ or $cm \cdot yr^{-1}$) can be calculated (Cobley and Till, 2017). Of particular interest is the topic of performance amongst adolescents and how performance varies through the pre-pubertal, pubertal, and post-pubertal stages of development.

Longitudinal research has identified the impact that maturity status can have on physical performance across a range measures, these include running speed (Wrigley et al., 2014, Philippaerts et al., 2006, Hammami et al., 2013), aerobic and anaerobic capacities (Armstrong and Fawkner, 2008, Rowland, 1985, Naughton et al., 2000, Armstrong and Welsman, 2000), jumping capacity (Deprez et al., 2015a, Philippaerts et al., 2006, Hammami et al., 2013) and muscular strength (Beunen and Thomis, 2000, Malina et al., 2004a, Philippaerts et al., 2006). Details of these will be reviewed in detail below.

2.8.1.1. Development of Motor Skill Competency Performance

Motor skill competency has been described as the development and the competence in fundamental movement skills associated with locomotion, stabilisation, and manipulation, for example, running, jumping, and throwing, and also fundamental sports skills such as catching, hopping, and galloping, allowing a child to move with confidence in a variety of physical activities and sporting conditions (Higgs et al., 2008). The establishment of proficient movement skills is associated with increased levels of physical activity and health in the youth population (Lubans et al., 2010). Gabbard (1992) highlighted that fundamental movement skills begin to develop from birth, and depending on complexity of the movement skill, continue to develop until the ages of 11 – 12 years. Development periods between the ages of 6 – 8 and 10 - 12 years seems to coincide with physical literacy (fundamental and sports specific) skills and improvement in motor coordination (Higgs et al., 2008, Balyi and Hamilton, 2004).

An early study by Beunen and Malina (1988) considered the adolescent growth spurt and influence it may have on motor performance in a longitudinal sample of boys. Boys that showed a decline in motor performance during PHV were identified. It was noted that the boys who experienced a general decline in motor performance during the period of PHV tended to be a good performer at the onset of PHV. Rapid periods of physical growth may disrupt motor performance amongst some individuals. Historically, numerous studies have investigated this motor performance disruption, commonly referred to in the literature as "adolescent awkwardness" (Davies and Rose, 2000). The adolescent growth spurt in height can be associated with certain amounts of clumsiness (performing a skill awkwardly), or apparent loss of control of limbs (Balyi et al., 2005). This spurt can lead to an adolescent having difficulty with the changing proportions of their body, with awkward gross motor activity and also struggling to determine how long or tall their limbs have become (Tanner, 1990). Despite the growth in limbs, Tanner (1990) highlighted there may be a period after the growth spurt of approximately six months before the muscles achieve their full size.

Although there has been comprehensive research that has considered factors such as body size, fitness and previous injuries, currently, one area that has rarely been tested in regard to a decline in performance and increased injury risk is that of adolescent awkwardness (Caine et al., 2008). The rapid growth during adolescence may cause alterations in the brain and sensorimotor system that accurately coordinate movements and environmental interaction. A delay or regression in sensorimotor functioning caused by rapid spurts in growth can offer some explanation towards the increased susceptibility of injury (Quatman-Yates et al., 2012, Philippaerts et al., 2006, Lloyd et al., 2014). For example, incidences in distal radius fractures have been highlighted as occurring most frequently when an individual is undergoing their pubertal growth spurt (Bailey et al., 1989). However, in previous research, the conclusions have been somewhat uncertain (Davies and Rose, 2000). In this study, 60 participants, 30 males and 30 females, aged between 7 - 18 years, had 13 motor tasks assessed, adapted from Bruininks-Oseretsky Test of Motor Proficiency (Krombholz, 1997), with tests such as balance, throwing, running speed and standing long jump being assessed. Participants were classified into their developmental stages (pre-pubertal, pubertal or post-pubertal) using the Pubertal Maturation Observational Scale, which included both parental questionnaires and an observational questionnaire completed by the investigator. The method of classifying developmental stage has shown to have strong reliability (R = 0.96 and 0.91 for girls and boys, respectively). Performance of these tasks throughout adolescence both in boys and girls improved with results demonstrating a significant age effect for eight out of the 13 tasks, with the majority of improvement being observed when performance was compared between youths in the pre-pubertal stage as opposed to the post pubertal stage, supporting earlier research (Tanner, 1990). Furthermore, the results showed no evidence of impaired coordination or awkwardness throughout puberty for boys or girls. Conversely, an earlier study identified a reduction in performance around the time of PHV (Visser et al., 1998). The study implemented a longitudinal design on a total of 37 boys aged 11.5 – 14.0 years of age. General motor skills were assessed twice a year using the Movement Assessment Battery for Children (ABC), a test originally designed for children aged 4 – 12 years (Henderson and Sugden, 1992). The movement ABC tests for manual dexterity, ball skills and balance, with eight variables being tested at each age level. From this sample, 15 boys were identified as being clumsy (performed poorly on both of the motor assessments) and the remaining boys were classed to have adequate motor skills. The results from this study support the view that high velocities in physical growth are negatively related to motor competency. The study also highlighted that some individuals who were classed as ‘clumsy’ prior to the study seemed to benefit from the growth spurt, possibly due to the development of the central nervous system through puberty, however, the majority still possessed poor skills at the age of 14 years, with similar findings being displayed in other research (Geuze and Börger, 1993, Cantell et al., 1994).

2.8.1.2. Development of Speed Performance

The term speed is classified as the distance covered within a specified time. In its simplest form, running speed can be defined as the product of stride length and stride frequency (Hunter et al., 2004). In terms of athletic capacity, speed can be viewed in a number of different ways and broken down into various elements that can be analysed. For example, acceleration, this is usually defined as the rate of change of velocity or the time it takes to achieve maximum velocity (Little and Williams, 2003). Both acceleration (rate of speed change over short distances) and maximum speed are fundamental elements for soccer, and monitored in youth soccer players (Tomáš et al., 2014).

Throughout childhood, overall improvements in speed do not follow a linear process, with a threefold increase in speed being observed from infancy to adulthood (Malina et al., 2004a, Schepens et al., 1998). Viru et al. (1999) suggested there was a pre-adolescent spurt in speed between the ages of 5 – 9 years, usually attributed to rapid development of the central nervous system throughout the first decade of life (Malina et al., 2004b), and a second adolescent spurt in speed occurring around the onset of sexual maturation. Both physiological (the refinement of motor recruitment and coordination patterns) and biomechanical changes (increases in muscle mass and growth of limbs) and improvements in muscle power, leg stiffness and peak horizontal force have been suggested as contributing to speed development during the adolescent speed spurt (Oliver et al., 2013).

When determining the differences in speed between the sexes, boys usually run faster than girls at all ages, however a plateau in performance has been highlighted in boys over the age of 15 years and between the ages of 12 to 13 years in girls (Papaiakovou et al., 2009). The plateau in performance post PHV may be attributable to the difference in developmental trajectories of various motor skills between boys and girls. Specifically, at the age of 12 years, both boys and girls have achieved approximately 75% of the sprint speed that they exhibit at 18 years (Bate and Jeffreys, 2014, Papaiakovou et al., 2009). Maturation has previously been identified to influence sprinting speed, although, many studies have previously assessed speed using shuttle runs and plate tapping (a measure of upper body speed) rather than actual sprint assessments (Malina et al., 2004a).

Longitudinal research that has examined the development of maximal running velocity in a small sample of boys has suggested that peak gains in speed typically occur during the late phase of the growth spurt (Yagüe and De La Fuente, 1998). However, research that examined physical performance in a sample of 33 Flemish male youth soccer players showed that peak gains in sprint performance coincided with peak height velocity (PHV) (Philippaerts et al., 2006). During this study, it was highlighted that boys typically showed a decline in speed performance in the 18 months preceding PHV and noted that the spurt in running speed may have reflected a natural long-term correction. Similarly, in earlier research by Beunen et al. (1988) examined 446 adolescent Belgium boys, a decline (decreased performances) by some adolescents in seven motor fitness tasks was observed whilst undergoing PHV. Specifically, the authors identified 33.5% of the boys demonstrated decreased shuttle run times during the period of maximum rate of growth.

Table 2-2. An overview of maturity and speed performance in youth participants.

Research	Participants	Determination of maturity status	Testing protocol	Conclusions and limitations
Nagahara et al. (2018)	99 (untrained) boys (6.5 – 15.4 years of age).	Maturity status was not measured for the participants as the study was conducted during physical education class, resulting in a limited time period for data collection.	50 m sprint speed.	Greater sprinting performance in older boys was a product of greater mean propulsive forces (measured by ground reaction forces) and longer stride length (greater effective vertical impulse and height).
Malina et al. (2004c)	69 male participants (13.2 – 15.1 years of age).	Stage of pubic hair development based on the criteria of Tanner (1962) was assessed by a paediatrician experienced in the assessment of secondary sex characteristics.	30 m sprint speed.	Stage of maturity accounted for 50% of the variance in the 30 m dash ($p < 0.001$). Pre-pubertal and early pubertal players did not perform as well in the 30 m dash compared to players more advanced in sexual maturity. Data collected from participants over a 2-week period in 1999, which may be out of date. The confinement of chronological age (13.2–15.1 years) made the contributions limited. Sprint speed was not broken down into split speeds.
Valente-dos-Santos et al. (2012)	83 male participants (11.0 – 13.0 years of age).	Posterior-anterior radiographs of the left hand-wrist were taken, and films were rated using the Fels method for the assessment of skeletal age (Roche et al., 1988).	Fastest time taken from 7 consecutive sprints - 34.2 m with 25 s of active recovery where participant is slowly	Sprint time of participants that were advanced in biological maturation improves more, on average, than that of the players that were on-time and late in maturation.

			jogging / walking back to the start line.	Participants were not studied beyond 17 years of age and therefore continued improvement in sprint performance in late adolescence and into young adulthood could not be considered.
McCunn et al. (2017)	306 male participants (9.7 – 16.6 years of age).	Somatic maturity status was calculated using the Mirwald et al. (2002) equation.	15 m sprint speed.	A trivial relationship was observed between maturity status at U11 and U12s. However, the relationship improved to small at U13, and improved again at U14s to possibly large, and again to very large at U15s, thus manifesting to faster sprint speeds in the more mature participants in the U14 and U15 age groups. The maturity offset protocol was implemented which has been shown to possess limitations, especially in populations such as the one involved in the current study (Malina and Kozieł, 2014).
Meyers et al. (2015)	336 male participants (11 – 15 years).	Somatic maturity status was calculated using the Mirwald et al. (2002) equation.	30 m sprint speed.	Maximal sprint speed was identified to develop around and post-PHV. The research implemented the maturity offset protocol which has been shown to possess limitations, especially in populations such as the

				one involved in the current study (Malina and Kozieł, 2014).
Rommers et al. (2019)	619 elite male participants (U10 – U15 age categories).	Somatic maturity status was calculated using the Mirwald et al. (2002) equation. To counteract the under/over estimation of age at PHV in younger or older participants, age specific *z*-scores were implemented (Malina et al., 2007).	30 m sprint speed. Split times at 5 m and 30 m were used.	Earlier maturing players were shown to outperform their later maturing peers in the 5 and 30 m sprint tests. The sample size is good, albeit limited to one country and no descriptive characteristics of the participants.
Figueiredo et al. (2009b)	159 elite male participants (11.0 – 14.9 years of age). The sample was then broken into two groups – 87 participants aged 11.0 – 12.9 years of age were classified as "infantiles" and 72 participants aged 13.1 – 14.9 years of age were classified as "initiates".	Posterior-anterior radiographs of the left hand-wrist were taken. The Fels method (Roche et al., 1988) was used to estimate skeletal age.	Fastest time taken from 7 consecutive sprints – 34.2 m with 25s of active recovery where participant is slowly jogging / walking back to the start line.	No significant differences were highlighted between the maturity groups within the "infantiles" or "initiates". Moreover, no significant differences were noted between the three maturity groups (late, on-time and early) and fastest or mean sprint times.
(Philippaerts et al., 2006)	33 male youth soccer players (10.4 – 13.7 years of age).	Peak height velocity and peak weight velocity were determined using non-smoothed polynomials. Velocity curves for height were	10 × 5 m shuttle run and 30 m dash.	The velocity curve for the 10 × 5 m shuttle run increased from 12 months pre-PHV (0.4 $s \cdot yr^{-1}$) reaching a peak that was coincident with PHV

	checked graphically to determine the location of the spurt, and peak height velocity was defined as the highest velocity recorded.		(1.6 s·yr^{-1}) but then decreasing approximately 12 moths post-PHV (0.1 s·yr^{-1}). The estimated velocity curve for the 30 m dash highlighted negative values for the period 12 months pre-PHV (– 0.6 s·yr^{-1}), however, this shifted towards positive values (0.4 s·yr^{-1}) reaching a peak that coincided with PHV. Subsequently, the velocity curve for the 30 m dash showed a plateau for 12 – 18 months after peak height velocity.

2.8.1.3. Development of Muscular Strength Performance

Though the ideal combination of physical characteristics needed to perform in professional soccer is multifactorial, many believe that developing a comprehensive strength base provides a platform from which other physical components can be developed (Gissis et al., 2006, Tan, 1999).

Strength can be defined by a number of indicators, and is a valuable characteristic to athletes as it provides a general base to sports specific training (Beunen and Thomis, 2000). Muscular strength can be defined as the maximum force or tension that can be produced by any given muscle group (Beunen and Thomis, 2000). The development of muscular strength can be viewed as a multi-faceted (muscular, neural and mechanical), performance related fitness element that is underpinned by muscular, neural and mechanical factors (De Ste Croix, 2008). Characteristics of strength follow a growth curve like most external bodily dimensions, which entails increasing somewhat in a linear fashion from early childhood until the onset of puberty in boys, ~13.8 years (Beunen and Thomis, 2000). In general, boys tend to be stronger than girls with increasing age, however distinctions become increasingly greater post adolescence (Beunen and Thomis, 2000, Malina et al., 2004a). These adaptations are usually the result of increases in androgen concentration, resting adenosine triphosphate (ATP) and architectural development of musculotendon units (Myer et al., 2011). Age-related trends in muscle strength in boys typically follow a growth curve that is comparable to most external body dimensions; an acceleration in early childhood, which increases relatively linearly until the onset of puberty (Malina et al., 2004a).

Information from American (Stolz and Stolz, 1951), Canadian (Carron and Bailey, 1974), Belgian (Beunen and Malina, 1988) and Dutch (Kemper and Verschuur, 1985) boys are reasonably consistent, identifying a distinct spurt in muscular strength post-PHV. In an early study, Stolz and Stolz (1951) collected information from 67 boys, aged between 9.5 - 12.5 years of age over the course of a seven year period. Muscular strength was assessed as a composite score that consisted of right and left grip strength and pushing and pulling strength in both arms. The study highlighted that peak gains in static strength in boys were achieved approximately 1.2 years post-PHV. Moreover, it is worth noting that within this study, a difference of 5.5 years in chronological age at which adolescence began was observed. Contrary to this, a longitudinal dataset of 94 girls, originally participants from a previous study (Jones et al., 1971), were observed from childhood to the fully mature state

(6 – 18 years), (Faust, 1977). The results highlighted that girls achieved peak strength gains much closer to the period of PHV than boys (Faust, 1977). Furthermore, Carron and Bailey (1974), also identified that a number of upper body and lower body strength tests showed peak gains post-PHV, consistent with data from Stolz and Stolz (1951). Moreover, Kemper and Verschuur (1985) and Beunen and Malina (1988) implemented a single test of upper body strength (arm pull) and identified that peak velocities in strength gain were achieved approximately 0.5 years post-PHV. In general for adolescent boys, maximal gains in muscular strength occurs, on average, post-PHV (Beunen and Malina, 1988, Malina et al., 2004a), and may be linked with the increased testosterone levels, and greater lean muscle mass gains following PHV (Malina et al., 2004a). Boys are usually stronger and more powerful than their female counterparts with increasing age, however, post adolescence, the difference becomes much larger (Beunen and Thomis, 2000). Beunen and Thomis (2000) noted that strength was related to body size and muscle mass, highlighting correlations from 0.3 – 0.6, with the highest correlations found between individuals of 13 – 15 years of age. Moreover, these sex differences in strength could be reflective of the size advantage held by boys over girls, as when size was accounted for, differences were negligible between both sexes for measures of lower body strength (Beunen and Thomis, 2000).

2.8.1.4. Development of Jump Performance

Explosive lower limb power, such as that demonstrated during jumping, is often considered crucial for outcomes in soccer matches (Bangsbo, 2004). Anaerobic performance measures are implemented in talent identification programmes for youth soccer players to forecast both their short-term (le Gall et al., 2010) and long-term competition level (Gonaus and Müller, 2012). Mechanical power is defined as the rate of doing work and refers to the moment where maximal or near maximal rate of force development occurs (Knudson, 2009).

Within the literature, there have been numerous methods implemented to evaluate lower limb power and in-particular, jumping capabilities such as a two legged countermovement jump (CMJ) or a drop jump (DJ) are commonly assessed (Malina et al., 2004c, Vaeyens et al., 2006, Gil et al., 2007, Carling et al., 2009, Figueiredo et al., 2010, Figueiredo et al., 2009b, Coelho-E-Silva et al., 2010, Vandendriessche et al., 2012b, Valente-dos-Santos et al., 2012). The CMJ is a method that is regularly used to measure leg power and explosiveness, and this assessment of power is commonly used as a monitoring tool in athletic populations, and for the youth population (Van Praagh, 2000, Lloyd et al., 2009).

The CMJ has been shown to be a valid (Cronin and Hansen, 2005, Peterson et al., 2006) and a reliable (Meylan et al., 2010b, Sheppard et al., 2008) method. A wide range of variables can be collected and measured from jumping tests, however, the main performance outcome of interest collected from the CMJ is usually jump height (Deprez et al., 2015a), and from the DJ is usually the reactive strength index (RSI) (Oliver et al., 2015). Often, jumping profiles are assessed using force platforms (Richter et al., 2010), jump mats (Vänttinen et al., 2010) or infrared beams (Deprez et al., 2015a).

The mechanics of jumping involves the stretch-shortening cycle (SSC), which is characterised by a pre-activation of the musculature, followed by an eccentric lengthening / stretching of the muscle (tendon unit) and then a transition to the shortening period (a powerful concentric contraction), (Pedley et al., 2020). The SSC is normally subdivided into either slow or fast actions, which are defined based on ground contact time (Schmidtbleicher, 1992). A slow SSC function is characterised by longer ground contact times, greater displacement of the centre of mass and larger displacements of the hip, knee and ankle joints. An example of this function is the CMJ, where ground contact times are prolonged, > 250 milliseconds (Lloyd et al., 2011a). A fast SSC function is characterised by shorter ground contact times, marginal displacement of the centre of mass and smaller displacements of the hip, knee and ankle joints. An example of this function is the reactive drop jump, where ground contact times are reduced, < 250 milliseconds (Lloyd et al., 2011a).

As noted above, the CMJ is regarded as a slow SSC activity, and as individuals develop and approach adulthood, trends indicate that their jump height increases (Lloyd et al., 2011a). Previous research has suggested that chronological age and maturity has an influence on jumping performance (Table 2-3). There have been two phases of observed improvements in power that have been identified, namely between the ages of 5 to 10 years in both sexes and between the ages of 9 to 12 years in girls and 12 to 14 years in boys (Beunen and Thomis, 2000, Malina et al., 2004a). This was further demonstrated by Fernandez-Gonzalo et al. (2010) and Gonaus and Müller (2012) whereby CMJ performance ranged from 26.5 ± 6.2 cm in elite soccer players (U10) from Spain (*n* = 15), to 40.2 ± 5.5 cm in national youth soccer players (U18) from Austria. However, these performance characteristics have been shown to vary across countries and playing levels, and in some instances, it seems younger participants may outperform older participants. For example, an elite sample (on youth teams of first (highest) or second division clubs) of U16 participants (*n* = 35) from

Belgium performed CMJs averaging 44.7 ± 5.0 cm, whereas an elite sample (first selections of the Premier National League teams of Serbia and Montenegro) of U18 participants (*n* = 66) from Serbia and Montenegro performed CMJs averaging 37.7 ± 3.9 cm, some 7.0 cm (on average) lower than their younger Belgian counterparts (Vaeyens et al., 2006, Nedeljkovic et al., 2007). These differences may be attributable to the various training techniques, familiarity with the test, quality and practice hours. Additionally, the quality of the coaching and level of players may also explain these discrepancies.

In addition, jumping performance also improves in young male soccer participants with increasing body size dimensions, such as stature, and also sexual maturity (Malina et al., 2004a). Philippaerts et al. (2006) described the point of highest improvement of jumping performance was around the moment of PHV (5.1 $\text{cm}\cdot\text{yr}^{-1}$), and this development remained positive for approximately 6 – 18 months post-PHV.

Table 2-3. An overview of maturity and jumping performance in youth participants.

Research	Participants	Determination of maturity status	Testing protocol	Conclusions and limitations
Philippaerts et al. (2006)	76 participants (10.4 – 13.7 years of age [mean = 12.2 ± 0.7 years]), of which 51 participants were measured annually over five consecutive years and 25 participants were measured annually over four consecutive years.	Height data from each participant were fit with a modified non-smoothed polynomial method, which has previously been implemented (Beunen and Malina, 1988). These growth velocity curves were then used to determine the location of the adolescent growth spurt (defined as the highest velocity).	Countermovement jump	Vertical jump performance peaked at the time of PHV, with a slight peak 12 months prior to PHV. Further, the research suggested there was a decline in jump performance approximately 12 months following PHV.
(Figueiredo et al., 2009b)	159 male participants (11.0 - 14.9 years of age). The sample was then split into two groups – 87 participants aged 11.0 – 12.9 years of age were classified as “infantiles” and 72 participants aged 13.1 – 14.9 years of age were classified as “initiates”.	Posterior-anterior radiographs of the left hand-wrist were taken. The Fels method (Roche et al., 1988) was used to estimate skeletal age.	Countermovement jump was measured using the ergo jump protocol. This involves the participant’s hands remaining on their hips.	Among the 13.0 – 14.0-year-old participants, jumping performance (CMJ) differed significantly between the maturity groups in a gradient identical to that for body size, i.e., early > on-time > late.
Vandendriessche et al. (2012a)	78 male participants (15 – 16 years of age). Each of the participants belonged to one of four groups - U16 (*n*	Somatic maturity status was calculated using the Mirwald et al. (2002) equation.	Countermovement jump performance was assessed with participant’s hands	A multivariate analysis of variance highlighted the U16 ($p < 0.05$) and U17 ($p < 0.05$) participants outperformed the

	= 22); U16 Futures (*n* = 20); U17 (*n* = 21) and U17 Futures (*n* = 15). The Futures team consisted of participants that were judged by coaches to be late maturers, in particular, when compared to their counterparts.		remaining on their hips. The height of the jumps was performed and recorded with Optojump, and the highest jump (participants performed three) was retained.	U16 and U17 Future groups (the two groups that contained the later maturing participants) for countermovement jump. The research used a limited age range. Additionally, there was no training history of the participants included. The research implemented the maturity offset protocol which has been shown to possess limitations, especially in populations such as the one involved in the current study (Malina and Kozieł, 2014). To capture the jumps, the Optojump system was used, which can be manipulated, i.e., bending of the knees.
Lovell et al. (2015)	1,212 male participants (9 – 18 years of age).	Somatic maturity status was calculated using the Mirwald et al. (2002) equation.	Countermovement jump performance was assessed with participant's hands remaining on their hips. CMJs were performed on a contact mat (Just jump). Participants performed five	The research did not directly assess the difference between the maturity status and the groups. Moreover, the research was more concerned at determining the differences that relative age has upon performance, and these two constructs need to be considered independently.

			countermovement jumps; the average of the three highest jumps was taken.	The research implemented a jump mat approach to capture the participants jumping performance, however this system can be inherently flawed if the athlete understands how to manipulate this approach, i.e., bending their knees.
Gil et al. (2014)	88 participants (9.8 ± 0.3 years of age).	Somatic maturity status was calculated using the Mirwald et al. (2002) equation.	The height of the jumps was performed and recorded with Optojump.	The research did not directly assess the difference between the maturity status and the groups. Moreover, it reported that older players did perform better in countermovement jump performance. To capture the jumps, the Optojump system was used, which can be manipulated, i.e., bending of the knees.
Malina et al. (2004c)	69 male participants (13.2 – 15.1 years of age).	Stage of pubic hair development based on the criteria of Tanner (1962) was assessed by a paediatrician experienced in the assessment of secondary sex characteristics.	Countermovement jump was performed with a 90° knee flexion using an Ergo Bosco system. Two trials were given for the CMJ; the better of the two trials was	Participants that were in pubic hair stage four performed significantly better ($p < 0.05$) than participants in pubic hair stage two and three. Additionally, it was suggested that the stage of a participant’s maturity can account for approximately 41% of the

	retained for analysis.	variance in jumping performance ($p < 0.001$). Data collected from participants over a 2-week period in 1999, which may be out of date. The confinement of chronological age (13.2 - 15.1 years) made the contributions limited.

2.8.1.5. *Development of Aerobic and Anaerobic Performance*

The ability of a soccer player to repeatedly generate explosive actions and complete rapid movements around the pitch, and compete in subsequent matches, requires high levels of both aerobic and anaerobic conditioning (Turner and Stewart, 2014).

Youths that lead an active and healthy lifestyle will develop both their aerobic and anaerobic fitness as a consequence of growth and maturation (Faigenbaum et al., 2019). Growth and maturation brings about physiological changes that adolescents have to learn to manage and adapt to, and the development of aerobic and anaerobic fitness is determined by these growth-related changes to the central and peripheral cardiovascular system, muscular functioning, body composition, and a potential shift towards greater proportions of type-II muscle fibres (Armstrong and Fawkner, 2008, Rowland, 1985). The degree of influence that these components may have upon aerobic and anaerobic fitness varies throughout childhood and adolescence (Naughton et al., 2000).

The key element of aerobic fitness is peak oxygen uptake (the maximal rate at which energy can be supplied by aerobic metabolism); the product of cardiac output and the muscles' ability to extract and utilise oxygen (Faigenbaum et al., 2019). Large increases are observed in VO_2peak (the maximum rate at which energy can be supplied by aerobic metabolism) and endurance performance as a function of increased body size, heart size and blood volume as a consequence of growth and maturation. Boys experience greater gains than girls, specifically between the ages of 8 – 16 years of age, whereby absolute VO_2peak can increase by approximately 150% in boys and 80% in girls (Armstrong and Welsman, 2000). Moreover, longitudinal research has highlighted that increases in VO_2peak values are consistent between English, Czech, Canadian and Dutch individuals between 8 – 16 years of age (Armstrong and Van Mechelen, 2008).

Anaerobic fitness is commonly measured as the capability to produce peak power and maintain power in maximal tests lasting from six to 30 seconds (Bar-Or and Rowland, 2004). The development of anaerobic capabilities during childhood and adolescence has been attributed to three key factors: an increase in muscle mass; an increase in glycolytic activity and an improvement in neuromuscular coordination (Bar-Or and Rowland, 2004). Williams (2008) identified that when maximal intensity exercise was measured and standardised for body size, significantly lower scores were obtained by children when compared to adolescents, who in turn had lower scores when compared to adults. Moreover, this highlights that anaerobic performance improves as individuals mature and reach adulthood.

During the time from childhood to adulthood, peak oxygen uptake increases in a somewhat linear fashion (Viru et al., 1999, Armstrong and Welsman, 1994). Moreover, there is a suggestion of possible periods of acceleration and deceleration in development during maturation (Figure 2-6), although, these are highly individualised (Viru et al., 1999).

2.8.2. Cross-sectional Studies on Measurement of Physical Performance

Cross-sectional studies typically use individuals that are measured or observed at a given age (or age range), but each individual is only measured once in the sample, giving a snapshot in time of the sample. The results of cross-sectional studies provide information on growth, maturity, performance, or physical activity status of a sample, and of the variability within that sample. In youth soccer, there is a large body of research that has investigated the effects of maturation upon physical indicators and performance. For example, previous research has investigated relative age and performance (Deprez et al., 2013, Lovell et al., 2015) and chronological age and performance (Carling et al., 2012, Gil et al., 2014, Malina et al., 2005a). However, there is a sparsity of evidence that has investigated performance characteristics amongst youth players using tests of strength speed and power across a range of ages when accounting for maturity status (pre-, circa- or post-PHV).

2.8.2.1. Measurement of Motor Skill Competency

As discussed in Section 2.8.1.1, the development of motor skill competency reflects the rapid development of the central nervous system from birth through to childhood. Within this, individuals will be expected to master fundamental movement skills associated with locomotion, stabilisation, and manipulation (Faigenbaum et al., 2019).

Ingle et al. (2006) demonstrated that a mixture of plyometric and dynamic resistance training may aid in developing fundamental sports skills amongst pubertal boys. This research measured strength-related performance outcomes on 54 male participants (aged 12.3 ± 0.3 years), and not the quality of the actual movement. Participants performed training three times a week for 12 weeks that included a combination of dynamic constant external resistance (back squat, bench-press, dumb-bell rows, calf raises, barbell lunges, overhead press, bicep curl and triceps extensions) and plyometric exercises (two-footed ankle hops, front cone hops, standing long jump and push-ups). The findings of the study suggested that pre-pubertal and early maturing boys demonstrated small improvements (≤ 5.5%) in anaerobic power, jumping and sprinting performance following complex training (a combination of resistance training and plyometrics).

In a study by Pichardo et al. (2019), 108 circa-PHV male participants (aged 13.9 ± 0.5 years) took part in a study which aimed to investigate to what extent the relative contribution of maturity (determined by the maturity offset), strength, and movement competency influences motor skill performance in running, jumping, and throwing tasks in adolescent boys. The isometric mid-thigh pull (absolute and relative measures of peak force) were used to quantify strength, 10 m, 20 m and 30 m sprint times, horizontal jump distance and countermovement jump height were collected.

Previously, movement competency has been assessed using the resistance training skills battery (which uses six bodyweight movements: squat, push-up, lunge, suspended row, standing overhead press, and front support with chest touches (Lubans et al., 2014). Movements were filmed with an iPad from the sagittal and frontal plane and were then rated according to the criteria set out by the aforementioned research by Lubans et al. (2014). The findings of this research suggested that relative strength was the greatest predictor of motor skill performance displaying larger correlations than the maturity offset, isometric mid-thigh pull absolute, and the resistance training skill battery with most measures of multi skilled performance. Moreover, this research identified that relative strength can be viewed as an important factor in differentiating Sprint and jump performance amongst 13- to 14-year-old boys. Maturity timing had further contributions to performance, but the range is task dependent. The resistance training skill battery was highlighted as not being a significant predictor of performance but did have significant relationships with running performance. The overall findings of this research highlighted that whilst youth athletes should be encouraged to train all components of fitness for an optimal and versatile development, a stronger emphasis should also be placed on developing levels of relative strength and movement skills, particularly around the timing of PHV. However, the overarching findings of this research may only be applicable to those individuals that are circa-PHV (i.e., it may not extend to the periods of pre-PHV and post-PHV). Furthermore, the study employed the maturity offset method to classify the maturity timing of participants, this method of assessment possesses major limitations, in particular with early and late maturing boys (Kozieł and Malina, 2018).

2.8.2.2. Measurement of Speed Performance

As discussed in Section 2.8.1.2, speed is defined as the distance covered within a specified time. (Hunter et al., 2004). Many cross-sectional studies have been designed to investigate the relationship between age and maturation and speed performance in youth participants (Table 2-2). For example, recently, Nagahara et al. (2018) highlighted similar results to the aforementioned research by Viru et al. (1999). This was done by recording ground reaction force signals (step-to-step spatiotemporal and mean force variables) in 50 m sprints on 99 (untrained) boys aged between 6.5 – 15.4 years. The results of this study highlighted a slower rate of development of speed between the ages of 8.8 – 12.1 years, which were characterised by unchanged propulsive forces and reduced step frequencies when compared with younger and older boys. For ages younger than 8.8 years and older than 12.1 years, performance in speed increased, with an increase in average propulsive forces throughout the middle acceleration (10 – 15 m) and maximal speed (20 – 25 m) phases.

Recently, Meyers et al. (2015) examined the influence of the maturity status and the mechanical features (maximum speed, stride length, stride frequency, flight time and ground contact time) of sprinting performance over a 30 m distance on 336 boys aged 11 – 15 years of age. The participants were grouped on their maturational status, estimated by age from PHV (Mirwald et al., 2002). No significant differences were identified in maximal speed between the pre-PHV group; however, this group was significantly slower than circa and post-PHV groups. Additionally, it was also recognised that stature ($R^2 = 0.37$, $p < 0.01$) and leg length ($R^2 = 0.34$, $p < 0.001$) were significantly related to speed when maturation was not controlled, suggesting that the association between stature and leg length with speed is due to the influence of maturity status. As such, the development of speed performance undergoes greater improvements following PHV; stabilisation of stride frequency and increases in stride length.

Oliver et al. (2013) highlighted that longer levers impact ground contact time; however, this contributes less to stride length than the aerial phase. Younger individuals typically compensate for their shorter levers (legs) by increasing their stride frequency (Nummela et al., 2007). Although, Oliver et al. (2013) noted that approximately 95% of final limb length has already been achieved by approximately 12 years of age, and therefore, any additional increases that are observed in speed are supplemented by reasonably small alterations in limb length.

2.8.2.3. Measurement of Muscular Strength

As discussed in Section 2.8.1.3, some authors believe that developing a comprehensive strength base provides a platform from which other physical components can be developed (Gissis et al., 2006, Tan, 1999).

