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Training load dose-responses in adolescent male football:

the importance of biological maturation

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Summary

The period surrounding the adolescent growth spurt is a turbulent but crucial stage of development for young footballers in their pursuit of becoming full-time athletes. At a time of almost constant talent (re)selection which coincides with major physical and physiological changes players experience large fluctuations in performance and a heightened injury incidence. Adding to the complexity of this period, the timing and tempo of biological maturation varies between individuals causing a diversity in physical and physiological capabilities, influencing the dose-response to training. Although differences in biological maturation and the links with injury are acknowledged in literature, little evidence exists to quantify the magnitude and extent to which these impacts perceptions of load and subsequent performance. This thesis aims to quantify the maturity-specific responses to load using ecologically valid approaches to aid the enhancement of provision offered to young academy players.

To provide a context and informed backdrop for the rest of the thesis, it was deemed important to first identify the current practices of, and perceived barriers to monitoring training load and biological maturation in academies. A cross-sectional survey design was used to ascertain perceptions of staff from male (EPPP) and female (RTC) academies during the 2017/18 soccer season. In total, 49 respondents completed the survey who advocated injury prevention as highest importance for conducting training load and maturation monitoring across academy groups, with overall athletic development, load management, coach and player feedback considered important. However, there were clear differences in monitoring strategies that academies of different categories adopted, which were often associated with resources or staffing. Survey responses suggest that despite routine monitoring of biological maturation and training load being commonplace within adolescent soccer the communication and dissemination of this information is often lacking, which may ultimately impede the impact of the monitoring practices for the players. Resource and environmental constraints create natural diversity around the strategies adopted, but academies are recommended to adopt sustainable and consistent approaches to monitor key variables to inform the coaching, selection, and development process.

The survey chapter identified that most clubs employ one of the various 'non-invasive', somatic equations to estimate biological maturation. However, the methodological differences associated with calculations often mean they provide variable estimations, even when using the same anthropometrical data. Therefore, it was deemed important to this thesis to observe the agreement of maturity estimations and compare concordance between methods when looking to estimate maturity status. Thus, anthropometric data from 57 participants was collected from a single assessment point during the 2017-18 season, with an additional 55 participants providing three repeated measurements during the 2018-19 season, resulting in 222 somatic estimations observed. Results indicated that all methods of maturity-offset (MO) produced an identical estimate of age of peak height velocity (13.3 years) with mean prediction of adult height (PAH%) providing a mean estimate of 93.6%, which also aligns closely. However, when looking to identify circa-PHV individuals there is greater concordance when using conservative thresholds (44-67%) than when using more stringent bandwidth thresholds (31-60%), with both being considered moderate concordance at best. Therefore, although overall findings indicate that there is very high to near perfect agreement between all approaches when predicting APHV, concordance of categorisation between these methods is less useful. Therefore, this chapter indicates that PAH% and MO methods are not interchangeable, and practitioners should utilise one approach routinely for all maturity-specific interventions.

Academy squads are comprised of players within chronological parameters but often present significant variations in physical characteristics including body mass (~50%), stature (~17%), percentages of predicted adult height (10-15%) and fat free mass (~21%). These maturational changes likely influence performance and dose-responses to load, but limited studies using standardised activity profiles have directly observed this influence. Therefore, this thesis aimed to quantify the neuromuscular performance (CMJ, RSI absolute and relative stiffness) and psycho-physiological (d-RPE) responses to a simulated soccer-specific activity profile (Y-SAFT^{60}) and analyse whether this dose-response was moderated by maturation in EPPP academy players. Data illustrated an interaction between perceived psycho-physiological load (RPE-T) and maturation, with absolute stiffness, relative stiffness and playerload (PL) showing slope significance across various stages of maturation (~86-96% PAH). These interactions suggest that psycho-physiological dose responses are influenced by maturation and should be considered for training prescription purposes, which is likely a result of the musculotendinous changes that occur around peak height velocity (PHV). Therefore, practitioners are urged to consider the maturational load-response variation to reduce injury incidence from inappropriate levels of physical and cognitive stress, which are likely compounded chronically with multiple weekly sessions.

Typically, players experience between 3-4 acute bouts of specific training on a weekly basis, proposing that the maturity-specific load-responses observed above may be exacerbated over the course of a season. 55 male soccer players from a Category 2 EPPP academy were monitored during the 2018-19 season. Self-reported perceptions of psycho-physiological (d-RPE) intensity were collected approximately 15-minutes after each training session for a period of 40-weeks using the CR100® centi-Max scale. Analysis indicated that a 5% increase in PAH%, resulted in a reduction of ~7AU per session, with a ~14AU difference for a 10% difference in PAH%. Therefore, players less biologically mature are consistently working harder just to compete with more biologically advanced teammates of a similar chronological age. Again, these changes are mostly attributed to musculotendinous changes because of maturation and therefore a higher relative mechanical load experienced by less mature individuals. When accrued, these small inter-individual differences lead to a substantial variation in training load (~40-50%) over the 40-week season. This has the potential to undermine the whole developmental pathway, as the assumption that players of a similar chronological age are experiencing similar load-responses is precarious. Failure to act, by adopting more maturity sensitive ways of working for example, will result in a 'survival of the fittest' environment, rather than the systematic, considered, and individualised approach to optimal loading proposed in policy documents and literature.

Bio-banding is a method to group individuals based on biological maturation rather than chronological age. Supplementing the chronological programme with bio-banded activities may offer practitioners a practical method to better control load exposure and ultimately mechanical load related injury risk. Therefore, the final thesis study explored effects of standardised chronological and bio-banded training sessions on neuromuscular performance and psycho-physiological perceptions of intensity in 55 male soccer players from a single academy. Players participated in bio-banded and chronologically categorised bouts (x5) of 5-minute 6v6 (including GK) SSG on a playing area 45 x 36 m (135m^2 per player). Prior to and following this, players performed a standardised sub-maximal run using the audio controlled 30-15^{IFT} wearing foot-mounted inertial devices. Findings indicate that the introduction of bio-banded training sessions minimises the decrement in neuromuscular and locomotor markers and psycho-physiological ratings of intensity for players across the maturation spectrum. From a load management point of view, the relatively smaller pre-post changes observed in bio-banded SSGs offer promising early indications that biologically categorising training may help to stabilise the stress-response for players across maturity groups and facilitate a load management option for practitioners. Based on this, practitioners should actively seek opportunities to integrate biologically classified training activity alongside chronologically categorised sessions within their training schedules. In doing so they may alleviate the consistent stress placed on less mature players as part of standard chronologically categorised sessions without compromising the development of those more mature and able to tolerate greater workloads.

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Peer-reviewed publications directly from this thesis

Chapter 4: **Salter, J.**, De Ste Croix, M.D., Hughes, J.D., Weston, M. and Towlson, C. (2020). Monitoring practices of training load and biological maturity in UK soccer academies. *International Journal of Sports Physiology and Performance,* 16(3), 395-406. doi: 10.1123/ijspp.2019-0624

Chapter 5: **Salter, J.**, Cumming, S., Hughes, J.D., and De Ste Croix, M.D. (2021). Estimating somatic maturity in adolescent soccer players: Methodological comparisons. *International Journal of Sport Science and Coaching*, Available online only (currently in-press)

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Chapter 7: **Salter, J.**, Julian, R., Mentzel, S., Hamilton, A., Hughes, J. and De Ste Croix, M. (2022). Maturity status influences perceived training load and neuromuscular performance during an Academy soccer season. *Research in Sports Medicine*, Available online only (currently in-press)

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Salter, J., Johnson, D. and Tolwson, C. (2021). A stitch in time saves nine: the impact of biological maturation for talented athlete development. BASES: The Sport and Exercise Scientist, 69.

Conference proceedings from the thesis

Salter, J. Current trends in monitoring biological maturation and training load in elite adolescent soccer. *Proceedings of the European Congress Sport Science*, Dublin Conference Centre, Ireland, July 2018.

Salter, J. Maturity status, not tempo, influences training load and neuromuscular performance during an academy soccer season. *Journal of Sport Sciences*, BASES Annual Conference, November 2021.

Symposia events associated with this thesis

Salter, J. Maturation in youth football training. Saarland University, Saarbrucken, Germany. 17th November 2021

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List of abbreviations

The following abbreviations have been defined in text in the first instance:

Abbreviation	Definition	Unit
ACWR	acute: chronic workload ratio	
APHV	age at peak height velocity	years
CMJ	countermovement jump	Centimetres (cm)
EPPP	Elite Player Performance Plan	
EWMA	exponentially weighted moving averages	
dRPE	differential rating of perceived exertion	Arbitrary units (Au)
GPS	global positioning satellite	
HR	heart rate	beats per minute (bpm)
K^{leg}	leg stiffness	$kN \cdot m^{-1}$
m.Min	metres per minute	metres (m)
MO	maturity offset	years
PAH%	percentage of predicted adult height	
PHV	peak height velocity	years
PL	player load	Arbitrary units (Au)
RPE	rating of perceived exertion	Arbitrary units (Au)
RSI	reactive strength index	
sRPE	sessional rating of perceived exertion	Arbitrary units (Au)
TD	total distance	metres (m)
Vel^{M}	maximum velocity	meters per second (m/s^2)
YDP	youth development phase	
Y-SAFT	youth soccer-specific aerobic fitness test	

Disclaimer

"I certify that this work contained in this thesis, or any part of it, has not been accepted in substance for any previous degree awarded to me, and is not concurrently being submitted for any degree other than that of Doctor of Philosophy being studied at the University of Gloucestershire. I also declare that this work is the result of my own investigations, except where otherwise identified by references and that the contents are not the outcome of any form of research misconduct"

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Chapter 1

Introduction

Chapter 1: Introduction

1.1 The importance of academy football

Football (soccer) is one of the most popular sports in the UK with well over eleven-million people participating in the sport (Statista, 2020a; The Football Association, 2015). This apparent popularity of football is most obvious between the ages of 11-15 where it is clearly the most participated sport, with approximately 45% of children involved in football to some degree, with swimming (30%) the closest competitor (Statista, 2020b). Despite this, there has been a sizable decline in participation in recent years, with ~61% of 11-15 year-olds participating in 2008/09 (Department for Digital, Culture Media and Sport, 2020). The biggest decline in participation stems from males, whose participation has dropped by 15% with females dropping by 2% (Department for Digital, Culture Media and Sport, 2020). This is in spite of the Football Foundation investing in more than £1.5 billion in recent years to provide better playing conditions for football in the UK, including significant investment into training and changing facilities (Football Foundation, 2020), in addition to The Football Association investing £1.2 million to help support football coaches, of which there are more than ever (>315,000) (The Football Association, 2015, 2020). Theoretical explanations for this decline in participation are broad, complex and beyond the scope of this thesis, but this backdrop offers a stark message of the collective need to consider every opportunity to create positive sporting experiences for young individuals and subsequently prevent drop-out and promote lifelong participation.

Football (and exercise in general) has recently been referred to as 'medicine' in relation to the physical, physiological and psycho-social benefits it offers those who participate (A. Evans & Ottesen, 2020; Faigenbaum & Myer, 2012; Krustrup & Parnell, 2019), with the vast majority of those doing so for recreational reasons. Although recreational in nature, there were 33,416 affiliated male youth teams in 2015 (The Football Association, 2015) which offers players exposure to structured coaching and learning environments. These opportunities are what stimulate the reported medicinal effect as they are comprised of social and physical interaction through deliberate-practice and deliberate-play which are deemed important for holistic development in young sports people (P. Ford et al., 2009). Of the reported 3.35 million participants aged between 5-15, only a minority (<3%) are involved in the nationally recognised talent development programme known as the Elite Player Performance Plan (EPPP) (Premier League, 2011). This programme, initiated in 2012, provides clear criteria and guidelines for the minimum expectations for elite players aged 8-23 dependant on the category rating of the academy, which can see players accrue between 3,760 and 8,500 deliberate coaching hours depending on their entry point (Premier League, 2011). This policy also stipulates the requirements for quantity and quality of facilities, staffing, coaching, recruitment, and games programme for each level of category (i.e., category 1 to 3) and in return awards financial investment to support the programme. This stimulates a shift in approach from purely participation and enjoyment towards a clear age-appropriate focus on long-term technical, physical, and psychosocial development with an end-goal of turning professional. Naturally, this professionalisation increases the demands on players to which some have suggested may be detrimental to the long-term development of individuals (Gledhill et al., 2017).

The introduction of the EPPP was partly stimulated by growing concerns around the increased financial presence Premier League clubs had within Europe and the relatively rapid increase in transfer expenditure (£2.43bn in 2009 to £3.43bn in 2014) due to increased television funding rights (Poli et al., 2015). Most of this expenditure (~67%) was received by teams from one of the other main European leagues (i.e., La Liga, Ligue 1, Bundesliga or Serie A) meaning the majority of transfers were foreign imports (Poli et al., 2015), which was indirectly having a negative impact on the number of academy graduates transitioning to the clubs senior and subsequently, national teams. The Union of European Football Associations (UEFA) recognised this and instigated a phased requirement for home-grown players. A home grown-player is defined as a player who, regardless of their nationality, have been trained by their club or by another club in the same national association for at least three years between the age of 15 and 21 (UEFA, 2014). This rule applies to several major leagues and all European competitions to protect young players and prevent the wealthiest clubs 'stockpiling' talent. This policy has progressively increased from four players in 2006/07 to now requiring a minimum of eight homegrown players in their 25-man squad which enables clubs to maintain a local-identity and has rejuvenated the emphasis for clubs to develop their own talent through academies.

This combination of elite level policy and professionalisation of the academy structure has encouraged clubs at all levels to invest in their talent development environments, safe in the knowledge that ultimately either of the following outcomes will follow; a) graduation of talented youth players into professionals that contribute to the club's future on-pitch success, or b) financial reward from transfer income by selling talented youth players. For smaller clubs, historically there has been limited protection from bigger, wealthier clubs 'preying' on their most talented youth prospects. However, the introduction of the EPPP includes an obliged 'compensation fee' awarded to the 'training club' for their role in developing the individual (Premier League, 2011). The standard fee received is dependent on several factors (i.e., age of player, category of academy) but varies between £3,000 and £40,000 and is then followed by an 'appearance fee' of up to £150,000 dependant on professional appearances for their new club (Premier League, 2011). In a recent example involving an academy involved in this thesis, a player moved for an initial fee of £150,000 with sell-on clauses securing a further £2.5 million three-years later (Mitchinson, 2020). This type of financial windfall offers clubs financial stability and secures the future of the academy for several years which, therefore, makes the academy system sustainable and vitally important to the local communities and the wider football pyramid.

1.2 The complexity of adolescent development

Sustainability and consistency are two primary components required when designing a long-term plan for developing talented athletes. Various historical models of talent or athletic development exist, each with their own idiosyncrasies surrounding the method of delivery, pedagogy and timing of intervention and how this should progress with chronological age and maturation (Lloyd, Oliver, Faigenbaum, et al., 2015). Despite various attempts to establish systematic consensus in talent development (Bailey et al., 2020; Côté & Vierimaa, 2014; P. Ford, De Ste Croix, et al., 2011; Gagné, 1985; Lloyd & Oliver, 2012), there is still limited agreement around the best approach to nurture individuals within sport. This disagreement stems from two primary mechanisms, either a) differentiating between a performance or participation driven domain and b) the non-linear development in biological maturation that impedes individual ability to align with the development frameworks (P. Ford, De Ste Croix, et al., 2011). The EPPP drives performance and aims to progressively nudge individuals towards competition, which aligns with the seminal model established by Balyi and Hamilton (2004). However, as with several others, this model fails to account for the individual variation in timing and tempo of biological maturation and the integrated but not necessarily linear development of genes, hormones and anthropometry (P. Ford, Collins, et al., 2011; Malina et al., 2004). The omission of these considerations are major limitations of the literature surrounding talent development and one that needs to be explored more intensively in future work.

As alluded to previously, various talent development programmes (and specifically the EPPP) utilise chronological age to stipulate transitions in frequency, intensity, exposure and focus of training activity. Academy age-groups are based on where an individual's birth date falls in relation to the cut off for the academic year (1st September to 31st August). An example would be that EPPP policy stipulates that coaching hours are dependent on the academy category and the chronological age of the players (i.e., U11s at a category 1 academy receive 8-hours coaching per week, whereas the U16s received 12-hours per week) (Premier League, 2011). Although in some perspectives, chronological-age categorisation offers an adequate method to group individuals (e.g., playing experience, cognitive, social and motor development) it fails to consider the large variation in biological maturation (Cumming, Brown, et al., 2018). Evidence from 11-12 year-old academy footballers shows body mass can vary between 30 to 49 kg, stature between 134 to 157 cm and skeletal age can differ between 9.6 to 14.1 years (Figueiredo et al., 2010) with similar disparities reported by Hannon et al (2020). Therefore, despite being chronological-age categorised, there can be a 4-5-year difference in biological maturation and therefore the physical preparedness or ability of these individuals to 'cope' with these systematic increases in training volumes becomes problematic.

These differences in biological maturation often manifest themselves into greater opportunities for early-maturing individuals (maturity-selection bias), as a result of favourable perceptions from recruitment staff in the academy (Malina, 2003; Malina et al., 2015). This can then negatively impact late-maturing individuals as they are potentially overlooked, excluded or denied as they try to 'catch-up' to compete with more physically able competitors (Cobley, 2016). There is mixed evidence around the long-term implications of maturation and success in football. A recent study (A. Johnson et al., 2017) illustrated a clear bias towards earlier-maturing players and their increased likelihood of being retained, with other studies showing unclear association (M. Hill, Scott, Malina, et al., 2020; Noon et al., 2020) and others reporting poor association between success and maturation (Craig & Swinton, 2020; Grendstad et al., 2020). Irrespective of whether maturation impacts long-term success or not, there is clear evidence to suggest an increase in injury incidence around the adolescent growth period (Bowerman et al., 2014; Bradshaw et al., 2014; A. Johnson et al., 2009; D. Johnson et al., 2020; Monasterio et al., 2020; Rommers et al., 2020; Wik, Martínez-Silván, et al., 2020). Tentatively, this may be due to the substantial variation in biological maturation and that potentially inappropriate, age-informed training exposures are super-imposed on vulnerable and often fragile physical frames (van der Sluis et al., 2013, 2015a), leading to inappropriate loading for some players. Evidence from multiple populations suggests that inappropriate management of training exposure/load is associated with increased injury risk (Brink, Nederhof, et al., 2010; Drew & Purdam, 2016; Gabbett, 2016a; D. Johnson et al., 2020; Soligard et al., 2016). Without adequate management, the negative implications associated with injury (e.g., psychosocial, physical and developmental) will more than likely have a significant impact on the long-term outcomes of athletic success and should therefore be considered high priority in talent development environments (Forsdyke et al., 2016; Gledhill et al., 2017).

It is important to remember that sporting demands are placed on the backdrop of other, potentially superior stressors, in the form of academic and personal development and therefore need to be managed accordingly. The period of adolescence is a significantly challenging time for self-development, during which individuals progress their understanding of personal roles, relationships and interests both inside and outside of sporting environments (D. Evans, 1994). Developmental changes in emotional, behavioural and hormonal interactions (termed 'daily hassle') significantly impact the way in which young individuals think, behave and respond to situations and even how they feel about themselves (D. Evans, 1994; Ivarsson et al., 2014; Malina et al., 2004). In turn, this can temporarily elevate an individual's appraisal of stressful situations (i.e., coping) which may then influence the athletes cognitive or physiological ability and even lead to injury (Ivarsson et al., 2014). Additionally, combined with the intense and 'professionalised' EPPP environment, these developmental changes can play a major role in self-identity formation, which may lead to young athletes developing a sense of self directly relating to sport (A. Hill, 2013). In such a case, youth athletes are deemed susceptible to stressful events within their sports domain (e.g., injury, de-selection) and may leave them vulnerable to undesirable consequences of youth sport, such as burnout (A. Hill, 2013). Burnout is characterised by several facets including reduced sense of accomplishment, physical and/or emotional exhaustion, and sport devaluation (Smith et al., 2018). It is believed that athletic burnout includes a strong psychological component with excessive training and insufficient recovery (i.e., overreaching) being a potential contributor (C. Williams et al., 2017), which is thought to negatively impact on wider performance and wellbeing (Cresswell & Eklund, 2007). It is therefore fundamental that we aim to minimise the incidence and likelihood of 'stressors' during this stage of development to protect the physical and mental health of young players.