Muscular strength is an essential factor in many activities (such as jumping and sprinting) and is an influential component in the selection process in youth soccer (Carling et al., 2012, Carling et al., 2009). Strength testing in youth populations be influenced by factors such as the participants, test equipment and availability, and costs (De Ste Croix, 2007). Isokinetic dynamometry, handheld dynamometry and repetition maximum have previously been cited among some of the literature as a method to test strength (Paul and Nassis, 2015). Isokinetic testing has previously identified that absolute peak torque improves with age in youth soccer players (Hansen et al., 1999, Hansen et al., 1997, Kellis et al., 2001). Further previous research that investigated general youth populations (10 – 14 years of age) also highlighted that stage of maturity does not influence the development of isokinetic and isometric leg strength once body size has been accounted for (De Ste Croix et al., 2002, Hansen et al., 1997). However, in both instances in the aforementioned research, maturational status of the participants was not reported or analysed. Additionally, the use of general youth participants rather than a specific soccer population reduces the impact somewhat of the research considering the advantages afforded with training exposure (Wrigley et al., 2014).This is an important feature that needs to be considered (non-elite v elite) given the overarching effect training exposure has on development (Malina et al., 2004a). Moreover, both pieces of research will not have depicted a true interpretation of the maturing adolescent and be capable of assessing the full impact of maturation on strength development.

Interestingly, there is a sparsity of evidence that exists regarding sensitive periods (periods of heightened adaptation), but there was a distinct difference between absolute strength across a wide variety of age categories (U12 – U18s). Previously the influence of the pubertal stage on isokinetic leg strength amongst youth soccer players has been discussed (Forbes et al., 2009). 157 elite youth soccer players (U12 – U18s) were grouped by maturational status by completing a self-reported questionnaire (Pubertal Development Scale), (Petersen et al., 1988). This scale has previously been reported to possess good reliability (0.68 – 0.83) and a moderate to high correlation (0.61- 0.67) with more direct measures of pubertal development. Participants were grouped into five development groups (PDS1 – pre-pubertal;

PDS2 – beginning pubertal; PDS3 – mid-pubertal; PDS4 – advanced pubertal and PDS5 - post-pubertal). The authors reported that more mature / older players (PSD4) presented a significantly greater (*p* < 0.001) concentric quadricep performance; PSD2 – 95.0 ± 23.4 Nm and PSD4 – 163.3 ± 34.8 Nm, a significantly greater (*p* < 0.001) concentric hamstring strength (PSD2 – 53.1 ± 13.7 Nm and PSD4 90.2 ± 20.4 Nm) and a significantly greater (*p* < 0.001) eccentric hamstring strength (PDS2 - 89.8 ± 24.3 Nm and PSD4 – 142.7 ± 32.5 Nm.

2.8.2.4. Measurement of Jump Performance

As discussed in section 2.8.1.4, lower limb explosive strength is commonly assessed through the countermovement jump, with jump height commonly being used as the outcome of interest. The impact of growth and maturation on jump height has been widely researched and has been identified to have an important contribution to jump performance (Rumpf et al., 2013).

Jump height, which is commonly used to monitor lower limb explosive strength, could be influenced by peak power. González-Badillo and Marques (2010), discussed an increase in power may be the cause of an increase in concentric maximum velocity which in turn increases take off velocity and will ultimately improve overall jump height. Around the time of PHV, the influence of maturation on jumping power may be due to the increase in muscle mass / volume which has a direct relationship with peak power (Meylan et al., 2014).

Within youth soccer players, there is evidence to indicate maturity status has an influence on jumping performance. For example, Figueiredo et al. (2009b) highlighted that within older age groups (13 – 14 years of age), maturational status (which was quantified using skeletal assessment) had an influence on jumping performance which followed a gradient, early > on-time > late (33.9 ± 3.9 cm, 31.5 ± 4.9 cm, 25.0 ± 0.2 cm, respectively). Similarly, Hammami et al. (2013) identified that maturational status (which was estimated using the maturity offset protocol) also had a significant effect on individuals (aged between 10 – 16 years of age) countermovement jump height, demonstrating that more mature participants (post-PHV = 27.2 ± 9.8 cm) outperformed less mature participants (pre-PHV = 23.5 ± 4.3 cm and circa-PHV = 22.4 ± 8.7 cm).

Leg stiffness, a measurement of a fast stretch shortening cycle activity, has also been identified in youths as increasing with age, however the mechanisms for this improvement remain unclear (Lloyd et al., 2011a). Additionally, another method of determining a fast stretch shortening cycle activity is reactive strength index (RSI), which is the measure of the ratio between jump height and contact time (Lloyd et al., 2012). This research identified that RSI increases with age with both 12- and 15-year-old individuals produced considerably higher values than 9-year-olds. Furthermore, the results from this research were supported by earlier research by Oliver and Smith (2010). This research investigated the differences in leg stiffness between adult males and boys. The findings of this research suggested that men were able to produce greater relative leg stiffness than boys when hopping at greater frequencies. To measure a fast SSC activity, RSI is often implemented which measures the ratio between jump height or flight time and ground contact time. Lloyd et al. (2012) noted age related differences in neural regulation during maximal hopping, where RSI was shown to increase with age. Individuals aged 12 and 15 years of age produced significantly greater RSI values than their 9-year-old counterparts ($p < 0.05$), although, the 15-year-olds did not produce significantly greater RSI values than their 12-year-old counterparts.

2.8.2.5. Measurement of Aerobic and Anaerobic Performance

As discussed in Section 2.8.1.5, the ability of a soccer player to repeatedly generate explosive actions and complete rapid movements around the pitch, and compete in subsequent matches, requires a high level of both aerobic and anaerobic conditioning (Turner and Stewart, 2014). As games typically last around 80 minutes at youth level (U14 - U16), having a good aerobic base allows for fast recovery between breaks in-play and contributes to maintaining concentration and preparation during matches (Bangsbo, 1994).

The assessment of cardiovascular fitness is commonly carried out amongst school children and athletic teams (Black et al., 2016). Cardiovascular fitness is dependent on the capacity for aerobic and anaerobic metabolism, this is influenced by physiological and hormonal changes which are encompassed in the natural process of growth and development (Gamble, 2014, Patel et al., 2017). Aerobic capacity is measured via peak oxygen consumption (VO_2peak) and can be measured via incremental exercise testing to exhaustion. The maximum capacity of an individual to perform aerobic exercise is measured via these tests, which occurs as a result of aerobic and anaerobic processes (Armstrong and McManus, 2011).

Despite VO_2peak values being partly genetically determined (Bouchard et al., 1999), structured training has been shown to produce changes of between 2.4 – 39.2% in the youth population (Helmantel et al., 2009). Comparable gains in cardiovascular fitness via aerobic training was demonstrated by both children and adolescents. Up to about the age of 12 years of age, absolute VO_2 levels were reported in boys of up to 2.5 l.min, which increased to approximately 4.4 l.min by the ages of 18 years of age (Helmantel et al., 2009).

Gamble (2014), contested the concept that young athletes are restricted in their receptiveness to high intensity anaerobic training. Furthermore, Sperlich et al. (2010), identified positive changes in rate of maximal lactate accumulation and VO_2peak, and a considerable improvement in endurance performance resulting from a high intensity, interval based anaerobic training programme intervention (five-week high intensity interval training) was observed in a study of pre-pubescent swimmers (11.5 ± 1.4 years of age), (Sperlich et al., 2010). Additionally, Baquet et al. (2010) identified increases in maximal aerobic velocity and VO_2peak in a sample of sixty-three boys and girls aged between 8 – 11 years of age when exposed to intermittent-running training. It can be noted that adequate combinations of intensity / duration exercises may be offered to pre-pubertal children, many modalities of exercise can successfully be used to increase aerobic fitness.

The individual response to cardiovascular exercise has been shown to be influenced by the stage of biological maturation. Boys that are advanced in maturation produce greater absolute stroke volume and aerobic power than boys that are biologically more immature but of the same chronological age (Malina et al., 2004a). Furthermore, the influence of sexual maturation on VO_2peak within 12-year-olds was examined by (Armstrong et al., 1998), whereby sexual maturation of 93 boys was analysed using the Tanner's indices of pubic hair. The research identified that more mature boys produced greater VO_2peak values than the immature boys.

When examining the development of aerobic power to measures of somatic maturity, both boys and girls demonstrate a growth spurt in VO_2peak during adolescence (Geithner et al., 2004). Typically, VO_2peak values in girls spike earlier than boys, though the magnitude of the spike in boys is greater (Geithner et al., 2004). Furthermore, Malina et al. (2004a) described peak sub-maximal power that coincided with peak height velocity in boys, which continues to increase post peak height velocity, however this peak in sub-maximal power occurred more than a year post peak high velocity in girls.

2.8.3. Summary of the Impact of Growth and Maturation on Physical Performance

In summary, the literature review has highlighted the impact growth and maturation has on performance, both longitudinally and cross-sectionally. At present, research is somewhat limited in assessing the longitudinal impact maturation has on performance indicators in youth soccer players between the ages of 12 to 18 years. This is important to understand (the maturational influence on performance indicators) in order to avoid the ‘maturation selection hypothesis’ and give coaches insights to help drive information informing their decision’s and opinions.

2.9. Monitoring Youth Athletes

Coaches and practitioners possess many tools that allow them to monitor the physical capacities of youth athletes (Murray, 2017). These monitoring tools are typically classified as either internal or external measures. The physiological strain resulting from the external training factors is commonly used to evaluate internal training load (Viru and Viru, 2000). Measures such as heart rate, blood lactate and ratings of perceived exertion (RPE) can provide an indicator of internal training load and are used to monitor training process. External training loads are objectively measured through the work performed by the athlete in training and competition. These measures include metrics such as distance, acute:chronic workload ratios and global positioning system (GPS) parameters. A summary of some of the commonly used methods to monitor internal and external training loads of athletes are documented in Table 2-4. Both internal and external measures can be used for within-session monitoring of athletes.

Table 2-4. Summary of some common methods implemented to monitor athlete training load and / or responses.

Method	Measures	Frequency
	Internal measures	
RPE	Load	Every session
Session RPE	Load	Every session
Wellness questionnaires	Sleep, soreness, fatigue, mood	Twice a week
Psychological inventories	Mood state	Once a week
Heart rate	Heart rate variability and recovery	Every session
	External measures	
Distance	Load	Every session
Acute: chronic workload	Relative measure of load	Every session
GPS measures	External load	Every session

Note: GPS – Global positioning system; RPE – Rate of perceived exertion.

Accurate analysis of both squad and individual training load is required (Castellano et al., 2011). Previously, methods such as session RPE and heart rate monitoring have been implemented in order to gauge the intensity of the session (Hill-Haas et al., 2011). Due to its ease in administration, session RPE (sRPE) is frequently adopted in team sports. This simple method quantifies internal training load, multiplying the sRPE, using the category ratio-10 scale, (CR10-scale) by the sessions duration (Kelly et al., 2016). In turn, this produces an arbitrary unit that represents the magnitude of internal load.

Traditionally, heart rate monitoring has been employed to measure the physiological demands of exercise. Previous research within various sports has aimed to quantify internal training load, based on heart rate, typically, the time spent in ‘zones’ defined by the percentage of the individuals maximum heart rate (Foster, 1998, Foster et al., 2001). Although heart rate can provide a reliable indicator through which exercise intensity is measured during endurance sports, within team sports such as soccer, the method is questionable, where overall training load may compromise more short-term, high-load components (Impellizzeri et al., 2004).

Previous research has shown sRPE to be significantly correlated with heart rate based methods of quantifying internal training load (Foster, 1998), albeit, the research was conducted on endurance athletes. Moreover, this method of quantifying internal training load has recently been implemented on basketball players, a sport characterized by aerobic and anaerobic activities, displaying a very large association, $R = 0.85$, (Manzi et al., 2010). Furthermore, Impellizzeri et al. (2004), assessed 19 soccer players (mean age 17.6 ± 0.7 years), highlighting that sRPE demonstrated significant correlations with methods based on heart rate response to exercise, $R = 0.50 – 0.85$, of quantifying internal training load during soccer training. Variables such as total distance and accelerations / decelerations are some factors which can be considered to quantify external training load. As soccer is a sport defined by explosive actions, the monitoring of the training process becomes vital, and these defining moments are somehow quantified. The use of global positioning systems has become more frequently used in the soccer setting as it offers a practical way of monitoring the external training load of players during soccer sessions (Casamichana et al., 2012).

2.9.1. Anthropometric and Physical Characteristics of Elite Youth Soccer Players

Soccer places varying physiological demands on players. These physiological demands require them to be capable in certain aspects of fitness, for example the ability to sprint (in repeated bouts) and to produce high-levels of force (muscle strength), (Svensson and Drust, 2005).

Previously, research has been conducted aimed at clarifying the physical components and characteristics of elite youth soccer players. Physical fitness testing is usually completed several times throughout a competitive playing season, aimed at evaluating different physical qualities. Throughout the literature (Bujnovky et al., 2019, Mendez-Villanueva and Buchheit, 2013), various tests have been used to quantify anthropometry (e.g., standing height, sitting height and body mass), and fitness variables (e.g., speed, agility / change of direction, jumping ability and aerobic capacity). These physical fitness tests are classified as either field (real world) or laboratory (controlled environment); which are usually determined by the practitioner and aligned to their specific needs. Common measurement techniques for anthropometry, strength, lower limb explosive strength, speed, agility and aerobic capacity are shown in Table 2-5.

Table 2-5. Overview of some commonly used physical performance tests.

Variable	Measurement/ Field	Measurement/ Laboratory
Anthropometry	Stature Body mass Girths Sum of skinfolds	Dual-energy x-ray absorptiometry (DXA)
Strength	Isometric mid-thigh pull (dynamometer)	Isometric mid-thigh pull (force plates)
Explosive strength	Countermovement jump Squat jump	Optojump jump assessments Force plate jump assessments
Speed	Sprint tests (5 – 50 m)	Sprint tests with force plates
Agility/ change of direction speed	505 Illinois agility test	Reactive agility (video-based stimulus)
Aerobic capacity	Multi-stage fitness test Repeated sprint ability 30-15 intermittent fitness test	Lactate threshold $\dot{V}O_2$peak

505 – Change of direction 505 test.

The development of the modern game appears to have impacted the physical demands required for successful participation at the elite academy level, and now, much like elite adult players, elite academy players need to possess a well-developed physical profile which is the underpinning of strength and power characteristics.

2.9.2. Overview to Global Positioning Systems

Over recent years, the implementation of technology is now becoming common place in sports research and practice (Malone et al., 2017). Global positioning systems (GPS) are satellite navigation networks that feedback information obtained from the tracking devices. Originally, the system was developed for military settings, however, the system has been implemented and used for athlete tracking and load monitoring. The basic components of GPS technology provide information on total distance, speed (thresholds), accelerations and decelerations, and these can be used to quantify external training loads completed by athletes. In turn, the quantification and exertion of physical stress encountered by athletes can be monitored, and sport practitioners can begin to evaluate athletic programs, changes in physical capacities and positional workloads (Malone et al., 2017). Additionally, the assessment of injury risk has previously been analysed (Gabbett and Ullah, 2012). Gabbett and Ullah (2012) investigated the risk of low (walking, jogging and total distances) and high- (high acceleration and velocity efforts and repeated high-intensity bouts) intensity movement activities on lower body soft tissue injuries. GPS data was collected from 34 elite rugby players (mean age 23.6 ± 3.8 years) in 117 training sessions. The findings suggested that the risk of injury was 2.7 times higher when very high-intensity ($> 7\ \text{m}\cdot\text{s}^{-1}$) velocity running occurred.

The large majority of GPS match analysis has been implemented amongst adult populations in soccer to classify match outputs. Moreover, with respect to talent identification, injury prevention and maturation status, the capacities of youth soccer players need to be quantified. The use of age specific velocity thresholds amongst U12 - 16 elite youth soccer players (along with than arbitrary thresholds) was implemented by Harley et al. (2010). The results highlighted that total distance, high intensity distance, very high intensity distance and sprint distance (in absolute terms) were significantly greater ($p < 0.05$) in the U16 age group than their younger counterparts. However, when the match running metrics were considered in relative terms, few differences were apparent. For example, U16 was significantly higher ($p < 0.05$) for total distance ($118.7\ \text{m}\cdot\text{min}^{-1}$) than U12 and U13 (103.7 and $98.8\ \text{m}\cdot\text{min}^{-1}$, respectively), however, U16 was $115.2\ \text{m}\cdot\text{min}^{-1}$.

2.9.2.1. GPS Reliability and Validity

The rapid growth of the use of GPS in elite sports has seen several companies offering GPS units that are continually developing. These units are constantly improving through advancements in the software and data processing (Malone et al., 2017). These developments are followed up by independent investigations into reliability (ability to reproduce values on repeat occasions) and validity (ability to accurately measure intended variables), (Scott et al., 2016). These two factors become significant within the applied setting as they allow for comparisons between sessions and athletes.

The majority of research has implemented 1-Hz to 15-Hz sampling frequencies when assessing the validity and reliability of the measurement precision. In general, measurement precision has improved with increased sampling rate, however, Johnston et al. (2014) noted that 10-Hz systems were somewhat better than the 15-Hz systems as these implemented interpolated data, which is not ‘true’ GPS sampling. A paired sample *t*-test highlighted significant differences between 10-Hz and 15-Hz GPS units when measuring peak speed, distance covered at very high speed, time spent completing low speed running and very high speed running, and the number of efforts performed in high speed running and very high speed running. Previously, numerous studies aiming to validate 1-Hz GPS units in sports have been conducted. Edgecomb and Norton (2006) carried out 59 trials of a marked circuit of known distance to assess the validity and the reliability of the GPS within Australian soccer. The distance that was covered by the GPS system was then compared to that of a trundle wheel whereby a significant difference was observed by the GPS, which significantly overestimated the distance on average by 4.8% ($p < 0.05$).

Moreover, issues have previously been discussed regarding 1-Hz and 5-Hz reliability when metrics such as high intensity velocity and change of direction are analysed. Previously, Jennings et al. (2010) aimed to determine the validity and reliability of distance data on movement patterns that are relevant to team sports, using sampling frequencies of both 1 Hz and 5-Hz. The results of this research suggested that using both 1-Hz and 5-Hz substantially underestimated distance when striding and sprinting over distances such as 10 m and 20 m. Moreover, measurement accuracy decreased as the velocity of the locomotion increased, with differences of 9.0 – 32.4% being observed.

2.9.2.2. Velocity and Acceleration Data

The GPS device detects and calculates distance and velocity using one of two methods; positional differences or the Doppler shift (Coutts and Duffield, 2010). The location of the GPS device is triangulated using information from the distance to each of three satellites. Distance is calculated using the positional differences (change in location), from which velocity can also be determined, distance over time. The change in frequency of satellite emitted periodic signals (Doppler shift) can also determine velocity, (Malone et al., 2017).

During a soccer game, approximately 1 – 4% of movement is spent ‘sprinting’. Spencer et al. (2005) identified the individual distance of a sprint is approximately 10 – 20 m, lasting approximately 2 – 3 s. Despite these moments being infrequent during a game, they typically define a moment of greater significance, e.g., scoring of a goal (Gaudino et al., 2013). The displacements of a player are typically banded into six thresholds (zones), and these thresholds are described below and in further detail in Table 2-6. The thresholds include: standing and walking (zone 1); jogging (zone 2); low speed running (zone 3); moderate speed running (zone 4); high speed running (zone 5); very high speed running or sprinting (zone 6), (Carling, 2013). However, these bands have been defined differently amongst the research, and this can make it difficult for comparisons to be made (Malone et al., 2017).

Table 2-6. Description of GPS zones utilised within the present thesis.

Zone	Description	Speed ($m.s^{-2}$)
Zone 1	Standing and walking	0.0 – 1.5 $m.s^{-2}$
Zone 2	Jogging	1.5 – 3.0 $m.s^{-2}$
Zone 3	Low speed running	3.0 – 4.0 $m.s^{-2}$
Zone 4	Moderate speed running	4.0 – 5.5 $m.s^{-2}$
Zone 5	High speed running	5.5 – 7.0 $m.s^{-2}$
Zone 6	Very high speed running or sprinting	7.0 – 11.0 $m.s^{-2}$

Moreover, another issue that needs to be addressed is the application of global thresholds, application of the same speed thresholds to all athletes, without accounting for differences in age and maturational status.

Due to the different analyses and various aims of other studies, numerous match running metrics have previously been collected. Table 2-7 highlights the five match running metrics that were collected in the present thesis, as well as their descriptions.

Table 2-7. Match running metrics utilised within the present thesis.

Global GPS match running metric	Definition
Total distance covered (m)	The total distance covered at all speeds (m)
High speed running (m)	The distance covered at 5.5 $m.s^{-1}$ and above
Very high speed running (m)	The distance covered at 7 $m.s^{-1}$ and above
Maximum speed attained ($km\cdot h^{-1}$)	Maximum speed attained during the match, measured in $km.h^{-1}$
Count of accelerations from zone 4 – zone 6	The number of accelerations above 3.0 $m.s^{-2}$ with a minimum duration of 0.5 s, and a starting speed in zone 4 and final speed within zone 6

Post-pubescent individuals have been shown to have increased muscle mass when compared to their pre-pubescent counterparts (Section 2.8.1.3), and therefore may display greater levels of strength, power and speed performance. Due to these inherent differences, speed thresholds placed upon individuals of different maturational statuses may not be suitable (Cummins et al., 2013). Thus, there is the potential for error in the quantification of training load (insufficient reflection) when using global speed thresholds (Cummins et al., 2013).

Research has highlighted that the frequency of accelerations during a game can be approximately three to eight times greater than sprint occurrence (Lockie et al., 2011). Moreover, as the average sprint usually lasts for approximately two seconds, the ability to accelerate and reach a high speed has been highlighted to be vital for on-field performance (Lockie et al., 2011).

2.10. Current Issues Relevant to the Present Thesis

With consideration of the extant literature, it is evident that growth and maturity play an important role in the development and selection of elite youth soccer players. That said, understanding of the most appropriate methods to assess and monitor growth and maturation in young athletes is still unclear. Further, the extent to which variance in maturation contributes towards indices of match performance is, as yet, unknown. Another question of interest is how fitness attributes, such as speed; developed through the growth spurt and whether the changes observed in young athletes will mirror those observed in the general population. With this in mind, the purpose of the current thesis was to examine these questions within a sample of elite youth soccer players at a professional soccer academy.

3. General Methods

3.1. Overview of Methods used throughout this Thesis

This chapter describes the methods that are implemented frequently throughout this PhD thesis. This chapter will also highlight the tests used to determine the influence of biological maturation on physical and match running performance. The data for this current PhD thesis will be collected from individuals that are part of an elite soccer academy, over a period of six consecutive playing seasons: 2013 – 2018. The group of tests that have been developed are a multi-disciplinary test battery and are shown in Table 3-1.

Table 3-1. Overview of methods implemented for testing battery for the current PhD thesis.

Predictor	Parameter	Test / Measurement
Physical	Anthropometry	Stretched stature (cm) Weight (kg) Stretched seated stature (cm) Estimated leg Length (cm)
	Maturity Status	Mid-parental Stature (cm) Predicted adult height (cm) Maturity offset (yr)
Physiological	Speed	5 m, 20 m (s)
	Explosive strength	Countermovement Jump (cm)
	Agility	505 R/L (s)
	Reactive Jump Capacity	30 cm Drop jump

Note: 505 – Change of direction 505 test; R/L – right or left foot turn.

For the foremost part of the thesis, serial stature records will be fitted for each participant with the Super-Imposition by Translation and Rotation (SITAR) growth curve model to define age at PHV (Cole et al., 2010).

Individual’s anthropometric data at each serial observation was used to calculate predicted adult height and maturity offset values. Cross-observations will be made between age at PHV, and forecasts made from the two commonly used formulas. It is anticipated that there may be a link between the period around PHV and a deceleration in particular physical abilities; therefore, there is a need for an improved ability to predict when this deceleration may occur.

The main focus of any sporting programme should be to develop the physical literacy of the participants by improving their capability to move with confidence and competence in a multiplicity of physical activities and various settings (Whitehead, 2001). The concept of physical literacy represents not only to the domain of performing skill but also to the attitudes, motivations, and psychosocial skills needed for continued participation in exercise and sports (Edwards et al., 2018, Edwards et al., 2017). Assessments of physical literacy can be quantified by how well an individual can perform fundamental movement skills such as static balance, vertical jumping and sprinting (Tompsett et al., 2014). These movement skills are considered important because of documented associations to lifelong participations in physical activity, health benefits and success in sports (Barnett et al., 2009, Lubans et al., 2010).

The key assessment methods for these anthropometric and physical metrics are described within this chapter. Additionally, an overview of the participants who were involved in this study is provided.

3.2. Participants and Procedures used within this Thesis

All participants that took part in the studies were involved in the youth development and professional development phases (U12 – U18s). Every participant was from the same professional soccer academy (category one status club) in England.

Every participant undertook the same anthropometric assessment (approximately every two months), carried out by the same, qualified anthropometrist. In addition, the physical testing battery was carried out at consistent time-points (approximately every three months) throughout the course of each of the seasons (Table 3-2). Institutional ethical approval for all research was established and approved by the Department of Life Sciences, Faculty of Science and Engineering, Manchester Metropolitan University (Ethics code: 17739). All participants that took part in the research provided verbal assent, whilst parents / guardians provided written consent.

Table 3-2. List of measures collected.

Participants	Anthropometric measurements	Locomotor capacities	Lower body explosive strength	Match running metrics
• Chronological age • Biological parental height (cm) – measured *in-vivo* (when possible) or self-reported	• Stretched standing height (cm) • Stretched seated height (cm) • Body weight (kg) • Leg length (stretched standing height (cm) − stretched seated height (cm))	• 5 m (s) • 20 m (s) • COD 180° turn (alternate right and left foot turns, (s))	• CMJ (jump height, (cm)) • RSI (dimensionless)	• Total distance covered at all speeds (m) • High speed running distance (m) • Very high-speed running distance (m) • Maximum speed reached (km.h^{-1}) • Count of accelerations from zone 4 to zone 6

3.3. Participant Measurements

All measurements were collected at the training facility of the soccer club. The lead researcher was directly responsible for the selection of all of the anthropometric measurements and assessments of data collection, with the support of other members of staff from within the academy.

A sample of 15 participants was selected and measured at the same time of day on a second occasion within four days (after their earliest measurement date). The initial and replicate measurements were taken by two experienced observers. Inter-observer technical errors of measurement for the repeated sample were as follows: weight (0.38 kg), height (0.24 cm) and sitting height (0.25 cm). Inter-observer technical errors detailed in the Wrocław Growth Study in the mid-1960s were 0.29 cm and 0.35 cm for height and sitting height, respectively (Kozieł, 1998); the inter- and intra-observed technical errors of measurement noted under field conditions were also well within the range of those reported in several small scale and national surveys of school age children and youth (Malina, 1995).

Prior to any testing or data collection commencing, each participant was informed to carry out their normal routines and diets. Anthropometric measurement collections were taken as soon as the participants arrived for testing and data collection. Prior to the participants carrying out any physical testing, they were provided adequate rest beforehand (48 hours) to minimise any fatigue that may impact the test results.

3.4. Anthropometric Measurements

Measures of anthropometry; stretched standing height, stretched seated height and body mass were collected every eight weeks throughout the duration of this thesis. All anthropometric measurements were collected by the lead author. Listed below are details of how the anthropometric measurements were obtained, following guidelines detailed by the research of Marfell-Jones et al. (2012).

3.4.1. Stretched Height

Definition: the perpendicular distance between the transverse planes of the vertex of the head and the inferior aspect of the feet (Marfell-Jones et al., 2012).

Following the guidelines of (Marfell-Jones et al., 2012), stretched stature, here on in referred to as height, was measured to the nearest 0.1 cm using a Holtain stadiometer (Holtain Ltd., UK). The process of measurement collection was:

1. Participants were asked to remove their footwear and socks;
2. Participants were asked to stand with their heels together and the heels, buttocks and upper part of the back touching the scale;
3. The participants head was then placed in the Frankfort plane (not touching the scale);
4. The participant was then asked to take and hold a deep breath whilst a gentle upward lift through the mastoid process was applied;
5. The headboard was placed firmly down on the participants Vertex;
6. The measurement of height was collected before the participant exhaled.
7. Height was recorded to the nearest 0.1 cm;
8. The participant was then asked to step away from the stadiometer;
9. The previous seven steps were then replicated. If the two measurements collected differ by more than 0.4 cm, a third measurement was collected;
10. If two measurements were collected without the need of a third measurement, the mean value of the two measurements was recorded. If there was a need for a third measurement, the median value was recorded.

3.4.2. Sitting Height

Definition: the perpendicular distance between the transverse planes of the vertex of the head and the inferior aspects of the buttocks when seated (Marfell-Jones et al., 2012).

Following the guidelines of (Marfell-Jones et al., 2012), sitting height was measured to the nearest 0.1 cm using a Holtain stadiometer (Holtain Ltd., UK). A participant had their sitting height measurement collected to allow for determination of their leg length. Leg length was calculated as: stretched height – sitting height (Malina et al., 2004a).

1. Participants were asked to sit on a 40 cm measuring box on a level surface with their hands resting on their thighs;
2. The participants head was then placed in the Frankfort plane (not touching the scale);
3. The participant was asked to take and hold a deep breath whilst a gentle upward lift through the mastoid process was applied;
4. The headboard was placed firmly down on the participants vertex;
5. The measurement of sitting height was collected before the participant exhaled;
6. Height was recorded to the nearest 0.1 cm;
7. The participant was then asked to step away from the stadiometer;
8. The previous seven steps were then replicated. If the two measurements collected differed by more than 0.4 cm, a third measurement was collected;
9. If two measurements were collected without the need of a third measurement, the mean value of the two measurements was recorded. If there was a need for a third measurement, the median value was recorded.

3.4.3. Body Weight

Definition: body mass was calculated through the measurement of weight, i.e., the force the matter exerted in a standard gravitational field (Marfell-Jones et al., 2012).

Participants body mass was measured to the nearest 0.1 kg using Tanita weighing scales (Tanita®, type BC-420 SMA, Japan). From here on in, body mass will be referred to as weight.

1. Weighing scales were set to a zero reading;
2. Participants were asked to remove all footwear and socks, and were asked to be wearing shorts and a T-shirt;
3. Participants were asked to stand on the centre of the scale without any support, and have their weight evenly distributed between both feet;
4. Weight was recorded to the nearest 0.1 kg;
5. Participants were then asked to step away from the weighing scales;
6. The first five steps were then replicated. If the two measurements collected differed by more than 0.4 kg, a third measurement was collected;
7. If two measurements were collected without the need of a third measurement, the mean value of the two measurements was recorded. If there was a need for a third measurement, the median value was recorded.

3.5. Age Groups

The chronological age of a participant would determine the age group they would participate in for each study. The age group system uses the same process as the schooling system within the UK. For example, any individual born on the 31st of August would be the youngest participant in their respective age group, whereas an individual born on the 1st of September would be the oldest within their respective age group. An individual had their chronological age calculated (Equation 3-1) relative to the date the test commenced, using Microsoft Excel.

$$\text{Chronological age} = (\text{date of test} - \text{date of birth}) / 365.25$$

Equation 3-1.

3.6. Assessment of Maturation

In the current thesis, each participant had their biological maturity status calculated using the somatic equation proposed by Khamis and Roche (1994) to allow for consistency throughout (apart from Chapter 3 which also used maturity offset and generic age methods for comparison). The Khamis-Roche equation allows for the calculation of predicted final adult height for a person, at a given point in time. The equation was calculated in a Microsoft Excel spreadsheet whereby stretched standing height (cm), body weight (kg) and mid-parental height (cm) were input along with three predictor variables. Additionally, date of birth at the time of observation and the date of test were used to allow for calculation of chronological age which is also required in the Khamis-Roche equation (Equation 3-2).

$$\text{Predicted adult height (cm)} = C_1 + (C_2 \times \text{H}) + (C_3 \times \text{W}) + (C_4 \times \text{MPS})$$

Here, H is height at time of observation (in), W is weight at time of observation (lb), MPS is mid-parental stature (in), and C_1, C_2, C_3 and C_4 are coefficients that depend on the age of the participant at time of measurement.

Equation 3-2

Classification of each participant on their maturity status involved using their current and predicted final adult height (Equation 3-3). Using percentage of predicted final adult height at time of observation, participants were then classified into maturity categories, similar to previous research (Cumming et al., 2017b). Participants whose PPAH was < 85% were classified as pre-pubertal; participants between 85 and 96% were classified as undergoing the adolescent growth spurt and participants that had a PPAH > 96% were classified as post-pubertal. Similarly, it was anticipated that peak height velocity typically occurred between 85 and 96% of predicted final adult height, peaking at approximately 91 – 92% (Sanders et al., 2017).

$$Percentage\ of\ predicted\ adult\ height = (current\ height\ at\ obseravation\ /\ predicted\ final\ adult\ height) \times 100$$

Equation 3-3.

3.7. Warm-Up

Prior to the participants undertaking any physical performance tests, a complete standardised warm-up took place. The warm-up took place on an artificial indoor 4G pitch and lasted approximately 15 minutes. Following the RAMP protocol suggested by Jeffreys (2006) whereby the aim was to gradually increase Raise (R) the heart rate, respiration rate, blood flow and elevate body temperature with low intensity activities; Activate and Mobilise (AM) key muscle groups and joints through ranges of motion that would be implemented during the session, and finally to Potentiate (P), by using exercises that would be similar to those that are carried out by the participants during the session, improving the effectiveness of the subsequent performance. A passive recovery period of 10 min was given between each of the performance tests to avoid fatigue-induced effects (Trecroci et al., 2018).

3.8. Physical Performance Testing

As part of a global vision for youth development in English professional football, the Premier League has provided a framework to facilitate the development of youth soccer players and provide support for practitioners working with these players. This framework is known as the Elite Player Performance Plan (EPPP). The EPPP was introduced in 2011 to aid player development from a tactical, technical, psychological and physiological standpoint (EPPP, 2019). The EPPP has emphasised the importance of the physical development of youth soccer players and implemented various ongoing projects (e.g., benchmark fitness testing, growth and maturation screening (EPPP, 2019)) throughout all academies with a category status. This framework serves to highlight the importance of youth development and the evolving physical requirements to compete at the highest level in soccer. Within the EPPP, a battery of fitness tests has been outlined that are implemented amongst clubs, these tests are outlined in sections 3.8.1 – 3.8.4.

3.8.1. Sprint Tests

The ability to be able to sprint has been identified as a critical factor in achieving success in many sports (Lloyd and Oliver, 2019). Furthermore, this physical characteristic is seen as a key element to progress as a professional soccer player and is something which is frequently tested amongst youth soccer players (Figueiredo et al., 2009b, le Gall et al., 2010, Carling et al., 2009).

The sprint assessments that were carried out were 5 m and 20 m. These were captured with gates positioned at 0 m, 5 m and 20 m, enabling a sprint time to be recorded between 0 m and 5 m, and 0 m and 20 m (shown in Figure 3-1). All participants performed a familiarisation session to become accustomed with the procedures. For all sprints, participants adopted a two-point stance, with the front foot placed 0.30 m before (-0.30 m) the initial timing gate (0 m) to prevent early triggering, and were instructed to sprint as fast as possible in a straight line to the turning point, which was placed 5 m beyond the final gate (25 m). Verbal encouragement was given to all participants throughout the tests by the assessor. Time was recorded using photoelectric cells (Witty, Microgate, Italy). The sprints were performed four times, separated by at least three minutes of passive recovery between each attempt. The time for each distance was recorded to the nearest 0.01 s and the best time for each test was recorded for statistical analysis as used previously in adolescent (elite) soccer players (Buchheit et al., 2010a). Intraclass correlation coefficient (ICC) and coefficient variation (CV) 5 m were ICC $r = 0.88$ and CV = 3.98 % and 20 m were ICC $r = 0.81$ and CV 3.14 %.

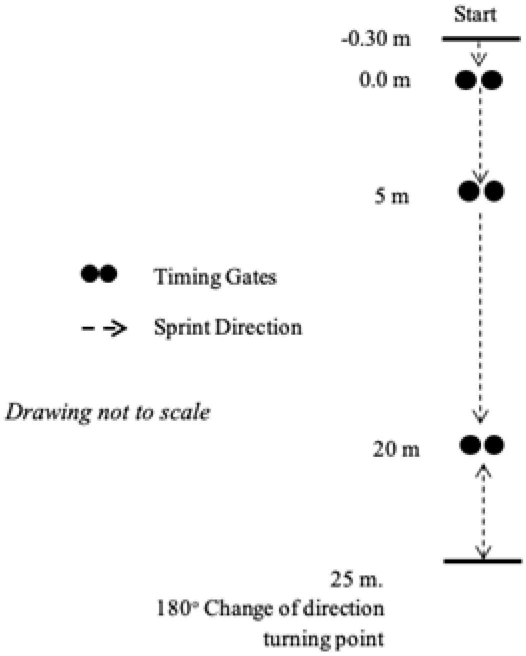


Figure 3-1. Schematic diagram of sprint and change of direction testing protocol.

3.8.2. Change of Direction Test

The ability to perform a change of direction can be influenced by technique, anthropometry, straight sprinting speed and leg strength factors (Lloyd and Oliver, 2019). Moreover, it has been highlighted that the ability to perform well in a change of direction test could be a distinguishing factor in a multidisciplinary talent identification battery test amongst youth soccer players (Reilly et al., 2000b).

The change of direction test was performed following a maximal sprint, a technique that has been described in the literature as a 'flying start' (Haugen and Buchheit, 2016). Participants were asked to sprint forward to a turning point 5 m beyond a 20 m timing gate (i.e., a point 25 m in front of them), to pivot 180° at this point and then sprint 5 m in the return direction. The test was concluded when the participant re-broke the 20 m timing gate shown in Figure 3-1.

This test requires the participant to decelerate, change their body direction, by rotating 180°, and then accelerate. The test was repeated four times, with the turning foot alternated between right and left foot. Tests were separated by at least three minutes of passive recovery between each trial. Time was recorded using photoelectric cells (Witty, Microgate, Italy), to the nearest 0.01 s. A practitioner was positioned at the turning point, and if the participant turned prematurely, with the wrong foot, or slipped, the trial was discarded and subsequently another trial was performed after a further rest of three minutes. The fastest trial for the change of direction test was recorded for statistical analysis as used previously in adolescent (elite) soccer players (Trecroci et al., 2019). Intraclass correlation coefficient (ICC) and coefficient variation (CV) for change of direction were ICC r = 0.72 and CV = 4.40 %.

3.8.3. Countermovement Jump Test

Countermovement jump (CMJ) tests are often used to determine neuromuscular performance amongst elite soccer players. The CMJ has previously been established as a reliable measure of explosive strength performance (Lloyd et al., 2009, Markovic et al., 2004).

Following the maximal sprints and change of direction test and a rest period of 10 minutes, participants performed three jumps on a hard, flat surface between a portable photoelectric cell system (Optojump, Microgate, Italy), with 60 seconds of rest between trials. To isolate the lower limbs, and reduce the influence of technique and arm swing, participants were asked to keep their arms akimbo during CMJs (Hara et al., 2008). Participants were instructed to begin the jump from an initial standing position with a downward movement to a self-selected squat depth, which was immediately followed by a concentric upward movement, resulting in a maximal vertical jump (Lloyd et al., 2011b). The final CMJ score was taken as the highest jump (cm) and used for statistical analysis as used previously in adolescent (elite) soccer players (Trecroci et al., 2019). Intraclass correlation coefficient for CMJ jump height (ICC) and coefficient variation (CV) were ICC r = 0.92 and CV = 7.56 %.

3.8.4. Reactive Strength Index Assessment

The measure of reactive strength index (RSI) is a function of jump height and ground contact time i.e., large jump height, low ground contact time. The RSI for each participant was determined using drop jump (DJ) tests. This involved the participants performing three separate jumps on a hard, flat surface between a portable photoelectric cell system (Optojump, Microgate, Italy). Participants performed DJs from a drop height of 0.30 m and were encouraged to use their hands during the jumps. Participants were asked to avoid slowly stepping down or hopping from the box and to avoid tucking their legs in the air (i.e., legs to remain straight and attempt to land in the same position as take-off). Initially, participants stepped off the platform, dropped down to the floor, landed on both feet and then immediately jumped up as quickly and as high as possible. The aim of the jumps was to minimise the contact time, whist attempting to maximize flight time (Flanagan and Comyns, 2008). Between DJs, a rest period of 60 seconds was given to avoid any residual fatigue effects (Read and Cisar, 2001), and a rest of 10 minutes was allowed between conducting CMJ and RSI tests for the same reason. All participants were allowed a practice jump before their first testing occasion to avoid any skewing of results due to familiarisation in early testing. The dependent variables calculated for the jumps were contact time (CT) and flight time (FT). The RSI was calculated using (Equation 3-4) for each test. The best (highest) score was then selected , as previously detailed in adolescent soccer players (Granacher et al., 2015).

The variables of interest for RSI reported with intraclass correlation coefficient (ICC) and coefficient variation (CV) were:

- Contact time (CT): ICC r = 0.96 and CV = 4.21
- Flight time (FT): ICC r = 0.95 and CV = 4.95
- RSI: ICC r = 0.97 and CV = 3.73

$$RSI = \frac{FT}{CT}$$

Equation 3-4.

3.9. Summary

These methods discussed are selected based on best practice and will be implemented throughout the following chapters but are provided here as a single point of reference. Chapter 4 relies heavily on the Khamis-Roche equation. Chapter 5, 6 and 7 also implement the Khamis-Roche equation. Additionally, Chapters 5 and 7 use the physical performance tests described in this chapter. For clarity, a timeline used in the testing protocol is provided in Figure 3-2.

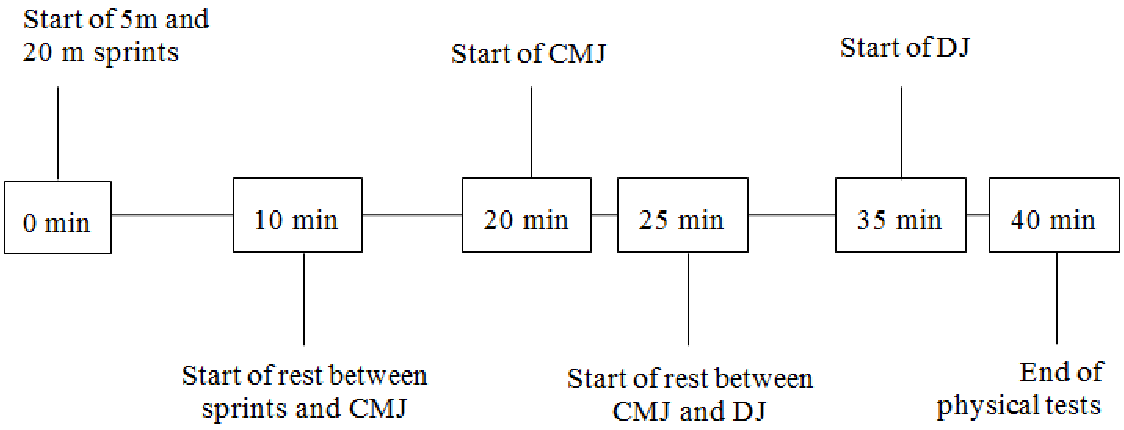


Figure 3-2. Approximate timeline of tests.

4. Predicting the Pubertal Growth Spurt in Elite Youth Soccer Players: Evaluation of Methods

Chapter 4

4.1. Introduction

This chapter compares two non-intrusive methods of identifying maturity status in elite youth soccer players (maturity offset and percentage of predicted adult height) against a generic age; these methods are explained in detail in Chapter 2. This work is the basis of a recently accepted publication, (Parr et al., 2020b).

The study of physical growth and maturation in children and adolescents has been on-going for over 150 years (Malina et al., 2004a). The characteristics associated with physical growth and biological maturation, and related changes in functional and behavioural characteristics can influence the development of athletic ability (Williams and Reilly, 2000). Although the processes of growth and maturation span approximately the first two decades of life, the interval spanning the onset of the adolescent growth spurt and pubertal maturation, sometimes labelled the pubertal growth spurt, is highly individual and variable in both timing and tempo (Malina et al., 2004a, Malina et al., 2015). The spurt begins with acceleration in the rate of growth in height (labelled take-off), continued acceleration in growth rate until peak velocity is attained - age at peak height velocity (PHV) - followed by deceleration and eventual cessation of growth in height (Malina et al., 2004a, Molinari et al., 2013). The interval of the growth spurt is of great interest and can present a challenge to those involved in the identification and development of youth athletes, including decisions regarding retention or exclusion.

Youth athletes are traditionally grouped by chronological age for the purpose of training and competition. Youth of the same chronological age can vary significantly in both maturity status at the time of observation (e.g., skeletal age, stage of puberty) and in maturity timing, the chronological age at which they enter puberty and attain peak velocity of growth in height (Beunen and Malina, 1988, Patel et al., 1998, Marshall and Tanner, 1970, Malina et al., 2004a). Estimation of the chronological age at which a youngster attains specific maturational landmarks requires longitudinal observations and inter-individual variation is substantial. For example, youth soccer players of the same chronological age can vary by as much as five to six years in skeletal age (Johnson, 2015), whist ages at take-off of the growth spurt varied from 8.2 to 12.7 years in boys from the Fels longitudinal study (Malina et al., 2016).

Although based largely on cross-sectional data, individual differences in maturity status have important implications for the development and retention / exclusion in a variety of sports, including youth soccer. Players advanced in maturity status have both size and functional advantages (e.g., strength and power) compared to later maturing teammates (Malina et al., 2013) and generally possess a competitive advantage (Cumming et al., 2017a). Data is lacking, however, on individual differences in size and function among soccer players relative to timing of the adolescent growth spurt (Malina et al., 2015). Data from longitudinal surveys of the general population clearly indicate a height advantage from 10 through to 15 years of boys who attain PHV earlier than peers and a weight advantage through adolescence (Malina et al., 2004a). Of relevance to the development of youth players, those who mature early experience the adolescent growth spurt at a chronological age when the training load is typically lighter and fewer decisions are made regarding the retention or release of players from the academy system (Cumming et al., 2017a). To accommodate individual differences in rate of growth during the growth spurt, many soccer academies systematically monitor the growth and estimated maturity status of youth players.

Assessment of growth status is rather straightforward and involves measurements of height, weight and perhaps other dimensions, such as sitting height. Assessing maturity status is a different issue as the established methods (stage of pubertal development and skeletal age) are often viewed as invasive and require expertise that may not be available at some clubs (Malina, 2017). Similarly, assays of hormonal levels are also invasive and expensive, but more importantly, may be influenced by behaviour factors such as sleep, stress, nutritional status and physical activity (Johnson et al., 1992, Dawes et al., 1999, Shirtcliff et al., 2009, Blakemore et al., 2010). On the other hand, estimated growth velocities based on longitudinal height and weight records may be useful in identifying the growth spurt; however, care in estimating velocities is essential and available longitudinal observations may not span the interval of the growth spurt. Such estimates are, nevertheless, retrospective and have limitations in the context of the needs of individual players.

There is considerable current interest in soccer and other sports in the application of two non-invasive and predictive methods to accommodate the perceived need for identifying the onset and subsequent progress of the growth spurt. Sex-specific equations based on chronological age, height, mass, sitting height and estimated leg length are available to predict maturity offset, defined as time before PHV (Mirwald et al., 2002); chronological age at observation minus predicted offset minus chronological age provides a predicted age at PHV. Predicted offset is commonly used to classify youth as pre-PHV, circa-PHV or post-PHV, while predicted age at PHV is also used to group youth into maturity categories, i.e., early, on-time or late (Malina et al., 2012a, Sherar et al., 2007). However, the validity, reliability and accuracy of predicted ages at PHV with the maturity offset protocol, have been questioned (Kozieł and Malina, 2018, Malina and Kozieł, 2014, Malina et al., 2016). In addition to dependence upon chronological age (and body size at prediction) and reduced variation in predicted relative of estimated or observed ages at PHV based on longitudinal data spanning late childhood and adolescence, the prediction equation has major limitations with early and late maturing boys defined by observed ages at PHV. Further, the median error tends to be magnified considerably in children that are either ‘early’ or ‘late’ maturing, who typically are of most concern in the context of sport (Cumming et al., 2017a). Accordingly, the reliability of this method merits attention.

Another strategy that is increasingly used with youth athletes is the percentage of predicted adult height (PPAH) attained the time of observation, an indicator of maturity status. The use of PPAH as a maturity indicator was recommended by Roche et al. (1983) and equations for the prediction of adult height without skeletal age were subsequently developed (Khamis and Roche, 1994) as highlighted in Chapter 3. Concordance of classifications of maturity status based on PPAH at the time of observation and on skeletal age amongst youth participants in American football aged 9 – 14 years (Malina et al., 2007) and in soccer aged 11 – 14 years (Malina et al., 2012b) were moderate, approximately 60%. Percentage of predicted adult height also had concurrent and predictive validity in samples of North American and British youth (Cumming et al., 2006, Cumming et al., 2014, Malina et al., 2005b, Malina et al., 2006). However, in more recent applications of academy soccer players 11 – 14 years of age with current heights ≥ 85.0% and < 90.0% of their predicted adult heights (Cumming, 2018, Cumming et al., 2018a) and 13 – 15 years of age with current heights ≥ 90.0% and < 95.0% of their predicted adult heights (Thomas et al., 2017) to participation in maturity matched (i.e., bio-banded) competitions have been monitored. The studies assumed that the ranges of PPAH spanned the interval of the growth spurt.

4.2. Expected Outcomes from Chapter 4

In light of the above discussion, the purpose of the present study was to evaluate three strategies for predicting the window in which PHV was most likely to occur for individual elite male adolescent soccer players. More specifically, the degree to which observed age at PHV (derived from longitudinal data) actually occurred within windows predicted by the three different strategies was examined. The three strategies included were (i) a ± 1.0 year age band around the mean age of PHV in European males, labelled the generic age band, 12.8 – 14.8 years; (ii) a band of ± 1.0 year around predicted age of PHV based on maturity offset equation (Mirwald et al., 2002); (iii) a window of PPAH 85 – 96% (Khamis and Roche, 1995). Additionally, to check whether the observed PHV matched with the predicted window, an assessment of the methods' ability to correctly identify the status of a youth as "in" or "out" of their pubertal growth spurt at the age of 13.0 years was also conducted. This age was selected as decisions on retention or exclusion, or "playing up" or "playing down" are commonly made around this time.

4.3. Methods

Prior to the study commencing, ethical approval was obtained and granted from the Ethics Committee of Faculty of Science & Engineering, at Manchester Metropolitan University (Ethics code: 17739). Parents / guardians of the participants were also notified of the aim of the study, research procedures, requirements, benefits, and risks and provided written informed consent. The youth participants also provided assent. Participants were advised that involvement in the study was voluntary and that they could withdraw from the study at any point.

4.3.1. Participants

Using a longitudinal design, a sample of 28 (19 Caucasian and nine non-Caucasian) male participants from a professional soccer academy within the English Premier League were observed across five consecutive competitive playing seasons, spanning 12.0 – 18.4 years of age. All participants were born between 2001 and 2004, and represented five age groups, defined by age on 1st September (beginning of the competitive year).

4.3.2. Anthropometry and Procedures

Height and sitting height and weight were measured every two months throughout each competitive playing season (six measurements per season). See General Methods (Section 3.4) for an explanation of the methods used to measure these values.

As previously noted, each participant's actual age at PHV was calculated by SITAR analysis (Cole et al., 2010). The model provided the actual age each participant experienced PHV based on their longitudinal data. The height at PHV was taken as the height recorded at the actual age of PHV. This data was collected for 28 players where a full data set, including actual final adult height (18.0 years), detailed by Khamis and Roche (1994), was available from at least the age of 13.0 years.

4.3.3. Super-Imposition by Translation and Rotation

Super-Imposition by translation and rotation (SITAR) is a form of growth curve analysis that models the biology of growth. The SITAR model is a shape invariant model with a single fitted curve (Stützle et al., 1980, Gasser et al., 1990) and involves the fitting of random effects (Equation 4-1). The model relies on the concept of developmental age and assumes that chronological age and developmental age amongst individual children are linearly associated. An individual may be advanced or delayed in terms of their chronological age (which is reflected in their timing parameter), and they also may be become more or less advanced over time (highlighted by their intensity parameter). Therefore, the analysis models on both the height scale (i.e., the size parameter) and the age scale.

$$y_{it} = \alpha_0 + \alpha_i + h\left(\frac{t - \beta_0 - \beta_i}{e^{-\gamma_0 - \gamma_i}}\right) + \varepsilon_{it}$$

Where y_{it} is the measurement height of the participant i at age t; α_i, β_i and γ_i are size, tempo and velocity, respectively random effects (along with corresponding fixed effects α_0, β_0 and γ_0); h (.) is a natural cubic regression spline curve; and ε_{it} are independently normally distributed errors.

Equation 4-1.

4.3.4. Age at Peak Height Velocity

The longitudinal height records for the 28 individual players were fit with the Super-Imposition by Translation of Rotation (SITAR) model (Cole et al., 2010) to estimate age at PHV. Ages at initial observation ranged from 11.2 to 13.1 years (mean 12.4 ± 0.6 years), whilst ages at final observation ranged from 14.5 to 16.4 years (mean 15.4 ± 0.6 years). The frequency of observations ranged from 13 to 20 (mean 18.6 ± 1.6); one participant had 13 height measurements, while observations among the remaining participants ranged from 17 to 20 measurements. The SITAR model was successfully fit to the height data for all 28 participants, with a mean age at PHV of 14.0 ± 0.9 years. The estimated age at PHV for one participant (12.2 years) preceded his first observation (13.1 years), while four players lacked a measurement of young adult height (see below). Thus, the sample for analysis was reduced to 23 players (15 Caucasian, 8 non-Caucasian), with a mean age at PHV was 14.2 ± 0.9 years for analysis. The height of each player at PHV was accepted as the height measured closest to the age at PHV with the SITAR model.

4.3.5. Pubertal Growth Spurt Prediction Strategies

The frequency with which observed age at PHV of each participant (estimated from longitudinal data) occurred within three windows based on different strategies was subsequently examined. The three strategies were as follows: (i) a ± 1.0 year age band around the estimated mean age of PHV of males of European ancestry, 12.8 – 14.8 years of age, labelled the generic age band; (ii) a band of ± 1.0 year for predicted ages at PHV based on the maturity offset protocol (Mirwald et al., 2002); (iii) a window of 85% to 96% of percentage of predicted young adult height (Khamis and Roche, 1994). Although the percentage of height window of 85% – 96% may not equate to ± 1.0 year, a PPAH in this range is accepted by some soccer clubs as indicative of the interval of PHV (Hill et al., 2019). Concordance of observed age at PHV with the "windows" defined by generic age at PHV, predicted age at PHV and percentage of predicted height between 85% and 96% was subsequently analysed, i.e., the extent to which the three methods correctly identified the status of a player as "in" or "out" of their pubertal growth spurt at the age of 13.0 years.

4.3.5.1. Generic Age at PHV

An interval of ± 1.0 year around observed age at PHV has been used previously in longitudinal studies to classify youth as late, on-time or early maturing (Malina et al., 2004b, Malina, 2017). Observed standard deviations for estimated ages at PHV in longitudinal studies have ranged from 0.8 to 1.3 years in boys with most clustering close to 1.0 year (Malina et al., 2004a). The estimated mean and standard deviation for age at PHV in the three samples upon which the maturity offset prediction equation was developed was approximately 13.8 ± 1.0 years (Malina et al., 2012b). Using the window of ± 1.0 year, the majority of boys should experience PHV within a window of 12.8 to 14.8 years of age. Accordingly, chronological age at the time of observation within this range was used as an approximate estimate of when an individual is likely to experience PHV. This was labelled the generic estimate of age at PHV. Participants with a current chronological age that falls within this band would be considered to be within the interval of the growth spurt, whereas those outside the band may be considered as having already attained peak velocity (early maturing) or not yet in the interval of peak velocity (late maturing), accordingly. A participant whose SITAR determined age at PHV was between 12.8 – 14.8 years would be correctly identified by using this method.

4.3.5.2. *Predicted Age at PHV*

Maturity offset at the observation closest to 13.0 years of age (13.0 ± 0.1 years, range 12.9 – 13.1 years) was predicted with the equation proposed by Mirwald et al. (2002), Equation 2-2. Note, the need to multiply the weight by height ratio by 100 was overlooked in the original publication (Mirwald et al., 2002), however, this has been included in Equation 2-2. The standard error of estimate for the prediction equation was 0.59. Chronological age at prediction minus maturity offset provided a predicted age at PHV (years).

4.3.5.3. *Window of Percentage of Predicted Adult Height*

The adult height of each participant at the observation closest to 13.0 years (See Section 4.1) was predicted with age-specific equations for males developed on youth of European ancestry from the Fels Longitudinal Study (Khamis and Roche, 1994). See Section 3.6 for a further explanation. Heights of the biological parents were mostly self-reported and as in other studies using the protocol, self-reported heights were adjusted for overestimation using sex specific equations (Epstein et al., 1995). See Section 2.5.2 for a further explanation. The height of each participant at observation (13.0 years) was then expressed as a percentage of their predicted adult height and also (2) the height at 13.0 years was also expressed as a percentage of the attained height at 18.0 years of age, i.e., young adult height.

Recent analyses of two early longitudinal studies of North American boys and girls noted that PHV occurred within a range of 85% – 96% of adult height, peaking at approximately 90% of adult height (Sanders et al., 2017). Citing this study, a window of 85% –96% within which PHV occurs is currently employed by a number of professional soccer academies to facilitate maturity-specific training strategies (Cumming, 2018, Cumming et al., 2018a). Note, however, the upper limit of 96% was noted in one of the longitudinal samples of girls (Sanders et al., 2017). Consistent with the strategy currently employed by some academies, the window of 85 – 96% of young adult height was used in the present analysis. Percentage of predicted adult height at 13.0 years and observed height at PHV (SITAR) expressed as a percentage of measured young adult height were compared with this window.

The height window can be converted into an age window. As longitudinal data were available for each participant, the progression of height with chronological age was known and measured heights were expressed as a percentage of observed young adult height at each chronological age. By taking the ages when 85% – 96% of observed young adult heights were attained, individual age windows were estimated for each participant.

4.3.6. Statistical Analysis

Chi-square tests were conducted in order to determine whether there was a significant difference for each of the three prediction strategies against an even chance of the prediction being correct, where values from the test which are greater than the critical value are significant. The predicted age at PHV and window of PPAH strategies were also compared with the Generic Age at PHV method to test for improvement in estimation. Concordance analyses (Cohen’s Kappa [κ] coefficients) were used to estimate the degree to which the strategies associated with predicted age at PHV and PPAH correctly identified individuals as being within or outside the respective windows based on maturity classifications at 13.0 years of age. Higher κ coefficients indicate more agreement between methods, while small or negative values indicate poor or no agreement. With the maturity offset protocol, an individual with a predicted age at PHV within ± 1.0 year of observed age at PHV was considered within the PHV window. For PPAH, an individual whose PPAH was between 85% – 96% observed young adult height was considered to be within the window of PHV. Subsequent analyses focused on the comparison of the observed age at PHV window and each of the three predictions.

4.4. Results

Data for individual participants at 13.0 years of age are summarised in Table 4-1. Descriptive characteristics of participants in consecutive competitive age groups are summarised by age group in Table 4-2. Observed ages at PHV based on the SITAR model ranged from 12.6 to 15.5 years with a mean of 14.2 ± 0.9 years. Applying the range based on youth of European ancestry (12.8 – 14.8 years) to categorise individuals as early, on-time, or late in maturity (based upon their observed age at PHV), participants were classified as follows: 14 on-time, three early and six late maturing.

Table 4-1. Characteristics of individual participants: observed and predicted estimates (at 13.0 years).

Participant	Observed (SITAR) age at PHV (years)	Maturity classification	Height (cm)	Weight (kg)	Predicted age at PHV (years)	Predicted minus observed age at PHV (years)	Attained height at 13.0 years as a % of observed young adult height	Attained height at 13.0 years as a % of predicted adult height	% of predicted minus % of observed young adult height (cm)	Window % of predicted adult height expressed as an age window
1	14.2	On-time	157.0	47.9	14.8	0.66	84.6	87.4	2.8	13.0 – 15.2
2	14.3	On-time	155.7	41.5	15.0	0.67	85.9	87.0	1.1	12.9 – 16.0
3	15.2	Late	154.6	42.7	15.1	-0.09	84.0	87.5	3.5	12.6 – 15.5
4	13.9	On-time	161.9	42.8	14.6	0.69	87.6	88.4	0.8	12.6 – 15.4
5	14.3	On-time	160.0	46.5	15.1	0.89	85.5	89.1	3.6	12.4 – 15.5
6	12.7	Early	169.6	61.5	14.3	1.58	92.2	92.0	-0.2	12.0 – 17.3
7	12.8	Early	157.7	44.9	15.3	2.50	89.3	88.4	-0.9	13.2 – 18.1
8	14.6	On-time	147.6	35.8	15.9	1.34	88.4	84.4	-4.0	14.0 – 17.3
9	13.0	On-time	164.4	54.2	14.9	1.97	89.6	84.2	-5.4	12.8 – 18.3
10	15.5	Late	151.0	40.0	16.0	0.55	88.6	85.6	-3.0	13.4 – 16.1
11	14.5	On-time	161.0	41.5	15.0	0.57	89.7	88.1	-1.6	13.2 – 15.7
12	15.1	Late	157.2	44.0	15.1	0.01	91.1	87.3	-3.8	13.2 – 15.9
13	15.5	Late	145.8	42.6	15.6	0.13	90.1	85.1	-5.0	14.9 – 18.3
14	14.8	Late	156.4	44.5	15.3	0.42	89.8	88.1	-1.7	13.0 – 16.8
15	15.0	Late	161.7	50.4	15.3	0.20	89.7	89.4	-0.3	13.0 – 15.7
16	13.7	On-time	160.7	42.6	15.1	1.32	87.0	88.2	1.2	13.1 – 16.0
17	13.9	On-time	152.0	38.9	15.5	1.66	89.2	86.7	-2.5	13.1 – 17.1
18	14.1	On-time	160.6	45.0	15.1	1.02	89.9	88.1	-1.8	12.4 – 16.6
19	14.2	On-time	155.4	41.3	14.8	0.57	89.0	87.7	-1.3	13.0 – 16.2
20	14.5	On-time	151.2	47.5	15.1	0.56	88.2	85.9	-2.3	13.4 – 17.0
21	13.7	On-time	169.7	53.0	14.8	1.12	90.1	90.6	0.5	12.5 – 15.0
22	12.6	Early	173.7	62.2	14.0	1.42	92.5	91.9	-0.6	12.1 – 16.6
23	14.7	On-time	152.4	42.4	15.4	0.64	86.2	86.9	0.7	13.7 – 16.3
Mean	14.2		158.1	45.8	15.1	0.89	88.6	87.7	-0.9	
±SD	0.9		6.9	6.6	0.5	0.65	2.2	2.1	2.5	

Table 4-2. Descriptive statistics for participant characteristics by competitive age groups through the 2013 – 2017 seasons

Variable	U13 (*n* = 20) Mean ± SD	U14 (*n* = 24) Mean ± SD	U15 (*n* = 23) Mean ± SD	U16 (*n* = 23) Mean ± SD	U17 (*n* = 16) Mean ± SD
Chronological Age (years)	12.6 ± 0.3	13.5 ± 0.3	14.5 ± 0.3	15.5 ± 0.3	16.5 ± 0.3
Maturity offset (years)	-2.3 ± 0.4	-1.6 ± 0.6	-0.6 ± 0.7	0.4 ± 0.7	1.8 ± 0.4
Predicted age at PHV	14.8 ± 0.4	15.1 ± 0.5	15.1 ± 0.6	15.0 ± 0.6	14.7 ± 0.4
Predicted age minus observed age at PHV	0.9 ± 0.6	0.9 ± 0.6	0.8 ± 0.6	0.6 ± 0.7	-0.3 ± 0.6
Current height (cm)	162.2 ± 7.6	167.8 ± 8.1	175.5 ± 7.0	178.8 ± 4.6	179.2 ± 4.2
Predicted adult height (cm)	190.2 ± 4.2	188.4 ± 4.5	187.1 ± 4.7	186.2 ± 4.7	188.5 ± 2.4
Height as a percentage of young adult height at 18 years (%)	82.6 ± 1.9	85.8 ± 2.5	89.9 ± 2.5	93.3 ± 2.1	96.6 ± 1.1

4.4.1. Concordance Comparisons of Prediction Methods

Concordance of predicted maturity status classifications of participants are summarised in Table 4-3. Percentage of predicted adult height within the 85% – 96% window has a higher degree of concordance with classifications based on observed age at PHV based on the SITAR model; the prediction protocol correctly classified 19 of the 23 participants as being within the recommended 85% – 96% band. Of the four participants that were misclassified, two were incorrectly identified as being outside of the PHV window and two were misclassified as being within the PHV window. Relative to predicted age at PHV based on the maturity offset protocol, PPAH at the time of observation showed a greater variance in the classification of players within or out of the PHV window.

Table 4-3. Concordance of predicted and observed classifications of participants based on predicted age at PHV and PPAH at 13.0 years relative to classifications based on observed age at PHV and observed percentage of young adult height at 18.0 years.

	Predictions within PHV window		Observed as being within the PHV window		κ
Method	Yes	No	Yes	No	
Maturity Offset	0 (0)	23 (15)	8	15	0.65
Window % of Predicted Adult Height	21 (19)	2 (0)	21	2	0.83

4.4.2. Concordance of Predictions against Chance

The results of concordance analyses of the three models for estimating age at PHV relative to observed age at PHV are summarised in Table 4-4. Among the 23 participants, 14 participants (61%) had an observed age at PHV within the window defined by generic age of PHV (12.8 – 14.8 years), and 14 of the 23 participants had a predicted age at PHV within the window defined by observed age at PHV ± 1.0 year. Only 11 of the participants (48%) were similarly classified by the two methods. In contrast, 22 of 23 participants (96%) attained PHV within the window defined by 85% – 96% predicted adult height. Results of the Chi-square analyses were not significant for generic age at PHV and predicted age at PHV ($\chi^2 = 1.09$), but that for PPAH was significant ($\chi^2 = 19.17$).

Table 4-4. Concordance of three methods for estimating age at PHV relative to observed age at PHV and results of chi-square analyses.

Method	Observed ages at PHV within the prediction window defined by each method	χ^2
Generic Age	14	1.09
Maturity Offset	14	1.09
Window % of Predicted Adult Height expressed as an age window	22	19.17^*

$^*p < 0.01$.

Chi square and concordance analyses were done, and Kappa coefficients were also calculated to evaluate whether the predictive methods improved upon the generic age method, i.e., generic age at PHV method at 13.0 years of age compared with predicted age at PHV based on maturity offset and with the PPAH within the 85% – 96% window. Predicted ages at PHV are concordant with the generic age method in 14 of the 23 participants (61%, $\chi^2 = 0.0$), but the κ coefficient (0.48) suggests moderate concordance. In contrast, the percentage height window method (converted to an age window) improved upon the generic age method ($\chi^2 = 11.68$) and the κ coefficient (0.65) suggests substantial agreement. At 13.0 years of age, the percentage height window converted to an age window correctly identifies status based upon observed age at PHV in 22 of the 23 participants (96%).