1.3 Measuring the unknown

Protecting players from the negative physical and psychological consequences of injury is multifactorial and multidisciplinary in nature (Bahr & Krosshaug, 2005; Impellizzeri, Menaspà, et al., 2020). There are various factors that contribute to injury and, conversely, injury itself is not the only factor to cause negative physical and mental wellbeing in athletes. However, there is a growing body of evidence that associates the management of training load and the reduction of injury in elite sports (Drew & Finch, 2016; Impellizzeri, Menaspà, et al., 2020; Jeffries et al., 2020; West et al., 2020; Windt et al., 2017; Windt & Gabbett, 2017). Methods of determining training load in sport have evolved in recent years (Impellizzeri, Marcora, et al., 2019a), with various new approaches (due to technological developments) and iterations of seminal concepts applied more readily (Akenhead & Nassis, 2016; Bourdon et al., 2017; Burgess, 2017a). However, the vast majority of this work has been conducted in adult populations, primarily due to resource, staff and practical barriers involved with load monitoring in adolescent environments (Booth et al., 2017), more specifically academies (see thesis chapter 4). It would be irresponsible to directly apply research from adult populations to youth athletes and expect a similar outcome based on the physical, physiological, and biomechanical characteristics of both populations. Effective load monitoring in these populations should be dynamic over time and adjustable to individual developmental factors according to competition phase, acute or chronic stress and biological maturation (Booth et al., 2017). For this reason, it is currently extremely difficult for academy practitioners to quantify adequate 'dose-responses' for their athletes, and almost impossible to do so when controlling for maturation, which may in turn be at least partly responsible for the elevated injury incidence during this stage of development (D. Johnson et al., 2020; Rommers et al., 2020).

Adding further complexity, there is a high possibility that these athletes are engaging in concurrent playing and/or training programmes supervised by multiple different coaches (Phibbs et al., 2018a). Although EPPP guidelines suggest that individuals should not play for 'grassroots' clubs alongside their academy activity, it does not prevent them participating for school teams, representative clubs or participating in other sports altogether. In some ways, this varied involvement (particularly across sports) can help to enhance athletic development by exposing them to a broad selection of movement tasks and coaches (Lloyd et al., 2016), but equally, each environment will expose the individual to accumulated load which may, in turn, elevate their risk of injury (Gabbett et al., 2014). For example, commonly a Wednesday during term-time is associated with after school-sports activities, which would more than likely involve the more talented individuals (i.e., those who are also part of EPPP academies). It may be that the individual plays for the school for the important social enjoyment of playing with their friends, but then attend a structured and intense academy training session the same evening. Rightly so, coaches in both domains would require commitment, application and endeavour from that individual but may be otherwise oblivious to the additional workload on that day leading to a 'spike' in load (worst case scenario) (Gabbett, 2016a).

In isolation, this could be considered an inconvenient coincidence, however anecdotally, this appears to be a common scenario that occurs frequently due to the proficiency of the young individuals. This potentially results in disproportionate training loads with insufficient rest and ultimately elevates the risk of particular overuse-type injuries and non-overreaching (Gabbett et al., 2014; C. Williams et al., 2017). Although this issue has not been explored within football explicitly, there were clear between individual differences in weekly training loads with some having significantly higher weekly loads than others in adolescent rugby (Phibbs et al., 2018a). To resolve these issues, suggestions for a coordinated and systematic conceptual model for training load monitoring during key development stages has been proposed (Booth et al., 2017). However, as the authors indicate themselves, this is problematic as the quality of training load regulation across sporting contexts and organisations likely range from not existent or 'dogmatic' to robust and effective (Booth et al., 2017). Implementing this strategy would facilitate either up- or down-regulation of load based on contextual variables (i.e., biological maturation, weekly exposure, phase in season) to mitigate the injury risk outlined above (Booth et al., 2017).

1.4 Promoting positive outcomes

Evidently there is work to be done to effectively manage training load in youth populations and specifically, for the context of this thesis, football. By addressing the complexities growth and maturation offer, reducing the barriers associated with limited resources and mitigating against overuse injury risk it is anticipated that as a discipline we can promote better long-term outcomes for adolescent individuals. A better outcome may be a successful transition from academy to senior team; or it could be that they transition from football into another sport (e.g., athletics), or it could be that young players develop a love for exercise and have the confidence to express themselves regularly in a physically active manner. Either way, as academics and practitioners in this field there is great opportunity to ease a currently turbulent developmental period for youth athletes. To do this we must enforce change, by focussing the following key areas; a) establishing age and maturity appropriate guidance for load tolerance, b) addressing ambiguity in developmental policy based on guidance, and c) enhance the education provided to coaches of young athletes to directly influence prescription.

This thesis primarily aims to quantify the maturity-specific responses to load using ecologically valid approaches to aid the development of adequate guidance for load management in youth football. It should not be assumed that individuals within the same chronological age, but with a wildly variable physical maturity respond in the same way to a given stimulus – this does not happen anywhere else in sport and exercise science disciplines, so why should it here? This thesis aims to identify the maturity-specific responses to standardised and 'typical' loads of academy soccer players, observing both the neuromuscular performance and psycho-physiological perceptions in response to these activities. Without this information, it becomes impossible to provide more robust guidelines in developmental policy or educate coaches on how they can modify or adapt their practice to better accommodate individual difference during this phase of development. It is hoped that this thesis will provide a springboard for further work in the area to specifically influence policy and coach education, which is ultimately where research influences applied practice.

Beyond the primary aim of establishing maturity-specific responses to load, it is hoped that the inferences made from the individual studies can help to inform some of the mechanisms that contribute to the increased incidence of injury during this stage of development (A. Johnson et al., 2017; D. Johnson et al., 2020; Rommers et al., 2020). Although not directly assessing injury incidence in response to loads, methods utilised to quantify responses facilitate an element of 'reading between the lines' which may also stimulate future work in the area. Additionally, by considering the activities that may provoke injury within this cohort, we can begin to protect against the potential negative physical or psychological impact of injury which may ultimately lead to catastrophic outcomes for young individuals, namely illness, athletic burnout and/or non-functional overreaching (Gabbett et al., 2014; Smith et al., 2018; C. Williams et al., 2017). Future policy recommendations or coach education suggestions will consider the whole athlete, despite this thesis being primarily physiologically and biomechanically informed.

1.5 Thesis Aims

1. Establish the current practices for monitoring growth, maturation, and training load in academy football
2. Establish the dose-responses to soccer-specific activity between players of different stages of biological maturation
3. Provide maturity-specific guidelines around load management to optimise development and minimise injury risk

1.6 Research Objectives

1. Investigate the current growth, maturation and training load monitoring strategies employed in academy football
2. Measure and compare the acute psycho-physical and neuromuscular responses to a fixed soccer-specific activity profile across maturation
3. Quantify and compare the psycho-physical response and neuromuscular performance to ‘typical’ football activity across maturation over an academy season
4. Ascertain dose-response comparisons between chronological-age categorised activities to those of maturity-categorised (bio-banded) activities
5. Provide maturity-specific guidelines to advance training prescription for academy practitioners

Chapter 2

Review of Literature

Chapter 2: Review of Literature

This chapter critically reviews the literature relating to injury reporting, injury incidence, maturity estimation and training load monitoring in elite adolescent soccer. Initially, injury definitions, incidence and aetiology are outlined before the importance of, and methods to estimate biological maturation are reviewed. The final sections critique literature relating to training load monitoring within adolescent soccer, whilst outlining the considerations when applying this in practice.

2.1. Monitoring Injury Risk in Adolescent Soccer

2.1.1 Injury definitions and reporting

Research investigating injury aetiology and incidence is commonplace within soccer and offers valuable information for the prevention and rehabilitation of injuries. However, inconsistent methodological approaches of epidemiological studies confound comparison of data, and often result in varied conclusions from similar research designs. It is therefore prudent to initially outline the definition of injury for this thesis but, in addition, to highlight some of the considerations regarding the injury reporting methods when interpreting this research. For the purpose of this thesis, an injury is defined as 'any physical complaint sustained by a player that results from a football match or football training, irrespective of the need for medical attention or time loss from football activities' (Fuller, 2006, p. 93). This FIFA Medical Assessment and Research Centre (F-MARC) consensus definition encompasses traumatic (e.g., injury arising from a specific, identifiable event) and overuse injuries (e.g., injury arising from repeated micro-trauma without a single, identifiable event) and may be contact or non-contact in nature (although F-MARC advice is to also sub-classify injuries). These injuries may be classified as medical attention ('an injury that results in a player receiving medical attention' [Fuller, 2006, p. 93]) or time loss ('an injury that results in a player being unable to take full part in future football training or match play' [Fuller, 2006, p. 93]). Additional classification guidelines regarding the systematic recording of injury type, location and exposure are also available to standardise the minimum requirements of an injury report within soccer (Fuller et al., 2006).

Injury severity is defined as 'the number of days that has elapsed from the date of injury to the date of the players return to full participation in team training and availability for match selection' (Fuller, 2006, p. 197) and classified as slight (0 days); minimal (1-3 days); mild (4-7 days); moderate (8-28 days) or severe (>28 days). Although the F-MARC consensus statement has been available for over a decade, most epidemiological studies fail to explicitly distinguish between 'any physical complaints' and 'medical attention' injuries, preferring to report these as 'slight injuries' (0 days) (Clarsen, 2017). Although these studies comply with consensus guidelines, the ability to investigate the nature and burden of injuries is somewhat diluted with this approach. Not all injuries result in time loss from football activity, with some athletes choosing to defer time loss if possible, often competing despite presence of pain and reduced function (Clarsen et al., 2013), particular overuse related injuries. Therefore, it is worth stating that studies adopting this approach may underestimate true injury incidence and is the primary reason that several studies (Le Gall, Carling, & Reilly, 2006; Price, 2004; Rumpf & Cronin, 2012) were excluded from this review, as these studies generally required a minimum of 48 hours' time-loss for an injury to be recordable, excluding some of the most common injury trends in youth soccer cohorts (i.e., insidious onset, overuse type complaints). Common symptoms such as movement limitation or insidious pain often appear gradually and can be transient in nature, which lures athletes into adapting their activity or seeking medical support before they cease completely (Clarsen et al., 2013). These injuries may be a 'physical complaint' but may not have required medical attention per se, therefore clouding judgement over their classification and the conclusions that are drawn from such studies. Therefore, where possible studies avoiding this approach have been included to present a clearer perspective on injury trends in adolescent soccer.

2.1.2 Injury Incidence

There have been several recent studies that conform with injury audit guidelines for soccer investigating the incidence of injury within elite adolescent soccer players (Bowen et al., 2017; Jones et al., 2019; Kemper et al., 2015; Materne et al., 2021; Read, Oliver, et al., 2018; Renshaw & Goodwin, 2016; Tears et al., 2018; Wik, Lolli, et al., 2020). These studies suggest that injury incidence tends to increase with chronological age and contain evidence of seasonal variation, peaking during the early competitive period (September) and during winter (January) (Jones et al., 2019; Read, Oliver, et al., 2018; Renshaw & Goodwin, 2016). On average, each player suffers 1.32 – 1.9 injuries and loses approximately 21.9 days per season due to injury, with this peaking around the adolescent growth spurt, gradually reducing as players mature (U14, 26.2; U15, 25.7; and U16, 23.1 days) (Read, Oliver, et al., 2018; Tears et al., 2018; Wik, Lolli, et al., 2020). These data illustrate a significant increased injury incidence (presented as number of injuries per 1000 player hours) in both training (8.2 vs. 3.4) and competitive matches (32 vs. 23.8) in elite adolescent populations than senior males (Ekstrand et al., 2021; Wik, Lolli, et al., 2020). Additionally, the same studies indicate that player availability between U13 and U15 age groups (87–90%) is comparable to seniors (85–90%) but dropped to 78% for U16 players (Ekstrand et al., 2021; Wik, Lolli, et al., 2020). Possible explanations may be the increased academic pressure on players due to exam commitments during this period or the potential for players to 'play-up' with U17-18 peers. This reduced availability may partly explain the slightly lower burden in U16 cohorts, but is conflicted by injury incidence data as there seems to be an increased injury occurrence following peak height velocity (PHV) (Bult et al., 2018; van der Sluis et al., 2015a), however this is critically discussed in more detail in section 2.1.3.2 below.

The most common injuries occur to the lower limb (72–93%), primarily to the thigh (21–24%), knee (11–20%), ankle (18–19%) and foot (7.3–10%) but also to the groin (7.2%), hip (5.5%) and lower back (5–9%) (Jones et al., 2019; Materne et al., 2020; Read, Oliver, et al., 2018; Tears et al., 2018; Wik, Lolli, et al., 2020). Soft tissue haematoma, muscle and/or ligament sprain were the most frequent injuries consistently across age groups with most injuries being non-contact (46–72%) and moderate severity in nature (30–43%) using a time-loss approach. Although injury aetiology is regarded as multifactorial, non-contact injuries are largely considered preventable, whereas contact injuries are mostly unavoidable (Bowen et al., 2017; Read et al., 2016a). Severe injuries (>4 weeks' time-loss) accounted for 18–26% of total injuries and were more frequent in the U15-18 age groups (>0.35 per player) (Jones et al., 2019; Read, Oliver, et al., 2018; Renshaw & Goodwin, 2016; Tears et al., 2018). This is a notable statistic, as one severe injury leads to approximately a 10% reduction in development time per player, which negatively influences the likelihood of positive long-term developmental outcomes (Jones et al., 2019). This period coincides with a critical ongoing (de)selection period where players are required to consistently perform to a high-standard or risk being removed from the talent development environment. Therefore, any potential period of unavailability may lead to heightened loss of confidence, disorientation, fear of failure and the associated negative psycho-physical effects (e.g., anxiety, depression, eating disorders) (Gustafsson et al., 2017; T. Mitchell et al., 2020).

Injury incidence rate was considerably higher during matches (18.2 – 32) than training (1.5 – 8.2) with the majority being traumatic in nature (Kemper et al., 2015; Wik, Lolli, et al., 2020), however around 17–25% of injuries were deemed as 'gradual onset' as players could not confirm when their symptoms began (Renshaw & Goodwin, 2016; Wik, Lolli, et al., 2020). Rommers et al (2020) reported that 45% of all injuries (*n* = 296) were characterised as overuse and agreed with other studies that this injury type was more prominent in U12-15 players, with the knee the considered most frequent site of symptoms (61%) (Read, Oliver, et al., 2018). Materne and colleagues (2020) reported that growth related injuries comprised of approximately 12% of all injuries, with approximately 6 incidences per season with each one leading to ~19 days' time loss. Alongside another ~7% of injuries being either physeal or overuse related, which combines to approximately 20% of all reported injuries from 551 9-19-year-old players over a four-year period. This is a substantial amount, and as outlined above, it is anticipated based on reporting methods (time-loss versus symptomatic reporting), that overuse injuries within these studies are underestimated and they are therefore significantly more common than reported (Bacon & Mauger, 2017; Clarsen et al., 2013). Therefore, there is a need for more epidemiological research to be conducted within adolescent populations utilising injury reporting methods that are more sensitive to the prevalence, severity and impact of these conditions, for which the Oslo Sports Trauma Research Centre Overuse Injury questionnaire (OSTRC-q) might offer value (Clarsen, 2017; Clarsen et al., 2020).

2.1.3 Injury Aetiology

2.1.3.1 Training Load Monitoring

Tears, Chesterton and Wijnbergen (2018) compared injury incidence leading up to and immediately after the introduction of the revised talent development legislation for academy football, the Elite Player Performance Plan (EPPP). This legislative introduction professionalised the academy system to some degree and resulted in a dramatic increase in the recommended on-pitch player exposure hours (3,760 vs. 8,500 accrued incrementally between 9 and 21) (Premier League, 2011). Although the data is only representative of one category 1 Premier League Academy, Tears and colleagues (2018) suggest that injury burden decreased in part-time age groups (U12-15) but increased considerably in full-time age groups (U16-18). In contrast, a similar study by Read et al. (2018) across six academies concluded that there had been a three-fold increase in the player incidence rate (0.40 to 1.32 per player, per season) since the inception of the EPPP, which they connected with the large escalation in on-pitch exposure for players across all age-groups. Although findings from Tears and colleagues (2018) cannot be discounted, the work of Read et al (2018) may be more informative as it represents multiple centres offering a broader perspectives free from any bias associated with individual academy practice. While injuries are multifactorial in nature, conclusions drawn by Read et al. fit the backdrop of the exponential rise in contemporary evidence that suggest high acute exposure and/or miss-managed training load is a major risk factor for injury risk in football players (Delecroix et al., 2018; Jaspers et al., 2017; Malone et al., 2015; McCall et al., 2018). The consensus from various adolescent studies suggest that 66% of injuries are non-contact in nature, with sprinting the most injurious activity (Jones et al., 2019; Nilsson et al., 2016), which would support the notion that inappropriate management of load is a substantial contributor to the presented injury incidence. This is most obviously presented by the reported seasonal trend, whereby injury incidence peaks during periods of relatively increased training load (early-competitive season and period following winter-break) suggesting that the increased exposure may exceed the physical capabilities of adolescent players to tolerate the loads placed on them (Jones et al., 2019; Read, Oliver, et al., 2018).

Despite these trends being unfortunate for the players involved, reassuringly they may be entirely preventable with smarter training prescription and load management that proactively considers the physical capabilities of the athletes in question. However, there is little precedent for doing this, likely because research has yet to provide clear guidance on how this can be achieved. Studies conducted specifically in youth populations (Abade et al., 2014; Bacon & Mauger, 2017; Bowen et al., 2017; Coutinho et al., 2015; Raya-González et al., 2019), particularly with adolescent participants (<16 years, part-time; Watson et al., 2017), offer ambiguous outcomes. These studies are complex to undertake and often propose an increased strain on resources (e.g., time, staff) to consistently collate reliable data, which may often be unmanageable due to logistical and environmental constraints. One study in full-time youth players (>16 years; Bowen et al., 2017) reported that a high chronic (28-day) total distance, moderate to high chronic high-speed distance (>20km/h) and total high acute training loads had the greatest association with injury risk whereas, a low acute (7-day) training load may be preventative of non-contact injury. Similarly, Watson et al (2017) identified that a higher acute training load was associated with increased injury risk, whilst an elevated chronic load increased the risk of illness in adolescent female soccer players. These studies appear to support established evidence within adult populations that acute 'spikes' or excessive accumulated training load (>10% fluctuation per week) may increase injury risk (Gabbett, 2016b). However, other studies including Raya-Gonzalez et al. (2019) found no associations and poor predictive ability of injury when utilising a subjective, internal psycho-physical perception of intensity to monitor the relationship between training load and injury over a full-season in Spanish U19 players. In addition, Dalen-Lorentsen et al. (2021) observed health complaints across 34 youth teams, comparing those with intervened loads (based on acute:chronic status) and those without (control) and reported no improvement in the prevalence of health problems. Therefore, although managing load appears to be associated with injury, there is much debate regarding the method utilised to determine load 'status' and whether this can be used to predict/explain injury trends. This is discussed in more detail in section 2.4.1 below.