4.5. Discussion

This study examined the degree to which chronological age, predicted age at PHV with the maturity offset protocol, and PPAH at the time of observation effectively predicted the window within which PHV was likely to occur.

4.5.1. Summary of Dataset Characteristics

The majority of participants (18 of 23, 78%) experienced PHV when their heights were between 88% – 92% of observed young adult height at 18.0 years of age, and all 23 participants attained PHV within the 85% – 96% window (Figure 4-1).

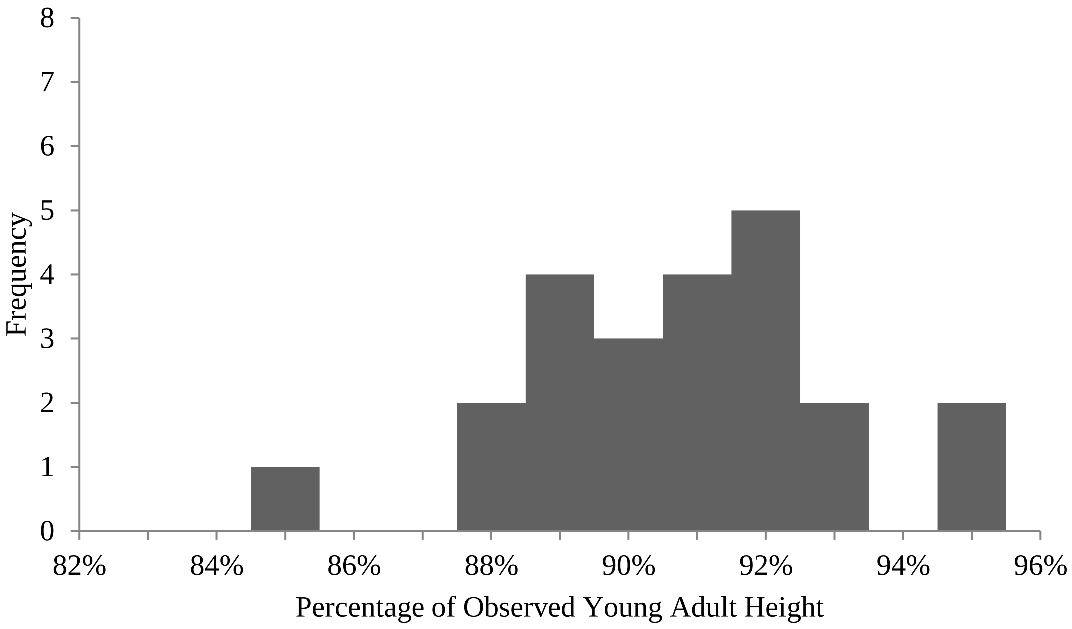


Figure 4-1. Frequency of observed participant PHV expressed as a percentage of observed young adult heights at 18.0 years.

The latter was consistent with the observation of (Sanders et al., 2017) which found that PHV occurred at approximately 90% of young adult height. Based on measurements taken at 13.0 years, the distribution of PPAH at PHV is shown in Figure 4-2. Percentages of predicted adult height in 22 of the 23 participants (96%) were within the 85% – 96% window. The only participant outside of this range had a PPAH < 85%, while no percentages of predicted adult height were > 96%, consistent with the observations of (Sanders et al., 2017).

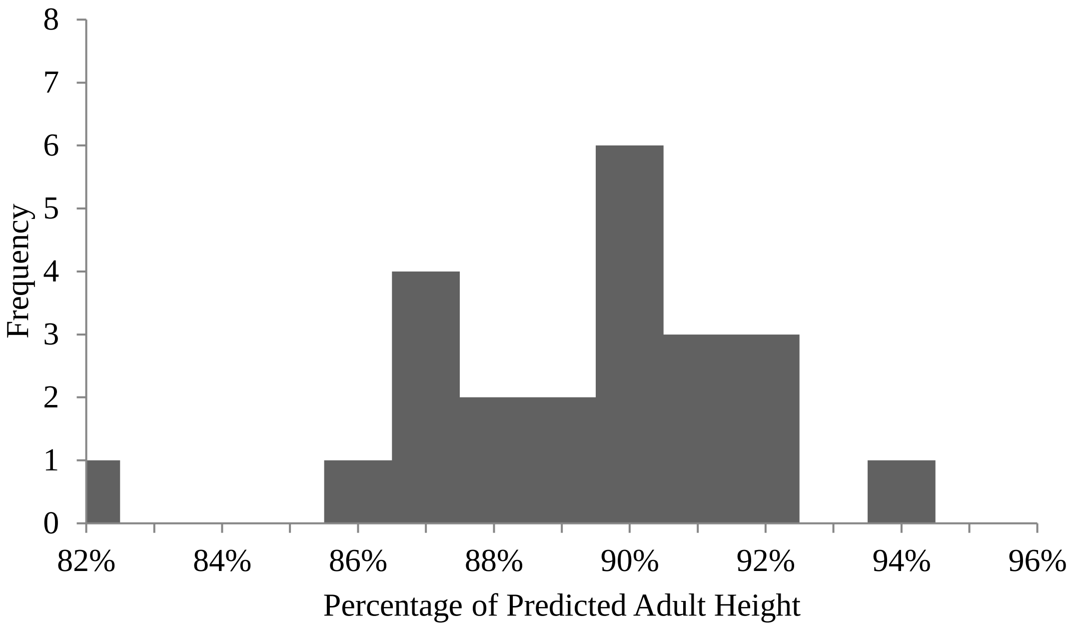


Figure 4-2. Frequency of observed participant PHV expressed as a PPAHs at 13.0 years.

Interestingly, participant #22 had an observed age at PHV of 12.6 years (determined with the SITAR model) while predicted age at PHV (estimated from predicted maturity offset method at 13.0 years of age) was 14.0 years, giving a difference of 1.4 years. By inference, this participant would not have had training loads adjusted for their interval of rapid growth; this inference also applied to each of the three early maturing participants in this sample. On the other hand, a participant with a predicted age at PHV more than 1.0 year beyond their observed age at PHV would be identified as having PHV after their pubertal growth spurt had already occurred and velocity of growth is in the deceleration phase. Within the sample, the six late maturing participants had a lower chance of such a misclassification.

Observed ages at PHV (determined with SITAR) in the 23 participants ranged from 12.6 - 15.5 years. Accordingly, the generic age at PHV, i.e., 13.8 ± 1 years, is an unreliable indicator of when PHV is likely to occur in academy soccer players. Observed ages at PHV in 9 of the 23 participants (39%) were outside the generic age window of 12.8 - 14.8 years of age.

As previously noted, soccer tends to select boys who are advanced in biological maturity status based on skeletal age and pubertal status; the selection bias emerges at approximately 12 – 13 years, although there is variation with the method of maturity assessment (Malina, 2011, Malina et al., 2013, Malina, 2017). Variation amongst methods of skeletal age assessment merits attention (Malina et al., 2018, Malina, 2011). In contrast, estimated mean age at PHV with the SITAR model in the sample of soccer players in the present study, 14.2 ± 0.9 years, was not early, although it was in the range of mean ages at PHV noted in previous longitudinal studies (Malina et al., 2004a). Although the SITAR model satisfactorily fit the longitudinal records of one participant, the estimated age at PHV (12.2 years) preceded the first observation. In addition, the estimated ages at PHV with SITAR of the four participants lacking a measurement of young adult height were 13.0, 13.2, 13.6 and 13.8 years. With these five players included (*n* = 28), the mean age at PHV was 14.0 ± 0.9 years.

Estimated age at PHV amongst 33 select Belgian youth soccer players, 13.8 ± 0.8 years, was slightly earlier than the present study (Philippaerts et al., 2006),but was also in the range of average ages at PHV. Of relevance to the present discussion, 76 Belgian youth players were tracked annually over four or five years beginning at ages ranging from 10.4 - 13.7 years, but the growth curves were successfully modelled with non-smoothed polynomials in only 33 players (43%); at initial observation, chronological age and skeletal age in this sample approximated each other, 12.1 ± 0.7 and 12.4 ± 1.3 years, respectively. In contrast, the majority of participants whose height records could not be successfully modelled comprised of two groups: 25 participants appeared to be early maturers with their skeletal age in advanced of their chronological age at initial observation, chronological age = 12.6 ± 0.5 and skeletal age = 13.5 ± 1.2 years, and 18 participants appeared to be late maturers with their skeletal age somewhat delayed relative to their chronological age at initial observation, chronological age = 11.6 ± 0.8 and skeletal age = 11.1 ± 1.1 years (Philippaerts et al., 2006).

Participants who experienced an earlier age at PHV were under-represented in the present study, this was also the case for the sample of Belgian youth players compared to the general population. Unfortunately, an indicator of skeletal maturity status at 11 – 12 years was not available for the current study. Among 20 U13 players in the present study with at a mean age of 12.6 ± 0.3 years (Table 4-2), height as a PPAH was 83.4 ± 2.6% and as a percentage of observed young adult height at 18 years was 82.6 ± 1.9%. Both percentages are somewhat lower than estimated percentages of adult height among boys in the Fels Longitudinal Study at 12 – 13 years of age (note, Fels participants were measured within one month of their respective birthdays), 84.9 ± 1.5% and 88.7 ± 1.8%, respectively (Roche et al., 1983) and boys in the Berkeley Longitudinal Study at 12.5 years, 85.4 ± 2.5% (Bayer and Bailey, 1959). The preceding thus suggests that the sample of participants in the present study was approximated to have average maturity status based on PPAH attained at the time of observation.

4.5.2. Comments on Performance of PPAH

Relative to the proposed band of 85% and 96% of adult height as reflecting the window of PHV (Sanders et al., 2017), 21 of 23 players had percentages of predicted adult height at 13.0 years of age that correctly identified them as being in the window of PHV; the range of percentages, however, was somewhat narrow, 84.2% to 92.0% (Table 4-1). This would suggest that the PPAH attained at 13.0 years of age was a comparatively more accurate predictor of age at PHV.

It is likely that participants who experienced an earlier age at PHV were under-represented in this sample versus the general population. As a consequence, many of these will enter puberty and experience PHV at an earlier age (although this was not an obvious feature of the current sample). Thus, age bands derived from the general population may be unsuitable for predicting PHV in such samples.

4.5.3. Comments on Performance of Age at PHV

Although the maturity offset prediction protocol is widely used with soccer players, predicted ages at PHV were not consistent with estimates based on the generic age method. Mean predicted age at PHV among 13.0-year-old players was 15.1 ± 0.5 years, with a range of 14.0 – 16.0 years; corresponding statistics for observed age at PHV were 14.2 ± 0.8 years with a range of 12.6 – 15.5 years (Table 4-1).

Of relevance, the three early maturing players with observed ages at PHV of 12.6, 12.7 and 12.8 years had predicted ages at PHV (based on maturity offset) at 13.0 years that exceeded their observed ages at PHV by 1.4, 1.6 and 2.5 years, respectively (Table 4-1). By inference, these participants would not have had training loads adjusted for the interval of rapid growth. A similar trend was apparent in the 14 participants classified as on time based on observed ages at PHV; all predicted ages at PHV exceeded observed ages at PHV by > 0.5 year (0.6 to 1.7 years). These participants would also be identified as having PHV after their pubertal growth spurt had already occurred. On the other hand, five of the six late maturing participants had a predicted age at PHV within 0.5 years of their observed age at PHV and thus had a lower chance of such a misclassification. Results were the same for the total sample of 28 players, 4 early, 18 on time and 6 late.

The results for the small samples of select soccer participants of contrasting maturity status were generally consistent with observations for males in the Wroclaw (Poland) and Fels (U.S.) longitudinal studies classified early, on-time or late maturing (Kozieł and Malina, 2018, Malina and Kozieł, 2014, Malina et al., 2016), allowing for the age ranges in the three series and for variation associated with the different methods for estimating age at PHV in the three studies, i.e., SITAR in the present study, Preece-Baines model 1 in Polish youth, and the triple logistic Bock-Thissen-du Toit model in U.S, youth. The contrast between predicted and observed ages at PHV was most apparent among early maturing youth, athletes and non-athletes.

The association between maturity status and the attainment of PHV is of considerable importance as it can highlight individuals that may have been preferentially selected due to their maturity status. Therefore, some individuals who are more talented and have the potential to achieve greater levels of performance may not be selected if they are less physiologically developed when decisions regarding retention and/or release are made. This may be more apparent in sports such as soccer where height, mass, velocity, power and strength could be advantageous (Meylan et al., 2010a). By comparison with the longitudinal data of the participants, heights calculated as 85% and 96% of predicted adult height can be converted into age values to provide an equivalent age window using the age corresponding to the height measurements closest 85% and 96%. When PPAH was related to age, the results were the same, 22 out of 23 players were correctly identified as being in the window of PHV. Percentage of predicted adult height was a comparatively more accurate predictor of age at PHV. Using the 85% – 96% window (Sanders et al., 2017) and heights measured at 13.0 years, the average age at PHV window was ± 1.7 years for the participants in this study.

It is important to note that this band was comparably larger than the window used for the maturity offset method; and results improved accordingly (Table 4-4). Based on calculations with data at 13.0 years, the age range equivalent to the 85% – 96% of adult height window was as small as ± 1.1 years but rose as high as ± 2.8 years. While performance was improved using a percentage height window, it was clear that the range provided by the 85% – 96% window was much larger than the age ranges applied to the generic age and maturity offset methods. That PPAH performed well was anticipated given the agreement of this dataset for youth soccer players with the PHV window suggested by (Sanders et al., 2017). Observed ages at PHV of all participants were within the height window (Figure 4-1). Further, when percentage of observed young adult height was used to establish an age window for PHV, κ coefficients highlighted near perfect agreement (κ = 0.87) between the predicted height at PHV window and age window for PHV.

4.5.4. Comments on the use of SITAR in PHV Derivation

Age, height and weight at SITAR derived age PHV were estimated from the longitudinal records for each participant and were used along with mid-parental height to predict adult height at this time (Khamis and Roche, 1994). Height at PHV was expressed as a PPAH attained at PHV. Accordingly, the 23 participants attained PHV at 88.9 ± 3.1% of predicted adult height (range 81.1 – 93.9%). When height at PHV was expressed relative to young adult height at 18.0 years, the 23 participants attained PHV at 91.2 ± 2.3% (range 84.9 - 95.7%). Both estimates were similar to those observed by Sanders et al. (2017), 90.0 ± 2.1% in the Brush Foundation (range 85.6 – 93.8%) and 90.2 ± 4.0% in the Berkeley (75.3 – 94.8%) longitudinal studies. Note, however, estimated ages at PHV in the present study (14.2 ± 0.9 years) was later than estimated for the Brush Foundation and Berkeley studies (13.0 ± 0.65 years and 13.4 ± 1.4 years, respectively).

Predicted age at PHV is used by many English professional soccer clubs to classify players as early, on-time or late maturing (Cumming et al., 2018a). Results of the present study highlight the need for caution when using maturity offset *per se* as a predictor of age at PHV and maturity timing for players. All predictions have associated errors and application to individuals, specifically select samples of adolescent athletes, requires caution. Inter-individual differences in the timing and tempo of the growth spurt need to be considered. As noted earlier in the discussion, many select adolescent soccer players are advanced in skeletal and pubertal maturation, and some may already be skeletally mature.

The contrast of maturity status and maturity timing (age at PHV) should be emphasised; the concepts are not equivalent. The former indicates the state of skeletal or sexual maturity, or the PPAH attained at the time of observation. The latter indicates when a specific maturity event occurs, in the present study, age at PHV. It is thus possible that some youth may be selected due to their advanced maturity status, whereas equally talented youth average or delayed in biological maturity status relative to their age peers may not be selected. This may be more apparent in sports such as soccer where height, mass, velocity, power and strength are viewed as advantageous (Meylan et al., 2010a). Indeed, youth soccer players tend to be, on average, advanced in sexual maturity status compared to non-athletes of the same age (Malina et al., 2010), while skeletal maturity status based on three commonly used methods of assessment, the Greulich-Pyle, Tanner-Whitehouse 2 radius-ulna-short bone (TW2 RUS) and Fels methods of skeletal age assessment (Malina et al., 2004a) were consistent in showing advanced maturity status among soccer players from several countries (Malina et al., 2018, Malina, 2011). Note, however, observations of soccer players using the modified TW3 RUS method did not indicate advanced skeletal ages among youth soccer players 11 – 15 years; rather, skeletal ages with the TW3 RUS methods were, on average, one year lower than corresponding skeletal ages with the TW2 RUS method at these ages (Malina et al., 2018).

A limitation of the present study was the limited number of early maturing players, which likely skewed the results and therefore may not be fully representative of a youth soccer population in general. Unfortunately, longitudinal data spanning 9 years of age through adolescence are lacking for youth soccer players.

The maturity offset prediction equation was established on samples of European ancestry (Mirwald et al., 2002). Ethnic variation in body proportions, specifically evident in the sitting height/standing height ratio and by inference in leg length merits attention (Malina et al., 2004a). Consequently, population variation in proportions of sitting height and leg length implies is a need for care when applying the prediction protocol to other ethnic groups (Malina, 2009). For example, in this study, the non-European participants were taller and displayed lower sitting height/height ratio than the European participants. Similarly, the Khamis-Roche method for the prediction of adult height was based on youth of European ancestry in the Fels Longitudinal Study (Roche et al., 1983).

Predicted maturity offset and in turn age at PHV, and the window of PHV based on PPAH in the present study were based on measurements taken at 13.0 years of age. Predicted age at PHV (15.1 ± 0.5 years) was later than observed age at PHV (14.2 ± 0.9 years) in the 23 soccer players; the standard deviation for the former was considerably less than that of observed age at PHV. Generic age at PHV and predicted age at PHV correctly predicted observed age at PHV for 14 participants (61%), while the percentage of adult height window correctly predicted 22 participants (96%). Generation of a specific age window based on predicted maturity offset did not improve estimation of PHV compared to the generic age method, while the PPAH window of PHV showed improvement in accuracy.

4.6. Conclusion

In conclusion, predicted age at PHV is influenced by chronological age and maturity status. The suggestion of this present study is that use of specific age at PHV does not appear to improve estimation of PHV above and beyond the use of generic age strategy. It is feasible to move to a percentage height window of PHV where improvement in accuracy was seen within the present study. Whilst the performance of PPAH performed statistically better, the Khamis-Roche equation requires the most information such that the improvement in prediction accuracy may be offset against the input data reliability and potential calculation complexity. Future work could consider improvement of existing methods in order to further constrict the age at PHV window or to consider alternative height at PHV calculations for scenarios where less information is available (e.g., extrapolation from Office of National Statistics data), as one must consider the trade-off between calculation complexity and accuracy of the results.

5. The Main and Interactive Effects of Biological Maturity and Relative Age on Physical Performance in Elite Youth Soccer Players

5.1. Introduction

Within this chapter, the effect of biological maturity on physical of elite youth soccer players is considered, as is the effect of relative age. Based on the finding of Chapter 4, the PPAH method was used to quantify the biological maturity status of the participants. As well as considering the effects of biological maturity and relative age separately, the study investigates whether there are interactive effects between these two phenomena. This work is the basis of a publication which has previously been published, (Parr et al., 2020a).

The identification and development of talented soccer players are primary objectives of professional soccer academies (Carling et al., 2009). The aspects that define talent in soccer are multi-faceted, meaning that the process of predicting future potential at early ages is challenging (Vaeyens et al., 2009, Reilly et al., 2000b). Previous research has attempted to identify factors that may predispose an individual towards becoming a successful soccer player such as anthropometric and physical (fitness) characteristics (Reilly et al., 2000a, Gil et al., 2007). Many of these attributes can, however, be confounded by the developmental differences that exist amongst players.

Biological maturation and relative age are two non-modifiable attributes that have been shown to influence player selection, evaluation, and performance in youth soccer (Meylan et al., 2010a, Sierra-Díaz et al., 2017). Biological maturation refers to the progress towards the mature adult state, varying among biological systems, and can be defined in terms of status, tempo and timing (Malina et al., 2015). Whereas ‘status’ refers to the stage of maturation attained at a specific time-point (e.g., skeletal age or stage of pubic hair development); ‘tempo’ describes the rate at which maturation advances in a specific system. ‘Timing’ refers to the age at which specific maturational events, such as puberty occur (Malina et al., 2004a). Of relevance, children of the same chronological age can demonstrate marked variation in both biological maturation and maturity status, with some individuals maturing well in advance or delay than their same age peers (Johnson, 2015, Malina et al., 2004a). For example, within an under 9’s soccer team, it is entirely possible to observe a child with a skeletal age (an established proxy of maturation) of seven years training and competing with a child who has a skeletal age of twelve years (Johnson, 2015). Individual differences in maturation are principally governed by a combination of heritable i.e., genotypic and environmental factors, such as stress, nutrition and social circumstances, as well as ethnicity (Malina et al., 2004a). The individual differences have been shown to directly and indirectly influence player performance and selection in youth soccer (Cumming et al., 2017b).

From the onset of puberty, boys who mature in advance of their peers possess a marked advantage in term of size and athleticism (Johnson et al., 2017). As the first individuals within their age group to experience the physical changes associated with puberty, these boys are typically taller, heavier, faster, stronger and more powerful than their later maturing peers (Figueiredo et al., 2009a, Johnson et al., 2017, Malina et al., 2015). Consequently, these players are more likely to succeed in sports and activities that demand or prioritise these attributes. Selection biases towards early maturing boys have been well established in soccer and are especially prevalent in professional soccer academies where there is an emphasis upon identifying and developing the most talented youth (Malina, 2003). To survive in these programmes, talented yet late maturing players must possess or develop exceptional technical, tactical and / or psychological attributes; a phenomenon known as the ‘underdog effect’. This hypothesises that younger and / or later maturing players must display these superior attributes (Fumarco et al., 2017, Malina et al., 2015, Cumming et al., 2018a). While these skills may serve as advantage in the long-term, research suggests that very few of these individuals are retained within the academy system (Hill et al., 2019, Johnson, 2015).

Relative age refers to a child’s chronological age within their age group and is determined by date of birth and the selection cut-off date. Children competing within a single year age group can vary by almost as much as 12 months in terms of their chronological age (Wattie et al., 2015). The relative age effect (RAE) describes a phenomenon whereby players that are born earlier in their selection year have a greater likelihood of representing and succeeding in their youth programmes. A bias has been reported highlighting the recruitment of individuals that are born earlier in their selection year (Helsen et al., 2005), with findings suggesting that 36 – 50% of soccer players were born within the first three months of their selection year, and only between 4 – 17% born within the last three months of their selection year (Carling et al., 2009, Augste and Lames, 2011, Williams, 2010). The underlying causes of the RAE have often been attributed to physiological growth and maturation (Cobley et al., 2009, Carling et al., 2009). However, RAE are observed well in advance of maturity associated selection biases and are also found in many achievement domains that do not require physical propensity e.g., soccer referees (Delorme, 2013), head coaches (Cobley et al., 2008) and academia (Musch and Grondin, 2001).

It is vital to note that relative age and biological maturation are not synonymous. Relative age and biological maturation are independent constructs that exist and operate independently of one another and are governed by separate factors (i.e., birth and cut-off dates versus genetics / environment). Within a single year age group there is also much greater scope for variation in biological maturity than relative age. Whereas differences in relative age are limited to 12 months, differences in maturity can vary by up to six years (Johnson, 2015). As a consequence, it is entirely possible to be the oldest and least mature player within one's own age group, or vice-versa. More recently, a study of relative age and maturation noted that Portuguese soccer players aged 11 – 13 years, born later in the year were more likely to be advanced in skeletal maturity for their chronological age and sex than their peers born in the first quarter (Figueiredo et al., 2019). The independent nature of relative age and biological maturity can also be observed in the age at which their associated selection biases emerge and how they change with age. Whereas RAE can be observed from six years of age and remain consistent through late childhood and adolescence, maturity associated selection biases only emerge with the onset of puberty and tend to increase in magnitude with age and competitive level (Malina et al., 2004a).

5.2. Expected Outcomes from Chapter 5

In light of the previous discussion, the aim of the present chapter was to investigate the main and interactive effects of maturation and relative age upon five fitness parameters; 5 m, 20 m, change of direction (COD), countermovement jump (CMJ) and reactive strength index (RSI) in elite youth soccer players. Specifically, it was predicted that maturation and relative age would be positively associated with physical performance as well as anthropometric measures. Further, it was proposed that the performance advantages might be greatest in players who were both more mature and relatively old for their age groups.

5.3. Methods

Prior to the study commencing, ethical approval was obtained and granted from the Ethics Committee of Faculty of Science & Engineering, at Manchester Metropolitan University (Ethics code: 17739). Parents / guardians of the participants were also notified of the aim of the study, research procedures, requirements, benefits, and risks and provided written informed consent. The youth participants also provided assent. Participants were advised that involvement in the study was voluntary and that they could withdraw from the study at any point.

5.3.1. Participants

A total of 84 male participants aged between 11.3 - 16.2 years from a professional soccer academy in the English Premier League took part in this research. Participants normally trained 2 – 3 times throughout the week and participated in competition once per week. Data collection occurred within the academy during the 2018 – 2019 season.

A preliminary analysis was conducted to analyse potential differences between anthropometric (chronological age, height and weight) and the fitness attributes (5 m, 20 m, COD, CMJ and RSI) between outfield players and goalkeepers. The observed differences were minimal and mainly non-significant. Goalkeepers were characteristically older, taller and weighed more, with a small to medium effect size ($p > 0.05$, Cohen's $d = 0.35$, $d = 0.40$ and $d = 0.51$, respectively) than outfield players. Moreover, outfield players performed better than the goalkeepers in all of the physical performance tests with a small to medium effect size; 5 m, $p < 0.05$, $d = 0.42$; 20 m, $p > 0.05$, $d = 0.38$; COD, $p > 0.05$, $d = 0.35$; CMJ, $p > 0.05$, $d = 0.07$ and RSI, $p > 0.05$, $d = 0.24$. The five physical attributes are of interest as they are relevant to both outfield and goalkeepers. Therefore, participants in the present chapter were treated as a single sample in subsequent analyses.

Table 5-1. Comparisons of descriptive variables and physical performance parameters between outfielders and goalkeepers.

Variable	Outfielders	Goalkeepers
CA (years)	13.2 ± 1.4	13.7 ± 1.5
Height (cm)	161.1 ± 11.7	165.9 ± 12.1
Weight (kg)	48.0 ± 10.9	53.5 ± 10.6
5 m (s)	$1.11 \pm 0.10^{*}$	1.15 ± 0.09
20 m (s)	3.33 ± 0.25	3.43 ± 0.27
COD (s)	2.34 ± 0.17	2.40 ± 0.17
CMJ (cm)	29.4 ± 5.64	29.0 ± 6.02
RSI	2.10 ± 0.37	2.02 ± 0.30

Note: CA – Chronological age; COD – Change of direction; CMJ – Countermovement jump; RSI – Reactive strength index. $^{*}p < 0.05$, difference between outfielders and goalkeepers.

5.3.2. Anthropometry and Procedures

Measurements of anthropometry were collected by the same experienced observer on each occasion. See General Methods (Section 3.4) for a full description for how the anthropometric variables were collected. The height of the participant's biological parents was collected either *in-vivo* by experienced academy staff or self-reported by the parents.

Self-reported heights were adjusted for overestimation using sex specific equations (Epstein et al., 1995). Please see Section 2.5.2 for a further explanation of this.

5.3.3. Measurement and Estimate of Maturity

Final adult height in youths can be predicted using the Khamis-Roche method (Khamis and Roche, 1994). This is the same index used to group players by maturation in recent studies of bio-banding (Bradley et al., 2019, Abbott et al., 2019, Cumming et al., 2018a). It can be assumed that for children of the same chronological age, those closer to their predicted adult height may be assumed to be more advanced in maturation compared to those further away from their predicted adult height. For example, a boy that is 90% of his predicted adult height would be considered less mature than a boy of the same chronological age who has achieved 95% of his predicted adult height.

Estimated biological maturity status was expressed as a ‘*z*-score’ relative to age and sex specific means and standard deviations for percentage of mature height attained at half-yearly intervals (Bayer and Bailey, 1959). The *z*–scores were also used to classify each participant as either ‘early maturers’, ‘on–time’ or ‘late maturers’, as used in previous studies (Drenowatz et al., 2013, Cumming et al., 2009, Gillison et al., 2017). Individuals that achieved a *z*-score of between –1 to +1 were classified as ‘on–time’ in maturity status, if an individual achieved a *z*–score greater than +1 ‘early maturers’ a *z*–score below than –1 ‘late maturers’. More detail on maturity *z*-scores is given in Section 2.5.2.

5.3.4. Relative Age Effect

The selection year for youth soccer in England spans 1st September – 31st August. Relative age was established for each participant using their date of birth and the cut-off date of their selection year group (31st August). To allow comparison with previous literature, relative age was classified into birth quartiles. These were defined as quarter one (oldest – Q1): 1st September – 30th November; quarter two (Q2): 1st December –28th (29th) February; quarter three (Q3): 1st March – 31st May; and quarter four (youngest Q4): 1st June – 31st August.

The measure of relative age was also expressed as a decimal, using the difference between a participant’s birthdate and the selection cut-off date, divided by the number of days in a year (Cumming et al., 2018b). Relative age was expressed as a value between 0.00 – 0.99, with these values representing the youngest to oldest, respectively. More detail on RAE is given in Section 2.7.

5.3.5. Physical Performance Tests

Following the collection of anthropometric variables, participants then undertook a dynamic 10-minute warm-up with a qualified youth soccer coach. All participants were tested in their respective age groups within the same week at the start of their training session. The sprinting and change of direction abilities of the participants was evaluated on 4G artificial turf. Participants were instructed to complete all tests in the following order: sprinting (5 m and 20 m), change of direction, countermovement jumps and finally, drop jumps. A recovery period of 10 min was given between each test to avoid fatigue-induced effects (Trecroci et al., 2018).

5.3.5.1. Running Speed

Sprinting abilities of participants were evaluated on 4G artificial turf, by 20 m sprint times (standing start), with 5 m and 20 m split times. Time for each distance was recorded to the nearest 0.01 s, the best time for each test was recorded for the statistical analysis as used previously in adolescent (elite) soccer players (Buchheit et al., 2010a). For full description, see General Methods section for a full description (Section 3.8.1).

5.3.5.2. Change of Direction

On completing the maximal sprint, participants were required to sprint forward to a turning point 5 m beyond the 20 m timing gate and pivot 180°, the test was concluded when the participant re-broke the 20 m timing gate. The fastest trial for the COD test was recorded for the statistical analysis as used previously in adolescent (elite) soccer players (Trecroci et al., 2019). For full description, see General Methods section for a full description (Section 3.8.2).

5.3.5.3. Countermovement Jump

The countermovement jump (CMJ) has previously been established as a reliable measure of explosive strength performance (Lloyd et al., 2009, Markovic et al., 2004). Following the maximal sprints, participants performed jumps on a hard, flat surface between a portable photoelectric cell system (Optojump, Microgate, Bolzano, Italy), with 60 seconds of rest between trials. The final CMJ score was taken as the highest jump (cm) and used for statistical analysis as used previously in adolescent (elite) soccer players (Trecroci et al., 2019). For full description, see General Methods section for a full description (Section 3.8.3).

5.3.5.4. Reactive Strength Index

The reactive strength index was determined using drop jump tests, which involved the participants performing five separate jumps on a hard, flat surface between a portable photoelectric cell system (Optojump, Microgate, Italy). Participants performed drop jumps from a drop height of 0.30 m and were encouraged to use their hands during the jumps. For a full description, see General Methods (Section 3.8.4).

Contact time (CT) and flight time (FT) were collected and RSI was calculated using Equation 3-4 for each test, with the best (highest) score selected, as previously detailed in adolescent soccer players (Granacher et al., 2015).

5.3.6. Statistical Analyses

Descriptive statistics were calculated for the variables of interest and were reported via mean and standard deviation (±SD). Pearson product moment correlations were calculated for the following variables: estimated maturity status, PPAH, relative age, height (cm), weight (kg), chronological age (years), 5 m (s), 20 m (s), COD (s), CMJ (cm) and RSI. Hierarchical regression analysis was used to evaluate the main and interactive effects of relative age (decimal) and maturation (*z*-score) upon the performance parameters. Step 1 of the hierarchical regression analysis considered just the main effects of biological maturity and relative age; step 2 then also considered the interaction effect between these two variables. The process of centring (subtracting current score from group average) was used to create the interaction score (multiplying the centred scores) between biological maturity and relative age to reduce potential issues associated with collinearity. SPSS (IBM SPSS 24) was used for all analyses.

5.4. Results

5.4.1. Descriptive Statistics

Descriptive statistics for estimated biological maturity, predicted adult height, relative age, height, weight, and performance parameters, including 5 m, 20 m, COD, CMJ and RSI are presented in Table 5-2. The mean value for relative age was 0.67 years (i.e., Q2) across all age groups and did not appear to increase or decrease with age. Among the total sample of 84 participants: 43 participants (51%) were born in Q1, 22 participants (26%) were born in Q2, 11 participants (13%) were born in birth Q3, and 8 participants (10%) were born in Q4. The mean maturity *z*–score was either approximately zero or had a positive value in the U13 to U16 age groups. Only in the U12 age group was the maturity *z*–score below zero.

In terms of biological maturation, the majority of the participants (89%) fell within ± 1.0 standard deviation of the reference mean for their sex and age. Whereas nine of the participants (11%) could be categorized as being advanced in maturation (i.e., > 1.0 standard deviation above mean reference value for age and sex); no participants were considered late maturing (i.e., < 1.0 standard deviation below the mean reference value for age and sex).

Table 5-2. Comparisons of descriptive variables and physical performance parameters per age group.

Variables	U12 (*n* = 24)		U13 (*n* = 19)		U14 (*n* = 21)		U15 (*n* = 8)		U16 (*n* = 12)	
	Mean	± SD	Mean	± SD	Mean	± SD	Mean	± SD	Mean	± SD
Chronological age	11.75	0.29	12.73	0.34	13.63	0.25	14.68	0.38	15.67	0.38
Height (cm)	150.2	6.4	160.7	8.7	162.2	8.3	175.2	6.7	176.4	6.7
Weight (kg)	39.2	4.30	45.90	8.10	48.10	6.20	63.10	8.30	63.50	7.20
Predicted adult height (cm)	182.4	5.30	185.7	6.3	180.5	7.1	183.5	2.7	182.2	4.9
Relative age	0.68	0.28	0.67	0.31	0.69	0.25	0.76	0.23	0.58	0.38
Maturity *z*-score’	-0.07	0.80	0.33	0.82	0.01	0.46	0.42	0.51	0.20	0.50
5 m sprint (s)	1.15	0.05	1.12	0.06	1.08	0.06	1.08	0.08	1.06	0.05
20 m sprint (s)	3.51	0.13	3.28	0.37	3.25	0.12	3.12	0.14	3.14	0.21
COD (s)	2.58	0.14	2.36	0.07	2.27	0.09	2.24	0.06	2.21	0.13
CMJ (cm)	25.0	3.6	27.1	4.7	31.6	4.5	36.6	5.7	32.9	4.5
RSI	2.00	0.40	1.73	0.27	2.07	0.31	2.43	0.27	2.49	0.37

Note: CMJ – Countermovement jump; COD – Change of direction; RSI – Reactive strength index.

5.4.2. Correlational Analyses

The results of the correlational analyses are summarised in Table 5-3. Of note, maturation was negatively correlated with 5 m, 20 m and the COD tests, indicating that players advanced in maturity status ran quicker over the set distances and COD more quickly. Maturity was also positively associated with performance on CMJ test, indicating that players advanced in maturation demonstrated greater ability for jumping higher. Thus, all four of these metrics improved with increasing development to the mature state. Relative age was negatively associated with performance on the sprint test, but only significantly at 20 m, and positively associated with performance on the CMJ test. Maturity correlations were statistically significant at $p < 0.01$ and relative age was statistically significant at $p < 0.05$. It is noted that chronological age is positively associated with maturity z-score ($p < 0.05$), indicating that early maturers are negatively selected for within the academy. The association is particularly prevalent in the older age groups, likely as a consequence of selection decisions being made at U14s.

Table 5-3. *R* values for correlational analyses between various anthropometric, maturity status, and fitness parameters.

Variables	CA	Maturity ‘*z’*	RA	Height	Weight	PAH	5 m	20 m	COD	CMJ	RSI
CA	-										
Maturity ‘z’	.19*	-									
RA	.11	-.04	-								
Height	.78**	.59**	.14	-							
Weight	.81**	.46**	.17	.90**	-						
PAH	-.03	.36**	.06	.53**	.35**	-					
5 m sprint	-.65**	-.35**	-.08	-.61**	-.58**	-.08	-				
20 m sprint	-.61**	-.34**	-.19*	-.60**	-.58**	-.10	.66**	-			
COD	-.77**	-.33**	-.08	-.64**	-.60**	.02	.66**	.61**	-		
CMJ	.70**	.32**	.23*	.62**	.67**	.01	-.62**	-.65**	-.60**	-	
RSI	.58**	-.06	.05	.31**	.43**	-.23*	-.36**	-.37**	-.42**	.46**	-

Note: CA – Chronological age; CMJ – Countermovement Jump; COD – Change of direction; Maturity *z* –Maturity *z*-score; *PAH* – Predicted adult height; RA – Relative age. *Correlation is significant at the 0.05 level (1-tailed). ** Correlation is significant at the 0.01 level (1-tailed).

5.4.3. Regression Analysis

The results for each hierarchical regression model for the different performance variables (5 m, 20 m, COD, CMJ and RSI) are presented in Table 5-4 – Table 5-8.

The final regression model for 5 m sprint times achieved statistical significance, F (3, 79) = 4.57, $p < 0.01$, (Table 5-4). In the final model, maturation served as a statistically significant negative predictor of time in both the main and interactive model. Relative age and the interaction between relative age and maturation did not predict any of the variance in sprint performance over 5 m.

Table 5-4. Summary of hierarchical regression analysis for variables predicting 5 m (s) sprint time.

Variable	Model 1			Model 2		
	B	SE *B*	β	*B*	SE *B*	β
Maturity Status (MS)	-0.03	0.01	-0.35^{**}	-0.07	0.03	-0.74^{**}
Relative Age (RA)	-0.02	0.02	-0.10	-0.01	0.02	-0.05
Interaction MS × RA				0.04	0.30	0.42
R^2	0.13			0.15		
F for change in R^2	5.93			4.57		

$^{*}p < 0.05$. $^{**}p < 0.01$.

The results for the regression model predicting variance in performance in the 20 m sprint task are presented in Table 5-5. The final model was statistically significant, F (3, 79) = 4.62, $p < 0.01$. As with the 5 m sprint test, a main effect was observed for maturity status but not relative age or the interaction term, although maturity status only had an effect in the main model. More specifically, maturation was inversely associated with 20 m sprint time.

Table 5-5. Summary of hierarchical regression analysis for variables predicting 20 m (s) sprint time.

Variable	Model 1			Model 2		
	B	SE *B*	β	*B*	SE *B*	β
Maturity Status (MS)	-0.13	0.39	-0.33^{**}	-0.17	0.12	-0.47^{**}
Relative Age (RA)	-0.17	0.86	-0.21	-0.16	0.09	-0.19
Interaction MS × RA				0.05	0.11	0.14
R^2	0.15			0.15		
F for change in R^2	6.90			4.62		

$^{*}p < 0.05$. $^{**}p < 0.01$.

The regression model for change of direction times was also statistically significant, F (3, 77) = 3.83, $p < 0.05$, (Table 5-6). Again, maturity status was shown to be significant for COD time in the main model. The interaction term for maturity status and relative age was shown to be non-significant. Specifically, maturation was positively associated with COD times indicating an athletic advantage associated with advanced maturation.

Table 5-6. Summary of hierarchical regression analysis for variables predicting change of direction (s) time.

Variable	Model 1			Model 2		
	B	SE *B*	β	*B*	SE *B*	β
Maturity Status (MS)	-0.08	0.02	-0.34^{**}	-0.14	0.07	-0.63^{**}
Relative Age (RA)	-0.05	0.05	-0.09	-0.27	0.06	-0.05
Interaction MS × RA				0.07	0.07	0.32
R^2	0.12			0.13		
F for change in R^2	5.29			3.83		

$^{*}p < 0.05$. $^{**}p < 0.01$.

The regression model for CMJ was also statistically significant, $F\ (3, 80) = 5.32$, $p < 0.05$, (Table 5-7). Again, maturity status was shown to be significant for CMJ in the main model. Unlike for the previous tests, the main and interaction effects revealed a statistically significant effect for relative age. The interaction term for maturity status and relative age was shown to be non-significant. Specifically, maturation was positively associated with CMJ heights indicating an athletic advantage associated with advanced maturation. Equally, relative age showed a positive association; participants born earlier in the selection year showed improved performance.

Table 5-7. Summary of hierarchical regression analysis for variables predicting CMJ (cm) height.

Variable	Model 1			Model 2		
	B	SE *B*	β	*B*	SE *B*	β
Maturity Status (MS)	2.80	0.86	0.33^{**}	3.82	2.58	0.45^{**}
Relative Age (RA)	4.65	1.94	0.24^{**}	4.34	2.09	0.23^{*}
Interaction MS × RA				-1.06	2.53	-0.13
R^2	0.16			0.17		
F for change in R^2	7.97			5.32		

$^{*}p < 0.05$. $^{**}p < 0.01$.

In contrast, the regression model for RSI did not achieve statistical significance, $F\ (3, 71) = 3.20$, $p > 0.05$, (Table 5-8). Inspection of the main and interaction effects revealed no statistically significant association between predictor variables and RSI performance.

Table 5-8. Summary of hierarchical regression analysis for variables predicting RSI performance.

Variable	Model 1			Model 2		
	B	SE *B*	β	*B*	SE *B*	β
Maturity Status (MS)	-0.04	0.08	-0.06	0.13	0.25	0.18
Relative Age (RA)	0.08	0.18	0.05	0.03	0.19	0.02
Interaction MS × RA				- 0.18	0.25	-0.26
R^2	0.01			0.01		
F for change in R^2	0.22			0.32		

$^{*}p < 0.05$. $^{**}p < 0.01$.

5.5. Discussion

The purpose of this present study was to investigate the main and interactive effects of maturity status and relative age upon physical performance during a series of fitness tests amongst a sample of 84 professional academy soccer players. It was found that the interactive effect of maturity status and relative age was small therefore showing that these are two independent constructs that must be treated separately when considering the development of male adolescent soccer players. Maturity status was shown to have a much greater influence on performance, which should be accounted for when considering soccer players of the same chronological age.

Consistent with previous literature (Helsen et al., 2005, Sierra-Díaz et al., 2017, Musch and Grondin, 2001), participants in the current study tended to be relatively older for their age group and average-to-advanced in biological maturity. The majority of participants (77%) were born in the first half of their competitive year, with more than half of the total participants being born in the first birth quarter (51%). Collectively, these values suggested the presence of a strong RAE that is present from late childhood and maintained throughout the academy structure. This observation is of concern as previous research suggests that late maturing and / or younger players, though under-represented in youth soccer, are psychologically and technically more proficient than their peers (Zuber et al., 2016, Cumming et al., 2018b, Votteler and Höner, 2014). The cause of this trend could be attributed to a need for less physically developed players to exemplify better technical and / or psychological ability in order to compete with early maturing individuals. Alternatively, this could be a feature of selection where coaches will only prefer a less physically developed player if their technical and / or psychological skills are already much advanced in comparison to physically developed individuals.

The results of the current investigation are consistent with previous research within youth soccer which have used skeletal age as an indicator of maturity status, whereby advanced maturity status appeared to act as a positive predictor of persistence, selection and retention (Carling et al., 2012, Johnson et al., 2017, Malina et al., 2015). Moreover, further research is required in order to understand the nature of the bias associated with advanced maturity status and redress the situation that is present where talented but late maturing players are being omitted from an academy system.

5.5.1. Discussion on Difference between Biological Maturity and RAE

The results pertaining to the associations between biological maturity, relative age and physical fitness are of particular interest (Table 5-4 – Table 5-8). First, it is important to note that biological maturity and relative age were found to be unrelated. This supports the contention that biological maturity and relative age are constructs or processes that exist and operate independently of one another. Accordingly, RAE cannot be attributed to the functional advantages that are associated with advanced biological maturation, which typically emerges around the onset of puberty (Johnson et al., 2017). It should be noted, however, that within this sample, relative age was found to present a positive, yet weak and non-significant association with height and weight. Thus, RAE may be more likely to be associated with individual differences in growth than maturation, *per se*. To better understand and counter the selection biases associated with relative age and biological maturation it is important that researchers and practitioners recognise the differences between these constructs. As noted, the selection biases associated with biological maturity and relative age emerge at different ages and it is likely that the mechanisms underpinning these biases are also different. Therefore, strategies designed to address and minimise the selection-induced RAE (e.g., average team age competitions, implementation of quotas for even representation of children of all birth months and age-ordered shirts) should focus on developmental attributes more closely associated with age rather than maturity (i.e., cognition, motor skills, and experience), which may need to be introduced from an earlier age and at the grass roots level. In contrast, strategies designed to address maturity selection biases (e.g., bio-banding) are better reserved for late childhood and early puberty, when maturity associated differences in size and function become much more salient.

5.5.2. Impact of Biological Maturity and RAE on Physical Performance

Contrary to expectations, relative age was found to be largely unrelated to measure of physical fitness. That is, relatively older players did not appear to perform any better on tests of speed, strength, and power than their younger peers. With respect to the correlational analyses (Table 5-3), relative age was only significantly associated with performance on the 20 m sprint and the CMJ tests. Older players did perform better on these tests; however, the magnitude of the associations was weak to moderate. In contrast, maturation was associated with performance on all but one of the physical performance tests (RSI). Specifically, advanced maturation was associated with superior performance on tests of speed, COD and CMJ. The magnitude of these associations was moderate and notably greater than those equivalent values observed for relative age. The results of the regression models provided further insight into the main and interactive effects of biological maturation and relative age upon performance on the physical tests. With the exception of the RSI test, all of the regression models were statistically significant. Maturation served as a statistically significant and positive predictor of performance in the 5 m and 20 m sprint tests, the COD test, and the CMJ test. In contrast, relative age only served as a significant predictor of performance on the CMJ. The interaction between biological maturation and relative age failed to serve as a significant predictor of performance on all of the fitness tests. Collectively, these results suggest physical fitness in academy soccer players is more likely to be associated with variance in biological maturity rather than relative age. Accordingly, any suggestions that RAE results from age-related differences in physical fitness are unfounded. Such selection biases are more likely to result from age related differences in other developmental attributes such as experience, motor skills, and cognitive and / or social skills (Cumming et al., 2018b). The results of the current investigation also suggest that maturation and relative age do not interact to influence fitness within this cohort. That is, being relatively older or younger within one’s age group appears to have little to no bearing on the fitness performances of players who are advanced or delayed in maturation.

The observation that RAE was associated with performance on CMJ should be noted. The CMJ is a lower limb explosive strength test, which is a fundamental variable for performance in soccer and therefore the fact that this influenced by RAE is of significant importance to the conclusion of this study. While other tests (e.g., running speed, COD and drop jump [RSI]) were not affected by RAE, it cannot be completely discounted from discussions around performance within a soccer setting.

5.5.3. Practical Implications

The results of the present chapter have important practical implications for those involved in the identification and development of talented young male soccer players. From a talent identification perspective, it is important to note that players who are advanced in biological maturity for their age group will possess a significant advantage in terms of their physical fitness (Deprez et al., 2015b). Consequently, players who mature early may perform better during competitions and on tests of physical aptitude. Technically gifted yet later maturing players are physically disadvantaged and may struggle to compete when matched against physically more able peers. As a consequence, late maturing players may be more likely to be overlooked or excluded from the academy system. From a developmental perspective, players who mature in advance of their peers may also be more likely to play to their physical strengths, neglecting their technical, tactical and psychological skills (Cumming et al., 2018a). While such a strategy may bring immediate success, its value in the long term is limited as maturity associated differences in size and function are typically attenuated, and in some cases reversed, in early adulthood. Through being side-lined or as a result of the magnitude of these differences, late maturing players may have less opportunity to apply, demonstrate or develop these skills, regardless of ability (Cobley, 2016). To address the aforementioned concerns, it is important that coaches and practitioners both recognise and become aware of individual differences in players' maturation. Individual differences in biological maturity status have been shown to directly and indirectly influence player performance and selection in youth football (Cumming et al., 2017b).

The results of the current study highlight the significant role of individual differences in biological maturity status in the physical performance capacity of adolescent soccer players. Recently the English Premier League has trialled the practice of bio-banding whereby players within a specific chronological age group are banded by estimated maturity status in an effort to balance maturity associated differences in size and function. In order to individualise the selection and training processes, the Royal Belgian Football Association distinguish players based on their developmental age, rather than birth year (Philippaerts et al., 2004, Vandendriessche et al., 2012a). However, there can be advantages for late developers mixing with players of different biological ages. The late developers will face challenges and will need to adapt technically, tactically and mentally; these challenges will be missed if they only practice with players of a similar developmental age (Wormhoudt et al., 2017).

A limitation of the present study was that the participants in terms of both of biological maturity status and RAE were not evenly distributed. Less than 10% of participants were born in Q4, whereas 51% were born in Q1. A more balanced distribution may have shown stronger correlations between RAE and physical performance tests; and it may be possible that there is preferential deselection of the weakest Q4 participants. Only nine of the participants were early maturers, and there were no late maturers in the selection sample, hence some of the correlations between maturity status and physical performance tests may be diluted as the majority of participants fell within ± 1.0 standard deviations of the average for their age. Note also that the current study included nine goalkeepers (11%) who may be expected to experience a different performance profile to that of an outfield player, a larger study in the future may be able to account for this.

5.6. Conclusion

The current study identified that physical performance (in the tests studied) is seen to be related to the biological maturity status of a player. Relative age was only seen to have an influence in one of the performance tests measured (CMJ), which is strongly related to this sport. The influence of RAE is much less significant than biological maturity status but may be an important secondary factor in some instances. Coaches and practitioners should be aware of this and can use this information to be better informed of the relative performance of the players within their academy. Further longitudinal research is required to assess the role of physical performance in relation to player retention and deselection, including the impact of non-physical parameters in this process. Alongside, studies investigating the influence of differences between academy settings, for example the impact of a January – December rather than September – August selection year may have on the relationship between RAE and physical performance tests would be beneficial. In addition, assessment of biological maturation and relative age on actual match performance rather than training data, as match performance is arguably more important and has a different set of motivational and environmental influences may give a greater understanding of the subject area.

6. Maturity Associated Differences in Match Running Metrics in Elite Youth Soccer Players

6.1. Introduction

Chapter 5 showed that maturity had an influence on the performance of elite youth soccer players in tests of their physical capability in a training environment. This chapter takes these results to the pitch and investigates the hypothesis that these effects may also influence match running metrics. It is important to be aware of factors that affect performance as this could influence selection and retention decisions and may result in more talented players being released from soccer academies. The effects of playing position (traditionally defined as defender, midfielder or attackers, but can also be spine, central or lateral) on match running metrics are also investigated. This work is the basis of a publication which is currently under review (Parr et al., 2021).

6.1.1. Biological Maturity Effects within Adolescent Males

The identification and development of talented young soccer players are the primary aims of professional football academies. Individual differences in maturation have been shown to impact player selection, fitness, and performance in male academy soccer, making it challenging to identify those players the most potential to succeed at the adult level. Maturation refers to the process of progress towards the adult or mature state and can be considered in terms of status, tempo and timing. Whereas status refers to the developmental stage that an individual has attained (e.g., pre-, circa- or post-pubertal) tempo refers to the rate at which maturation progresses. In contrast, timing refers to the age at which specific maturation events, such as menarche or peak height velocity, occur. Individuals of the same chronological age can demonstrate significant variance in the timing of maturation, with certain individuals maturing well in advance or delay of their same age peers. Indeed, children of the same chronological age have been shown to vary by as much as five to six years in terms of their skeletal age, an established proxy of maturation in youth (Johnson, 2015).

The timing of puberty has important implications for physical, psychosocial and athletic development. From the onset of puberty, boys who mature in advance of their peers are typically taller, heavier and possess greater amounts of absolute and relative lean mass (Figueiredo et al., 2009b). The influence of greater body dimensions and physical performance has also been suggested to impact on match outcomes and / or results. Early maturing boys also tend to hold higher perceptions of fitness, sports competence and physical self-worth, known drivers of motivation and participation in competitive sport

(Cumming et al., 2017b). Not surprisingly, early maturing boys tend to perform better on tasks and / or sports that involve strength, speed or power and are more likely to be represented in sport that require these attributes (Figueiredo et al., 2009a, Johnson et al., 2017, Malina et al., 2015). Male soccer players who are advanced in maturation have been shown to present greater height, weight, mass-for-stature, but also demonstrate superior performance on tests of speed, strength, power, agility, and endurance (Figueiredo et al., 2009a, Malina et al., 2015). The physical and athletic advantages associated with earlier maturation emerge at the onset of puberty and remain relatively stable through mid and late adolescence. Longitudinal data suggests that it is only in early adulthood that these advantages are attenuated or, in some cases, reversed (i.e., over 20 years of age), (Malina et al., 2004a).

Given the physical and functional advantages afforded by earlier maturation, it is not surprising that a bias towards the selection and retention of early maturing soccer players also emerges at the onset of puberty. The bias towards boys that are advanced in maturity generally increases with age and becomes most evident in elite level programmes (i.e., professional academies, national age group teams). Previously, a study of academy soccer players at Manchester United and Aspire Academies reported that approximately 60 – 80% of all academy players in the U16 and U17 year age groups had a skeletal age that was at least one year greater than their chronological age (Johnson, 2015, Johnson et al., 2009). In contrast, there is a systematic exclusion of individuals that are the youngest / least mature in soccer academies (Figueiredo et al., 2009a), with late maturing individuals more likely to be overlooked or released from the academy setting or national level programmes, regardless of the technical, tactical and / or psychological competency (Zuber et al., 2016, Cumming et al., 2017b).

When considering physical performance, Malina et al. (2004c) highlighted that Portuguese elite youth soccer players aged between 13 – 15 years of age, that possessed a higher stage of pubic hair development, performed significantly better on physical performance tests (30 m sprint, standing vertical jump and endurance tests) than individuals of a lower stage of pubic hair development. Similarly, Portuguese players aged between 11 – 12 and 13 - 14 years of age performed better in intermittent endurance tests and vertical jumping if they were more mature (determined by skeletal age) than their counterparts (Figueiredo et al., 2009b). As biological maturity has been determined to have an influence of physical performance, the possibility of biological maturity influencing match running metrics is somewhat possible.

6.1.2. Factors that Influence Match Running Metrics

Buchheit et al. (2010b) suggested that biological maturation (using maturity offset) was positively associated with locomotor capacity during competitive play in highly trained youth soccer players. Match performance profiles were captured on 77 outfield participants from six different age groups (U13 – U18s) across 42 matches, with each participant being assessed between 1 – 9 times, using GPS (capturing data at 1-Hz). It is worth noting, Randers et al. (2010) highlighted the possible underestimation of activities performed at a high intensity (such as high and very speed running) when capturing these actions using systems of 1-Hz. The accuracy of the device for high speed running (HSR) was reported as only moderate, 11 – 30% (Coutts and Duffield, 2010). Buchheit et al. (2010b) further highlighted that earlier maturing compared to later maturing boys presented significantly higher values for peak speed (km.h^{-1}), distance covered at high speed (distance covered above 16.0 km.h^{-1}), absolute higher intensity actions during competition (at least 1 second runs greater than 19.0 km.h^{-1}).

Accordingly, players that are delayed in maturity status may possess a significant athletic disadvantage during competition. This observation may contribute towards the overrepresentation of early maturing in comparison to late maturing boys during the adolescent phase of development. It should be noted however, that both of the aforementioned studies employed the variations of the maturity offset equation as in index of maturation. The maturity offset method and its variations, have been shown to demonstrate a significant degree of systematic error associated with age. Further, these errors tend to be magnified in early and late maturing males and females (Kozieł and Malina, 2018, Malina and Kozieł, 2014). Accordingly, the result of these studies should be interpreted with some degree of caution, particularly due to the issues that were previously highlighted in Chapter 4.

Buchheit and Mendez-Villanueva (2014) previously highlighted the influence of maturation on match running metrics and specific tests with running capability in competitive soccer matches over the course of two successive playing seasons. Thirty-six highly trained soccer players (14.4 ± 0.4 years, 163.4 ± 6.2cm and 50.5 ± 6.9 kg) represented two squads of U15s from the same elite academy. GPS analysis was implemented on the participants between 2 – 16 times during a total of 19 matches. Participants were identified as either being less or more mature, again using the maturity offset method (Mirwald et al., 2002). Their 1st half match running metrics (total running distance, distance covered at high speed, maximum speed, number of high intensity actions [at least 1s runs > 19 km.h^{-1}] and repeated high intensity actions [a minimum of two consecutive ≥ 1s high intensity actions interspersed with a maximum of 60 s of recovery]) were analysed and compared. The results highlighted that the players who were advanced in their maturity status demonstrated greater peak speeds and distances covered at greater speeds (> 16 km·h^{-1}) in a match, however, between the two maturity groups, no differences in total distance covered were identified. Moreover, a moderate to very large (0.5 – 1.0) magnitude of correlation between midfielders and wingers and an advanced maturity status and match running metrics was identified. This association is likely attributable to the playing space that is afforded to these playing positions (allowing for high intensity actions to take place), and also the tactical / technical roles of the specific playing positions.

Additionally, measures of match running metrics in youth soccer players, in particular high-speed running (HSR) has been shown to be associated with playing position within youth soccer players aged between 12.2 – 14.0 years (Buchheit et al., 2010b). More recently, Lovell et al. (2019) examined the influence of maturity timing and the interaction with playing position upon physical match running metrics amongst U15 soccer players. Data were obtained from 278 male youth soccer players (15.3 ± 0.4 years, 173.5 ± 7.1 cm, 61.8 ± 7.4 kg). Two matches per day took place with durations of 50 minutes each and an estimate of participants somatic maturity was estimated using the maturity ratio algorithm, Equation 2-6, (Fransen et al., 2018b). The research concluded that maturity timing was influential across all playing positions, for example, for each position, later maturing players covered greater distances. Therefore, it is important to consider position when assessing relationships between maturity and match running metrics.

It has previously been shown that maturity status does influence elements of match running metrics, and there may also be a further interaction with playing position, however, previously published research has only been carried out in a single half of a match (Buchheit and Mendez-Villanueva, 2014). The focus of the present study was to investigate maturity status (measured using percentage of predicted adult height (PPAH)) and playing position associated variance in match running metrics (total distance covered, distance covered at HSR, distance covered at VHSR, maximum speed and the number of accelerations from zone 4 – zone 6) in elite academy male soccer players across the course of one competitive playing season. Following the results of Chapter 4, PPAH was used in preference to maturity offset to classify the maturity status of the participants which contrasts work by other researchers, as described in this section.

6.1.3. Expected Outcomes from Chapter 6

A major benefit of the current study is that participants cover each of the three maturity categorisations (pre-, circa- and post-PHV) meaning that associations can be focussed in on particular stages of maturation, whereas the majority of previous studies have focussed on a single age group, which may not encompass this full range. However, one previous study, (Buchheit et al., 2010b), examined several age groups, however, the maturity status of the participants was determined by maturity offset.

It was anticipated that players advanced in maturation would present higher performance scores across a range of match running metrics, consistent with the findings of previous literature. Furthermore, as previously demonstrated in the literature, it was expected that midfielders and attackers would undertake the most amount of HSR and VHSR, whilst defenders would undertake the least amount. By analysing a cohort of participants that cover three age groups within the academy, and displaying position-specific results, coaches will be able to see the different demands placed on players as they move between age groups or play in different positions.

6.2. Methods

Prior to the study commencing, ethical approval was obtained and granted from the Ethics Committee of Faculty of Science & Engineering, at Manchester Metropolitan University (Ethics code: 17739). Parents / guardians of the participants were also notified of the aim of the study, research procedures, requirements, benefits, and risks and provided written informed consent. The youth participants also provided assent. Participants were advised that involvement in the study was voluntary and that they could withdraw from the study at any point.

6.2.1. Participants

A total of thirty-seven elite male youth soccer participants (born between 2001 and 2005) from an English professional soccer academy (15.1 ± 1.4 years, height 172.5 ± 9.4 cm, weight 61.2 ± 11.0 kg) participating in the U14, U15, and U16 age groups were assessed over the course of one competitive playing season (2018 – 2019). The U14 age group consisted of 21 participants. As a number of participants from the U15 age group are frequently asked to ‘play up’ in U16 age group, these two groups were combined to make a single U15/16s group, totalling 16 participants. Additionally, the analyses for the U14 and U15/16s samples were conducted separately as each sample included players from different stages of the maturation process. For example, all of the players in U15/16s age group were in the later stages of post-PHV; in contrast, the U14 age group included players that were pre-, circa- or post-pubertal. Participants from the U14 age group participate in approximately 8 hours of combined soccer specific training sessions per week (2 – 4 soccer training sessions, 2 athletic development / conditioning sessions and 1 – 2 competitive matches). Participants in U15/16s age group partake in approximately 10 hours of combined specific training sessions per week (3 – 6 soccer training sessions, 3 – 4 athletic development / conditioning training sessions and 1 – 2 competitive matches).

6.2.2. Anthropometry and Procedures

Measurements of anthropometry were collected by the same experienced observer on each occasion. See General Methods (Section 3.4) for a full description for how the anthropometric variables were collected. Throughout the course of the season (2018 - 2019), anthropometric variables (heights and weights) for each participant were collected every two months.

6.2.3. Measurement and Estimate of Maturity

Biological maturity status for each participant was estimated and expressed as a ‘*z*-score’ relative to their group mean and standard deviation; these were specific to their age group, calculated based on the most recent three years of anthropometric data collected within the academy. The approach was the same as the (Bayer and Bailey, 1959) method, however, specific sample mean and standard deviation were used as they differed from the population data, demonstrated in Table 6-1.

Table 6-1. Comparison of attained adult height for 13 year olds in population (Bayer and Bailey, 1959) and for sample used in the present study.

	Mean	SD
Attainment of percentage of predicted adult height for population at 13.0 years of age (Bayer and Bailey, 1959)	87.3	3.0
Attainment of percentage of predicted adult height within the current academy at 13.0 years of age	91.4	2.5

As an observed measurement of final adult height was not available, the relative *z*-scores were based on the PPAH, calculated using the Khamis-Roche equation (Khamis and Roche, 1994), attained by an individual on the date of the match from which running data was collected, more details are given in the General Methods (Section 3.6).

6.2.4. Overview of Playing Positions

A global positioning system (GPS) device was used between 2 and 30 (mean = 8 ± 5) times on each outfield player in matches over the course of one competitive playing season (n = 274 player-files / match observations). Matches were performed on standard outdoor natural grass fields (85 × 64 m^2 (U14) and 105 × 68 m^2 (U15/16s)), with 11 players per side. Playing time was 2 × 40-minute halves. Participants were assigned an outfield playing position (defender, midfielder or attacker and also whether they were a spine [central] or lateral [wide] player) by the head coach. Playing positions were defender (n = 14), midfielder (n = 15) and attacker (n = 8); and spine (n = 20) and lateral (n = 17) for both groups (U14s and U15/16s combined). Each participant only featured in one playing position throughout the collection process. Tactically, all teams played in a 4-3-3 formation, as shown in Figure 6-1. The formation implements a holding midfield player tasked to assist the defenders and allow lateral defenders to support offensive play. Lateral midfield players are instructed to adopt a higher starting position on the pitch, with a predominant focus on offensive strategy. Central defenders, midfielders and the striker operate in a more traditional manner as described in other football match running literature. GPS metrics for each fixture was aligned to the nearest anthropometric collection.

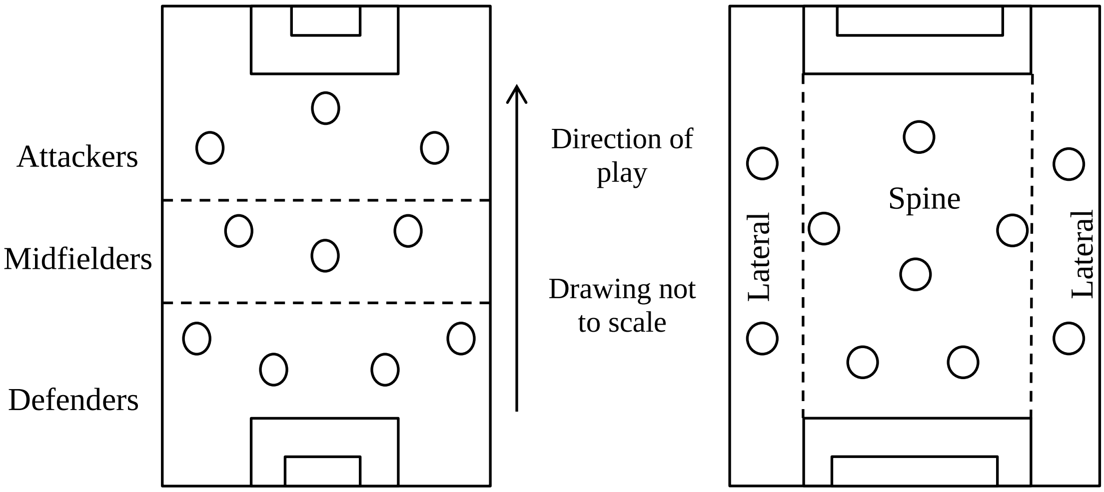


Figure 6-1. Schematic diagram of 4-3-3 playing formation.

6.2.5. Description of Match Running Metrics

All outfield players wore their own individual GPS device for every match (10-Hz, Viper Units; STATSports, Newry, Ireland). The GPS device sampled at 10-Hz with an integrated accelerometer which sampled at 100-Hz. Previous literature has demonstrated greater accuracy and reliability of these devices over higher frequency devices (Coutts and Duffield, 2010, Hoppe et al., 2018). Moreover, Beato et al. (2016) identified the STATSports Viper units demonstrated an average error of 0.31 ± 0.55 m over 10 m shuttles (with a distance bias of 2.53%). Furthermore, Beato et al. (2018) further validated the Viper GPS units across 400 m, 128.5 m and 20 m distances. The absolute error of the Viper systems was 7.9 m ± 7.2 m; 3.5 m ± 1.5 m and 0.25 m ± 0.21 m, respectively (with a positive distance bias of 1.99 ± 1.81%; 2.70 ± 1.20% and 1.26 ± 1.04%, respectively).