One alternative perspective is to consider the composition of weekly training loads, rather than solely the volume and how this may impact players over time. Studies in Portuguese football (Abade et al., 2014; Coutinho et al., 2015) compared the composition and progression of a micro-cycle in U15, U17 and U19 elite Portuguese players. The U15 age group had a notably greater emphasis on elementary technical and tactical skills (through small-sided games) alongside physical conditioning, which altered the training load schedule in this group compared to others. This illustrates how coaching preferences and styles may influence the loads experienced by players and how this may increase/decrease the frequency of exposure to movements (i.e., high velocities, accelerations, decelerations, and total distance covered), consequently biasing mechanical load values. The constitution of particular loads (e.g., high propulsive and braking forces though frequent acceleration and deceleration) may elicit greater mechanical load upon players (Vanrenterghem et al., 2017). Unless adequately constrained, the diverse variation of load-adaptation during adolescence may exacerbate stresses placed on connective tissues at a key developmental time, resulting in tissue capacity thresholds breached. Mechanical load-adaptations take place within all musculoskeletal tissues in direct response to the stresses to which they are exposed to, which can become excessive and lead to structural failure in the form of chronic injuries (e.g., stress fractures, tendinopathy) (Vanrenterghem et al., 2017). These circumstances may partly explain the injury incidence trends in academy football, in that, adolescent players are often required to repeatedly conduct the same movement actions, potentially generating excessive mechanical load accumulation which are difficult to observe and diagnose due to lagging indicators (e.g., pain and or discomfort).

One objection to this theory could be that exposure to high chronic loads may be preventative of injury by facilitating a 'vaccine' like tolerance to load, which has been suggested in both youth and adult research (Bacon & Mauger, 2017; Gabbett, 2016a). However, the limitation with this is that this load tolerance appears to be driven by chronological age, not the physical capability of the player, which may differ considerably and thus undermine the approach (discussed in section 2.1.3.2 below). Wrigley et al. (2012) quantified the typical weekly training loads of chronological age groups from U14 (part-time) to U18 (full-time) and identified systematic age-related increases in intensity and volume of training. Similar findings were observed in Portuguese players between ages of U15, U17 and U19 (Abade et al., 2014; Coutinho et al., 2015). Although these findings are not surprising, it indicates that prescription is chronologically driven and may fail to account for transient and highly variable maturity timing and that training exposure may increase despite biological 'readiness'. This apparent oversight of the influence of biological variation in the dose-response, in that some individuals may require less stimulus for physiological adaptation and performance optimisation, may also contribute to inflated injury trends or related negative responses (i.e., injury, fatigue, illness and overtraining) in adolescent populations (Gabbett et al., 2014).

2.1.3.2 Pubertal Growth Period

The adolescent growth spurt aligns with changes in joint stiffness, bone density and creates imbalances between strength and flexibility, which contributes to '*skeletal fragility*' (K. Ford et al., 2010; van der Sluis et al., 2013). This sensitive period can see boys grow up to 12 cm per year (Mirwald et al., 2002), which may partially explain the phenomenon 'adolescent awkwardness' whereby the trunk and lower limb length have increased, but soft tissues have yet to adapt to the size and weight of the frame, causing abnormal movement mechanics that negatively impact performance (Sheehan & Lienhard, 2019). Adolescent individuals that grow >0.6 cm in the previous month have been linked with a 1.63-fold increase in their risk of injury (Kemper et al., 2015). In a similar study, Rommers et al (2020) identified that older players (U13-U15) experienced a greater rate of growth per year (6.2 vs. 5 cm) and weight change (6.4 vs. 3.4 kg) than younger players (U10-U12), which contributed to more than double the frequency of overuse injuries (93 vs. 40) and almost three-fold increase in injury burden (14.6 vs. 4.7 days/season). This rapid change in musculoskeletal structure (triggered by the onset of PHV) and apparent lag time to adequate relative strength is individually variable based on maturity timing and tempo, which likely corresponds to a variation in readiness to perform, ability to recover and by inference vulnerability to injuries (Dudink, 1994; Rommers et al., 2020).

These anthropometric changes led Dupre and colleagues (2020) to investigate differences in abductor force activity between pre-PHV players and those circa-PHV. They concluded that PHV increases hip abduction moments and alters movement mechanics during cutting and inside passing manoeuvres compared to pre-PHV individuals, which in turn increases groin injury risk. Similarly, due to relative strength-deficits during this period, conservative calculations have suggested that lower-limb muscles are required to develop approximately 30% more force to produce the same relative acceleration, such as in kicking (van der Sluis et al., 2013). These strength-frame deficits are often prolonged with only gradual gains in relative strength over time, which places the athlete at sustained risk (Beunen & Malina, 1988). Performing the same sport-specific actions repeatedly, on skeletally fragile and strength-deficient frames may well explain the high prevalence of overuse injuries explained above. That said, overuse (i.e., excessive frequency) may oversimplify the issue, in that, maybe the increased relative force that they are required to produce and absorb means they are capable of less volume before injury. These musculoskeletal changes are often associated with osteochondral disorders such as Osgood Schlatter, Sinding Larsen Johansson and Severs disease. Collectively these are termed 'growth related injuries' and occur in around 25% of adolescent players, generally stimulated by excessive strain on immature ligaments, cartilage, musculotendinous and bone-tendon junctions (DiFiori, 2010; Le Gall, Carling, & Reilly, 2006; van der Sluis et al., 2015a).

Le Gall et al (2006) and Materne et al (2020) both identified a peak in apophyseal growth-related injuries within the U14-U16 age groups, which aligns with PHV or the period immediately following, which supports the narrative that rapid changes in anthropometry with lagging strength is a primary cause. Van der Sluis et al. (2015a) outlined a moderate ($d = 0.42$) increase in overuse injury incidence between pre-PHV (0.81) and post-PHV (1.42), with a small (*d* = *0.26*) incidence increase from pre-PHV to circa-PHV (± 6 months of age predicted PHV; 1.15). Similar work in adolescent male European soccer (Bult et al., 2018) concurred that injury incidence peaked during the first 6 months' post-PHV (10.92/1000 hours) before returning to pre-PHV levels (8.69/1000 hours) approximately >6 months post-PHV. Materne et al. (2016) identified a broad period of 1-year pre-PHV to 1-year post-PHV as the highest risk of increased injury amongst U9-U18 Qatari academy players. Although nuances between the exact point and duration of highest injury risk exists amongst these studies, clearly the period circa-PHV to immediately post-PHV is consistently an area of major concern. The injuries during this period are not only more common, but also tend to have a higher injury burden than other stages of maturation. The number of days missed through injury (15.69 days), injury burden (89.45/1000 hours) and the incidence of traumatic injuries (1.42/1000 hours) peaked circa-PHV, which may be explained by the increased joint stiffness, decreased bone density and abnormal movement mechanics during this period (Bult et al., 2018; van der Sluis et al., 2013). This increased absence from training reduces the exposure to quality coaching, negatively impacts the opportunities for deliberate practice and can stimulate psycho-social stress associated with (de)selection anxiety (Jones et al., 2019; T. Mitchell et al., 2020). Data above highlights the stage of maturation that elicits the highest incidence of risk; however, the timing of maturation is also an important variable. Later maturing (>13.92 years) players had a small difference in traumatic injury incidence (3.96/1000 hrs) than earlier developing (3.14/1000 hrs) players, reiterating that overuse injuries are the greatest risk to late developers, again likely because they are '*skeletally fragile'* in comparison (van der Sluis et al., 2015a). This is likely owing to the imbalance in the mechanical load-adaptation pathway at this time, potentially compounded by the 's*keletal fragility'* of less developed players repeatedly competing with more developed peers to maintain their status in the talent development environment (Cumming, Searle, et al., 2018; Vanrenterghem et al., 2017).

2.2 Monitoring Maturity Characteristics

2.2.1 Maturity Characteristics

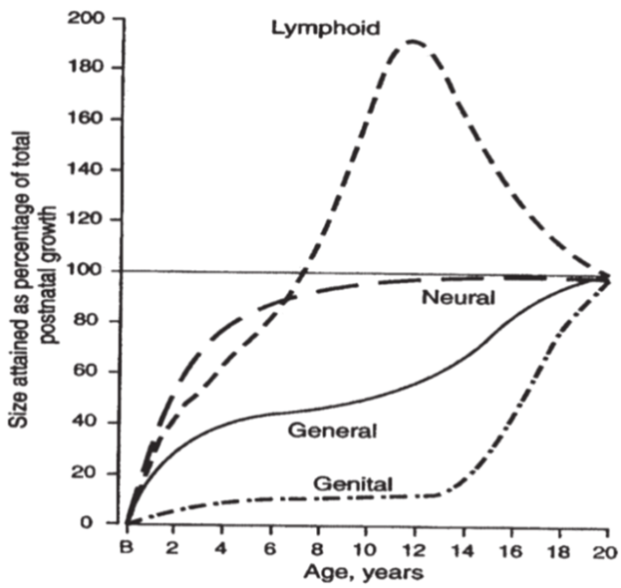

Figure 2.1: Scammon growth curves for different systems within the body (Malina et al., 2004)

Maturation can be defined as 'the progress towards adult stature, which varies in timing and tempo between individuals and genders' (Baxter-Jones et al., 2005, p. 19). Timing refers to the chronological age at which specific maturational events occur (e.g., age of peak height velocity) and tempo refers to the rate at which maturation progresses (i.e., growth velocity) (Baxter-Jones et al., 2005; Malina et al., 2004). Characteristics of growth (change in size of entire individual or component of) and maturation are implicit within models of talent identification, selection and development, and should therefore be considered crucial to long term development (Malina et al., 2012; Stratton et al., 2004). The inter-individual and non-linear variation that exists in morphological parameters and physiological functions (e.g., heart volume, aerobic power, and muscular strength) during maturation can notably impact the acute and chronic responses of adolescents to exercise (Baxter-Jones et al., 2005). As individuals grow, they become heavier, taller, organ size and lean-to-fat tissue ratios change which all impact physical performance, and thus responses to physical activity. Seminal work by Scammon (1930) identified how growth of various systems within the body fluctuate in tempo at different stages of development (Figure 2.1) which amplifies during puberty (typically aged 11-16 years). The dynamic nature of maturation results in the unreliable timing of puberty onset, with individuals of the same age varying dramatically biologically, posing significant challenges for the individuals and supporting practitioners (Baxter-Jones et al., 2005; Cumming et al., 2017). An individual with a chronological age of 12, could potentially have a biological age of anything between 9 and 15 years (Borms, 1986), which likely influences their relative physical and physiological capabilities compared to their more/less mature peers. Evidence suggests that developing earlier may offer some advantages related to the maturity-selection-bias, but late maturers who can 'survive' the system during this period may well grow into more rounded athletes (Cumming et al., 2017; Cumming, Searle, et al., 2018; M. Hill, Scott, Malina, et al., 2020).

Although evidence suggests that both timing and tempo varies between individuals, longitudinal height and weight growth curves exist and offer 'typical' patterns for comparative purposes (Figure 2.2) (Malina et al., 2004). Rate of growth in height occurs at a constantly decelerating rate through infancy and childhood, as individuals get taller but at a progressively slower rate, until the initiation of the adolescent growth spurt where change in height begins to accelerate. In contrast, growth in weight occurs at a slight, but constant increase after the initial post-birth deceleration. Although this thesis specifically relates to male individuals, it is worth highlighting that until the adolescent spurt, both height and weight curves are almost identical between genders, with more obvious disparities beginning at adolescence. Additionally, Figure 2.2.a. illustrates that the male adolescent growth spurt occurs approximately two years after that of the females, which leads to a lengthened period where males experience normal growth rate (~5 cm/year) before their adolescent growth spurt. This in conjunction with the ~2 cm greater increase in height during the growth spurt, accounting for the average 12-13 cm difference in full stature between males and females (Malina et al., 2004).

While individual variability exists for the chronological timing of the adolescent growth spurt, this information can be used as an indicator of maturity. The maximum rate of growth during this spurt is known as peak height velocity (PHV) and the age at which this occurs (APHV) can provide an indication of the intensity and timing of the spurt (Malina et al., 2004). Further discussion on the various methods that adopt this approach to predict maturity status are included within section 2.3. However, it is worth highlighting that the 'typical' growth curves suggest that PHV occurs around 13.8-14.2 years in male football players (Malina et al., 2004; Philippaerts et al., 2006), which aligns with the increased injury incidence information outlined in section 2.1.3.2.

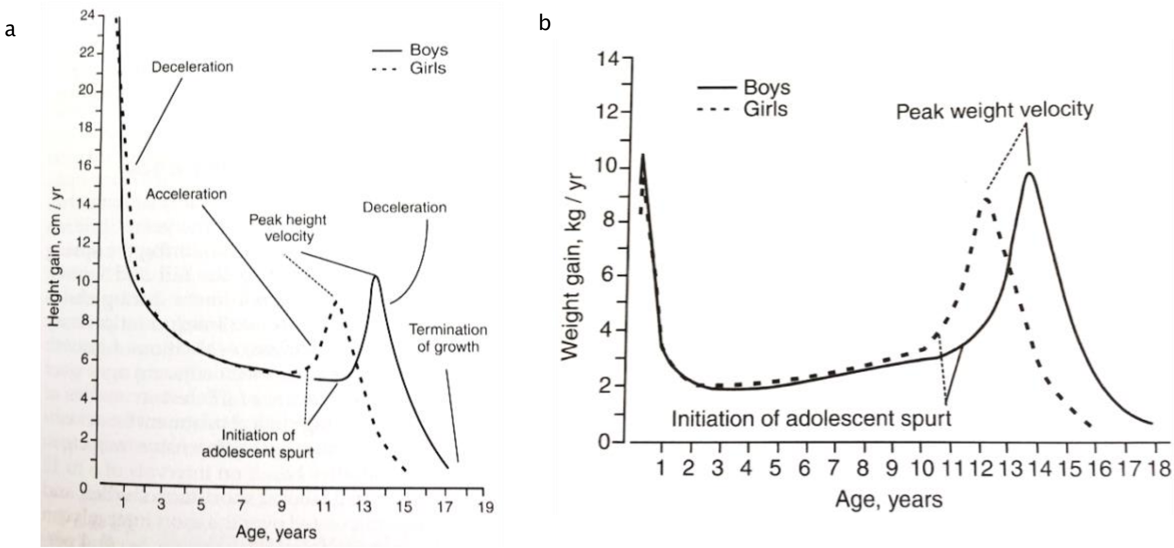

Figure 2.2: a) velocity curve for height (cm/yr); b) velocity curve for weight (kg/yr; Tanner, Whitehouse & Takaishi, 1966)

Data suggests that adolescent football players have skeletally, and sexually advanced maturity status compared with non-athletic males (Malina, 2003). This supports evidence from several sports (i.e., swimming and athletics) that indicates that a higher proportion of individuals are biologically advanced (early developers) compared with those delayed in maturation (late developers) (Cumming et al., 2017; Figueiredo et al., 2010; Malina, 2003; Malina et al., 2012). Males that mature earlier are on average taller and heavier than their peers from late childhood, whilst experiencing a more intense growth spurt which leads to increased gains in height, weight and lean mass (Cumming et al., 2017). The variation in timing and tempo of maturational development may afford the early developer potential performance advantages, particularly around the ages of 11 to 14 where these differences in size, stature and strength are at their greatest (Cumming et al., 2017). Conversely, late developers suffer performance disadvantages and potentially heighted injury risk as they are having to compete with more developed peers during this period (van der Sluis et al., 2015a). Therefore, identifying individuals in both categories is important for practitioners to effectively mitigate the potential issues associated with timing and tempo of development.

2.2.2 Somatic Growth

Growth and maturation are commonly used synonymously when discussing the development of children as they are both dynamic components of development, however each has its own biological meaning. As outlined above, maturation relates to the process towards becoming ‘mature’, whereas growth simply refers to the increase in size of the body, or component of (Malina et al., 2004). Observation and measurement of the rate and magnitude of change in body and segment size is referred to as ‘somatic maturation’ and can be used to predict maturity status, with the use of large-scale longitudinal studies (discussed further in section 2.3) (Beunen & Malina, 1988). Changes in size are a result of either a) an increase in cell number (hyperplasia); b) an increase in cell size (hypertrophy); or c) an increase in intercellular substances (accretion) which all have predominance at specific stages of the maturation process (Malina et al., 2004). Quantifying somatic change uses a set of standardised ‘anthropometrical’ techniques, which involve specific positioning and measurement of landmarks on the body using appropriate instruments (Malina et al., 2004). There are limitless measurements that can be conducted, however the selection of these is of paramount importance in respect to the intended application. Common measures of somatic observation include body stature (height), body mass (weight), sitting stature and leg length (subischial length). However, other somatic measurements (e.g., skeletal breadths, limb circumference, skinfold thickness and head circumference) are sometimes used to help further inform on the robustness of the skeleton, relative muscularity and subcutaneous adipose tissue (Malina et al., 2004). Beunen and colleagues (2006) claimed that body size itself is a not a valid indicator of biological maturity, since the adult state is not the same for all individuals. However, continuing multiple measurements over a longitudinal time may facilitate the identification of age at the onset of adolescent growth spurt and the age at maximum growth velocity (PHV). Additionally, through the use of large-scale empirical studies these measures can also be used to ascertain the percentage of adult height at a given age which can then be used to indicate maturity (Beunen et al., 2006).

Accurate and true changes in somatic measures over time require robust and reliable data. Repeated anthropometrical measurements assume that protocols are standardised, and that data is obtained by a trained individual (Malina et al., 2004). The domain of sport and exercise science is plagued with error (noise) and where small changes in somatic measures (signal) are likely, it is possible that this error may mask true changes in growth, and therefore maturity classifications. This raises doubt over the clinical importance of the data and how this then informs practice, as we are unsure as to the fidelity of the data within the real-world. Anthropometric methods should therefore look to quantify the error to help distinguish the signal from the noise, potentially through producing a threshold for a meaningful change known as a minimum clinically important difference (MCID) (Buchheit, 2016). Firstly, random error is a normal aspect of anthropometrical assessment and represents the individual variation within and between individuals as a result of technical instruments, hardware recording errors, diurnal variation, circadian rhythm, sleep or mood (Buchheit, 2016; Malina et al., 2004). Secondly, systematic error is often derived from the practitioner, poorly calibrated equipment or incorrect protocol which consistently measure incorrectly in the same dimension (over/under measure), leading to bias (Malina et al., 2004). This is a common limitation within anthropometry when the measurements are conducted by different practitioners, leading to poor inter-rater reliability with this error reported to be between 3-8.8% (Marriott et al., 1992). Therefore, repeated and replicated measurements by the same practitioner can provide an estimate of imprecision, which we can combine with random error to provide overall typical error of measurement. These 'typical errors' are usually reported to be between 0.2-1.1% for commonly used anthropometric measures used to estimate somatic maturity (Massard et al., 2019), therefore changes greater than these could be regarded clinically important.

2.2.3 Musculoskeletal Growth

When discussing injury risk and the associated mechanical and physiological load within adolescent populations, it is prudent to consider the physical development of the musculoskeletal system. A detailed breakdown of the systematic formation and maturation of musculoskeletal tissue is beyond the scope of this thesis; however, readers are directed to Malina et al. (2004) where this content is reviewed in depth. Elements of the development of these systems are important to provide context and underlying physiological support for the thesis, and consequently will be reviewed below.

As outlined previously, the onset of the adolescent growth spurt stimulates an exponential rate of growth in musculoskeletal structures, initially bone tissue. This increase in bone size serves as a stimulus for morphological adaptation of the muscular system, which, in turn responds to the increased tension generated by the larger and heavier skeleton (Read et al., 2016a). This process generates an inherent lag-time between the increased rate of bone (hard tissue) growth and thus mechanical load, and the response from the muscular system (soft tissue) to establish appropriate muscle length and force production capacity

(Kemper et al., 2015; Read et al., 2016a). This is often accompanied by a change in joint stiffness and susceptibility of cartilaginous structures, which combined have been linked to a temporary 'skeletal fragility' and thus overuse type injuries through a mechanical-load pathway (Bult et al., 2018; K. Ford et al., 2010; Kalkhoven et al., 2021; van der Sluis et al., 2013). To further compound the issue, a disproportionate rate of growth exists between the legs and trunk, whereby long bones of the limbs grow in advance of shorter bones. This lag and variable rate in growth exposes individuals involved in football to a greater risk of traction apophyseal injuries, with increased stress on connective tissue, particularly in a relaxed state (also referred to as tissue preload) during the period immediately following PHV (Read et al., 2016a).