It has previously been highlighted that there can be high variability in match-to-match running metrics (Gregson et al., 2010), therefore, data obtained was taken only for players who performed in at least two matches. For each match, participants wore their GPS device, located between the scapulae, in a designated tight-fitting vest. Prior to the warm-up, the GPS devices were switched on 15-minutes beforehand to allow acquisition of satellite signals in accordance with manufacturer’s instructions, and following competition, were immediately switched off. Following each match recording, the data was downloaded to a computer and analysed using STATSports software package (Viper Version 1.2, 2012). A total of five match performance metrics were collected from the GPS data which were (as defined previously in Table 2-7): the total distance covered; high speed running (HSR); very high speed running (VHSR); maximum speed attained and number of accelerations from zone 4 to zone 6. Match performance data collected was then aligned with corresponding age and maturity measures. For example, matches that were played between September and November were associated with anthropometric data collected within the same period. Only data where participants played for at least the full 80 minutes of a match were used. To allow all data to be compared on the same basis, four of the metrics (total distance covered, HSR distance, VHSR distance and the number of accelerations from zone 4 to zone 6) were divided by the total playing time of that participant in each game and then multiplied by 80 (representing the minutes of the game); as added time in matches could skew data. These values were then inputted for statistical analysis. By treating the data in this manner, there was no advantage to playing a greater number of minutes (more opportunity to run further distances), yet factors such as tactics and fatigue are still accounted for.

6.2.6. Statistical Analysis

6.2.6.1. Overview

Descriptive statistics were calculated for growth and maturation characteristics and GPS metrics, with normality tested with Kolmogorov-Smirnov and Shapiro-Wilk tests. Scatter plots were generated to examine concurrent relationships between PPAH and the match running metrics of interest. Multilevel modelling (i.e., hierarchical linear modelling), using maximal likelihood estimation, examined predictive associations between biological maturity status, position (defender, midfielder or attacker), spine or lateral position and the GPS metrics of interest amongst the U14 and U15/16s age groups. Correlation plots were carried out using Microsoft Excel 2010 Excel, Microsoft Corporation, USA), all other analysis was carried out using with IBM SPSS 24.0 (SPSS Inc., Chicago, USA) software with the level of significance set at $p < 0.05$.

6.2.6.2. Multilevel models

A series of linear multilevel models were generated to examine the predictive associations of biological maturation and playing position upon match running metrics. In accordance with processes described and recommended by Field (2005), a stepwise approach was used whereby additional predictors were added to the model. The baseline model with only the dependent variable (GPS metrics) were initially tested (Model 1). Following the evaluations of the baseline models, a random intercept model that took into account participants and repeated measures across matches was entered into the model and conducted (Model 2). The slopes describing the relationship between biological maturation and the match running metrics were allowed to vary as fixed factors; maturation, playing position and spine/lateral (Model 3). In the final model, the slopes were allowed to vary for the position and the spine/lateral positions, maturity remained fixed throughout all models as this was treated as a continuous variable (Model 4). The matches which the participants competed in were entered as the repeated factor in the models.

6.3. Results

6.3.1. Descriptive Statistics

Descriptive statistics for chronological age, biological maturation and GPS match running metrics are reported in Table 6-2. The participants in the older age groups (U15/16s) typically covered greater distances in all of the match running metrics, consistent with the existing literature. Similarly, participants in the older age groups (U15/16s) were on average 12.0 cm taller (7%), 16.1 kg heavier (24%) and were more advanced in maturation than players in the U14 cohort. Likewise, the U15/16s participants presented greater match running metrics; on average they displayed greater absolute total distance in competitive matches, 484 m (5.5%), high speed running, 185 m (34.0%), very high-speed running, 49 m (52.0%), were quicker, 1.9 $km \cdot h^{-1}$ (6.4%) and typically made 14 (24.6%) more accelerations from zone 4 to zone 6 than the U14 age group. Match running metrics and the positions of the players are displayed in Table 6-3. On average, midfielders typically covered greater total distance, however, attackers characteristically covered greater distances at higher speeds (HSR and VHSR), and also achieved the greatest maximum speed and number of accelerations from zone 4 to zone 6. There was also a split between the spine and lateral participants, when it came to HSR and VHSR, lateral participants appeared to complete more of these types of actions.

Table 6-2. Mean (SD) physical characteristics and match running metrics shown for U14 and U15/16s age groups.

	U14 (*n* = 21)	U15/16s (*n* = 16)
Anthropometric and maturity characteristics		
Chronological age (years)	14.1 (1.4)	15.6 (1.4)
Height (cm)	164.8 (7.2)	176.8 (5.7)
Weight (kg)	51.1 (7.0)	67.2 (6.7)
Predicted adult height (cm)	180.0 (6.5)	182.1 (6.5)
PPAH	91.6 (2.3)	97.2 (1.5)
Match running metrics$^{\#}$		
Total distance covered (m)	8521 (964.9)	9005 (733.0)
High speed running (m)	355 (224.8)	540 (196.9)*
Very high-speed running (m)	45 (72.9)	94 (68.4)*
Maximum speed (km.h^{-1})	27.9 (2.2)	29.8 (2.9)*
Accelerations zone 4 to zone 6	42.7 (13.8)	57.0 (12.4)*

PAH – Predicted adult height; PPAH – Percentage of predicted adult height. $^{\#}$Match running metrics shown on a per 80-minute basis. $^{*}p < 0.05$.

Table 6-3. Mean (SD) physical characteristics and match running metrics shown across playing positions.

Physical characteristics	Defender (n = 14)	Midfielder (n = 15)	Attacker (n = 8)	Spine (n = 20)	Lateral (n = 17)
Anthropometric and maturity characteristics					
Height (cm)	175.5 (8.5)	166.3 (8.5)	179.0 (9.6)	172.8 (8.5)	171.9 (8.5)
Mass (kg)	65.0 (10.5)	54.8 (10.3)	66.5 (10.4)	60.5 (10.3)	62.3 (10.4)
Mat. z score	0.37 (0.48)	-0.03 (0.47)	0.56 (0.48)	0.34 (0.47)	0.10 (0.48)
Rel. z score	0.47 (0.93)	-0.28 (0.90)	1.01 (0.92)	0.32 (0.90)	0.14 (0.92)
PAH (cm)	182.8 (4.8)	178.0 (4.8)	184.6 (5.3)	181.7 (4.8)	180.5 (4.8)
PPAH (%)	96.0 (3.3)	93.4 (3.3)	97.0 (3.7)	95.1 (3.3)	95.2 (3.3)
Match running metrics[#]					
Total Distance (m)	8280 (664)	8665 (680)	8372 (591)	8407 (663)	8477 (668)
High speed running (m)	447 (219)	395 (215)	641 (246)	384 (217)	540 (218)
Very high speed running (m)	68 (72)	54 (70)	151 (85)	58 (71)	92 (71)
Maximum Speed (km.h^{-1})	29.3 (2.3)	28.3 (2.0)	30.7 (3.0)	28.8 (2.2)	29.5 (2.3)
Accelerations Z4 to Z6	51 (14)	46 (14)	52 (13)	46 (14)	53 (14)

Mat. *z*-score – Maturity *z*-score; PAH – Predicted adult height; PPAH – Percentage of predicted adult height; Rel. *z*-score – Relative *z*-score.
[#]Match running metrics shown on a per 80-minute basis.

6.3.2. Correlations

Pearson’s correlations (1-tailed) of relative biological maturity and match running metrics are presented for all GPS metrics in Figure 6-2 (U14) and Figure 6-3 (U15/16s) where each completed 80 minute match for every player within the age group was plotted. Relative biological maturity was positively associated with all the GPS metrics assessed for U14 age groups. The U15/16s age group had variation in the associations amongst the GPS metrics. Although the magnitude of the association between maturity status and match running metrics was small, all were positively associated; suggesting that more mature players will achieve greater scores on their match running metrics and that an individual would be expected to increase their outputs on all metrics as they themselves mature.

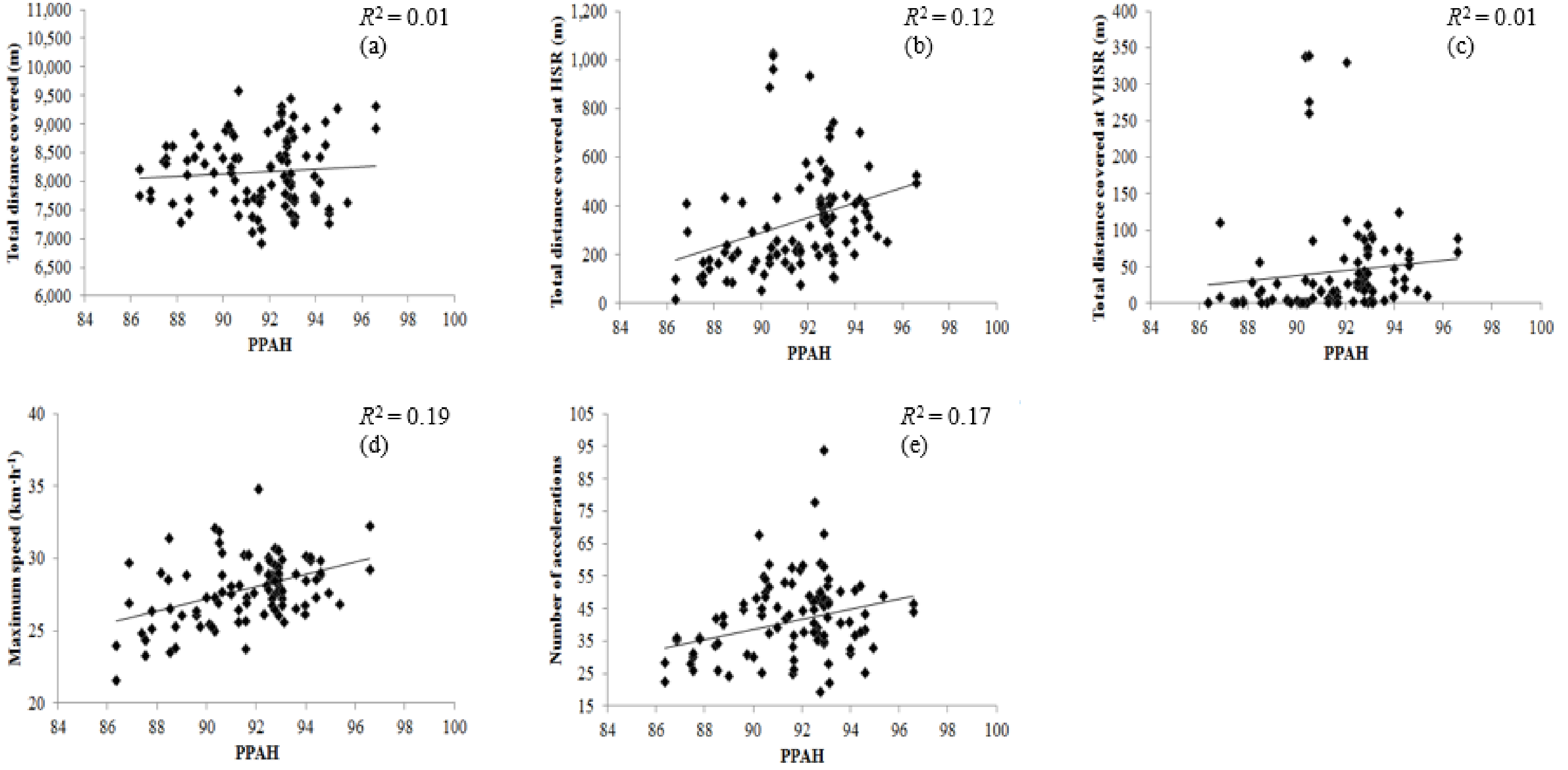


Figure 6-2. U14 scatter pots and correlation coefficients between percentage of predicted adult height (PPAH) and (a) total distance; (b) total distance at HSR; (c) total distance at VHSR; (d) maximum speed; and (e) count of acceleration from zone 4 to zone 6.

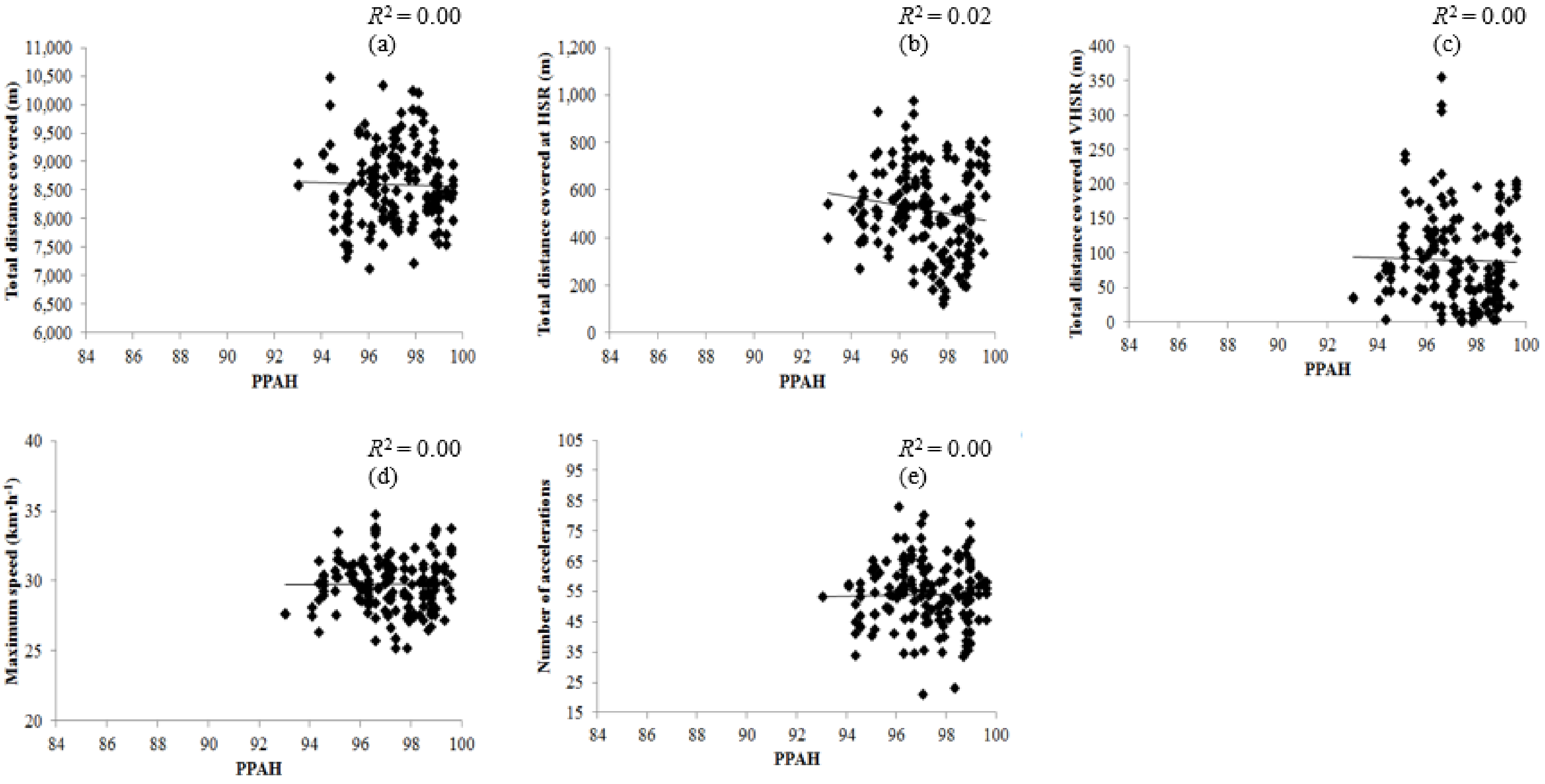


Figure 6-3. U15/16s scatter pots and correlation coefficients between percentage of predicted adult height (PPAH) and (a) total distance; (b) total distance at very high speed ;(c) total distance at high speed; (d) maximum speed; and (e) count of acceleration from zone 4 to zone 6.

6.3.3. Multilevel Models

Multilevel models were generated to examine the predictive associations of biological maturation and playing position upon match running metrics. Parameters associated with the best fitting model are presented in Table 6-4 for U14s and Table 6-5 for U15/16s. Any modifications to the models beyond Model 3 were rejected if it did not improve the model fit (how well a developed model fits the observations). A model fit was evaluated using the Akaike Information Criterion (AIC), (Akaike, 1974).

6.3.3.1. Multilevel Models Predicting Running Metrics – U14

Table 6-4 shows coefficients (β), standard errors (SE), significance value *(p)* and confidence associated with each if the final models (95% CI) associated with the best fitting model for U14s for each of the five match running metrics. In the table, attackers and lateral positions are the respective base against which the other positions are compared. For all of the indices of match running metrics in the U14s cohort, Model 3 provided the best level of fit. That is, allowing the slopes to vary randomly for position and spine / lateral did not result in any improvements in model fit. Moreover, Model 4, which allowed the slopes to vary randomly for position and spine / lateral, did not result in improvements in model fit.

The results associated with each of the final models (Model 3) are presented in Table 6-4. Controlling for the nesting of repeated measures within players and across matches, advanced maturation was associated with greater HSR. The rest of the match running metrics were not impacted by maturity.

Table 6-4 U14 multilevel models (final Model) explaining biological maturation and the effect on match running metrics.

Multilevel models	β	SE	*p*	95% CI
Total Distance (Model 3)				
Intercept	7402.4	397.2	<0.001	6562.7,8242.1
Maturity	40.9	61.5	0.51	-81.2, 162.9
Defenders	-810.8	285.0	0.01	-1416.7, 204.8
Midfielders	-188.3	265.2	0.49	-748.3, 371.7
Attackers	-	-	-	-
Spine	-56.4	167.9	0.74	-417.3, 304.5
Lateral	-	-	-	-
High speed running (Model 3)				
Intercept	-85.8	145.1	0.56	-389.6, 218.0
Maturity	32.4	16.2	0.04	0.3, 64.6
Defenders	-332.5	103.3	0.01	-548.6, 116.4
Midfielders	-338.3	97.2	0.01	-541.3, 135.3
Attackers	-	-	-	-
Spine	-139.0	56.6	0.13	-257.3, -20.6
Lateral	-	-	-	-
Very high speed running (Model 3)				
Intercept	-100.6	.49.5	0.06	-203.7, 2.5
Maturity	9.4	4.8	0.06	-0.2, 18.9
Defenders	-126.5	34.1	<0.001	-197.9, -55.1
Midfielders	120.8	32.1	<0.001	-187.7, -53.8
Attackers	-	-	-	-
Spine	-37.2	18.7	0.06	-76.3, 1.9
Lateral	-	-	-	-
Maximum speed (Model 3)				
Intercept	25.3	1.6	<0.001	21.9, 28.7
Maturity	0.2	0.2	0.25	-0.2, 0.6
Defenders	0.7	0.8	0.38	-0.9, 2.3
Midfielders	-2.1	1.3	0.12	-4.9, 0.6
Attackers	-	-	-	-
Spine	-0.8	0.72	0.29	-2.3, 0.7
Lateral	-	-	-	
Accelerations (Model 3)				
Intercept	25.0	6.9	<0.01	9.4, 40.7
Maturity	2.2	1.4	0.11	-0.5, 5.0
Defenders	-7.3	5.7	0.22	-19.6, 4.9
Midfielders	-4.6	5.5	0.42	-16.2, 7.1
Attackers	-	-	-	-
Spine	-6.4	3.1	0.06	-13.1, 0.4
Lateral	-	-	-	-

6.3.3.2. Multilevel Models Predicting Running Metrics – U15/U16s

Table 6-5 shows coefficients (β), standard errors (SE), significance value *(p)* and confidence associated with each if the final models (95% CI) associated with the best fitting model for U15/16s for each of the five match running metrics. In the table, attackers and lateral positions are the respective base against which the other positions are compared. For all of the indices of match running metrics in the U15/16s cohort, Model 3 provided the best level of fit. That is, allowing the slopes to vary randomly for position and spine / lateral did not result in any improvements in model fit. Moreover, Model 4, which allowed the slopes to vary randomly for position and spine / lateral, did not result in improvements in model fit.

The results associated with each of the final models (Model 3) are presented in Table 6-5. Consistent with the correlational analyses, maturation was found to be unrelated to all of the GPS metric.

Table 6-5. U15/16s multilevel models (final Model) explaining biological maturation and the effect on match running performance.

Multilevel models	β	SE	*p*	95% CI
Total Distance (Model 3)				
Intercept	7934.6	645.8	<0.001	6567, 9301.3
Maturity	63.4	91.6	0.49	-117.6, 244.4
Defenders	339.7	605.7	0.58	-947.7, 1627.1
Midfielders	703.2	638.2	0.29	-645.2, 2051.6
Attackers	-	-	-	-
Spine	315.4	298.5	0.31	317.4, 948.1
Lateral	-	-	-	-
High speed running (Model 3)				
Intercept	780.2	136.1	<0.001	484.4, 1075.9
Maturity	7.3	25.4	0.77	-43.2, 57.8
Defenders	-190.9	126.2	0.16	-467.2, 85.3
Midfielders	-167.3	135.3	0.24	-460.0, 125.4
Attackers	-	-	-	-
Spine	-171.1	62.8	<0.05	-307.3, -34.8
Lateral	-	-	-	-
Very high speed running (Model 3)				
Intercept	172.9	57.7	<0.01	49.9, 295.8
Maturity	11.4	9.4	0.23	-7.2, 29.9
Defenders	-67.7	53.9	0.23	-183.0, 47.7
Midfielders	-52.7	57.2	0.37	-174.2, 68.8
Attackers	-	-	-	-
Spine	-48.3	26.6	0.09	8.5
Lateral	-	-	-	-
Maximum speed (Model 3)				
Intercept	31.5	1.7	<0.001	27.9, 35.0
Maturity	0.2	0.3	0.43	-0.3, 0.8
Defenders	-1.3	1.6	0.40	-4.7, 2.0
Midfielders	-1.3	1.7	0.45	-4.8, 2.2
Attackers	-	-	-	-
Spine	-0.9	0.8	0.29	-2.5, 0.8
Lateral	-	-	-	-
Accelerations (Model 3)				
Intercept	56.9	6.5	<0.001	42.7, 71.1
Maturity	1.6	1.6	0.33	-1.7, 4.9
Defenders	0.8	5.9	0.89	-12.1, 13.8
Midfielders	-0.5	6.6	0.94	-14.7, 13.7
Attackers	-	-	-	-
Spine	-6.7	3.1	<0.05	-13.2, -0.13
Lateral	-	-	-	-

6.4. Discussion

The purpose of the present study was to investigate the influence of biological maturity and playing position associated variance in match running metrics amongst elite youth male soccer players from U14 – U16 age groups. One of the main outcomes from this work is a better understanding of how the influence of maturity on match running metrics effects elite youth soccer players. Significant effects were seen from maturity when studying across the range of maturity classifications (i.e., herein the U14s age group, encompassing pre-, circa-, post-PHV) but not when only considering individuals of a single maturity classification.

The findings of the current study are in line with previous research whereby older age groups displayed higher absolute total distances, greater high and very-high intensity distances, and were also quicker than the younger age groups (Harley et al., 2010). These results reflect the superior physical and athletic attributes of the older players and the greater physical demands associated with competing in older age groups.

6.4.1. Correlations between Maturity and Match Running Metrics

The correlations and associated scatterplots between maturation and the various running metrics of match performance were of particular interest (Figure 6-2 and Figure 6-3). Across the competitive season, there appears to be a positive association between relative maturation status and the majority of the GPS metrics in the U14 age group. Participants that were more advanced in maturity typically covered greater distances at high speed, were quicker and made more accelerations from zone 4 to zone 6. These findings suggest that throughout the season, those players who were most advanced in maturity status, typically outperformed their peers on certain aspects of the match running metrics (i.e., actions that involve HSR). That is the same athletic advantages afforded to early maturing boys on tests of speed also seem to be existent in match conditions also. Similar findings have been observed in Australian Rules Football players, with more mature players demonstrating superior performance on match running metrics than their less mature counterparts (Gastin et al., 2013). However, this association was not as apparent amongst the U15/16s individuals, whereby there was a lower R^2 between maturity status and match running metrics (Figure 6-3). This may be a reflection on the fact that there appears to be a much greater variance in maturity status amongst the U14 participants (86.4 – 96.6%, pre-, circa-, post-PHV) than the U15/16s age groups (93.0 – 99.6%, mostly post-PHV). Many of the individuals in the U15/16s age groups are fully mature or much closer to reaching the mature state and this may reflect the fact that there is much less variation in maturity. As individuals approach the point of reaching the mature state, differences in maturity become less of an important factor. It is worth noting however that these analyses do not take into account repeated measures over time. Another consideration is that at the U14 to U15 age groups progression, retention decisions are made. If as shown here, less mature players perform less well than their more mature counterparts, then they are more likely to be released and hence not present in the older age groups.

The analyses in this study could have been conducted with all participants within a single group (contrast individual age groups). This can be seen from Figure 6-4. This may have shown stronger associations of the running metrics with maturity, however, for the reasons explained in the previous paragraph, the weighting of the U15/16s being most mature waters down the results that can be obtained from using separate age groups. That is to say, mature (i.e., post-PHV) individuals cover greater distances and do so at higher speeds, but the results of this study showed that there is not a significant association across the range of maturities (percentages of predicted adult height) within this classification. As in the U14 age group, there was a distribution of maturity classifications, the expected outcome that maturity was positively associated with match running metrics was observed.

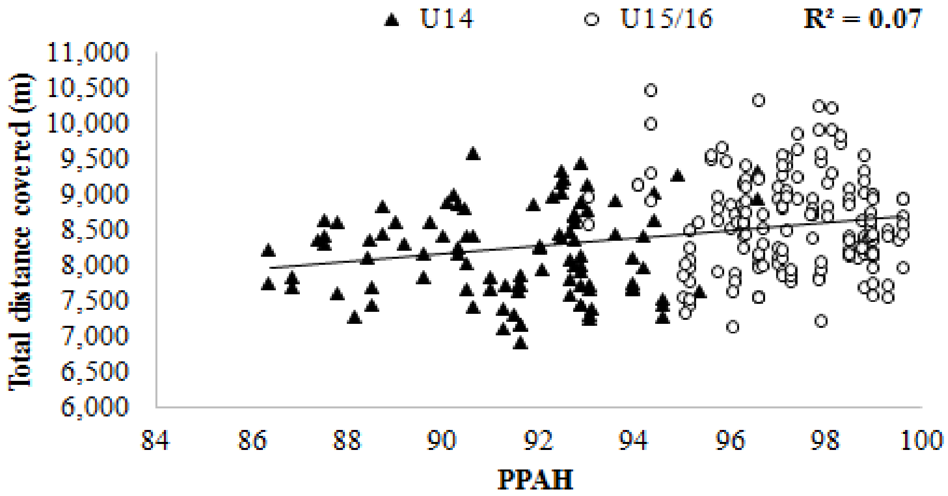


Figure 6-4. Scatter pots and correlation coefficients between percentage of predicted adult height (PPAH) and total distance with all age groups combined.

6.4.2. Findings from Multilevel Models

To examine the degree to which maturation and playing position were related to match running metrics, while simultaneously accounting for repeated measures within individuals across matches, a series of linear multi-level models were conducted. Amongst the U14s participants, only HSR was statistically significant, the rest of the match running metrics were not impacted by maturity (Table 6-4). This may suggest that much of what was observed amongst the correlations scatter plots (Figure 6-2) could have been down to the most and least mature players repeatedly over or under performing, on the match running metrics, respectively, across the season. This does not imply that maturation is not a significant contributor towards match running metrics. Rather, it suggests that much of this variance observed is due to nesting effects.

Consistent with the correlational analyses, maturation was found to be unrelated to GPS performance metrics in the models conducted for the U15/U16s players. The lack of association between maturation and match running metrics may be due to a number of factors. Firstly, variance in maturation within these age groups was more limited with less disparity between the most and least mature players. Further, all of the players within the U15/U16s age groups were well beyond the mean percentage of adult stature associated with PHV (91%). Maximum gains in speed and lean muscle mass tend to fall just before and after age at PHV, respectively (Viru et al., 1999).

Similar findings were observed by Buchheit et al. (2010b) in games involving players aged 12.2 – 14 years of age where older and / or more mature players consistently outperformed their younger more immature counterparts, covering greater distances at higher speeds. This could suggest that maturation may impact positively on match running metrics, in particular, those instances in a match that requires an action performed at high speed. In turn, this may translate to more playing opportunities in matches and the possibility of competing at a higher standard. Rampinini et al. (2009) further highlighted this in the Italian Serie A elite adult male league. It was identified that better players (players from more successful teams) typically covered more high speed distance with the ball. The selection bias, whereby older and / or more mature players are selected into soccer academies (Figueiredo et al., 2009a), but also national teams (Buchheit et al., 2014, Gissis et al., 2006) could be somewhat described by the aforementioned data. Amongst the U15/16s age-groups, the multi-level models (Table 6-5) were consistent with correlations; maturation had no significant effect. However, significance was observed in the spine / lateral playing positions when undertaking actions that required covering distance at high speeds. Across the entire match running metrics, maturation had no significant effect.

6.4.2.1. Differences between Playing Positions

The results of the current chapter demonstrated defenders had the lowest total distance covered in a match, similar findings were reported by Buchheit et al. (2010b). However, midfield players produced the lowest amount of HSR and VHSR distances, contrasting results which have previously been shown (Dellal et al., 2011), although, this data was collected from professional soccer players. Moreover, Bradley et al. (2009) reported that central midfielders produced highest total distances, this may be due to the positional role of these players, whereby they often link the defence with the attack, and are commonly involved in both phases of play, however, in the current study, this was not the case. The current study supports results reported by Carling (2013) that wide (lateral) players cover the greatest total distances in a match. The differences between the results of the present study and those of Dellal et al. (2011) and Bradley et al. (2009) may be due to the differences in demand of the tactical roles of the lateral players between the teams analysed in the respective studies.

The positional differences with HSR and VHSR are comparable to previous research which highlights that attackers and lateral players produce the highest distances for these two match performance metrics (Bradley et al., 2010). Similarly, in the present study, attacking players achieved on average 194 m (30%) and 246 m (38%) more HSR than defenders and midfielders, respectively. Moreover, they also covered 83 m (55%) and 97 m (64%) more VHSR than defenders and midfielders, respectively. Defenders, in particular central defenders and midfielders, operate in highly congested area of the pitch, therefore, the opportunity to achieve high speeds unopposed can prove somewhat challenging (Di Salvo et al., 2007), potentially owing to the fact that they do not achieve the same distances covered at high and very-high speed running as attacking players. In Table 6-3 the positional variation in match running metrics is provided for the combined cohort of participants. Although Table 6-2 shows that older players cover greater amounts of distance and run at higher speeds (on average), this does not influence the conclusion that position impacts match running metrics as the proportion of players represented in each position is consistent across the age groups.

The positional differences in accelerations has been reported by Ingebrigtsen et al. (2015) whereby a higher frequency of accelerations seemed to occur in lateral players compared to central players. The results of the current study indicate similar findings where lateral players experienced on average seven (13%) more accelerations from zone 4 to zone 6 throughout a match. This may be due to the frequent requirement of wide positions to achieve high speeds, with rapid acceleration necessary to reach this.

Due to these differences in playing positions, a one-boot fits all training approach would be unreasonable. Amongst the various playing positions, each one requires a bespoke emphasis on the physical components (Dalen et al., 2016). According to Bangsbo et al. (2006), central (spine) defenders undergo the least amount of physical demand in a competitive match, which in turn equates to a greater emphasis on volume of tactical and technical training, something which is important for the position.

A limitation of the present study was that the data was collected on a routine basis within the academy; however, it was not always possible to have an equal distribution of measurements across participants. For example, in this chapter, some participants had two measurements, whereas others had up to 30 measurements. This was an unavoidable outcome of the study design (where a minimum playing time was set), but this did restrict number of points taken for some players which was undesirable. Having a more even distribution of matches represented across individuals might reduce repeated measure effects whereby the same individuals over / underperform in matches.

Additionally, post-pubescent individuals have been shown to have increased muscle mass when compared to their pre-pubescent counterparts (Section 2.8.1.3), and therefore may display greater levels of strength, power and speed performance. Due to these inherent differences, speed thresholds placed upon individuals of different maturational statuses may not be suitable (Cummins et al., 2013). Thus, there is the potential for error in the quantification of training load (insufficient reflection) when using global speed thresholds. The thresholds that are defined on the GPS systems are absolute scores; they are not relative to each individual. The ultimate desire, therefore, would be to have a specific performance level that is expected, per position, per maturity classification.

6.5. Conclusion

The results of this study are of particular interest to practitioner involved in the development in youth elite soccer players. There is a suggestion that maturation does have an impact on match running metrics within the U14s age group, however much of the variance may be attributable to individuals under / over performing consistently in matches. Furthermore, within the U15/16s age group, the influence of maturation on match running metrics appeared to have less of an impact. From a practical perspective, such as bio-banding, which has previously been used to address factors of growth and maturation (Cumming et al., 2018a, Cumming et al., 2017b), this concept may be better suited towards individuals between the ages of 11 – 14 years, where those factors are going to be more important / influential.

Chapter 7

7. Athletic Performance during the Interval of Rapid Growth through Adolescence

7.1. Introduction

As identified in Chapters 5 and 6, biological maturity can influence performance in both training and match situations, with more mature individuals showing greater performance. This chapter aims to identify the points at which physical performance increases most during adolescent development for a series of fitness tests. This allows practitioners to be wary of large accelerations or decelerations of performance improvements that may be attributable to the particular point of development an individual is at.