The increase in musculotendinous tension is related to muscle length, however the disproportionate rates of development between soft and hard tissue also have negative connotations towards the muscle cross-sectional area. Reduced muscular size may negatively influence the neuromuscular control and therefore inhibit movement, particularly dynamic stability, which is likely caused by the concomitant increase in joint torque in the absence of relative muscle hypertrophy and strength (K. Ford et al., 2010; Read et al., 2016a). This period of increased physical stress is often combined or followed by 'adolescent awkwardness', which is when the individual has grown significantly, but the accompanying muscle size has yet to develop. This temporal musculoskeletal imbalance stimulates changes in motor control, whereby individuals lose ability to perform the same physical and technical tasks with the same efficiency (Read et al., 2016a; Ryan et al., 2018; van der Sluis et al., 2013). Empirical findings suggest that added mechanical stress, abnormal movement mechanics and continued frequent exposure to training and match-play during this period contributes to an increase in traumatic and apophyseal injuries, particularly in the lower limbs where long bones amplify issues (Read et al., 2016a; van der Sluis et al., 2013, 2015a). Therefore, practitioners should be mindful of 'superimposing' typical training exposures onto adolescent athletes during this period, with the aim of reducing the mechanical-load related stress.

2.2.4 Athletic Performance

The non-linear, inter-individual variances in physical, biomechanical, and physiological systems outlined above are not isolated constructs. These physical attributes and transient shifts in mechanical-load and stress tolerance also contribute towards athletic performance. Young adolescents involved within academy football are striving to become the most athletic versions of themselves, yet this may be inhibited by non-modifiable factors, in particular their maturity status. Football is an athletically demanding sport, with high levels of neuromuscular demand through frequent (every 4-6s) variations of acceleration, deceleration, sprinting, jumping and change of direction (COD) (Beato et al., 2018). These athletic movements are largely based on the efficiency of the stretch-shortening cycle (SSC) which involves an eccentric muscle 'stretch', followed by a rapid concentric 'shortening' of the muscle (Radnor et al., 2018). SSC efficiency is governed by effective neuromuscular function, most specifically the interaction between the neural and muscular systems and the musculotendinous unit (MTU) (Radnor et al., 2018). Neuromuscular performance assessed through various forms of jumping and hopping tasks, increases in a non-linear fashion throughout maturation, with the underlying mechanisms of development still under-researched (Lloyd et al., 2011; Radnor et al., 2018). Although there is evidence that neural changes may positively influence athletic performance, it is clear that the onset of the adolescent growth spurt acts as a component specific 'trigger' for enhanced development, likely attributable to a change in the hormonal milieu and related growth factors (Mcnarry et al., 2014). A visual presentation of the proposed underlying mechanisms of SSC development throughout maturation is shown in Figure 2.3.

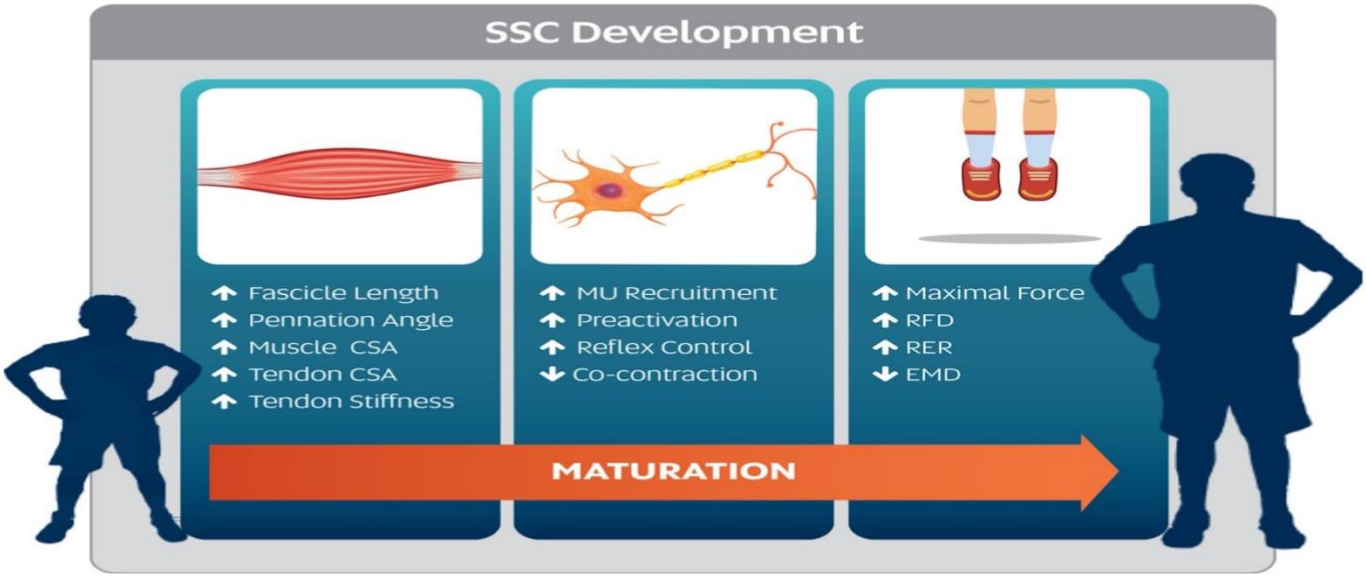

Figure 2.3. Visual presentation of the mechanisms underpinning growth and maturity related changes in stretch-shortening cycle function. *CSA*, cross sectional area; *EMD*, electromagnetic delay; *MU*, motor unit; *RFD*, rate of force development; *SSC*, stretch-shortening cycle; *RER*, rate of EMG rise (Radnor et al, 2018)

Primarily due to ethical constraints associated with exploratory methods (i.e., muscle biopsies), there is a paucity of research into the specific muscle' characteristics throughout childhood and into adolescence, however the consensus is that children have a greater proportion of Type I fibres than adults. These fibres produce less force and have shorter contraction velocity than Type II fibres (Radnor et al., 2018), which likely impedes SSC performance in less mature individuals. Developments in muscle size occur throughout growth, however the contribution of fibre hyperplasia has been suggested as small, with fibre hypertrophy being a greater predictor of strength and power production in both adults and children (Tonson et al., 2008). Further ambiguity around muscle development exists when, evidence suggests that voluntary strength increases in children are larger than the extent of anthropometric measures suggest (i.e., hypertrophy), indicating that the level of neuromuscular activation is of high importance (Grosset et al., 2008). This is biologically variable and results in children unable to activate their muscles to the same extent as adults, recruiting a smaller percentage of the motor-unit pool than adults during voluntary contractions (78 v 95%), ultimately limiting their force production capabilities (Grosset et al., 2008). Similarly, less mature individuals demonstrate greater co-contraction than mature individuals, which increases joint stability. However, this increased contraction also increases the energy cost of exercise and reduces force output, ultimately resulting in irregular neural co-contraction and poor movement efficiency (Radnor et al., 2018). This is further compounded by a greater density and size of golgi-tendon organs in less mature individuals, which may inhibit motor neuron innervation and efficiency of the SSC. Therefore, the maturation process facilitates a desensitisation process for the golgi-tendon organs, reducing co-contraction and improving the efficiency of the SSC (Radnor et al., 2018), facilitating more biologically developed athletes towards having greater force production capacity, efficiency of the SSC, and are subsequently be more equipped to execute the athletic demands of football proficiently, and with reduced risk.

Central to the SSC and therefore the athletic performance is the MTU, and the associated tendinous properties of these to permit heavy forces whilst maintaining structural integrity to facilitate transfer of force between muscle and bone (Radnor et al, 2018). Long, thin tendons provide compliance, which amplify force by taking advantage of the storage of elastic energy, whereas shorter, thick tendons are stiffer and more effective at transferring force due to their stretch resistance (van Soest et al., 1995). It is suggested that tendon hypertrophy is a major influencing factor on tendon stiffness, and it is anticipated that chronic loading through increased body mass and force production with age stimulates around 78% of tendon variation (Radnor et al., 2018). Lower stiffness values have been observed in 10-year-olds than 13-year-olds, reaching adult values around the age of PHV (Kubo et al., 2014), therefore illustrating the growth and maturity mediated properties of the MTU (Waugh et al., 2012). This suggests that the difference between adolescent (circa-PHV) and adult SSC, is most likely down to the stiffness of the contractile tissues (muscle), as opposed to the tendon. The fact that tendon stiffness is relative to adult around PHV, suggests that the muscle may not be able create optimal stiffness (i.e., more than the tendon) and therefore yields under load, reducing the motor-unit recruitment (Dotan et al., 2012; Radnor et al., 2018). This is likely augmented during the identified lag-period between hard and soft-tissue development and the associated relative strength deficiency this creates and may contribute to vulnerability during the period associated with heightened injury incidence.

Recognising the maturity specific changes in stiffness is important when considering injury causation and load management strategies. Joint stability and protection against injury is reliant on appropriate feedback and feed-forward loops to modify MTU stiffness during sport-specific actions (De Ste Croix et al., 2021). Increased stiffness is considered to indicate an enhanced ability to generate strength and resist deformation stimulated by the rapid changeover from eccentric to concentric contractions, which improves performance but also positively modifies injury specific load-adaptation pathways (Kalkhoven et al., 2021; Padua et al., 2006). Stiffness (leg) has been previously used as a measure to characterise SSC function and generally represents how well an individual can control multi-joint movements involving the SSC (e.g., jumping and sprinting) (De Ste Croix et al., 2021; Komi, 2000). It is therefore important to assess these qualities during biological maturation to provide valuable information for practitioners regarding the athlete’s neuromuscular pre-activation and feed-forward control. Considering effective measurement of SSC tasks require contact times of <250ms and involvement of a stretch reflex, typical squat or countermovement jump tests do not appropriately permit this assessment (De Ste Croix et al., 2021; Pedley et al., 2020). Therefore, rebound based tests adopting a spring mass model approach that do elicit rapid contact times and stretch reflex involvement are better suited, and have been shown to be reliable measures of SSC capability in adolescent populations (De Ste Croix et al., 2017a; Komi, 2000; Lloyd et al., 2009). In such assessments the leg could be modelled as a spring, whereby the ground reaction force and centre of mass displacement would present ‘U’ shaped parabolic images of each other (Blickhan, 1989), allowing for effective monitoring of biological adaptations in these parameters throughout maturation.

From a musculoskeletal perspective, we appreciate that systematic changes occur throughout maturation, albeit in a non-linear fashion. However, what is of more interest to practitioners is how this manifests itself within an athletic performance perspective, which may then influence how practitioners prescribe training and assess proficiency (Ryan et al., 2018). For example, Ryan et al. (2018) observed *likely large* to *very likely large* changes in 10m sprint time and countermovement jump (CMJ) between maturity groups (pre, circa and post PHV) and a *likely moderate* relationship between functional movement screen and CMJ performance. They concluded that movement quality was non-linear in development and potentially stagnated around PHV, which is likely associated with ‘adolescent awkwardness’ outlined previously. This suggests that a period of training aimed towards developing movement quality may be advantageous in minimising the impact of adolescent awkwardness and maintaining holistic athletic performance. However, although the findings from Ryan et al. (2018) outline intuitive relationships between movement quality and performance, it is likely more complex to ascertain the impact on performance throughout this period. For example, Philippaerts et al. (2006) outlined that improvements in standing long jump were optimised 18 months prior to PHV (10.5 $cm \cdot year^{-1}$), with reductions to around 6.3 $cm \cdot year^{-1}$ at PHV, with vertical jump contrasting this and peaking in coincidence with PHV (5.1 $cm \cdot year^{-1}$). Read et al. (2017) showed greater variability in single leg jump and landing performance when the raw data (distance jumped and peak landing forces) were normalised for leg length. This was illustrated that although peak forces and jump distance generally increased with maturation, instigated by increases in strength and body mass, pre-PHV players showed higher ground reaction forces relative to body mass. This was likely attributable to the landing kinematics adopted and that less mature individuals have reduced hip and knee flexion angles on landing, increasing stiffness and ground reaction forces (Read et al., 2017).

This poor force attenuation upon landing may provide some indication as to injury mechanism within youth football, illustrating a potential lag between the maturational enhancements in jump performance and the ability to adequately control the mechanics of this (Read et al., 2017). Conversely, the larger increases in horizontal jump performance and lower relative landing forces post-PHV is a clear indication of the increased strength and motor control within this group, suggesting that the negative kinematic impact caused by adolescent awkwardness is minimised and a more hip-dominant landing strategy adopted. This provides a mechanical advantage by stimulating the hamstrings and concomitantly reducing quadricep activation for a better landing positively influencing performance (Read et al., 2017). Additionally, and from a similar perspective Murtagh et al. (2018) suggested that when looking to identify young talented players, it is these jump related components (i.e., horizontal and vertical countermovement) that have the best ability to differentiate the physiological capacity of players during the circa-post PHV period.

From a running performance perspective Moran et al. (2018) explored the responses to a set protocol of sprint training to groups of varied biological maturation. They revealed that the dose of sixteen 20m sprints (interspersed with 90s recovery) was more effective in developing sprint performance for those pre-PHV (effect sizes: 10m, 1.54; 20m, 1.49; 505, 0.92) than those circa-PHV (10m, 0.00; 20m, -0.12; 505, -0.41). Further, research conducted from match-play suggests that later maturing players cover substantially greater distance at higher absolute running speeds, despite covering only minimal total distance (R. Lovell et al., 2019). These findings indicate that later maturing players are incurring a higher, relative external load during match-play, and therefore more likely susceptible to the negative consequences associated with accumulated fatigue long-term. This stimulated by later maturing players having lower physical capacities may provide some explanation for the increased injury incidence reported around the timing of the adolescent growth spurt.

Identifying maturity characteristics (i.e., status, timing, tempo) to apply specific interventions is not easy and is further discussed in section 2.3 below. However, a large multi-centre study by Towlson et al. (2018) aimed to identify transition time points where the tangible influence of maturation increased or waned. The developmental tempo of height, weight and sprint performance accelerated -3.2, -1.6 years PHV respectively, and ceased approximately 1-year post PHV. However, no such accelerated tempo was apparent for lower limb power, agility or endurance performance, although a small reduction in tempo was observed mid-post PHV (Towlson et al., 2018). Contrastingly, Lloyd et al. (2011) indicated that a stagnation or negative trend of neuromuscular power-based traits such as reactive strength index (RSI; -11.48%), leg stiffness (-8.87%) squat (1.32%) and countermovement jump (7.68%) was evident approximately 12-18 months before PHV. These asynchronous and staggered trajectories highlight the need for component specific consideration to training, and that although practically difficult, various components of ‘fitness’ may be more effectively stimulated at specific time points of the maturation process. For the context of this thesis, the literature provided throughout this section highlights that prescribing ‘age-classified’ doses of training is sub-optimal and that maturity specific interventions are required to optimise training and development.

2.3 Biological Classification of Soccer Players

To provide biologically relevant training prescription, it is important that valid and practical methods are used to measure, observe, and quantify maturity status. There are various methods (e.g., skeletal, sexual and somatic) in which we can assess maturity status, tempo and/or timing, with each having methodological and ethical considerations (Malina et al., 2004). For example, assessing skeletal maturity is considered the gold-standard assessment by comparing radiographs of the bone formation of the hand and wrist (left) against standardised radiographs. The ossification of bone from child to adult in this area occurs in a uniform, definite and irreversible manner and therefore can be termed ‘maturity indicators’ (Malina et al., 2004). The methods in which clinicians observe these maturity indicators vary in criteria but all aim to match a hand-wrist radiograph to a standard set of criteria, with three predominant skeletal age (SA) protocols used, a) Greulich-Pyle (1959); b) Tanner-Whitehouse (1966) and c) Fels (1989). These protocols look to aggregate the maturity of the bones of the short and long bones of the hand and wrist (carpals, metacarpals, phalanges, radius and ulna) to provide a SA in relation to a reference sample from an extensive longitudinal study (Malina et al., 2004). However, with the reference sample for each method varying quite markedly (ranging from 1931-1986 across two continents), the resultant SA may vary considerably, therefore it is important that the SA protocol is stated (Malina et al., 2004). SA is often expressed as the difference between SA and chronological age (CA) and provides an inference at a given point in time of whether the individual is advanced or delayed in maturation (i.e., 1.5 years delayed).

The logistical and resource derived requirements of estimating skeletal maturity make this an unrealistic approach in many circumstances, despite it being widely regarded as the best method. Sexual maturity is a commonly used surrogate as puberty is considered the transitional process between childhood and adulthood (Malina et al., 2004). The assessment of sexual maturity is based on secondary sex characteristics such as breast development and onset of menarche in females, penis and genital development in males and stage of pubic hair growth in both sexes. These outward indicators of maturity are limited to the period of puberty and therefore are restricted in application compared to skeletal maturity which can be completed periodically throughout childhood (Malina et al., 2004). Five stages of sexual maturation have been established, which illustrate progress towards the full adult state for each characteristic, although some scales include a sixth scale (Tanner et al., 1966). Obvious ethical issues make the direct assessment of sex characteristics difficult in non-clinical settings, therefore self-assessment of pubic hair or body development against standardised pictures is common practice (Malina et al., 2004). However, there are limited studies that assess the concordance of self-assessment and the ratings of experienced assessors, with correlations ranging from 0.59 to 0.92 (Matsudo & Matsudo, 1994). An additional female only method to estimate maturity stages is age at menarche, which is a simple and therefore commonly used approach. However, with the current thesis concerning male athletes, further discussion of this approach is beyond the scope of the review and therefore interested readers are directed to detailed explanations such as Malina et al. (2004).

The methods outlined above coincide with significant resource, logistical or ethical requirements and therefore their application to youth football is limited beyond exceptional cases. It is far more common for practitioners within football to employ less invasive and logistically simple methods derived from anthropometrical measurements, known as somatic maturity estimation. These body measurements themselves are not indicators of maturity, however algorithms derived from repeated longitudinal data can be used to observe the inflection in growth curves to provide indicators of maturity, such as the onset of the growth spurt and APHV (Malina et al., 2004). If combined with additional data (i.e., parental heights) the percentage of predicted adult stature can be calculated and then used as a maturity indicator. As outlined above, these methods are highly prevalent methods to categorise individuals within adolescent soccer and therefore are discussed in more detail in the following sections.

2.3.1 Maturity Offset

Predicting the APHV is regarded as one of the most accessible and therefore widely used indicators of maturation (Malina et al., 2004). This equation based approach uses the known differential in the growth characteristics between sitting height and leg length derived from three longitudinal studies (Pediatric Bone Mineral Accrual Study [PBMAS]; Saskatchewan Growth and Development Study [SGDS]; Leuven Longitudinal Twin Study [LLTS]) to provide a non-intrusive prediction of maturity status (Mirwald et al., 2002). A one-time standardised assessment of standing and sitting stature, weight and leg length are computed into a regression equation to provide an estimation of maturity offset (MO) in years (i.e., time prior to or post PHV). There have been several iterations of the MO equations developed in recent years, however initially an equation presented by Mirwald et al. (2002) is commonly applied (equation 2.1), which was later corrected by Malina and Koziel (2014) (equation 2.2).

Equation 2.1. Maturity Offset for Males

$$\text{Maturity Offset} = -9.236 + (0.0002708 \times \text{Leg Length \& Sitting Stature Interaction}) + (-\,0.001663 \times \text{Age \& Leg Length Interaction}) + (0.007216 \cdot \text{Age \& Sitting Stature Interaction}) + (0.02292 \times \text{Body mass by Stature Ratio})$$

Equation 2.2. Revised Maturity Offset for Males

$$\text{Maturity Offset} = -9.236 + (0.0002708 \times \text{Leg Length \& Sitting Stature Interaction}) + (-\,0.001663 \times \text{Age \& Leg Length Interaction}) + (0.007216 \cdot \text{Age \& Sitting Stature Interaction}) + (0.02292 \times (\text{Body mass by Stature Ratio} \times 100))$$

Despite very good correlation with data from longitudinal studies ($R^2 = 0.91$) and acceptable standard error of the estimate (SEE; 0.490) the authors suggest that an acceptable limit of ± 1 year should be considered with any estimation (Mirwald et al., 2002). Therefore, a predicted MO of 14.2 years could be anywhere between 13.2 or 15.2 years, reducing the precision and thus impact of the calculation to when looking to implement maturity-specific interventions. In addition, the accurate measurement of sitting height is outlined as crucially important based on its significant weighting within the calculation, and therefore inaccurate measurement of this could magnify error further (Massard et al., 2019; Mirwald et al., 2002). Although useful for providing an approximate prediction of PHV, the bandwidth of these prediction is somewhat large and therefore reduces the practical impact this can have when biologically classifying young soccer players. Additionally, the timing of estimation may also further negatively impact the accuracy of the equation, with predictions obtained before expected APHV better (Malina & Kozieł, 2014). Moore and colleagues (2015) attempted to enhance this prediction equation by utilising data from other large mutli-ethnic longitudinal studies (Healthy Bones Study-111 [HBS-111]; PBMAS and the Harpenden Growth Study [HGS]) that identified that the original MO equations may underestimate PHV in those with later onset and overestimate PHV in those with earlier onset.

Additionally, Moore et al. (2015) suggested that the original MO equations were subject to overfitting, reducing the prediction of the equations within populations external to the study. Therefore, they established simplified gender specific equations (Equation 2.3) that removed some complexity and enhanced the usability in the field, by minimising the estimation error to <0.5 year, with an alternative equation that omits sitting height available for males (Moore et al., 2015).

Equation 2.3: Enhanced Maturity Offset

$$\text{Maturity Offset} = -8.12841 + (0.0070346 * (\text{age} * \text{sitting height}))$$

Despite some of the 'systematic error' of the original studies being reduced, there is still likely to be a slightly higher 'prediction error' associated with extreme early or late developers and that predictions are more reliable as individuals' approach PHV (Malina & Kozieł, 2014; Moore et al., 2015). However, the redeveloped equations by Moore et al. (2015) found that a higher percentage (90% v 80–85%) of MO was accurately predicted within ±1 year compared to the original equations (Mirwald et al., 2002). Therefore, despite some evidence of overfitting in both equations, the higher reliability and enhanced ability to estimate maturity status without measuring sitting height advocates the redeveloped equation by Moore et al. (2015) over the original. However, there is a tendency for the error to increase when applied to children further from their APHV, likely caused by attempting to apply linear regression estimates to an inherently non-linear biological process (Rogol et al., 2000). Irrespective of the specific MO equation utilised however, the principle by which the estimate is used to biologically classify individuals is the same and concerns the MO. Once the MO has been calculated it is common for players to be grouped as either pre-PHV, circa-PHV or post-PHV with 0.5- or 1-year intervals applied (e.g. ±1 year of PHV for circa-PHV) to cater for the prediction error outlined previously (De Ste Croix et al., 2019; Morris et al., 2018; van der Sluis et al., 2013).

2.3.2 Fransen Maturity Ratio

Considering the reliability issues and pitfalls of linear estimations of non-linear biological processes raised above, a new equation for the prediction of APHV from somatic variables by adding a maturity ratio to maturity offset data has recently been established (Fransen et al., 2018). This polynomial equation facilitates more precise representation of the non-linear relationship between MO and anthropometric variables whilst using a ratio (Equation 2.4) allowing more consistent fitting throughout childhood to late adolescence (Fransen et al., 2018). The higher of coefficient of determination (R^2) indicates that the anthropometric variables explain the offset to the greatest extent within the polynomial model (90.8%) and why this model was the best fit.

Equation 2.4: Maturity ratio

$$
\begin{gathered}
\text{Maturity ratio} = 6.986547255416 \\
+ (0.115802846632 * \text{Chronological age}) \\
+ (0.001450825199 * \text{Chronological age (2)}) \\
+ (0.004518400406 * \text{Body mass}) \\
(0.000034086447 * \text{Body mass (2)}) \\
(0.151951447289 * \text{Stature}) \\
+ (0.000932836659 * \text{Stature (2)}) \\
(0.000001656585 * \text{Stature (3)}) \\
+ (0.032198263733 * \text{Leg length}) \\
(0.000269025264 * \text{Leg length (2)}) \\
(0.000760897942 * [\text{Stature} * \text{Chronological age}])
\end{gathered}
$$

Whilst this approach has a similar variance in accuracy as the previous approaches explained (Malina & Kozieł, 2014; Mirwald et al., 2002; Moore et al., 2015), there is no systematic change in prediction error as the maturity ratio changes (i.e., when the age of estimation is further removed from APHV). Although in theory this facilitates greater accuracy and subsequently confidence to collect non-invasive maturity data, the relative immaturity of the predictive model therefore requires further validation utilising longitudinal datasets. It has however, successfully been applied to high-level male athletes and youth male soccer players illustrating no clear outliers and therefore a superior fit within this population than previous methods (Fransen et al., 2018). Therefore, the superior reliability and the population specific validation of this equation suggests it is an appropriate approach determine maturity status in male adolescent soccer players both pre and post PHV (Fransen et al., 2018).

2.3.3 Predicted Adult Height

An increasingly common approach to predicting somatic maturity within adolescent football is the percentage of predicted of adult height (PAH%) attained at a given age. In contrast to MO which calculates time from PHV, PAH% estimates the status (percentage) of full estimated adult stature based on values for size attained at specific chronological ages. This approach offers a mechanism by which practitioners can differentiate between adolescent players that are genetically tall or those that are tall because they are advanced in maturity and have attained a higher percentage of adult stature (Malina et al., 2004). There are several methods to calculate PAH% available (Bayley & Pinneau, 1952; Khamis & Roche, 1994; Tanner et al., 1975), but as with approaches discussed previously most of these require skeletal age (SA), or at least an estimation of SA which limits their applicability within adolescent football. Each of these approaches has an associated error of between 3-5 cm exclusive to SA prediction error, which may then be overestimated or underestimated (Bayley & Pinneau, 1952; Roche et al., 1975). The Roche-Wainer-Thissen method (Roche et al., 1975) was modified to facilitate more feasible predictions of adult height without the need for SA by providing age-specific regression equations from a child's current age, height, weight and the mid-parent height (Khamis & Roche, 1994) (Equation 2.5).

Equation 2.5: Predicted Adult Height

$$
\text{PAH} = \beta_o + \text{stature}^* \beta_1 + \text{weight}^*(\beta_2) + \text{mid-parent stature } {}^*\beta_3
$$

Note: β_o, β_1, β_2, and β_3 are the intercept and coefficients by which age, stature (in), weight (lbs) and mid-parent stature (in) respectively should be multiplied from the appropriate table (male or female) in Khamis & Roche (1994)

This was based on clinical perception that mid-parent height provides an appropriate genetically informed target range within which the adult height of the child will likely fall (Malina et al., 2019). Additionally, the standard errors associated with this approach are only slightly higher than the original equation which includes the SA (1.5-3% for males) and is applicable on children aged between 4 and 18 years old (Khamis & Roche, 1994; Malina et al., 2019). However, this is exclusive to the technical error associated with intra and inter observer measurement variability and the fact that in some cases one or both parents may not be available to provide their stature (Khamis & Roche, 1994; Malina et al, 2017). In the absence of one or more of the birth parents, Khamis and Roche (1994) suggest estimating the missing adult height or using mean published stature for adults. However, self-reported adult heights tend to be overestimated and require correction equations (Cumming et al., 2017) and the use of published means reduces the individual variation and genetic component that is so pertinent when observing the maturity status, thus questions the utility of this approach in such cases. A similar method that encompasses skinfold measurements of the subscapular and triceps in addition to age, height and weight was developed by Beunen and colleagues (1988) although there is limited evidence of its application within adolescent sport.

The use of PAH% is central to the recent iteration of historical biological classification approach, termed bio-banding. Bio-banding attempts to group young athletes of a certain age (typically 11-15 years) into 'bands' based on biological maturation rather than chronological age (Malina et al, 2017). Bio-banding has been described as an adjunct to chronological grouping rather than a replacement and has drawn attention primarily for its ability to assist with the maturity-associated selection and deselection aspects of adolescent sport (Beunen et al., 2006; Malina et al., 2004). Predetermined biological 'bands' exist and are assumed to span the adolescent growth spurt (≥85% and <90% or ≤95% and <90%), however these may be adapted to suit the needs of the environment in which they are applied (Malina et al, 2017). Previous studies observing the use of bio-banding competitions with EPPP based populations have used the 85-90% maturation band as this represents both late childhood and the onset of the pubertal growth spurt (Abbott et al., 2019; Cumming et al., 2017). Similarly, PHV typically occurs between 88-96% of adult height, with peaks in growth occurring between 90-92% (Malina et al., 2013).

2.4 Training Load

Quantifying and monitoring athletes' response to a training stimulus is critical when looking to optimise athletic performance and reduce injury risk (Drew & Finch, 2016). When delivered appropriately, training induces a specific functional adaptive response that underpins positive changes in performance, health and injury risk relative to the nature, intensity and duration of the task (Impellizzeri, Marcora, et al., 2019a). These transient acute adaptive responses can be produced by a single exercise exposure, whilst systematic repetition of such stimulus leads to chronic adaptation (Impellizzeri, Marcora, et al., 2019a). The outcome of acute or chronic training stimulus and the subsequent dose-response paradigm forms the basis of training theory and is highly influenced by an individual's accumulative 'load' over a given time (Impellizzeri, Marcora, et al., 2019a; McLaren et al., 2017a). This load has been defined as the input variable that is manipulated to elicit the desired training response and is generally classified as either internal or external (Bourdon et al., 2017; Coutts, 2020; Halson, 2014). External load is considered as the work completed by the athlete, measured independently of their internal characteristics, with internal load regarded as the relative psychophysical stress imposed and consequently determines the training response (Bourdon et al., 2017; Halson, 2014). For the greatest insight into training stress, both internal and external loads should be integrated as fixed external loads may produce variable internal loads dependant on the fatigue, hydration and recent training status of the athlete (Burgess, 2017b; Halson, 2014). Specific measures of internal (section 2.4.1) and external (section 2.4.2) training load are discussed in more detail in the following sections of this thesis.

Physical preparation for high-intensity team sports athletes such as football, requires the systematic and periodized exposure to appropriate physiological and biomechanical load, achieved by manipulating the volume, intensity and frequency (McLaren et al., 2017a; Vanrenterghem et al., 2017). It is therefore prudent for practitioners to establish an appropriate load monitoring system (Gabbett & Whiteley, 2017) to effectively gauge internal response from prescribed external loads (Foster et al., 2017). Successful management of these loads can lead to enhanced performance through improved speed, power and strength, however poor management of load has been associated with overload of the system and possible injury or illness (Gabbett, 2016b; McCall et al., 2018; Vanrenterghem et al., 2017). Emerging evidence has highlighted the association between training and competition exposure and the incidence of injuries and illness within football (Bowen et al., 2017; Jaspers et al., 2017; S. Williams et al., 2017), however debate exits whether training load can be used to predict injury risk (Hulin & Gabbett, 2019; Impellizzeri, Wookcock, et al., 2019). Jaspers and colleagues (2017) indicated that a higher 2-3-week cumulative load for total distance, high-speed running distance and deceleration efforts was associated with an increased subsequent injury risk in professional male soccer players. However, in contrast they also concluded that moderate exposure to accelerations and decelerations can be protective against injury, highlighting the need for delicate balance, often regarded as the 'goldilocks' principle (Jaspers et al., 2017; Murray et al., 2017). These findings were supported by Bowen et al. (2017) who suggested that high accumulative loads in acceleration, high speed running, and total distance increased the risk of injury within youth (18-23 years) football players. However, both of these studies incorporated the use of acute: chronic workload ratios in some form, which has faced some criticism regarding the mathematical integrity of these methods to monitor load (Carey et al., 2017; Impellizzeri, Wookcock, et al., 2019; Windt & Gabbett, 2019). More detailed discussions on methods employed to monitor training load are included in section 2.4.3 below.

Since the inception of this thesis in late 2016, there has been >8500 studies published using the term 'training load' with reference to sport (PubMed, 2021). Despite this recent proliferation of research into training load and injury associations in adult populations, relatively very few studies have directly investigated this in adolescent (<16 years old) soccer populations (Brink, Visscher, et al., 2010; Hannon et al., 2021; Nobari, Alves, et al., 2021; Watson et al., 2017; C. Williams et al., 2017; M. Wright et al., 2020; Wrigley et al., 2012). Finding the optimal dose-response is a highly individual process that is amplified during adolescence as individuals experience rapid puberty-related changes, often in conjunction with systematic increases in training load (Brink, Nederhof, et al., 2010; Gabbett et al., 2014; Premier League, 2011). Inappropriate, or excessive training loads imposed on young athletes may interact with growth and maturation to negatively impact future development in sport and/or injury risk, as discussed in section 2.1.3.1 (Gabbett et al., 2014; Mountjoy et al., 2008; C. Williams et al., 2017). One explanation as to the relative paucity of literature in this area is the complexity surrounding programme scheduling of adolescent athletes (Phibbs et al., 2017; Scantlebury et al., 2020). It is common that adolescent athletes are involved in concurrent training or activity programmes across various locations (e.g., school sport, academy, regional representative teams) delivered by various coaches and/or practitioners making effective and accurate load monitoring highly complex (Phibbs et al., 2017). This complicated training structure, and thus the absence of a congruent and systematic approach to load monitoring, makes it difficult for practitioners to make informed decisions on whether individuals are participating in excessive or insufficient training (Phibbs et al., 2017; Scantlebury et al., 2020), let alone conduct reliable research in the area. One study (Phibbs et al., 2017), illustrated large inter-individual and within-subject variation in weekly training loads in adolescent rugby union players, suggesting that even players on the same development programme lack 'typical' training exposures. This supports the notion that stakeholders involved in youth sport provision (i.e., coaches, teachers, and parents) need to communicate and establish a coordinated system to monitor load and protect young athletes better, to prevent mismanagement of load prescription based on best intentions of coaches. This does not necessarily require the use of hi-tech equipment or resource intensive approaches to load monitoring, which have previously been outlined as barriers to implementing monitoring strategies (Akenhead & Nassis, 2016; Weston, 2018).

2.4.1 Measures of Internal Load

The aim of physical training is to systematically induce the optimal relevant psychological, physiological or biomechanical response (fitness) from minimum energy cost (fatigue) (Calvert et al., 1976; Impellizzeri, Marcora, et al., 2019a). It is this dose-response that corresponds to the internal load which is generally considered a reflection of the athlete's ability to cope with the requirements elicited by external load (Impellizzeri, Marcora, et al., 2019a). In addition to the individual's level of fitness, various other factors such as injury, illness, environmental conditions, fixture congestion and psychological status can all impact internal training responses (Impellizzeri et al., 2004). By recognising sub-optimal dose-responses between individuals or more pertinently within-individuals for a given external load, practitioners could identify risk of injury or illness earlier (Brink, Nederhof, et al., 2010). Recent literature has illustrated associations between internal load (e.g. s-RPE) and injury (Gabbett et al., 2014; McCall et al., 2018; Watson et al., 2017), however there are significant questions regarding the ability of this approach to be predictive of injury (Fanchini et al., 2018; McCall et al., 2018). Quantifying internal load to assess the psychophysical response is a complex and multifactorial construct, in that there is no single or gold-standard measure that is relevant across contexts (e.g. endurance, team-sport activity and resistance training); and thus requires informed selection from a myriad of possible variables (Bourdon et al., 2017; Coyne et al., 2018; Gabbett & Whiteley, 2017). Although the method of monitoring internal load may vary between activities, it is common that these variables will be analysed using a training impulse, derived as a product of intensity and volume/duration (Calvert et al., 1976; Coyne et al., 2018). Several approaches have been used to measure internal training load, with likely the most popular being ratings of perceived exertion (RPE), originally employed by Borg et al. (1987) as a simplification of the Banister et al. (1976) training impulse concept. Originally used within clinical populations as a gestalt metric of global intensity for the entire session, Foster (1998) adapted this by multiplying the intensity from a category ratio scale (CR10-scale) (Figure 2.4) by the duration of the session (in minutes) to provide a 'sessional-RPE' (s-RPE) in arbitrary units (AU).

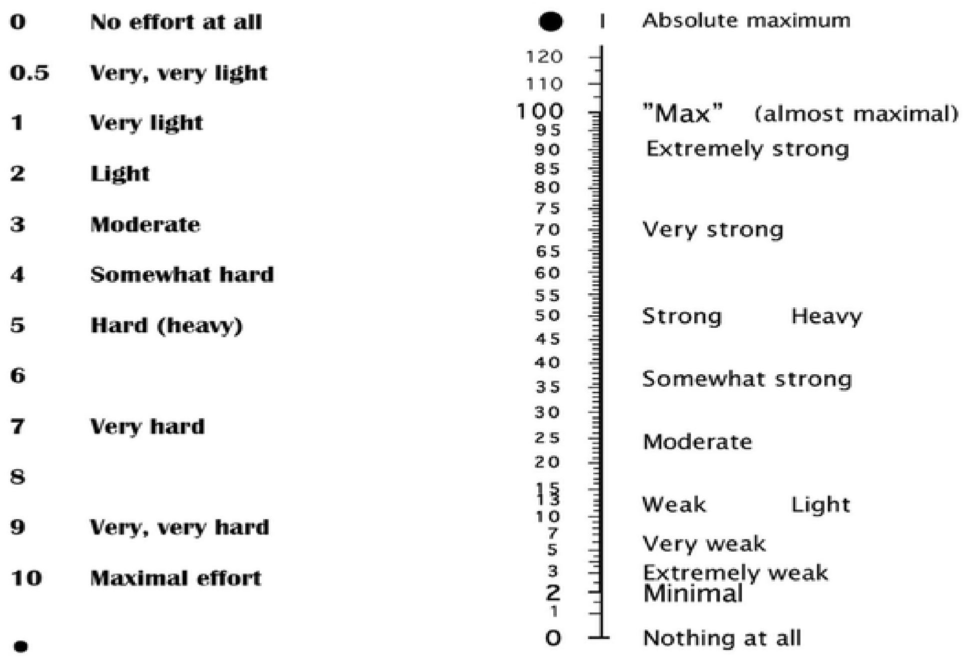

Figure 2.4. CR10-scale (Borg et al, 1987) and CR100-scale (Borg & Borg, 2002)

Since the original validation, a new centiMax scale (CR100-scale; Figure 2.4) has been proposed with the aim of reducing the tendency to use whole numbers related to the verbal anchors to improve sensitivity and quality of training load data (E. Borg & Borg, 2002). The s-RPE approach has been validated in clinical (E. Borg & Borg, 2002) and various soccer populations to observe holistic psychophysical dose-responses, with strong relationships with other indices of exercise intensity demonstrating concurrent validity (Fanchini et al., 2016; Impellizzeri et al., 2004; Weston, 2013). It was first validated within youth soccer players by Impellizzeri et al. (2004) who reported good correlations (r = 0.50–0.85) between s-RPE and heart-rate (HR) based methods, and since supported by various other studies in varied soccer populations (Akubat et al., 2014; Casamichana et al., 2013; Wrigley et al., 2012). One major strength of using s-RPE is the portability and accessibility of the scale, particularly since studies have confirmed the interchangeability of the CR10 and CR100 scales (Fanchini et al., 2016) with the added ability to retrospectively recall session RPE up to 48-hours post session without systematic recall bias (Christen et al., 2016; Fanchini et al., 2017a). This coupled with its simplicity and intuitive use are primary reasons that s-RPE is appealing to practitioners of all levels of football and other sports.