Physical growth and biological maturation, and associated functional and behavioural characteristics are central to discussions of talent in many sports (Williams and Reilly, 2000). A significant theme in human growth is the inter-individual variation in the timing, tempo and process of biological changes during the adolescent growth spurt (Beunen et al., 2000). Although the processes of growth and maturation span approximately the first two decades of life, the interval of the adolescent growth spurt and pubertal maturation, occasionally labelled the pubertal growth spurt, is highly individual and variable in timing and tempo (Malina et al., 2004a, Malina et al., 2015). Moreover, individual differences in timing and tempo of biological changes during the growth spurt are commonly the focus of attention (Beunen et al., 2000). Allowing for these inter-individual differences, peak height velocity (PHV) has frequently been implemented instead of chronological age to characterise changes in size, body composition, and performance parameters during the interval of the adolescent growth spurt (Beunen and Malina, 1988, Beunen et al., 1988, Malina et al., 2004a). These changes have also been discussed in relation to peak weight velocity (PWV) by some authors (Beunen et al., 1988).Young athletes are traditionally grouped by chronological age (CA) for the purpose of training and competition, although youth of the same CA can vary significantly in terms of maturity status at the time of observation (skeletal age, stage of puberty, and in maturity timing), (Beunen and Malina, 1988, Patel et al., 1998, Marshall and Tanner, 1970, Malina et al., 2004a, Tanner, 1962). Although the adolescent growth spurt in height has been comprehensively researched, the variability in the timing, intensity and the duration of the growth spurt in physical performance has received less attention (Silva et al., 2019). Individuals that are advanced in maturity typically demonstrate superior physical performance than their less mature peers (in absolute terms), (Silva et al., 2019, Cumming et al., 2018a, Cumming et al., 2009, Parr et al., 2020a). However, Lefevre et al. (1990) demonstrated that these later maturing individuals catch-up to their earlier maturing counter-parts, and in some instances, may achieve better performance outcomes by early adulthood. Cross-sectional research has been relatively consistent in identifying that early maturing boys are typically more successful in soccer in mid to late adolescence. Moreover, boys that are approximately 14 years of age, advanced in their maturity status (both sexual and skeletal) are better represented in youth soccer teams (Cacciari et al., 1990, Malina, 2003, Peña Reyes et al., 1994).

Previous research on adolescent males from the general population has highlighted that strength and power attain maximum rate of improvement post-peak height velocity, and maximal rate of improvement has been observed in running speed post-PHV (Malina et al., 2004a, Beunen and Malina, 1988). Philippaerts et al. (2006) reported similar findings after investigating longitudinal changes across a five-year period in height, weight and physical performance parameters in 33 Flemish male youth soccer players. The majority of the physical performance metrics, such as running speed and agility, showed peak rates of improvement at the time of estimated PHV. Moreover, following PHV, running speed demonstrated a plateau in rate of improvement. There is therefore limited information on longitudinal changes in strength and motor performance relative to PHV in adolescent males, in particular soccer players, and no studies have longitudinally investigated these features in a cohort of British soccer players.

7.2. Expected Outcomes from Chapter 7

Therefore, the purpose of the present chapter was to investigate the adolescent growth spurt in height and the overall development of five physical performance metrics over a six-year period relative to the period of the maximum growth in height in a group of 30 elite male adolescent soccer players.

7.3. Methods

Prior to the study commencing, ethical approval was obtained and granted from the Ethics Committee of Faculty of Science & Engineering, at Manchester Metropolitan University (Ethics code: 17739). Parents / guardians of the participants were also notified of the aim of the study, research procedures, requirements, benefits, and risks and provided written informed consent. The youth participants also provided assent. Participants were advised that involvement in the study was voluntary and that they could withdraw from the study at any point.

7.3.1. Participants

The sample included 30 male participants from a professional soccer academy within the English Premier League, who were followed for the duration of six years. Ages at the start of the study ranged from 11.30 – 12.33, with a mean of 12.06 ± 0.66 years of age. All participants were born between 1997 and 2001.

The longitudinal series was followed from entry into U12s through to the U18 age group and spanned 2012 – 2017. Heights and weights were collected at two-month intervals, while performance items were tested every three months across the six consecutive age group years.

7.3.2. Anthropometry and Procedures

Measurements of anthropometry were collected by the same experienced observer on each occasion. See General Methods (Section 3.4) for a full description for how the anthropometric variables were collected. All anthropometric measurements were carried out by the lead researcher throughout the longitudinal study to ensure that the quality of the data collection was high.

7.3.3. Calculation of Changes in Growth and Performance

It is easier to analyse the anthropometric data (collected bi-monthly) and performance test data (collected quarterly) if they are presented on a consistent basis. It was also thought preferable to have a higher frequency of data points for both. Therefore, the data were interpolated to provide values on a monthly basis by way of a modified non–smoothed polynomial method (Figure 7-1), with median values used for analysis. The method selected followed previous longitudinal studies of adolescent growth and performance (Yague and De La Fuente, 1998, Silva et al., 2019, Beunen et al., 1988), including soccer players (Philippaerts et al., 2006). This method was selected due to resemblance between the current dataset and that of the Belgian (Beunen et al., 1988), Spanish (Yague and De La Fuente, 1998) and Brazilian (Silva et al., 2019) boys, and due to similar physical performance tests measures being assessed.

The modified non-smoothed polynomial method works by interpolating the data points available but by accounting for the local directional changes and being forced to include all measured data points, thus improving on a linear interpolation method. This method was originally used in paper by Beunen et al. (1988) and more recently employed by Philippaerts et al. (2006) and Silva et al. (2019) and requires an interval between consecutive measurement points. As measurements were taken with fixed frequency for the duration of the assessment period in this study (either two months or three months), the interval is known for all points.

The final data, therefore, consisted of anthropometric and performance data of a frequency of one month, aligned to each other. Any performance improvements (or deteriorations) can be identified at the time they occur, and this can be matched to the height and weight increases that occur through growth.

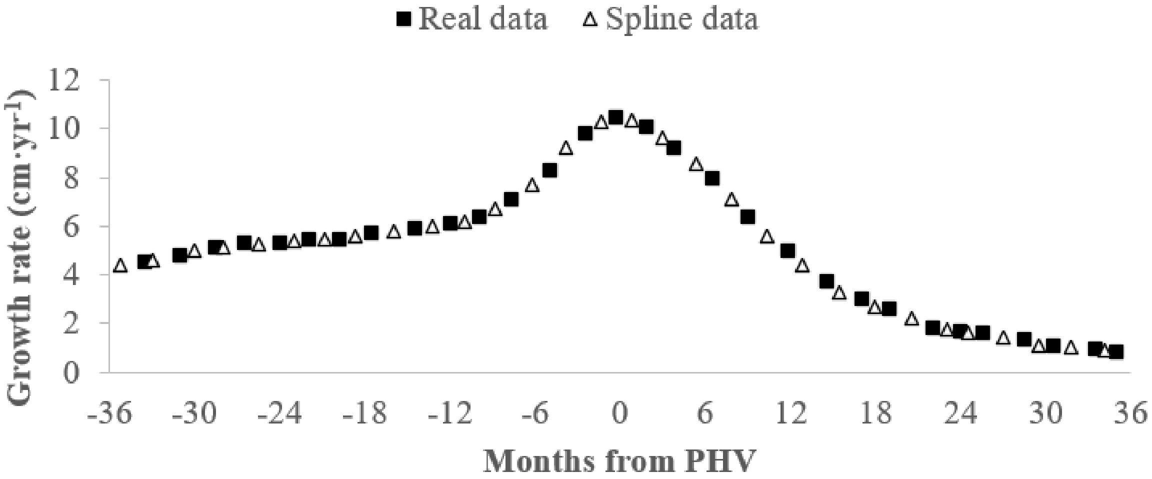


Figure 7-1. Example of a spline interpolation for change in height data for a single participant.

7.3.4. Indicators of Performance

Participants undertook a dynamic 10-minute warm-up with the lead researcher. See General Methods (Section 3.7) for a full description of warm-up. Several indicators of performance were tested: running speed; change of direction (COD) and lower limb explosive strength (Table 7-1) by the lead researcher and an experienced test leader throughout the longitudinal study to ensure that the quality of the data collection was high. All participants were tested in their respective age groups within the same week at the start of training sessions. All running tests and COD tests were performed indoors on artificial 4G turf, whilst explosive strength was performed indoors on a gym floor.

Table 7-1. Physical performance factors and their associated tests.

Factor	Test
Running speed	5 m and 20 m sprint
Change of direction	505
Explosive strength	Countermovement jump
Reactive jump capacity	Drop jump

7.3.4.1. Running Speed

Running speed is seen as a key element to progress as a professional soccer player and is something which is frequently tested amongst youth soccer players (Figueiredo et al., 2009b, le Gall et al., 2010, Carling et al., 2009). The sprint assessments that were carried out were 5 m and 20 m. The running abilities of participants were evaluated on 4G artificial turf by 20 m sprint times (standing start), with 5 m and 20 m split times. See General Methods (Section 3.8.1) for a full description.

7.3.4.2. Change of Direction - 180^o Test

It has been highlighted that the ability to perform well in a COD test could be a distinguishing factor in a multidisciplinary talent identification battery test amongst youth soccer players (Reilly et al., 2000b). The COD test was performed following a maximal sprint (described above). Participants were required to sprint forward to a turning point 5 m beyond the 20 m timing gate and pivot 180°, the test was concluded when the participant re-broke the 20 m timing gate. See General Methods (Section 3.8.2) for a full description.

7.3.4.3. Countermovement Jump

The CMJ has previously been established as a reliable measure of explosive strength performance (Lloyd et al., 2009, Markovic et al., 2004). Following the maximal sprints, participants performed three jumps on a hard, flat surface between a portable photoelectric cell system (Optojump, Microgate, Italy). See General Methods (Section 3.8.3) for a full description.

7.3.4.4. Reactive Strength Index

The reactive strength index (RSI) was determined using drop jump tests, which involved the participants performing five separate jumps on a hard, flat surface between a portable photoelectric cell system (Optojump, Microgate, Italy). See General Methods (Section 3.8.4) for a full description.

7.3.5. Statistical Analyses

Individual height velocity data was centred on the individual's PHV and then median values for the group were taken at six-month intervals between three years pre- and post-PHV. Individual velocity data for height, weight and the physical performance tests were fitted with a modified non–smoothed polynomial method, described above.

7.4. Results

Table 7-2 shows the results of the median constant curves for height and weight of all participants, alongside Figure 7-2, which represents the median velocity curve for their height and weight. Peak height and weight velocity were determined in 30 participants. The median velocity curve for the 30 individuals (Figure 7-2) highlights that height velocity increases from approximately 3.0 cm·yr^{-1} at 36 months before PHV to approximately 10.0 cm·yr^{-1} at the moment of PHV. Following this, height velocity decreases to approximately 0.3 cm·yr^{-1}, 36 months following PHV. The mean age at PHV was 14.0 ± 1.0 yr.

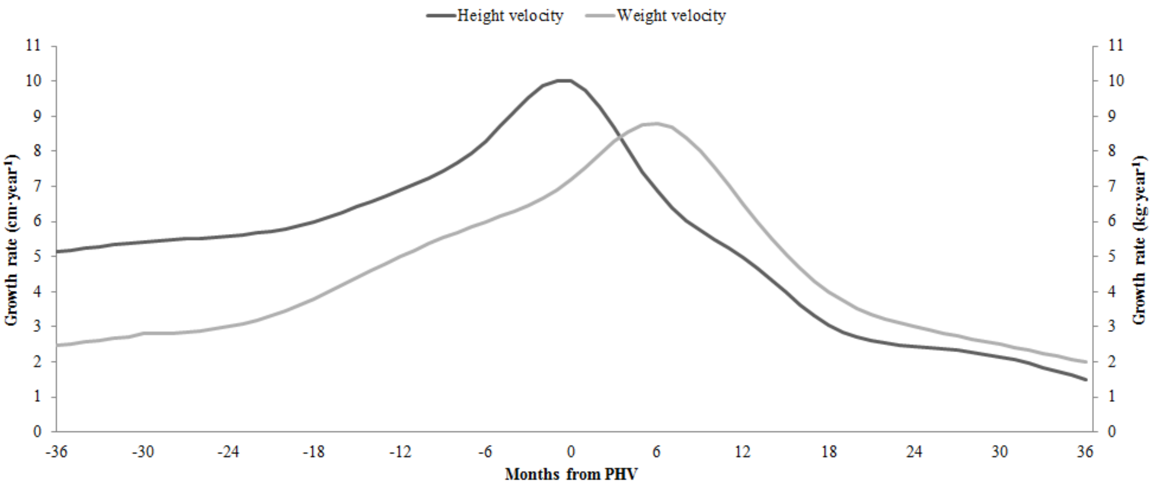


Figure 7-2. Median velocity curve for height and weight of participants in this study. *Note*: Negative values indicate months before PHV, positive values indicate months after PHV

Table 7-2. Median growth velocity for height when individual data are aligned to PHV.

		Months from PHV												
Variable		−36	−30	−24	−18	−12	−6	0	6	12	18	24	30	36
Frequency		14	16	20	22	27	29	30	30	30	29	29	24	24
Height (cm•yr^{-1})	median	4.74	6.39	5.51	5.87	6.95	7.06	10.00	7.29	6.61	3.98	3.16	3.47	2.84
	IQR	1.22	1.94	1.75	5.00	2.48	4.70	3.14	6.64	0.97	2.51	3.64	0.35	0.20
Weight (kg•yr^{-1})	median	2.44	2.47	2.46	2.92	3.34	4.78	5.74	7.82	7.26	6.14	5.20	3.78	2.19
	IQR	2.65	3.56	5.44	6.34	0.74	0.50	0.88	6.49	7.26	0.64	5.88	6.52	3.71

[*] The frequency of participants decreases as the data separates from PHV, because of the alignment of individual curves on this parameter.

Note: Mean age at PHV = 14.0 years. Mean age at PWV = 14.7 years.

Peak weight velocity (PWV) was also calculated for the 30 participants. The median velocity curve for the 30 individuals highlights that weight velocity increases from approximately 2.5 kg·yr^{-1} at 36 months before PHV, to approximately 8.0 kg·yr^{-1}, six to seven months after the moment of PHV. Subsequently, weight velocity decreases to approximately 2.0 kg·yr^{-1}, 36 months after the moment of PHV. The mean age at PWV was 14.7 ± 0.8 years. Table 7-3 displays the median performance velocity for the physical performance of all participants, aligned at 6-month intervals. Additionally; Figure 7-3 shows the median velocity curves for the five physical performance tests, for the three years pre- and post-PHV.

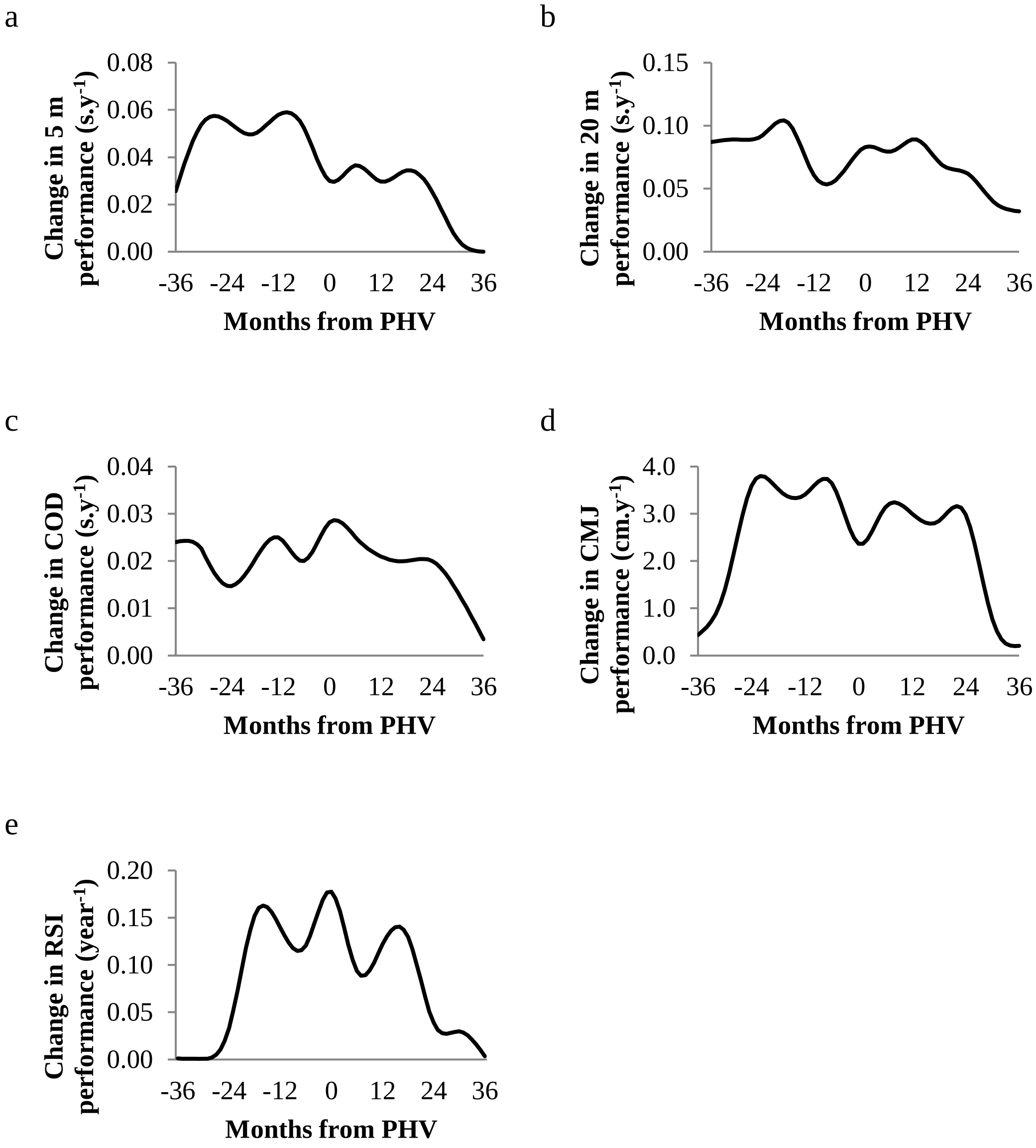


Figure 7-3. Physical performance median velocity curves for (a) 5 m sprint; (b) 20 m sprint; (c) change of direction; (d) countermovement jump and (e) RSI.
Note: Negative values indicate months before PHV, positive values indicate months after PHV.

Table 7-3. Median performance velocities when individual data are aligned to PHV.

		Months from PHV												
Variable		−36	−30	−24	−18	−12	−6	0	6	12	18	24	30	36
5 m sprint (s)	median	0.03	0.05	**0.06**	0.05	**0.06**	0.05	0.03	0.04	0.03	0.03	0.03	0.01	0.00
	IQR	0.07	0.17	0.14	0.02	0.07	0.09	0.08	0.09	0.06	0.11	0.06	0.00	0.00
20 m sprint (s)	median	0.09	0.09	0.09	**0.10**	0.06	0.06	0.08	0.08	0.09	0.07	0.06	0.04	0.03
	IQR	0.20	0.12	0.02	0.07	0.10	0.20	0.15	0.21	0.18	0.14	0.12	0.06	0.05
COD (s)	median	0.02	0.02	0.01	0.02	**0.03**	0.02	**0.03**	**0.03**	0.02	0.02	0.02	0.01	0.00
	IQR	0.09	0.01	0.03	0.08	0.06	0.06	0.12	0.03	0.06	0.06	0.06	0.04	0.02
CMJ (cm)	median	0.4	1.4	3.6	3.5	3.4	**3.7**	2.4	3.1	3.0	2.9	3.0	0.8	0.2
	IQR	1.0	8.0	5.6	3.0	1.2	5.1	2.1	9.2	1.4	1.4	6.0	1.2	0.1
RSI	median	0.00	0.00	0.03	0.15	0.14	0.12	**0.18**	0.09	0.12	0.13	0.04	0.03	0.00
	IQR	0.00	0.00	0.01	0.01	0.00	0.01	0.47	0.12	0.14	0.00	0.00	0.00	0.00

Note: Maximum velocities for each performance variable are bolded.
IQR – Interquartile range; COD – Change of direction; CMJ – Countermovement jump.

7.4.1. 5 m Sprint Performance

The median changes in 5 m sprint performance as a function of time from PHV are shown in Figure 7-3 (a). Changes in performance are positive values, indicating that the participants were improving their 5 m sprint times as they matured. The graph shows that improvement increase from 0.03 $s \cdot yr^{-1}$ 36 months before PHV to a peak at 12 months before PHV (0.06 $s \cdot yr^{-1}$). Following this, at the moment of PHV, any improvements reduce back to 0.03 $s \cdot yr^{-1}$, before further reducing 30 months after PHV (0.01 $s \cdot yr^{-1}$). After 36 months post PHV, there appears to be no improvements in 5 m sprint performance, as no change is observed (0.00 $s \cdot yr^{-1}$).

7.4.2. 20 m Sprint Performance

The changes in 20 m median velocity curve as a function of time from PHV are displayed in Figure 7-3 (b). Changes in 20 m sprint performance are positive, indicating that as participants mature, 20 m sprint performance increases. The graph highlights a small improvement approximately 18 months before PHV (0.10 $s \cdot yr^{-1}$). Between the moment of PHV and 12 months post PHV, an improvement in 20 m sprint performance was observed (0.08 to 0.09 $s \cdot yr^{-1}$, respectively). Approximately 18 to 30 months after PHV, any improvements reduced back to 0.07 to 0.04 $s \cdot yr^{-1}$, respectively. Between 30 to 36 months post-PHV, changes in 20 m sprint performance reduce back to 0.03 $s \cdot yr^{-1}$.

7.4.3. Change of Direction Performance

The median change as a function of time from PHV for COD is shown in Figure 7-3 (c). Measured changes in COD performance are positive, indicating that as the participants were maturing; their change of direction performance was improving. A small improvement in COD performance was observed approximately 12 months before PHV (0.03 $s \cdot yr^{-1}$), and again at the moment and six months post-PHV (0.03 $s \cdot yr^{-1}$). Approximately 12 months post PHV, any improvements reduce back to 0.02 $s \cdot yr^{-1}$. Subsequently, between 12 to 36 months post PHV, any improvements reduce back to 0.00 $s \cdot yr^{-1}$.

7.4.4. Countermovement Jump Performance

The estimated changes in CMJ performance as a function of time from PHV are displayed in Figure 7-3 (d). Estimated changes in countermovement jump performance were positive, indicating that as participants become more mature, their CMJ performance improves. The graph shows a maximum improvement approximately six months before PHV (3.7 cm·yr^{-1}). At the moment of PHV, the improvements reduce back (2.4 cm·yr^{-1}), before a second improvement increase approximately six months post PHV (3.1 cm·yr^{-1}). Subsequently, improvements reduce back to approximately 3.0 cm·yr^{-1} 24 months post PHV. Countermovement jump performance improvement reduces back to 0.2 cm·yr^{-1} approximately 36 months post PHV, which is close to the limit of measurement (0.1 cm).

7.4.5. Reactive Strength Index Performance

Median changes for RSI performance as a function of time from PHV are shown in Figure 7-3 (e). Estimated changes in RSI performance are positive, indicating that with advanced maturity, reactive strength performance improves. Approximately 36 to 24 months before PHV, there is an improvement increase of a small value (0.00 to 0.03, respectively). At approximately 18 months before PHV, the graph highlights an improvement increase in reactive strength performance to 0.15. Moreover, at the moment of PHV, a further improvement increase in performance was observed (0.18), before this improvement is reduced back at approximately eight months post PHV (0.09). Moreover, a gradual improvement increase in reactive strength performance was observed between six to 18 months post PHV (0.13). Between 24 to 36 months, improvements reduced back to approximately 0.00.

The peak performance identified from the rate of improvement (Figure 7-3) was also the point at which the highest frequency of participants experienced their peak performance for each of the five metrics.

7.5. Discussion

Longitudinal research of the influence growth and maturation and on physical performance is limited. The current study is unique as at present there is a scarcity of available longitudinal data for age related trends in physical performance, in particular, amongst youths that are part of an elite soccer academy. It has been highlighted by this chapter that there are obvious accelerations and decelerations in performance gain relative to observed age at PHV in a sample of elite male youth soccer players.

In the current sample, the average age at PHV was 14.0 ± 1.0 year, which was concordant with that observed in the Saskatchewan Growth and Development Study (Mirwald, 1978), which also had a mean age at PHV of 14.0 ± 1.0 year. It was also similar to the Leuven

Longitudinal Twin Study (Beunen et al., 2000), which had an mean age at PHV of 14.2 ± 0.8 years, but relatively later than the Bone Mineral Accrual Study (Bailey, 1997, Bailey et al., 1999), where the mean age at PHV was 13.4 ± 0.7 years, yet there is some overlap between these groups. The current sample age at PHV was also similar to estimates of Welsh youth soccer players, 14.2 ± 0.9 years (Bell, 1993), and fell within the range of estimated age of PHV for samples of European boys; 13.8 – 14.2 years (Malina et al., 2004a). The estimated median PHV of the current sample of youth soccer players (10.0 $\text{cm}\cdot\text{yr}^{-1}$) falls within the normal range that has previously been described by Malina et al. (2004a), (Beunen and Malina, 1988), which was reported between 8.2 – 10.3 $\text{cm}\cdot\text{yr}^{-1}$ in European boys. The estimates of age at peak height velocity and peak weight velocity are consistent with other research (Yague and De La Fuente, 1998, Silva et al., 2019). The drop-off in frequency of participants seen in Table 7-2 for 36 and 30 months pre-PHV is explained by the recruitment method of the academy. Based on the average age at PHV of 14.0 years, 36 months pre-PHV would be 11 years of age; players are generally invited into the academy at around the ages of 11 – 12 years (an exact range for participants in this study is given in Section 7.3). The mean age of participants entering this study was 12.06 years, and therefore some missed this earliest data collection.

Five physical performance tests were studied, with the intention of identifying points of greatest improvement relative to PHV. Absolute changes, as reported in the present study, are not comparable. For example, the peak median 5 m spurt in improvement rate is 0.06 $\text{s}\cdot\text{yr}^{-1}$, however, the median peak CMJ improvement rate was 3.7 $\text{cm}\cdot\text{yr}^{-1}$. 3.7 $\text{cm}\cdot\text{yr}^{-1}$ is approximately 60 times greater than 0.06 $\text{s}\cdot\text{yr}^{-1}$, however, when these values are compared as a percentage change of the performance, the values are much closer together (5.7% for 5 m sprint and 21.3% for CMJ). Therefore, peak changes in performances are not as different between the performance metrics on a relative basis. Table 7-4 shows the median peak percentage change in the performance metrics measured.

Table 7-4. Percentages of peak change in physical performance tests.

Test	Percentage change
5 m sprint	5.7%
20 m sprint	2.6%
COD	2.8%
CMJ	21.3%
RSI	16.6%

7.5.1. Outcomes of 5 m and 20 m Sprint Results

The two running speed performance tests showed their main peak in improvement more than a year prior to PHV. 5 m showed a dual peak (24 and 12 months pre-PHV), whereas 20 m has a single peak at 18 months pre-PHV. However, the 20 m sprint also showed a secondary peak at 12 months post-PHV, unlike the 5 m test. Viru et al. (1999) identified the maximum rate of improvement in speed performance occurs at 18 months before PHV. This is reflected by an accelerated improvement in 5 m sprint speed (following the preadolescent spurt in speed between the ages of 5 – 9 years of age) and is evident around the ages of 12 – 14 years. Around the timing of PHV, consequent anthropometric changes (height, weight and muscle mass) and improvements in strength (Armstrong et al., 2000, Forbes et al., 2009) have been shown to occur, and these changes through puberty have been suggested to affect force production and sprint capability. The eccentric-concentric coupling - also termed the stretch-shortening cycle (SSC) - and vertical and leg stiffness could affect an individual's performance when sprinting, in particular, when maturity status is taken into consideration. Rumpf et al. (2013) highlighted that the capability to store and / or absorb power improves until the moment of PHV, whilst the ability to utilise and / or produce power develops during maturation. When quantifying the 5 m sprint, the demands require high force, low velocity, and are mainly concentric muscle actions. However, when considering the 20 m sprint demands, the force production is at a higher velocity, and an individual’s stretch-shortening capabilities / stiffness becomes more important (Colyer et al., 2018). This could, therefore, explain the occurrence of a secondary peak post-PHV for 20 m, which is not present for 5 m.

Post-hoc test of equivalence were employed with a ± 0.2 equivalence bound (Cobley, 2016), Cohen’s *d* revealed that the improvements in 20 m performance 18 months pre-PHV and the drop-off in performance approximately nine months before PHV were not significantly different from ($p > 0.05$), and not equivalent to one another (Cohen’s $d = -0.30$, CI 95% = 0.00 to 0.82). Moreover, following the drop-off in performance at approximately nine months pre-PHV, improvements in performance observed at the moment of PHV were not significantly different ($p > 0.05$) and not equivalent to one another (Cohen's d = 0.24, CI 95% = -0.27 to 0.75).

7.5.2. Outcomes of COD Results

Change of direction performance increased steadily throughout the growth period, peaking at the moment of PHV, and tailing off rapidly after two years post-PHV. Similarly, Philippaerts et al. (2006) observed that running agility peaked in improvement at the moment of PHV and had smaller but continued improvements in the years either side of PHV. In contrast, results from Belgian boys in Beunen et al. (1988) witnessed a maximum rate of improvement for COD approximately one to two years before the adolescent growth spurt. Note that this is also one to two years before PWV in Beunen et al. (1988), where PHV and PWV were observed at 14.5 years. In this study, there was a secondary peak at six months before PHV, which is also approximately one year before PWV, indicating some similarities between this and the present study. In the Beunen et al. (1988) and Philippaerts et al. (2006) studies, the distance covered in the COD test was 67% greater than the present study, this may place greater emphasis on anaerobic system performance. Change of direction tests are performed at maximal physical effort, but also include a technical / skill element. Therefore, clustering of the performance increases around the timing of PHV may be attributable to the development of the nervous system and the hormonal circulation / changes that accompany these processes (i.e., an increase in testosterone – whereby boys can experience a tenfold increase), neural progression and mechanical factors that are initiated by the onset of puberty, (Malina et al., 2004a, Viru et al., 1999, Ford et al., 2011). Change of direction performance may be associated with quantitative changes (increases in muscle mass) and qualitative changes (modifications in muscle tendon structure), that are attained at the time of PWV, and are influenced by maturation (Oliver et al., 2013).

7.5.3. Outcomes of CMJ Results

Peak improvements in CMJ performance were observed two years before PHV and remain large until approximately two years post-PHV. However, there was a notable drop in performance at the moment of PHV; this could be ascribed to the asynchrony between PHV and PWV. Peak weight velocity occurs later, and usually brings with it increases in lean muscle mass, which would assist performance in this test. After the dip in performance improvements, there is an increase in rate of performance, as increases in weight catch up with increases in height, but this does not return to the pre-PHV levels. Philippaerts et al.

(2006) identified an estimated peak in vertical jump improvement (5.1 $cm \cdot yr^{-1}$) that coincident with estimated age at PHV. However, in Philippaerts et al. (2006) there was no delay between PHV and PWV, which may partly explain the reason for the difference between the two results. Beunen et al. (1988) highlighted that peak performance improvements occurred approximately six months post-PHV, which aligns with the rebound in performance in the current study. The CMJ is an assessment of explosive strength, therefore the results of the current study are relatable to that of Silva et al. (2019), whereby a different assessment of explosive strength (standing long jump), was measured. Silva et al. (2019) also found that improvement in performance dipped at the moment of PHV, peaking approximately six months before and rebounding approximately six months post.

Post-hoc test of equivalence employing a ± 0.2 equivalence bounds (Cobley, 2016), Cohen's *d* revealed that the improvements in CMJ performance six months pre-PHV and the drop-off in performance at the moment of PHV were significantly different from ($p < 0.05$), and not equivalent to one another (Cohen's $d = 0.74$, CI 95% = 0.22 to 1.26). Moreover, following the drop-off in performance at the moment of PHV, improvements in performance six months post-PHV were not significantly different ($p > 0.05$) and not equivalent to one another (Cohen's $d = -0.61$, CI 95% = 0.13 to 1.13).

Viru et al. (1999) suggests that explosive strength performance increases are highest from the moment of PHV to one year post-PHV, however, also indicates a chronological age timing that spans 4 years (12 – 16 years). This is much greater than the chronological age window for sprint velocity provided by Viru et al. (1999), which was 12 – 14 years.

7.5.4. Outcomes of RSI Results

Peak performance increase for RSI appeared at the moment of PHV, with significant peaks at both 18 months before and after PHV. Contrastingly, Lloyd et al. (2011b) reported that approximately 12 – 18 months before the estimated mean age of PHV, a decline in RSI performance was observed (-11.5%). This reduction is RSI performance was attributed to the concept of adolescent awkwardness. However, differences between the current study and Lloyd et al. (2011b) may be the result of the different methods employed to estimate age at PHV (Khamis-Roche and Mirwald maturity offset, respectively). Stretch-shortening cycle performance is governed by effective neuromuscular functioning. Moreover, this requires an efficient interaction between both neural regulation and muscular systems, and is naturally developed from childhood through to adulthood (Radnor et al., 2018).

Developmentally, morphological changes (i.e., increased motor size unit) that are attained post-PHV have been highlighted to be a major predictor of concentric force production (Cronin and Radnor, 2019). In the present study, peak weight velocity occurred at approximately 14.7 ± 0.8 years of age, at this moment, changes in RSI performance reduced to 0.09 yr^{-1}. The increase in muscle mass attained during PWV (and hence the additional weight accrued) coupled with longer limbs (legs and arms) could explain the reduction in performance from the moment of PHV to six months post-PHV. Again, this could allude to the concept of ‘adolescent awkwardness’. Tanner (1978) described a six-month period of ‘awkwardness’ amongst adolescents. Approximately six months post-PHV, a gradual improvement increase in reactive strength performance was observed. At this point, a greater force output may be achievable during both the concentric and eccentric phases of the SSC. Increased concentric strength (attributable to the increased muscle size attained during growth) will produce larger impulse and rate of force development, resulting in a greater performance in SSC tasks such as the reactive drop jump.