RPE validation studies have generally done so against other internal metrics (i.e., HR), however knowledge of the relationship between internal and external loads is crucial to understanding the dose-response, in addition to providing evidence for the construct validity and sensitivity of the load indicators (T. Lovell et al., 2013; McLaren et al., 2017a). A recent meta-analysis (McLaren et al., 2017a) identified consistent positive associations between internal measures (RPE and HR) with locomotive and accelerometer-derived external load metrics from team sports, although the magnitude of these associations is measure and training mode dependent. The strongest associations between internal and external load surround the amount of running completed, which seems conceptually intuitive based on locomotion being a centrally driven neurological process of the corollary discharge which is believed to drive perception of effort (Bartlett et al., 2017). There were fewer substantial relationships as the locomotive speed increased above arbitrary high-speed thresholds, possible attributable to the increased measurement error global positioning system (GPS) devices, individual differences in maximum speed or the velocity at which perceived high intensity are attained (Abt & Lovell, 2009; McLaren et al., 2017a). However, there was considerable uncertainty between the relationships of some internal-external load indicators when individual modes of training were considered, explaining 24-100% of the between-estimate heterogeneity (i.e., all modes combined). The various intricacies of mode dependent training such as work: rest ratios, high force or velocity movements exclusive of locomotion and/or collisions potentially cause an uncoupling of the relationship between internal and external loads (Jaspers et al., 2017; McLaren et al., 2017a, 2018). For example, s-RPE showed a stable ~5% between-match coefficient of variation (CV) for soccer referees, despite 17-54% CV for key measures of external load (i.e., high-speed running and sprinting; Weston et al, 2012)). Therefore, although s-RPE may be a suitable indicator for some activities it may be limited in sensitivity for some modes of training, and therefore why a multivariate (combining internal and external indicator) approach to load monitoring is encouraged where possible (Gabbett et al, 2017; Impellizzeri et al, 2019; Weaving, 2017). (Gabbett & Whiteley, 2017; Impellizzeri, Marcora, et al., 2019a; Weaving et al., 2017).

In light of these critiques, mode specific variations of RPE scales such as repetitions in reserve (RIR) (Zourdos et al., 2016) and pictorial representations of RPE (OMNI scales) have been developed for use in various sports including resistance training, cycling and running (Robertson et al., 2017). More specifically, a growing body of research is developing for the use of differentiated rating of perceived exertion (d-RPE) which may improve the accuracy of perceived exertion by differentiating the psycho-physiological mediators (McLaren et al., 2017a, 2018; Weston et al., 2015; M. Wright et al., 2020). This specific mediator approach (e.g., central, and peripheral exertion) has the potential to inform practitioners and coaches of the nature more sensitively, and magnitude of the response elicited by a training stimulus. Ratings of d-RPE are usually graded using the same CR-100 scale, but require separate ratings for breathlessness (RPE-B), leg muscle exertion (RPE-L), upper body exertion (RPE-U) and cognitive/technical demands (RPE-T) (McLaren, Weston, et al., 2016). Studies (McLaren et al., 2017a; Weston et al., 2015) suggest that d-RPE more accurately represents the distinct sensory inputs of exercise and consequently provides more precise evaluations of the dose-response, with a meaningful difference threshold of 10% recommended for individuals. Each of the psycho-physiological mediators made a unique contribution to the s-RPE, outlining the multidimensional nature of internal load and the importance for practitioners to recognise the disparity between central and peripheral responses to external loads (McLaren, Weston, et al., 2016).

While s-RPE and d-RPE are accessible and cost-effective methods to quantify internal load, they are not the only indicator of the internal response, with HR and training impulse (TRIMP) approaches also common (Akubat et al., 2014). Based on RPE often being validated against HR based methods as criterion measures of internal load (Foster, 1998), it seems appropriate to briefly review the use of these methods independently. HR (beats per minute) is commonly measured in concordance with global positioning satellite (GPS) devices, but often in isolation to provide an individual and direct measurement exercise intensity through central responses to exercise (Akenhead & Nassis, 2016). It is common for accumulative time spent within specified arbitrary HR zones (Edwards, 1993; Morton et al., 1990) or the use of lactate threshold to be used to devise a Training Impulse (TRIMP) in an effort to 'weight' exercise intensity (Akubat et al., 2014). However, these arbitrary zones reduce the individualised response and even the use of individualised lactate thresholds rely on arbitrary weightings to inform internal response (Akubat et al., 2014). Further, although logistically simple and fairly established, heart rate-based approaches have been suggested to lack sensitivity to accurately relate to the stochastic demands of team sports (Weston, 2013). Akubat and colleagues (2014) attempted to address this issue by applying the iTRIMP to changes in aerobic performance in youth soccer. Although their findings illustrate close relationships between iTRIMP and lactate threshold, they do outline the logistical and technical resources required to conduct the approach. Therefore, this may be beyond practical in most academies due to time, resource, and staff requirements.

2.4.2 Measures of External Load

The complexities of identifying accurate individual 'responses' has been discussed above, but equally important is the objective knowledge of the 'dose' elicited to suitably prepare athletes for performance and reduces injury risk (Weston, 2013). Recent years has seen an exponential rise in the use of microtechnology within team sports to quantify external workloads, with most professional teams now utilising GPS or alternative systems (e.g., Prozone or Inmotio) (Akenhead & Nassis, 2016). The gradual acceptance of this technology has led to the integration of various micro inertial sensors housed within the GPS device, such as triaxial accelerometers, magnetometers and gyroscopes, collectively termed micro-electrical mechanical systems (MEMS). The relative wealth of data and simplicity of computation of these MEMS devices has typically seen them used to evaluate athletic training programmes and competition demands, explore load-injury relationships and facilitate more accurate applied research questions (Malone et al., 2017). Variables such as distance covered in various speed zones, accelerations/decelerations and accelerometer derived metrics (e.g., PlayerLoad™) are the most common within professional soccer (Akenhead & Nassis, 2016). However, the choice of variables utilised needs to be understood and in turn trusted by practitioners within the organisation, and therefore not all metrics are suitable for all organisations. A simple classification has been suggested which identified the levels of complexity around MEMS metrics; Level 1) typical distances and velocity zones; Level 2) all events relating to changes in velocity (e.g., accelerations, decelerations and change in direction; and Level 3) all events derived from the inertial sensors (e.g., PlayerLoad™, impacts, stride variables and stride imbalances) (Buchheit & Simpson, 2017). Technological advances are continuing in this field with foot-mounted iso-inertial devices now appearing within professional domains (Barrett, 2020). These devices offer comparable reliability with torso-mounted GPS devices, but due to their lower-limb location reported higher velocities in acceleration and deceleration tasks. This is likely more representative of the true lower limb demands and therefore offers a novel method to monitor technical involvements, limb-symmetry, mechanical loads and locomotive patterns (Barrett, 2020; Marris et al., 2021).

Although all of these devices have potential regarding injury prevention and performance enhancement, it is important that practitioners recognise the limitations in relation to the validity and reliability and how this may impact the data (Malone et al., 2017; Scott et al., 2016). Naturally the developments in soft and hardware have seen improvements in the accuracy of devices, particularly the improvement of sampling frequency from 1Hz, 5Hz, 10Hz, 15Hz and now 18Hz with locomotive movements at lower speeds much more reliable than higher speeds (Malone et al., 2017; Scott et al., 2016). However, faster sampling rates do not always mean better data fidelity with questions over the interunit and precision error associated with the technology (R. Lovell et al., 2019). Mean levels of error between 5.1-10.9% was observed for 10Hz sampling rates when comparing 15m and 30m straight line sprint distance, but the same study illustrated good interunit reliability (<1.5% CV) (Castellano et al., 2011). Johnston and colleagues (2014) suggested that 10Hz sampling rates are more reliable than 15Hz, but that both sampling frequencies were incapable of reliably measuring movement demands above 20km·h^{-1}. This level of distance error could potentially lead to the true external demands of a match being misinterpreted by approximately ±1 km, leaving uncertainty particularly around the higher intensity locomotive work which is often the most physically demanding due to their neuromuscular-orientated loading type (Buchheit & Simpson, 2017). Therefore, variable reliability is inversely related to their importance in that the least valid and reliable variables are regarded as the most important for injury prevention (Bowen et al., 2017) and load monitoring (Buchheit & Simpson, 2017; Haugen, 2019).

The units themselves have developed over time, but the quality of signal they receive is largely dependent on the location, environmental obstructions and ultimately impact the data quality obtained (Malone et al., 2017). The recent development of the Global Navigation Satellite Systems (GNSS) has meant that signal quality has generally improved, and it is now easier for GPS devices to access the minimum required four satellites, but it is suggested that anything below six is considered as poor signal strength. In addition, the horizontal dilution of precision (HDOP) provides a measure of accuracy of the GPS signal determined by geometrical organisation of satellites. The HDOP score can range from 0 to 50, with values less than 1.5 considered ideal (Malone et al., 2017) and should therefore be monitored by practitioners and/or researchers. Although some studies report this information, others do not which is partly influenced by some manufacturers who make this information inaccessible for users, making comparisons in research difficult (Buchheit & Simpson, 2017; Malone et al., 2017). In addition, various manufacturers produce these units each with different sampling rates, chip sets, data processing algorithms and filtering methods which may further complicate comparisons within research and for practitioners (Malone et al., 2017). This uncertainty can negatively impact the decision making of practitioners around the true dose-response and subsequently load management strategies (Buchheit & Simpson, 2017).

2.4.3 Approaches to monitoring training load

Obtaining accurate and reliable data is of primary importance for effective observation of the individual dose-response, but systematic tracking of this response over extended periods of time has received extensive attention in recent empirical research (Gabbett, 2016b; Lolli et al., 2019; Windt & Gabbett, 2017). This recent upturn in interest builds on the seminal fitness-fatigue work of Banister et al (1976), whereby a 'sweet-spot' between a negative function (fatigue) and positive function (fitness) elicits the optimum net training stimulus. For practitioners identifying this 'sweet-spot' and imposing appropriate loads to augment this is of primary importance. This pursuit of the 'holy-grail' was stimulated by the work of Orchard et al. (2009) who identified that high acute workloads led to a seemingly delayed increase in injury risk which occurred up to 3 to 4 weeks after the overload. The 14-day, 21-day and 28-day periods following periods of increased workload in cricket, showed an increase in injury risk of 9%, 13% and 16% respectively (Orchard et al., 2009). This triggered further work by Hulin et al. (2014) who was the first to employ the acute-to-chronic training-stress balance in this manner to model the associations between workload and injury risk. Hulin et al. (2014) defined a rolling average load for the previous 7-days as the acute period, with a rolling 28-day average as the chronic period, although variations in these time periods have since been explored (i.e. 3 or 6 days for acute and 21 days for chronic) (Carey et al., 2017). This initial study calculated the training-stress balance by dividing the acute workload by the chronic workload and expressing this as a percentage. This was considered to inform practitioners on the 'preparedness' of the players to tolerate loads, whereby injury risk would decrease as chronic workload outweighed acute load. In addition to this, they concluded that increases in acute relative to chronic workloads heightened injury risk, and that large increases in acute load (200%) led to a subsequent three-four-fold increase in injury risk (Hulin et al., 2014). This led to the breakthrough paper from Blanch & Gabbett (2015) swiftly followed by the now heavily cited review by Gabbett (2016b) presenting the 'training-injury prevention paradox'. Theis suggested that using an acute-to-chronic workload ratio (ACWR; Equation 2.6) was a better approach to modelling training-injury relationships, and that athletes should train 'smarter and harder' (Gabbett, 2016b).

Equation 2.6: The ACWR

$$\frac{A}{0.25 \cdot (C1 + C2 + C3 + A)}$$

Where A is the 7-day acute workload and hypothetical C1, C2 and C3 are the preceding 7-day chronic workloads respectively. This suggestion was based on changes of >10% of weekly load (usually increasing load) associated with a subsequent increased injury risk (Gabbett, 2016b; Windt & Gabbett, 2017), and that exposure to more regular moderate-high loads could act as a vaccine to injury. Blanch & Gabbett (2015) suggested that using the ACWR to provide an index can clearly illustrate the preparedness of an athlete, whereby if acute load is low (e.g., minimal fatigue) relative to chronic load (e.g., well-developed fitness) the athlete is well prepared. Conversely, high acute with low chronic workloads (i.e., rapidly increased acute loads) would lead to a fatigued athlete with workload ratios exceeding 1. A ratio considers the training the athlete has performed relative to the training load that they are prepared for, and that practitioners should strive for a 'sweet-spot' of ACWR between 0.8 and 1.3 (Gabbett, 2016b). This suggests that 'spikes' in acute training load or similar undertraining (troughs) could contribute to increased injury risk (Bourdon et al., 2017). However, the level of evidence, and more specifically the methodologies to support this is debated and practitioners are encouraged to consider ACWR outside of this range for activities they deem suitable (e.g. rehabilitation or tapering) (Coyne et al., 2018), as well as question the applicability of a ratio in general in this situation (Atkinson & Batterham, 2012)

Despite the undoubted impact and subsequent application of the ACWR within professional sport since its inception, significant debate remains regarding the mathematical calculation to ascertain ACWR and how this impacts workload-injury relationships (Coyne et al., 2019; Impellizzeri, Wookcock, et al., 2019; Lolli et al., 2019). One concern is that the use of rolling averages as outlined above fails to consider the decaying nature of fitness and fatigue over time. That is, that workload completed 28-days ago is of less significance to the athlete, than the workload completed the previous day, and that this should be exponentially weighted as a result (S. Williams et al., 2017). Therefore, the ACWR has since been adapted to an exponentially weighted moving average (EWMA), which is suggested to cater for this decaying nature of fatigue-fitness and better informs practitioners of the workload-injury risk (Murray et al., 2017). These authors compared the original ACWR with the EWMA and concluded that the latter was more sensitive to changes in load when informing practitioners of injury likelihood, particularly at higher ACWR (i.e., 1.5-1.99 and >2.0). This is partly explained by the assumed linear relationship between load and injury by the ACWR, without the consideration of time (Murray et al., 2017). Nonetheless, this approach is still to be used with caution as this model assumes that each individual has a similar decay rate in both fitness and fatigue, when in fact they likely have individual idiosyncrasies (Coyne et al., 2019).

Although it is important that the numerator and denominator of any ratio are related (e.g., biological mechanism), one concern of the ACWR is that the acute workload constitutes a substantial (i.e., 25%) of the chronic workload. This 'mathematical coupling' between the two variables may lead to spurious correlations (r = 0.5) irrespective of the true physiological/biological associations between them, compromising the monitoring process (Lolli et al., 2019). The suggestion by Lolli et al. (2019) that the calculation should be 'uncoupled' whereby the acute workload is not part of the chronic load, is refuted by Windt & Gabbett (2019). In response they suggested that with the coupled calculation, approximately 25% of the total variation in the outcome (chronic load) is explained by its linear relationship with acute load, and is therefore expected (Windt & Gabbett, 2019). They continued that both coupled and uncoupled calculations to derive ACWR are valid and therefore neither is superior, however practitioners and researchers should thoughtfully consider their approach and explicitly state the method used to obtain ACWR (Coyne et al., 2019; Hulin & Gabbett, 2019; Windt & Gabbett, 2019). Despite the apparent impact of the ACWR and various iterations since it's development, there is still ambiguity around its application, with no current studies of this application in adolescent athletes available. Significant criticism of the ACWR persists, particularly its ability to be predictive of injury (Andrade et al., 2020; Impellizzeri, Marcora, et al., 2019b; Impellizzeri, Menaspà, et al., 2020; Impellizzeri, Wookcock, et al., 2019, 2020), leaving practitioners to adopt variations of accumulated load-monitoring specific to their environment. These methods are often associated with collating week-on-week changes in or by summating key metrics (i.e., RPE, total, distance, high-speed running, accelerations) to quantify group or individual specific deviations from 'normal', whether this be through ACWR or alternative (i.e., percentage change, absolute change). The benefit of this approach is that practitioners can visualise the data and interpret this free from error attributed to the mathematical method employed, as outlined above. Either way, the important consideration is that practitioners employ an approach that facilitates timely intervention of training prescription in response to sub-optimal physical or physiological response, to optimise performance and reduce injury risk.

2.5. Summary

This review of literature has identified that despite a growing body of research in training load and injury in adolescent football populations, there is a need to further enhance knowledge in key areas. Firstly, it is clear that a large proportion of injuries in adolescent football are non-contact, and overuse in nature (albeit under-reported), yet the specific mechanistic causes of these injuries and the magnitude to which biological maturation influences these mechanisms is less clear. Importantly, there also seems to be debate around the most appropriate method to estimate biological maturation which may convolute comparisons between studies that have adopted varying approaches, leading to a general lack of consensus in the literature. Secondly, there has been a growing body of evidence linking training load and injury in adult populations but a paucity supporting the same notion in younger (<16 years) athletes, which creates ambiguity around the true impact of maturation on the specific dose-responses to acute and more chronic exposure to training and match-play. Additionally, this the lack of specific training load studies in adolescent populations leads researchers into applying principles of adult research to younger populations, which may be inappropriate and therefore needs exploring purposefully. This subsequently means there is very little current knowledge about maturity-specific interventions to mitigate any variable dose-responses in adolescent populations, resulting in practitioners lacking evidence informed guidance. Finally, the exponential growth in training load research in recent years has included studies adopting several different approaches to monitoring training loads and athlete 'status' (e.g., A:C, EWMA), which has also led to a lack of consensus around 'best-practice' to load monitoring beyond combining internal and external load metrics. This thesis aims to advance current knowledge and understanding around several of these literature gaps and offer some conceptual and mechanistic evidence for the increased injury trends, dose-responses, and possible mitigation of risk in this population.

Chapter 3

General Methods

Chapter 3: General Methods

3.1 Operational Terms

3.1.1 Adolescent Soccer Player

For this thesis adolescent soccer players are defined as young soccer players that are actively participating in the Youth Development Phase (YDP) of a Premier League Elite Player Performance Pathway (EPPP) (The Premier League, 2011). All players receive between 6-12 hours' football contact time at their respective centres, including technical coaching, sport science support and weekly competitive fixtures.

3.1.2 Injury

Throughout this thesis, an injury is defined as 'any physical complaint sustained by a player that results from any academy football match or training session, irrespective of the need for medical attention or time loss from football activities' (Fuller, 2006, p. 193). Where relevant, injuries are classified as either 'medical attention' whereby the player received an assessment of their medical condition by a qualified medical practitioner, or 'time-loss' when they were unable to take full part in football training or match.

3.2. Protocol

3.2.1 Participants

Male adolescent football players from two EPPP professional football club Academies (Category 2 and Category 3) from the U12 to U16 age groups were included in the experimental chapters of this thesis. The specific sample size and characteristics are stated within each chapter of the thesis. Data that required face-to-face collection was done so at the usual training venue and within normal training time of all participants, ensuring no additional burden was imposed on participants or clubs involved. Data for chapter 6 investigated the acute responses to a simulated soccer activity profile and was therefore collected through various visits to each academy, with each participant included on one occasion. Longitudinal data from chapter 7 observed accumulated training loads over a 40-week season and included anthropometric and neuromuscular performance measurements from three occasions per participant throughout the season. Small-sided game (SSG) and the associated performance data for chapter 8 was recorded over an 8-week period including twice-weekly visits to the academy involved. Although much of the data collated for this thesis was routinely collected by the clubs in accordance with the EPPP (2011) guidelines, it was deemed appropriate that parental informed consent and participant assent was obtained for the use of such data and for the additional collection of any non-routinely collected data for research purposes. In accordance with the British Olympic Associations position statement on athlete confidentiality (Macauley, 2000), each participant was informed of their right to withdraw from the research at any point, free from any repercussions from a club or research perspective. Ethical approval was obtained from the University of Gloucestershire Research Ethics Committee which included the approval of an existing Disclosure and Barring Services check prior to any data collection taking place.

3.2.2 Anthropometric Assessments

In accordance with ISAK recommendations (Stewart et al., 2011) anthropometrical measurements were conducted on all participants to facilitate maturity estimations using common somatic equations (Fransen et al., 2018; Khamis & Roche, 1994; Kozieł & Malina, 2018; Moore et al., 2015). A portable stadiometer (Seca© 217, Chino, USA) was used to measure standing stature when participants stood barefoot with feet together and heels touching the scale, with their head in the Frankfort plane.

The stretch stature method was adopted by where the participants were required to take a deep breath and hold their head still whilst duplicate measures of standing stature were recorded to an accuracy of 0.1cm and subsequently the mean was calculated (Stewart et al., 2011). Following similar procedures, participants seated stature was measured whilst sat on a standardised plinth (40cm high) with feet together and hands rested on thighs. Leg length was measured using illiospinale height guidelines (Stewart et al., 2011). The participant stood barefoot with feet together facing cut-out aspect of the standardised plinth (40cm). The base of the segmometer was placed on top of the box and the moving branch positioned at the illiospinale landmark. Leg length was calculated by summing the plinth height and measure to illiospinale landmark. Duplicate readings were taken, and the mean calculated, with a third taken if necessary and the median being employed in such cases. Body-mass was recorded using portable weighing scales (Seca© robusta 813, Chino, USA) whilst participants were stood barefoot wearing normal training attire. Duplicate readings were taken and if measurements varied by 0.2kg a third measure was taken and the median recorded. For each study within the thesis, all data was collected by the same individual to minimise systematic inter-rater error (Stewart et al., 2011).

3.2.3 Estimations of somatic maturity

With the exception of chapter 5 which compared several methods, estimations of maturity status, tempo and timing for this thesis were calculated using the predicted adult height (PAH%) method through appropriate anthropometric measures (standing stature and body-mass), decimal age (years) and self-reported parental height, corrected for overestimation (Epstein et al., 1995; Khamis & Roche, 1994). A detailed explanation of the methodological differences of the various approaches and rationale for use of this method for this thesis are included within chapter 5. This approach utilises anthropometric measurements to estimate progression (expressed as a percentage) towards final stature at the time of observation (Cumming et al., 2017; Khamis & Roche, 1994). The equation (equation 2.5) required mid-parental stature, which for various reasons was logistically difficult to obtain from academy players. Therefore, this study sought to minimise error whereby if possible objective measurement of parent stature was obtained using a stadiometer available at multiple data collection sessions. In many cases, this was not possible, therefore self-reported stature was collected and subsequently corrected for overestimation in line with validation guidance (Epstein et al., 1995; Khamis & Roche, 1994). There were no cases where either of the two previous approaches were not possible, therefore using national male and female mean stature's was not required, therefore it can be assumed that error is within that reported in the validation study (Khamis & Roche, 1994). The PAH% method can be used to categorise individuals based on their percentage of mature stature. Where categorisation was required (chapter 8), the following scale was used: pre-PHV, <88%; circa-PHV, 88-96% and post-PHV, >96% (Cumming et al., 2017; Sanders et al., 2017).

Equation 2.5 Predicated Adult Height

$$\text{Predicated Adult Height} = \beta_o + \text{stature}^* \beta_1 + \text{body mass}^*(\beta_2) + \text{corrected mid-parent stature}\ ^*\beta_3$$

Note: β_o, β_1, β_2, and β_3 are the gender specific intercept and coefficients by which age, stature (in), body mass (lbs) and mid-parent stature (in) respectively should be multiplied from the coefficients table available in Khamis & Roche (1994). Correction factor for self-reported height in males is (Parental Height [cm]*0.955) + 2.316

3.2.4 Soccer-specific activities

To simulate soccer match-play in chapter 6, an adapted soccer-specific aerobic field test (SAFT^{90}) was used, termed Youth-SAFT (Y-SAFT^{60}) (Barrett et al., 2013). The Y-SAFT is a 15-minute fixed-intensity activity profile based on global-positioning satellite (GPS) locomotion data from elite male academy competition matches and includes acceleration, deceleration, lateral shuffling, jogging, back-pedalling and sprinting to replicate the mechanical and physiological demands of match-play (Barrett et al., 2013). The intensity and locomotor activity throughout the shuttle course (Figure 3.1) is controlled by audio cueing which adopts the same multidirectional model of the original SAFT^{90} (Barrett et al., 2013; Marshall et al., 2014). The 15-minute Y-SAFT was repeated a total of four times (Y-SAFT^{60}), interspersed with a 10-minute half time interval to approximately replicate mean adolescent competition duration between U13 and U16 (Premier League, 2011). All Y-SAFT^{60} simulations were completed on 3G pitch whilst participants wore their normal training attire to reduce the variance associated with different surfaces and maintain ecological validity.

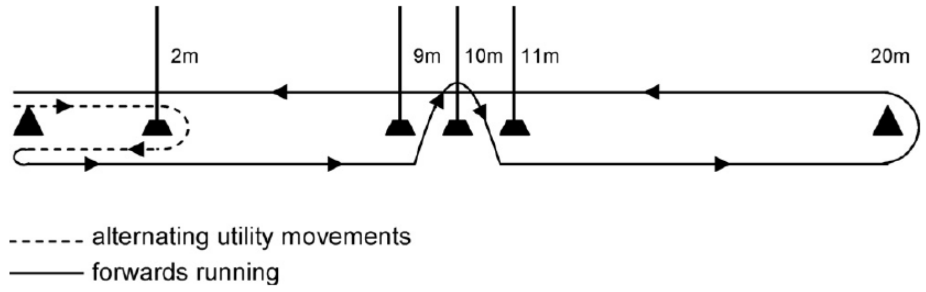

Figure 3.1. Diagrammatical presentation of the Y-SAFT^{60} setup (Barrett et al., 2013)

3.2.5 Standardised sub-maximal run

In chapter 8, at the start of each session following a standardised FIFA11+ (Stage 1 & 3) warm-up players performed a standardised sub-maximal run using the audio controlled 30-15^{IFT}, with starting velocity set at 10 km·h^{-1} (Buchheit, 2008). Each 30-second shuttle across the 40-m area was separated by 15-second passive recovery with the velocity increasing by 0.5 km·h^{-1} each shuttle up to and including 12.5 km·h^{-1}. Participants were instructed to run at a consistent pace throughout and to keep in time with the audio signal, with a member of the research team running as a 'guide' runner for pace. Players completed this wearing a PlayerMaker™ device, located on the lateral aspect of the calcanei, which included a 1000 Hz IMU microprocessor and comprised of a 3-axis 16 g accelerometer and 3-axis gyroscope (MPU-9150, InvenSense, California, USA) (Waldron et al., 2020). This system calculates whole-body velocity-based metrics which permits detection of the orientation and translation of the participants limbs during gait cycles and through algorithms can detect heel strike, toe-off, zero-velocity and non-gait patterns (e.g., ball contact). This is then computed through a Kalman filter to provide metrics more often associated with soccer performance (i.e., stride length, contact time, flight time etc). Data is synchronised to the manufactures cloud-based software system and subsequently exported to Excel (Microsoft, Redmond, USA). for analysis (Marris et al., 2021; Waldron et al., 2020).

3.2.6 External load monitoring

To quantify external load during the Y-SAFT^{60} (chapter 6) and SSG intervention (chapter 8) each player wore a microtechnology Global Positioning Satellite (GPS) unit (Catapult, Optimeye S5, firmware version 7.27, Melbourne, Australia) which included a tri-axial accelerometer, gyroscope and magnetometer and sampled at a rate of 100Hz. Total distance (TD), playerload (PL), meters per minute (m.min) and maximum velocity (Vel^{M}) for each Y-SAFT^{60} period, with similar metrics used for SSG activities were measured to objectively assess the external load completed by each participant. In addition, foot-mounted iso-inertial devices (PlayerMaker™) were also worn for to observe SSG and sub-maximal locomotive running patters (chapter 8). Internal load was measured directly using a Heart Rate (HR) belt (Polar, Finland) and indirectly using sessional rating of perceived exertion (sRPE) on the centiMAX scale (CR100) (E. Borg & Borg, 2002) (outlined in section 3.2.7 below).

3.2.7 Self-reported perceptions of intensity

In the absence of consistent access to MEMS devices for an entire season (chapter 7), and in addition to GPS, PlayerMaker™ and HR data (chapter 6 and 8), self-reported perceptions of psycho-physiological intensity were employed throughout this thesis. sRPE has been widely used at various levels of football, particularly within adolescent populations, likely due to the relative in-expense and validity of its application to measure exercise intensity (Impellizzeri et al., 2004; M. Wright et al., 2020; Wrigley et al., 2012). However, using sRPE as a global and gestalt metric of exercise intensity has been critiqued due to the limited sensitivity to differentiate between domain specific markers of intensity and leads to oversimplifying the psycho-physiological response to exercise (McLaren, Graham, et al., 2016; McLaren et al., 2017a; Weston et al., 2015). Therefore, by including differential rating of perceived exertion (dRPE) for breathlessness (RPE-B), leg muscle exertion RPE-L) and cognitive/technical demands (RPE-T) to distinguish between specific 'local' and 'central' mediators, precision in scaling exertional signals during exercise is likely enhanced (Weston et al., 2015). Players used a touch-screen tablet (Acer Iconia One 8 B1-850, Taipei, Taiwan; Acer Inc) to record their perceptions of intensity using a customised application allowing confidential responses free from conformation bias (McLaren et al., 2017a; M. Wright et al., 2020). The application utilised a numerically blinded centi-MAX CR100® scale (Figure 2.4) with verbal anchors which offers enhanced sensitivity, and precise measurements in comparison to the traditional CR10® scale (E. Borg & Borg, 2002; Fanchini et al., 2016).

3.2.8 Neuromuscular Performance

Neuromuscular performance was measured consistently throughout chapters 6, 7 and 8. Countermovement jump (CMJ), leg stiffness and reactive strength index (RSI) were measured at specific times to (e.g., immediately before and after the Y-SAFT[60]) objectively assess the impact of simulated or SSG match-play. A detailed explanation and rationale of measurement timing if provided in each chapter as appropriate. Participants were given opportunity to practice each test to familiarise themselves with the protocol after a standardised 8-minute dynamic Fifa11+ (Stage 1 & 3) (Bizzini & Dvorak, 2015, p. 11) warm-up consisting of bodyweight activities (e.g., squats, lunges, squat jumps). After sufficient rest (3-5 mins) participants were required to complete a minimum of two attempts of each protocol with the best score taken from test each for analysis. All CMJ, leg stiffness and RSI data were collected using the Optojump photocell system (Microgate, Bolzano, Italy), except for chapter 8 which calculated RSI and leg stiffness during the standardised sub-maximal run (30-15 IFT).

When using OptoJump, CMJ and RSI were calculated from five consecutive, maximal bilateral jumps (Oliver et al., 2015a). Participants started in an upright, standing position with hands on hips and then squatted to a self-selected depth and without pausing jumping maximally five times. Participants were encouraged to perform the eccentric phase of the movement as quickly as possible to maximise vertical jump height and to minimise ground contact time. Jump height (m) was calculated from the first maximal jump using flight time from the following equation (equation 3.1) (Oliver et al., 2015a). Jump height and ground contact time were averaged across the five rebound maximal bilateral jumps to calculate RSI using the following equation (equation 3.2).

Equation 3.1: Jump Height

$$\text{Jump height} = (\text{Flight time}^2 * \text{gravity}) / 8$$

Equation 3.2 Reactive Strength Index

$$\text{RSI} = \text{jump height (m)} / \text{ground contact time (s)}$$

Contact time and flight time were measured using twenty consecutive bilateral sub-maximal hops. These hops were performed at a frequency of 2.5 Hz as this was deemed to have the highest reliability of leg stiffness measured in adolescent populations (CV 7.2%) (De Ste Croix et al., 2017b). Participants were asked to place hands on their hips to minimise upper body interference; rebound for height and land within the photocell gates; land with legs fully extended and to look forwards. Subsequently vertical leg stiffness ($kN \cdot m^{-1}$) was calculated the equation proposed by Dalleau et al. (2004) (equation 3.3) where K_{leg} refers to leg stiffness, M is total body mass, Tc refers to ground contact time and Tf is equal to flight time (Dalleau et al., 2004; Lloyd et al., 2009). To account for the influence of mass on leg stiffness and leg length on mechanical properties of locomotion between participants, absolute values of leg stiffness were divided by body mass and leg length to provide a dimensionless value of relative leg stiffness (De Ste Croix et al., 2017b; McMahon & Cheng, 1990).

Equation 3.3 Absolute Leg Stiffness

$$K_{leg} = [M*\pi\ (T_f+T_c)]\ /\ T_{c2}\ [T_f+T_c/\pi) - (T_c/4)$$

3.2.9. Methods summary

Table 3.1. Summary of methods adopted for each investigation chapter

Method	Study 1 (Chapter 4)	Study 2 (Chapter 5)	Study 3 (Chapter 6)	Study 4 (Chapter 7)	Study 5 (Chapter 8)
3.2.3. Somatic maturity estimation	x	✓	✓	✓	✓
3.2.4. Y-SAFT^{60}	x	x	✓	x	x
3.2.5. Standardised sub-maximal run	x	x	x	x	✓
3.2.6. Catapult GPS	x	x	✓	x	✓
3.2.6. PlayerMaker™	x	x	x	x	✓
3.2.7. Differential RPE	x	x	✓	✓	✓
3.2.8. Neuromuscular performance	x	x	✓	✓	✓

Chapter 4

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Human Kinetics
ORIGINAL INVESTIGATION

Monitoring Practices of Training Load and Biological Maturity in UK Soccer Academies

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Purpose: Overuse injury risk increases during periods of accelerated growth, which can subsequently impact development in academy soccer, suggesting a need to quantify training exposure. Nonprescriptive development scheme legislation could lead to inconsistent approaches to monitoring maturity and training load. Therefore, this study aimed to communicate current practices of UK soccer academies toward biological maturity and training load. ***Methods:*** Forty-nine respondents completed an online survey representing support staff from male Premier League academies (n = 38) and female Regional Talent Clubs (n = 11). The survey included 16 questions covering maturity and training-load monitoring. Questions were multiple-choice or unipolar scaled (agreement 0–100) with a magnitude-based decision approach used for interpretation. ***Results:*** Injury prevention was deemed *highest* importance for maturity (83.0 [5.3], mean [SD]) and training-load monitoring (80.0 [2.8]). There were *large* differences in methods adopted for maturity estimation and *moderate* differences for training-load monitoring between academies. Predictions of maturity were deemed *comparatively low* in importance for bio-banded (biological classification) training (61.0 [3.3]) and *low* for bio-banded competition (56.0 [1.8]) across academies. Few respondents reported maturity (42%) and training load (16%) to parent/guardians, and only 9% of medical staff were routinely provided this data. ***Conclusions:*** Although consistencies between academies exist, disparities in monitoring approaches are likely reflective of environment-specific resource and logistical constraints. Designating consistent and qualified responsibility to staff will help promote fidelity, feedback, and transparency to advise stakeholders of maturity–load relationships. Practitioners should consider biological categorization to manage load prescription to promote maturity-appropriate dose–responses and to help reduce the risk of noncontact injury.

Keywords: maturation, injury, adolescence, workload

Chapter 4: Monitoring practices of training load and biological maturation in UK soccer academies

4.1. Introduction

To provide a context and informed backdrop for the rest of this thesis, it is first important to identify current practices of, and perceived barriers to monitoring training load and biological maturity in soccer academies. It is then anticipated that the subsequent experimental studies within this thesis can be moulded around the common practices and methods employed to safeguard applied relevance for clubs, which will ultimately enhance the application of findings to real-world environments. Whilst informing methodological approaches for later chapters in this thesis, this chapter also intends to gauge the appetite and rationale for monitoring these important components of athletic development.

For academy soccer players, the pubertal growth period is a particularly sensitive time and should be managed with caution (A. Johnson et al., 2009; van der Sluis et al., 2015b). This period coincides with progressive, age specific increases in prescribed training exposure (hours), irrespective of individual biological maturation based on development scheme legislation (policy) (Premier League, 2011; The FA, 2016). Elite Player Performance Pathway (EPPP) (Premier League, 2011) and FA Women's Talent Pathway for Regional Talent Clubs (RTC) (The FA, 2016) policies provide recommendations for multifaceted components of player development, including minimum weekly training time, staff requirements, monitoring training load and biological maturation. The systematic increases in training exposure across both genders are predominantly influenced by development stage and/or age specific increases in weekly training load (20-50% depending on academy category) during adolescence (Wrigley et al., 2012). Most injuries within this population are non-contact and soft tissue in nature (Read, Oliver, et al., 2018; Tears et al., 2018) implying that these injuries may be preventable and possibly attributable to inadequate training load prescription or growth-related physical and/or anthropometrical changes (Bowen et al., 2017; Kemper et al., 2015). Significant time loss through injury, or illness may have major implications for (de)selection and long-term development (Myer et al., 2015).

Most (58-69%) injuries within professional soccer academies occur during training rather than match-play, likely due to the relatively higher proportion of time spent training. Injury incidence tends to peak following periods of relatively increased (relative risk of 3.5 following pre-season) or reduced training exposure (mid-season break) (Le Gall, Carling, Reilly, et al., 2006; Le Gall, Carling, & Reilly, 2006; Read, Oliver, et al., 2018). These findings are consistent with adult populations, where large (>10%) and sudden fluctuations in training load can amplify injury risk (Ekstrand et al., 2019). This highlights the importance of quantifying training load to mitigate injury risk (Fanchini et al., 2017a), particularly during periods of accelerated biological development (A. Johnson et al., 2009). These high instances of injury may result in players missing considerable development time and negatively impact their chances of progression within academy settings. Consequently, to enhance long-term development and improve the sensitivity of (de)selection criteria, fluctuations in physical and functional attributes of players owing to maturation, and the associated response to training exposure, should be monitored and communicated to key stakeholders (e.g., coaches, medical staff and parents/guardians) (Ekstrand et al., 2019).

EPPP and RTC policies aim to outline minimum standards for each category to facilitate adequate talent development environments for players. Adherence to these standards is assessed and used to classify each academy (e.g., category 1/tier 1) in return for financial investment and associated prestige helping with recruitment and retention. Yet, the extent of EPPP guidelines related to training load and biological maturation monitoring is somewhat non-prescriptive and open to interpretation (e.g., '188.2. anthropometric assessments' and '188.7. monitoring of physical exertion [Category 1 academies only]' (Premier League, 2011), with no minimum standards or guidelines provided in RTC legislation (The FA, 2016). Although this ambiguity facilitates context and environment specific approaches which are warranted (Gabbett et al., 2017a), it may subconsciously reduce consistency and generate opportunity for 'mixed-practice' rather than 'best-practice'. Particularly when you consider that there are various methods to predict maturity status and timing with each having logistical, systematic or resource-based confines (Malina et al., 2012). Similar logistical confines exist for training load monitoring which influences the methods adopted by academies (Gabbett et al., 2017a). As a result, considerable ambiguity remains around approaches to monitoring training load in adolescent environments and which combination of internal (e.g., heart rate, rating of perceived exertion [RPE]) or externally derived metrics (e.g., total distance covered, activity profiles) offer most value for practitioners (Gabbett et al., 2017a).

Previous surveys investigating training load monitoring have been conducted within professional populations (Akenhead & Nassis, 2016; Weston, 2018) and identified varied approaches to collating and disseminating data to stakeholders, with resource and communication-based limitations apparent. Despite strong evidence outlining its relevance within academy settings, no such attempt to investigate current practices of maturation and training load monitoring within male or female academy soccer currently exists. The nature of the developing athlete and the relatively high prevalence of non-contact injury within this population make these concepts an important consideration for athlete health and long-term outcomes. Assessing the current extent of, and the methods used to monitor these concepts would provide a platform to develop practice and subsequently optimise athletic development environments. Therefore, given likely disparities in situational, logistical, and environmental factors that govern both male and female academy practices, the aim of this thesis chapter was to establish and compare current perceptions and perceived barriers of practitioners to maturation and training load monitoring within UK soccer academies to provide context for the remaining chapters in the thesis.

4.2. Methods

4.2.1. Design

A cross-sectional survey design was used to ascertain perceptions of staff from male (EPPP) and female (RTC) academies during the first trimester (August to December) of the 2017/18 soccer season. Following ethical approval from the University of Gloucestershire ethics committee and in accordance with the Declaration of Helsinki, voluntary informed consent was included prior to survey completion. No personal details of the respondent or club were requested to maintain respondent anonymity. Two eligibility questions 1) *Have you already completed the survey?* (Yes or No); 2) *Are you currently working with academy players within an EPPP or RTC setting?* (EPPP, RTC or No) followed the consent page to prevent duplicate responses and ensure construct validity respectively. Each respondent was required to state which professional league their club competed in, the academy category (e.g., Cat/RTC), job role, employment status accompanied by which age category (Foundation [<9 to <12 years], Youth Development [<13 to <16 years], Professional Development [<18 to <23 years]) they primarily worked with.