Post-hoc test of equivalence employing a ± 0.2 equivalence bounds (Cobley, 2016), Cohen’s *d* revealed that the improvements in RSI performance at the moment of PHV and the drop-off in performance six months post-PHV were not significantly different from ($p > 0.05$), and not equivalent to one another (Cohen’s $d = 0.21$, CI 95% = 0.30 to 0.72). Moreover, following the drop-off in performance six months post-PHV, improvements in performance observed approximately 18 months post-PHV were not significantly different ($p > 0.05$) and not equivalent to one another (Cohen’s $d = -0.17$, CI 95% = 0.00 to 0.69).

The study had a large number of participants who had their maturity status classified as on-time, and therefore the number of data points is highest closest to the average (central) age at PHV, with lower frequency at times further away. The study could be improved by having a greater representation of participants who were early or late maturing. Additionally, only indicators of running speed, COD, lower body explosive strength and reactive jump capacity metrics were assessed. While these have been shown to be crucial to success in soccer, there are other metrics that could be assessed, e.g., aerobic capacity.

7.6. Conclusion

In conclusion, the results in the present study confirm and further identify the overall dynamics of performance relative to the interval of rapid growth through adolescence. Measured velocities for 5 m, 20 m, COD, CMJ and RSI did not express themselves at the same time relative to age at PHV. In all five of the performance metrics measured, performance continues to show improvements following PHV. These improvements may further reflect the differential timing of growth in muscle mass during the adolescent growth and weight spurt. Additionally, these improvements may further be influenced by the specificity of an elite academy soccer training programme i.e., specialised / individualised training programmes during the growth spurt, where the idea of critical or optimal windows of training relate to each individual's maturity status. The results of the present study further highlight the need to assess individuals' physical performance metrics relative to their biological rather than their chronological age.

8. Conclusion and Applications from Outcomes of this Thesis and Future Work

8.1. Overview of Thesis Findings

This PhD was funded by a professional club in the English Premier League in order to better understand how individual differences in growth and maturation may impact on player selection and performance in the context of soccer. The chapters described in the present thesis aimed to investigate the effect of maturity status had on running speed, change of direction (COD), countermovement jump (CMJ), reactive strength index (RSI) and running metrics in elite youth soccer players aged 11.3 – 18.0 years of age.

As such, Chapter 4 used a longitudinal research designed to compare two common non-invasive methods for assessing maturity status, and a simple age-based strategy in order to determine the accuracy in differentiating youths of varying maturity status. Of interest, the comparison between the two methods and being able to retrospectively identify (using the SITAR method) when PHV occurred in a sample of elite youth soccer players is novel, contributes to the body of research in paediatric science.

Following the results from Chapter 4, an established reliable method for determining maturation status had been identified. Therefore, Chapter 5 investigated the association of biological maturation (determined from the results of Chapter 4) and RAE upon performance indicators (running speed, COD and lower body explosive strength) within elite youth soccer players aged 11.3 – 16.2 years. Moreover, the interaction between these two constructs was considered. Commonly, these two terms are used synonymously, however the results of Chapter 5 identified that maturation was positively associated with all of the physical metrics except CMJ. When both maturation and relative age effect were considered by interaction, it showed as a non-significant predictor in all physical performance tests.

Following the results of Chapter 5, it was considered whether maturation would have an effect on match running metrics as well as physical performance metrics. Hence, Chapter 6 aimed to examine the extent to which variance in biological maturation also contributed to match running metrics (total distance covered, distance at high speed, distance at very high speed, maximum speed and the number of accelerations made from zone 4 to zone 6) in a sample of 37 elite youth soccer players competing across three age across one competitive playing season. By considering these three age groups allowed for comparison of players that were identified as either pre-, circa- or post-pubertal in maturity status. Again, there was an indication that maturation had an impact on match running metrics within the U14 age group, however much of the variance may be attributed to individuals under / over performing consistently in matches on the running metrics. Furthermore, within the U15/16s age group, the influence of maturation on match running metrics appeared to have less of an impact. Finally, Chapter 7 aimed to identify the overall dynamics of performance indicators (running speed, COD and body explosive strength) relative to the interval of rapid growth through adolescence in 30 elite youth soccer players measured for six consecutive years. The measured velocities for physical performance metrics did not express themselves at the same time relative to age at PHV; however, these physical performance metrics reached a peak around the time of maximal growth in height (12 months pre-PHV to 12 months post-PHV). In all of the physical performance metrics measured, physical performance continued to show improvements following PHV.

The overall findings of this thesis have demonstrated the effects of maturity status on match running and performance indicators such as running speed, change of direction and lower limb explosive power in elite youth male soccer players aged 11.30 – 18.0 years of age.

The outcomes of this research provide information regarding the effect of maturity status and the influence it has on running speed, change of direction, lower limb explosive power and match running metrics.

8.2. Applications and Integration of Outcomes from this Thesis within an Elite Soccer Academy

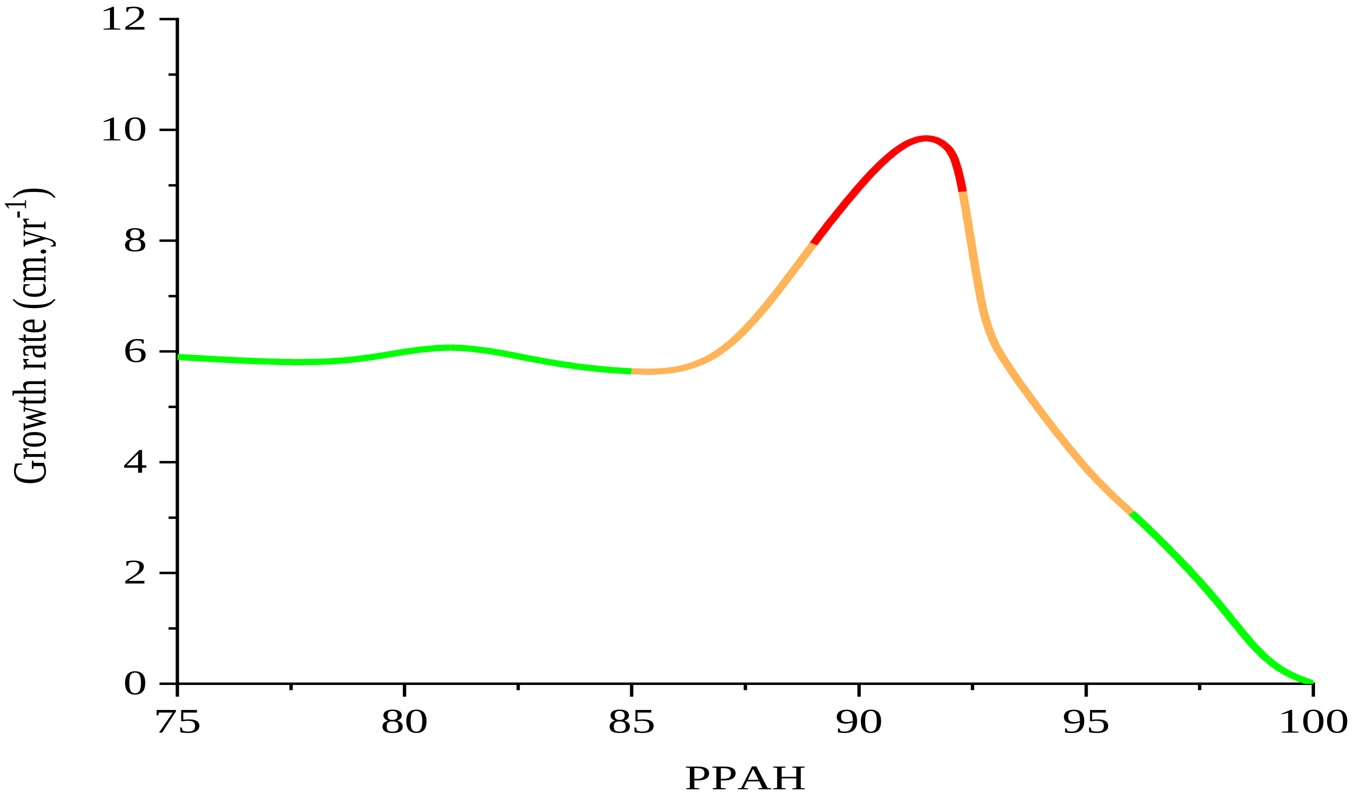
8.2.1. Key Outcomes

The present PhD was supported by a current English Premier League soccer academy, which represents the highest standard of youth development in England. The thesis aimed to gain a better understanding of the inter-individual differences in growth and maturation. It also aimed to identify the possible influences this may have on participant selection and match and physical performance parameters. Accordingly, the purpose of the present section is to summarise the main outcomes of this research and detail how these outcomes have impacted and influenced current practice within the soccer club, alongside the effects on soccer research.

8.2.2. The Integration of Percentage of Predicted Adult Height for the Assessment of Maturity Status. Outcomes from Chapter 4.

Historically, the current soccer academy has implemented the Mirwald et al. (2002) maturity offset protocol to define an individual’s maturity status at the time of observation. Despite the inherent systematic methodological problems associated with the offset method, the maturity offset protocol was integrated into the monitoring programme for the simplicity of use and its easy interpretation and understanding by coaches and relevant stakeholders. One of the important features for the predictive equation was being able to communicate the information in language that the coaches could understand. For example, if a coach was advised that an individual was currently two months away from their PHV, that was something that they (coaches) could understand and measures (e.g., adaptations to individual training programmes) could be put in place if required. Following the results of Chapter 4, it was clear that each individual needed to have their maturity status classified using the percentage of predicted adult height (PPAH) (Khamis and Roche, 1994) rather than the maturity offset protocol (Mirwald et al., 2002), because of the improved accuracy of this method. However, one of the major difficulties that had to be overcome when trying to integrate the PPAH protocol into the programme was the language barrier. How could we as practitioners try and relay that a child was at 91% of their predicted adult height, what does this information mean to a coach?

An example of how this information could be communicated to coaches and other relevant stakeholders (such as medical practitioners and physiotherapists) is shown in Figure 8-1. To overcome the language barrier, a typical growth chart has been plotted with growth zones identified by colour (where red indicates the adolescent growth spurt and represents the point of highest likelihood of a player experiencing adolescent awkwardness, green indicates the least likely period and orange is identified as medium risk). Therefore, when discussing players during inter-departmental meetings, their current PPAH is given in a similarly colour-coded table and when discussing an individual player, coaches can easily visualise where a player is in their growth journey by comparing to the growth chart. So previously, where this information was described to coaches, i.e., a particular individual is undergoing their PHV it is now a visual representation to the relevant stakeholders.



Player Name	PPAH
Player a	79%
Player b	85%
Player c	91%
Player d	93%
Player e	97%

Figure 8-1.Representation of a growth velocity chart used to communicate maturation status relative to the adolescent growth curve in an academy.

Note: PPAH – Percentage of Predicted Adult Height.

8.2.3. Quashing the Belief That Biological Maturation and Relative Age are Synonymous. Outcomes from Chapter 5.

Contrary to lay opinion, biological maturation and relative age are not synonymous. Biological maturation and relative age are independent constructs which exist and operate independent of one another and are governed by separate factors (i.e., birth and cut-off dates versus genetics / environment). Within a single year age group there is also much greater scope for variation in biological maturity than relative age. Whereas differences in relative age are limited to 12 months, differences in biological maturity can vary by up to six years (Johnson, 2015). As a consequence, it is entirely possible to be the oldest and least mature player within one's own age group, or vice-versa. Biological maturation and relative age are two terms that are commonly confused amongst coaches and others alike; "that child is a September birthday; he is already at an advantage".

The outcomes from Chapter 5, demonstrated that these two constructs are not synonymous; highlighting that a commonly held belief that the relative age effect influences performance may be somewhat overstated. The results of the linear regression models emphasised that four out five performance tests (5 m, 20 m, change of direction and countermovement jump) were positively associated with the biological maturity status of an individual. However, the linear regression models highlighted that only countermovement jump performance was associated with being relatively older in your respective age group. This finding is important as from a talent identification perspective, it is important to note that players who are advanced in biological maturity for their age group will possess a significant advantage in terms of their physical fitness (Deprez et al., 2015b). As a consequence, players who mature early may perform better during competitions and on tests of physical aptitude. Technically gifted yet later maturing players are physically disadvantaged and may struggle to compete when matched against physically more able counterparts. As a consequence, late maturing players may be more likely to be overlooked or excluded from the academy system. From a developmental perspective, players who mature in advance of their peers may also be more likely to play to their physical strengths, neglecting their technical, tactical and psychological skills (Cumming et al., 2018a). Moreover, the English Premier League recently trialled the practice of bio-banding whereby players within a specific chronological age group are banded by estimated maturity status in an effort to balance maturity associated differences in size and function. This would be expected to have advantages based on the outcomes of this study. The current academy also now makes use of this practice.

Following the outcomes from Chapter 5, academy coaches may no longer have discussions regarding the RAE when comparing individuals and their performances. While it is evident that the RAE currently still exists within the academy, the current thesis provided a limited insight into the nature and mechanisms that underlie this phenomenon. Future research examining attributes that are more likely to follow age and experience than maturation, for example, experience, technical or psychological skills, would be important. Additionally, scouting effects and biases could be focused on, as the apparent RAE may be the result of the process by which players are recruited into the academy.

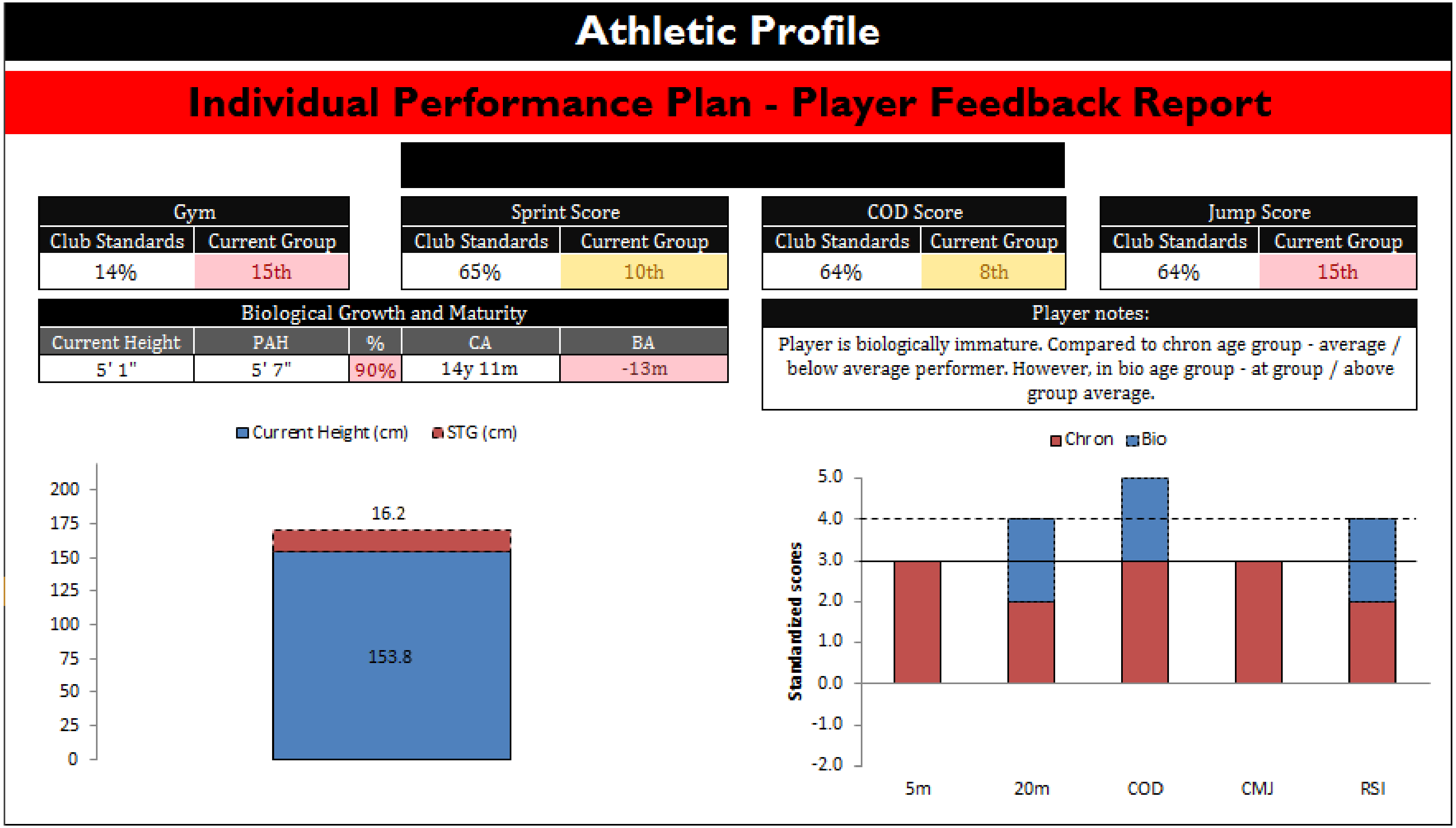
8.2.4. Chronological versus Biological Age.

Previously, it has been demonstrated that individuals in the same selection age groups can vary by up to as much as 5 – 6 years in skeletal age (Johnson, 2015). With this in mind, strategies such as bio-banding have become more popular. Proponents of bio-banding have highlighted that constraining maturity associated differences (such as variance in size, strength, power and skill in turn) results in more competitive competition and a potential reduction in injuries (Baxter-Jones, 1995).

Following this, the soccer academy has implemented a monitoring strategy to identify the differences (if any) that are presented for each individual when they are placed into their relevant biological maturity age groups. For example, Figure 8-2 is an athletic profile of an individual that is approximately 12 months delayed in terms of their biological maturity. When particular aspects of this individual's athletic profile are considered within their current chronological age group, they may be considered an average performer (red bars). However, when their biological maturity status is considered (green bars displayed on the chart), and they are assigned a biological age, the current individual would be classified as better than average on performance aspects such as 5 m, 20 m and countermovement jump capacity.

Moreover, if the athletic profile of an individual that is 11 months advanced in terms of their biological maturity (Figure 8-3) was considered, their performance in their chronological age group would suggest that they are above average for their 5 m, 20 m and reactive strength index performance variables (red bars). However, when this individual is compared to their biological age group, it becomes clear that they are mostly average in almost all of their performance aspects, except their reactive strength index where they remain above the group average. Therefore, if this individual was bio-banded into their appropriate biological age group, they could no longer rely on their superior physical attributes that they may have been relying on in their chronological age groups to get them through training or matches, rather they would be faced with a whole new technical / tactical challenge.

Coaches at the club are now extremely interested in both the individual’s chronological and biological ages. In addition, as part of the recruitment process for a new signing into the academy, individuals’ physical capacities are not only compared to peers within the same chronological age group, but also compared to individuals of a similar biological age.



Athletic Profile

Individual Performance Plan - Player Feedback Report

[redacted]

Gym	
Club Standards	Current Group
14%	15th

Sprint Score	
Club Standards	Current Group
65%	10th

COD Score	
Club Standards	Current Group
64%	8th

Jump Score	
Club Standards	Current Group
64%	15th

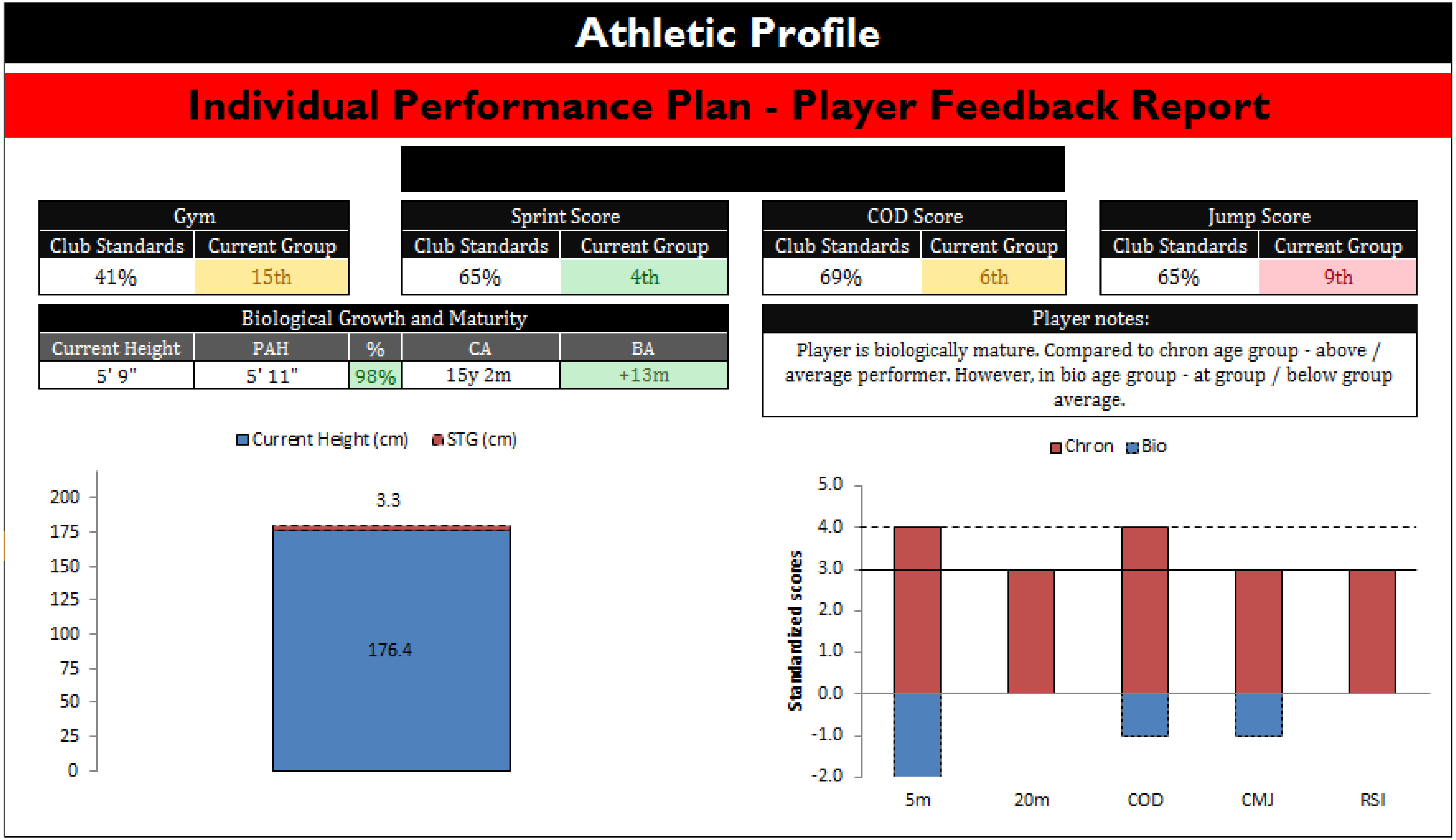
Biological Growth and Maturity				
Current Height	PAH	%	CA	BA
5' 1"	5' 7"	90%	14y 11m	-13m

Player notes:

Player is biologically immature. Compared to chron age group - average / below average performer. However, in bio age group - at group / above group average.

Figure 8-2. Representation of a player profile used for communication between relevant stakeholders. Current individual is biologically immature (delayed by 13 months).

Note, the solid black line represents the current chronological age group average; the dashed black line represents one standard deviation more than group average.



Athletic Profile

Individual Performance Plan - Player Feedback Report

[redacted]

Gym		Sprint Score		COD Score		Jump Score	
Club Standards	Current Group	Club Standards	Current Group	Club Standards	Current Group	Club Standards	Current Group
41%	15th	65%	4th	69%	6th	65%	9th

Biological Growth and Maturity				
Current Height	PAH	%	CA	BA
5' 9"	5' 11"	98%	15y 2m	+13m

Player notes:

Player is biologically mature. Compared to chron age group - above / average performer. However, in bio age group - at group / below group average.

Figure 8-3 Representation of a player profile used for communication between relevant stakeholders. Current individual is biologically more mature than their current chronological age group (advanced by 13 months).

Note, solid black line represents the current group average; dashed black line represents one standard deviation more than group average.

8.2.5. Do GPS Match Running Metrics Give the full Picture of Player Ability, or does More (Maturity) need to be Considered? Outcomes from Chapter 6.

Global positioning systems are becoming ever more popular within soccer academies, even more so now as modern-day coaches are beginning to take a keen interest in what outputs they are getting from particular drills. Chapter 6, demonstrated that running metrics that are collected from the GPS units need to be treated with caution as they need to be considered by position (defence; midfield; attack, spine or lateral). Furthermore, within the younger age group (U14s) there was a suggestion that maturity seemed have an impact on match running metrics, however much of the variance may be attributable to individuals under / over performing consistently in matches on the running metrics. However, this wasn't apparent in the older age groups (U15/16s) as the influence of maturation on match running metrics appeared to have less of an impact.

The outcomes of Chapter 6 highlight the requirement in some instances for concepts such as bio-banding, which has previously been used to address factors including growth and maturation (Cumming et al., 2018a, Cumming et al., 2017b). The outcomes from this chapter suggest that bio-banding may be better suited to individuals between the ages of 11 to 14 years of age, where those factors are more influential and where greater variance would be seen of participants at difference stages of their development.

Interestingly, Chapter 6, identified that in order for academies to identify and recognise 'good' players (high performing in match running metrics), much more needs to be considered rather than GPS metric outputs alone. The GPS metrics that are collected need to be considered per playing position. It is worth noting however, one of the key philosophies of the current academy appreciates that every child needs to develop as much as possible towards their full potential. This involves each individual facing success and also learning to deal with failure, which can be experienced through playing in a position that is not their natural playing position. Therefore, defining a position that an individual regularly plays in (especially in younger age groups) can be a challenge, meaning that there are further difficulties when analysing GPS metrics and linking to performance or consistency.

Following the outcomes from Chapter 6, the academy has recently begun to start exploring what is a good performance and / or what does a good performance look like. To do this, younger individuals, between the ages of 13 – 16 years, are monitored, and their match metrics (GPS metrics) and maturity status are tracked. Furthermore, it would be expected that an increase in match running metrics would coincide with an increase in the individual's maturity status. Furthermore, when individuals are more mature (e.g., when they are in the U16 – U18s squads), they are compared between the same positions only. For example, if there are two central defenders, the match running metrics between these two participants would be compared; they would not be compared to any other position on the pitch i.e., a central midfielder or attacker. As per the outcomes of Chapter 6, it was recognised that the influence of maturity does not affect match running metrics as much for the more mature individuals.

Identifying whether an individual performed better because their match running metrics were higher than the rest of the team can be somewhat misleading. For example, the individual that achieved a higher peak speed than the rest of the squad may be the only participant that is capable of achieving the threshold defined on the GPS system. The thresholds that are defined on the GPS systems are absolute scores; they are not relative to each individual. If the previous figure examples (Figure 8-2 and Figure 8-3) are taken into consideration, the individual in Figure 8-2, is biologically almost two years more mature than their counterpart, and therefore, may be more likely to achieve greater speeds during a game. The ultimate desire, therefore, would be to have a specific performance level that is expected, per position, per maturity level. It is infeasible to make this assessment with the finite regularity necessary, and so the current plan for the Academy is to produce bands for maturity ranges (pre-, circa- or post-pubertal) for different spine / lateral and playing positions so as to identify the top performing players, in addition to tracking players through their development to ensure their improvement as described above.

8.2.6. The Dynamics of Physical Performance. Is it really a One Boot fits all? Outcomes of Chapter 7.

Young athletes are traditionally grouped by chronological age for the purpose of training and competition, and the chronological age of the Youth can vary significantly in terms of maturity status at the time of observation (skeletal age, stage of puberty, and in maturity timing), (Beunen and Malina, 1988, Patel et al., 1998, Marshall and Tanner, 1970, Malina et al., 2004a). Despite the adolescent growth spurt in height being comprehensively researched, the variability in the timing, intensity and the duration and influence of peak velocities on physical performance tasks is somewhat less investigated (Silva et al., 2019). Individuals that are advanced in maturity typically demonstrate superior physical performance than their less mature peers (in absolute terms) (Silva et al., 2019). However, Lefevre et al. (1990) suggested that these later maturing individuals catch-up to their earlier maturing counter-parts, and in some instances, may achieve better performance outcomes by early adulthood. Cross-sectional research has been relatively consistent in identifying that early maturing boys are typically more successful in soccer in mid to late adolescence. Moreover, boys that are approximately 14 years of age, advanced in their maturity status (both sexual and skeletal) are better represented in youth soccer teams (Cacciari et al., 1990, Malina, 2003, Peña Reyes et al., 1994).

As shown in Section 8.2.4 individuals that mature 'early' when compared to their chronological peers, will show better performance. Chapter 7 shows that a large proportion of the improvement that an individual undergoes can be ascribed to developmental processes. This can therefore explain why (also in Section 8.2.3) the same individuals did not show greater performance than individuals of the same maturity status (biological age).

This therefore adds weight to comparing individuals within the academy on a biological rather than chronological basis as is now becoming standard practice in the Academy. Training is important, but kids aren't just getting better from the training, but also through maturing. If there is a kid that is mature and ahead of age group, performance should improve first (kid get better first) but as the individuals performance plateaus, this should not be a cause for concern, as their performances may continue to get better but at a slower rate.

8.3. Limitations to the Results

The elite nature of the sample and practical constraints (numbers and availability) provided challenges in sample sizes. Although the numbers of participants in each of the studies was statistically powerful, larger sample sizes would have helped build confidence in the results and could have allowed for additional investigations. Additionally, as the results are specific to samples of elite youth soccer players; they may not be immediately applicable to, for example, the general population.

The data was collected on a routine basis within the academy; however, it was not always possible to have an equal distribution of measurements across participants. For example, in Chapter 6 some participants had two measurements, whereas others had up to 30 measurements. This was an unavoidable outcome of the study design (where a minimum playing time was set), but this did restrict number of points taken for some players which was undesirable.

This PhD tested for maturity effects on physical parameters such as running speed and jumping, yet there are more facets to the game of soccer and selection / retention decisions within academies such as tactical, technical, social and psychological. These factors were not investigated in any of the studies in this thesis.

A final limitation of this work is that maturity statuses were not normally distributed. This is likely to be a feature of the elite academy setting, in which participants were selected. It was commonly thought that early maturing boys would be over-represented within elite academies, however, within this study the majority of participants were classified as on-time. In contrast, it was also anticipated that most participants would be from Q1 of the selection year, and this was observed. Both of these factors could prevent comparison with other population distributions.

8.4. Future Work

The findings of this research have highlighted that there is an influence of biological maturation of physical performance, both in training and match situations in elite youth soccer players. Being aware of the effects of growth and maturation on individuals at different stages of their playing journey is necessary to optimise their development and club retention decision. However, future work could investigate further in several areas, some examples of which are given below.

8.4.1. Identifying Age at PHV within Multi-ethnic Groups

The Khamis-Roche method of pubertal growth spurt that was used within this research to identify age at PHV was developed based on individuals of North American Caucasian ethnicity. Therefore, this may not be a suitably accurate method for studies where participants are of different ethnicity to the original study. A study similar in nature to that undertaken in Chapter 4 but with two larger cohorts, one of Caucasian and one of non-Caucasian participants would be of interest. This would allow comparison between the two ethnic groups and highlight any variations which may place limitations on the use or accuracy of this method with non-Caucasians. Note that the group in this study was multi-ethnic and Khamis-Roche still outperformed the maturity offset method considerably and so ethnic diversity is not expected to have a large impact.

8.4.2. Improvements to Age at PHV with PPAH

The window selected for the interval of the pubertal growth spurt calculated by PPAH was based on observations by (Sanders et al., 2017). However, this percentage height window equated to a relatively large age window. Further work could be conducted to narrow this window. This would further improve the accuracy of the PPAH method.

Additionally, it would be interesting to see if the analysis and the proposed percentages that form the height window (85 – 96%) are valid for participants who are early, on-time or late maturing. The sample used in this research consisted of participants who mostly matured on-time, and so analysis of this type was not possible. An ideal dataset would include large longitudinal cohorts with even distribution across the three maturity categories.

8.4.3. Selection of Additional Relevant Performance Tests

Within this research, maturity influence on training and match performance was analysed. The indicators used for performance were those commonly used within academies, with a focus on running speed, COD and lower body explosive strength. However, soccer requires skills from across a broad range. Further work could be done investigating metrics such as aerobic capacity training tests, positional or tactical GPS data, technical actions in either training or matches, or any number of relevant social or psychological concepts in a similar manner to that undertaken within the body of this thesis.

The analysis performed in Chapter 7 looked at changes in physical performance metrics in relation to the adolescent growth spurt (i.e., maturity status). A further question could be raised as to whether the timing of maturity also had an influence on changes in these physical performance metrics. A complete further investigation would also look for any interaction between these parameters.

8.4.4. Analysis of Match Running Metrics

Within this study, the collection of match running metrics by GPS was analysed taking only matches where participants completed a full 80 minutes. This contrasts with some previous research, e.g., Buchheit and Mendez-Villanueva (2014), where only half-match data was used. The influence of this difference is not well understood, and there are reasons for choosing either option. Half-match data abstracts factors such as fatigue and tactical changes which appear late on in matches, and so this can remove some of the variation between matches where difficulty and result will differ. Full-match data does include these factors, which shows the realistic demands of a match. To appreciate the degree to which this affects results (if at all) should be studied through a like-for-like comparison.

The match running metrics that were studied in this thesis were from matches that involved U14s, U15s and U16s. As discussed within Chapter 6, the older age groups included individuals who were almost exclusively post-PHV. The U14s age group had individuals that ranged from pre-PHV to post-PHV. An effect of maturity on match running metrics was not found for the older age groups, and this is ascribed to the homogeneity. Future work could look at whether this is also seen in homogeneous groups where all individuals are pre-PHV, for example, an U12s age group team.

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