4.2.2. Participants

118 respondents started the survey, however, there were 23 incomplete responses and 46 respondents failed eligibility criteria (question 2) and were excluded from analysis. In total, 49 respondents completed the survey (Cat1: n = 15 [31%]; Cat2: n = 13 [27%]; Cat3: n = 10 [20%]; RTC: n = 11 [22%]). Most respondents worked in the Youth Development Phase (YDP; 57%) or Professional Development Phase (PDP; 39%); with 4% working with the Foundation Phase (FP). Most responses were from sport

science support staff (i.e., sport scientists, strength and conditioning coaches, athletic development, or physical development coaches; 77%) with medical (physiotherapists, sports therapists, rehabilitation specialist or doctor; 15%) and technical coaching staff (lead or age group coach; 8%) providing the remainder of the responses. Most of the respondents were employed either full-time (57%) or part-time (23%), with a smaller number of responses coming from sessional staff (hourly paid; 14%) and internship students (6%). Most respondents worked for Championship (43%) or Premier League (29%) clubs, but some responses were from League One (14%), League 2 (6%) and clubs within the National League or below (8%).

4.2.3. Procedures

Content validity (Stoszkowski & Collins, 2016) of the initial survey was reviewed via communications between the research team and practitioners (*n* = 5) and academics (*n* = 4) with experience of academy soccer and survey-based studies. This process removed five questions, combined six questions into three and had language amendments for clarity. The final survey consisted of 16 questions that included 2 unipolar (0 = *not important*; 100 = *highly important*) and 6 multiple choice questions each, covering two concepts: 1) *monitoring of biological maturity* and 2) *training load monitoring*. Response analysis to establish internal consistency of each concept using Cronbach's alpha (Tavakol & Dennick, 2011) yielded alphas rated as '*good*', which ranged from 0.78 [95% confidence interval 0.72 to 0.86] (*monitoring of biological maturity*) to 0.83 [0.72 to 0.86] (monitoring *training load*). The survey was then published using an online survey tool (surveymonkey.com, California, Palo Alto, USA), with completion time of ~10 minutes. A web-link invite to participate was distributed to coaches, sport science support staff and medical practitioners within EPPP and RTC clubs via personal networks and social media.

4.2.4. Data Analysis

Responses from the multiple-choice questions were converted into a proportion of the total number of respondents from each academy category. Independent-group proportion differences for multiple choice questions were calculated with the following scale used to classify magnitudes of difference 10%, 30%, 50%, 70% and 90% as *small*, *moderate*, *large*, *very large* and *extremely large* respectively (Hopkins, 2010). Given the small sample size and the large number of inferences, we elected to use moderate as our threshold for meaningful differences.

Numerical data from unipolar-scaled questions were rank ordered and presented as mean ±SD to qualitatively illustrate perceived importance. To facilitate distribution-based interpretations and overcome the limitations of few verbal anchors on the unipolar scale, four perception levels were devised based on percentage thresholds of the overall mean; *lowest* (<25%), *comparatively low (*25% to 50%), *comparatively high* (50% to 75%) and *highest* (>75%) (McCall et al., 2014). Inferential analysis (ANOVA) was conducted using Jeffreys Amazing Statistics Package (JASP) computer software (v0.11.1, Amsterdam, Netherlands) to establish independent group mean differences in perceived importance and 99% compatibility limits (CL) to reduce inferential error rates, which were subsequently translated into probabilistic terms using a customised Magnitude-Based Decisions (MBD) spreadsheet (Hopkins, 2010). A clear standardised difference for non-clinical substantiveness of 10% was adopted, as this is considered the smallest important effect threshold for between-group differences (Hopkins, 2010). Only those effects that were above the smallest important effect were reported and these were then interpreted against the following Bayesian scale: 0.5% *most unlikely* or *almost certainly not*; 0.5-5% *very unlikely*; 5-25% *unlikely* or *possibly not*; 25-75% *possibly*; 75-95% *likely* or *probably*; 95-99% *very likely*; and 99.5% *most likely* (Hopkins, 2010) to express uncertainty. For both approaches to analysis, all comparisons were made against EPPP Cat1 academies. Considering the EPPP infrastructure being more mature than RTC, and these Cat1 academies fulfilling significant requirements to be awarded this status, they should be regarded as the benchmark of best practice within UK academy football.

4.3 Results

4.3.1. Biological Maturity

Injury prevention was identified as *highest* importance for maturation estimation across academy groups, with overall athletic development, load management, coach and player feedback considered *comparatively high* (Table 4.1). Legislative expectations from clubs and governing bodies as well as bio-banded competition were considered *lowest* importance. Cat1 academies placed more importance on EPPP legislation than Cat3 academies and a *likely* to *very likely* lower importance on player feedback than all other academies. Time constraints, staff numbers, resource limitations and staff competency were all perceived to be *comparatively higher* barriers to implementing maturity predictions (Table 4.1). Staff numbers and resource limitations are *likely* to *very likely* bigger barriers in lower ranked academies than Cat1. Coach support, financial budget limitations, management and parental/guardian support were all perceived as *comparatively low* barriers, with differences between Cat1, Cat3 and RTC academies *possible* to *likely*.

There were *large* differences between the methods of maturation estimation utilised by Cat1 and Cat2 academies (Table 4.2). Cat1, 3 and RTC academies preferred the prediction adult height whist Cat2 had a clear preference for maturity offset (i.e., time from peak height velocity). Sport Science support staff were primarily responsible for collection of maturation data consistently across all academies. There were small to large differences in the methods used by academies communicate maturation feedback and *moderate* to *very large* differences suggesting that fewer Cat1 academies report this data to parents/guardians. There were small to moderate differences that suggests that academy status is linked to the activities influenced by maturation monitoring (i.e., pitch-based training, competitive fixtures).

Table 4.1: Perceived importance (mean ± SD) of biological maturation estimations between clubs sorted by percentiles (sample mean ± SD), with chances that the true magnitude of difference is important. Effects below the smallest important threshold are not reported. All comparisons made against Category 1 academies (Cat1).

	Cat1	Cat2	Cat3	RTC	Mean	Between-group differences and *probability* of important differences
	(*n* =15)	(*n* =13)	(*n* =10)	(*n* =11)	(*n* =49)	Mean difference ± 99% CL
Perceived level of importance of the estimations of biological maturation for….						
[H] injury prevention	79 ± 13	84 ± 19	79 ± 11	91 ± 10	83 ± 14	*Possibly*, RTC 11%; ±11%
[CH] overall player development	74 ± 15	87 ± 14	80 ± 12	80 ± 12	80 ± 14	*Possibly*, Cat3 6%; ±15%
[CH] load management	79 ± 10	79 ± 20	75 ± 12	80 ± 21	78 ± 16	
[CH] coach feedback	75 ± 11	80 ± 12	72 ± 9	76 ± 10	76 ± 11	
[CH] player feedback	58 ± 18	73 ± 19	72 ± 14	81 ± 14	71 ±1 9	*Likely*, Cat2 15%; ±17%; Cat3 14%: ±18%; *Very Likely*, 23%; ±19%
[CL] player retention	72 ± 13	78 ± 22	64 ± 22	59 ± 19	68 ± 19	*Possibly*, Cat3 -8%: ±21%; RTC -13%; ±20%
[CL] reports to parents	64 ± 13	75 ± 22	56 ± 22	75 ± 19	68 ± 17	*Possibly*, Cat2 11%; ±16%; Cat3 -8%; ±17%; RTC 11%; ±16%
[CL] player recruitment	71 ± 16	71 ± 22	67 ± 17	58 ± 24	67 ± 20	*Possibly*, RTC -14%; ±21%
[CL] bio-banded training	59 ± 27	64 ± 23	57 ± 21	63 ± 22	61 ± 23	
[L] club legislation	54 ± 17	60 ± 25	51 ± 26	64 ± 15	58 ± 21	
[L] bio-banded competition	53 ± 28	57 ± 32	55 ± 23	57 ± 21	56 ± 26	
[L] EPPP/RTC legislation	59 ± 15	50 ± 28	39 ± 25	52 ± 26	50 ± 23	*Likely*, Cat3 -20%; ±23%
What are the primary barriers to implementing estimations of biological maturation?						
[CH] time constraints	57 ± 23	65 ± 33	73 ± 28	66 ± 26	65 ± 27	*Possibly*, Cat3 16%; ±29%
[CH] staffing numbers	47 ± 27	42 ± 35	76 ± 33	47 ± 32	53 ± 33	*Likely*, Cat3 29%; ±34%
[CH] resource limitations	30 ± 19	31 ± 26	59 ± 29	45 ± 33	41 ± 28	*Possibly*, RTC 15%; ±28%; *Very Likely*, Cat3 29%; ±29%
[CH] staffing competency	41 ± 26	37 ± 28	32 ± 26	53 ± 32	41 ± 28	*Possibly*, RTC 12%; ±29%
[CL] coach support	37 ± 26	38 ± 35	42 ± 27	31 ± 23	37 ± 28	
[CL] financial budget limitations	25 ± 24	30 ± 31	53 ± 37	35 ± 27	36 ± 31	*Possibly*, Cat2 5%; ±30%; RTC 10%; ±32%; *Likely*, Cat3 28%; ±33%
[CL] management support	36 ± 28	36 ± 32	35 ± 26	26 ± 21	33 ± 27	*Possibly*, RTC -10%; ±29%
[CL] Parent/guardian support	17 ± 16	26 ± 32	27 ± 22	29 ± 30	25 ± 25	*Possibly*, Cat3 10%; ±28%; RTC 12%; ±27%

Perceived importance: 0 = not important, 100 = highly important; Perception level: [L] lowest; [CL] comparatively low; [CH] comparatively high; [H] highest
Probability of important differences: <0.5%, most unlikely; 0.5-5%, very unlikely; 5-25%, unlikely; 25-50%, possibly; 75-95%, likely; 95-99.5%, very likely; >99.5% most likely (Hopkins, 2019)
Cat1, Category 1 academy; Cat2, Category 2 academy, Cat3, Category 3 academy; RTC, Regional Talent Club.

Table 4.2: Number of responses (percentages) and qualitative differences magnitude for questions relating to biological maturation estimations. All comparisons made against Category 1 academies (Cat1) with only magnitudes of *Small* or greater reported.

Question and Responses	Cat1 (*n* =15)	Cat2 (*n* =13)	Cat3 (*n* =10)	RTC (*n* =11)	Proportion Difference Magnitude
Which approach is primarily adopted for estimating biological maturation?					
Prediction of adult height	9 (60)	1 (8)	6 (60)	5 (46)	*Small: RTC; Large: Cat2*
Maturity offset	5 (33)	12 (92)	3 (30)	3 (27)	*Large: Cat2*
Skeletal maturity	0 (0)	0 (0)	0 (0)	2 (18)	*Small: RTC*
Other	1 (7)	0 (0)	1 (10)	1 (9)	
Who is primarily responsible for collecting biological maturation data?					
Medical staff	1 (7)	2 (15)	0 (0)	3 (28)	*Small: RTC*
Sport Science support staff	14 (93)	11 (85)	8 (80)	8 (72)	*Small: Cat3; RTC*
Other	0 (0)	0 (0)	2 (20)	0 (0)	*Small: Cat3*
**Who is biological maturation data reported to?*					
Academy manager	10 (67)	8 (62)	7 (70)	6 (55)	
Lead age group coach	12 (80)	12 (92)	8 (80)	9 (82)	*Small: Cat2*
Age group coaches	14 (93)	10 (77)	7 (70)	9 (82)	*Small: Cat2, Cat3, RTC*
Medical staff	15 (100)	11 (85)	9 (90)	9 (82)	*Small: Cat2, Cat3, RTC*
Sport Science support staff	14 (93)	12 (92)	9 (90)	9 (82)	*Small: RTC*
Intern/student	2 (13)	6 (46)	2 (20)	2 (18)	*Large: Cat2*
Player	7 (47)	5 (39)	5 (50)	7 (64)	*Small: RTC*
Parent/guardian	1 (7)	5 (39)	4 (40)	9 (82)	*Moderate: Cat2, Cat3; Very large: RTC*
What is the primary method of feedback on biological maturation estimations?					
Infographic	1 (7)	0 (0)	0 (0)	0 (0)	
Verbal communication	1 (7)	2 (15)	1 (10)	8 (73)	*Large: RTC*
Visual presentation	9 (60)	8 (62)	6 (60)	2 (18)	*Moderate: RTC*
Written report	4 (27)	3 (23)	3 (30)	1 (9)	*Small: RTC*
**When using biological maturation to group players, what activities is this for?*					
Pitch-based sessions	8 (25)	8 (29)	4 (25)	2 (25)	*Small: Cat3; Moderate: RTC*
Gym-based sessions	7 (22)	8 (29)	4 (25)	4 (50)	*Small: Cat2, RTC*
Recovery sessions	0 (0)	0 (0)	0 (0)	1 (12.5)	
Competitive fixtures	5 (16)	2 (7)	1 (6)	0 (0)	*Small: Cat2, Cat3; Moderate: RTC*
Ad-hoc fixtures	7 (22)	6 (21)	3 (19)	1 (12.5)	*Small: Cat3; Moderate: RTC*
Specific fixtures	5 (16)	4 (14)	4 (25)	0 (0)	

*Question permitted multiple responses

Scale of magnitudes: <10%, trivial; 10-30%, small; 30-50%, moderate; 50-70%, large, 70-90%, very large; >90%, huge[22]

Cat1, Category 1 academy; Cat2, Category 2 academy, Cat3, Category 3 academy; RTC, Regional Talent Club.

Table 4.3: Perceived importance (mean ± SD) of training load monitoring between clubs sorted by percentiles (sample mean ± SD), with chances that the true magnitude of difference is important. Effects below the smallest important threshold are not reported. All comparisons made against Category 1 academies (Cat1).

	Cat1 (*n* =15)	Cat2 (*n* =13)	Cat3 (*n* =10)	RTC (*n* =11)	Mean (*n* =49)	Between-group differences and *probability* of important differences Mean difference ± 99% CL
Perceived level of importance for monitoring training load for…						
[H] injury prevention	80 ± 17	80 ± 24	77 ± 16	84 ± 19	80 ± 19	
[CH] coach feedback	80 ± 10	72 ± 26	74 ± 7	66 ± 21	73 ± 19	*Possibly*, RTC -14%; ±19%
[CH] prescription of training	72 ± 18	70 ± 17	61 ± 23	80 ± 9	71 ± 19	*Possibly*, Cat3 -11%; ±20%
[CH] individualisation of training	71 ± 18	65 ± 21	71 ± 10	77 ± 13	71 ± 17	
[CH] overall player development	75 ± 18	65 ± 25	73 ± 12	68 ± 20	70 ± 20	*Possibly*, Cat2 -10%; ±20%
[CH] systematic progression	66 ± 22	68 ± 15	68 ± 15	63 ± 21	66 ± 21	
[CH] player feedback	62 ± 21	52 ± 26	69 ± 10	72 ± 7	64 ± 20	*Possibly*, Cat2 -10%; ±19%
[CL] EPPP/RTC legislation	57 ± 22	44 ± 26	53 ± 13	47 ± 28	50 ± 24	*Likely*, Cat2 -13%; ±24%
[CL] player retention	45 ± 26	44 ± 25	57 ± 24	48 ± 25	49 ± 25	*Possibly*, Cat3 12%; ±28%
[CL] Parent/guardian feedback	32 ± 18	47 ± 31	51 ± 15	56 ± 21	47 ± 24	*Likely*, Cat2 15%; ±23%; Cat3 19%; ±25%; RTC 24%;
[CL] club legislation	48 ± 19	39 ± 21	50 ± 13	45 ± 27	46 ± 21	
[CL] player recruitment	45 ± 26	27 ± 23	44 ± 25	40 ± 28	39 ± 26	*Possibly*, Cat2 -18%; ±26%
What are the primary barriers to implementing training load monitoring?						
[CH] resource limitations	54 ± 34	64 ± 29	84 ± 24	80 ± 9	71 ± 32	*Possibly*, Cat2 10%; ±31%; *Likely*, Cat3 30%; ±34%
[CH] staffing numbers	59 ± 28	69 ± 28	80 ± 26	63 ± 29	67 ± 28	*Possibly*, Cat2 10%; ±28%; *Likely*, Cat3 21%; ±31%
[CH] financial budget limitations	57 ± 31	72 ± 29	82 ± 18	50 ± 31	65 ± 30	*Possibly*, Cat2 15%; ±29%; *Likely*, Cat3 25%; ±31%
[CL] limited opportunity for intervention	48 ± 26	69 ± 33	63 ± 28	53 ± 28	58 ± 29	*Possibly*, Cat3 15% ±32%; *Likely*, Cat2 2%;1 ±29%
[CL] staffing competency	38 ± 28	43 ± 27	44 ± 24	55 ± 32	45 ± 28	*Likely*, RTC 17%; ±30%
[CL] coach support	31 ± 20	51 ± 38	37 ± 24	42 ± 26	40 ± 28	*Possibly*, Cat3 6%; ±30%; RTC 11%; ±30%; *Likely*, 20%;
[CL] management support	43 ± 28	39 ± 38	34 ± 25	30 ± 22	36 ± 29	*Possibly*, Cat3 9%; ± 32%; RTC 13%; ±32%

Perceived importance: 0 = not important, 100 = highly important; Perception level: L lowest; CL comparatively low; CH comparatively high; H highest
Probability of important differences: <0.5%, most unlikely; 0.5-5%, very unlikely; 5-25%, unlikely; 25-50%, possibly; 75-95%, likely; 95-99.5%, very likely; >99.5% most likely (Hopkins, 2019)
Cat1, Category 1 academy; Cat2, Category 2 academy, Cat3, Category 3 academy; RTC, Regional Talent Club

Table 4.4: Number of responses (percentages) and qualitative differences magnitude for questions relating to training load monitoring. All comparisons made against Category 1 academies (Cat1) with only magnitudes of *Small* or greater reported

Question and Responses	Cat1 (n = 15)	Cat2 (n = 13)	Cat3 (n = 10)	RTC (n = 11)	Proportion Difference Magnitudes
What is the primary approach to training load monitoring?					
GPS devices	7 (47)	4 (31)	0 (0)	0 (0)	*Small: Cat2; Moderate: Cat3, RTC*
Rating of Perceived Exertion	6 (40)	3 (23)	7 (70)	8 (73)	*Small: Cat2; Moderate: Cat3, RTC*
Physiological (TRIMP)	1 (7)	0 (0)	0 (0)	0 (0)	
Coach perceptions	1 (7)	4 (31)	2 (20)	1 (9)	*Small: Cat2, RTC*
Support staff perceptions	0 (0)	0 (0)	1 (10)	0 (0)	*Small: Cat3*
Wellness data	0 (0)	0 (0)	0 (0)	2 (18)	*Small: RTC*
Verbal discussion	0 (0)	2 (15)	0 (0)	0 (0)	*Small: Cat2*
How is your training load data compiled?					
Player Management Application	4 (27)	4 (31)	5 (50)	0 (0)	*Small: Cat2, RTC*
Customised spreadsheet	9 (60)	8 (62)	3 (30)	9 (82)	*Small: RTC ; Moderate: Cat3*
Monitoring application	1 (7)	0 (0)	0 (0)	1 (9)	
Other	1 (7)	1 (8)	2 (20)	1 (9)	*Small: Cat3*
Who is primarily responsible for collating training load data?					
Academy manager	0 (0)	0 (0)	1 (10)	0 (0)	*Small: Cat3*
Lead age group coach	0 (0)	1 (7)	1 (10)	1 (9)	*Small: Cat3*
Age group coaches	0 (0)	1 (7)	0 (0)	1 (9)	
Medical staff	0 (0)	1 (7)	1 (10)	2 (18)	*Small: Cat3, RTC*
Sport Sciences support staff	14 (93)	9 (69)	7 (70)	6 (55)	*Small: Cat2, Cat3; Moderate: RTC*
Intern/student	1 (7)	1 (7)	0 (0)	1 (9)	
Players	0 (0)	0 (0)	0 (0)	0 (0)	
Who is training load data reported to?					
Academy manager	0 (0)	0 (0)	2 (20)	3 (27)	*Small: Cat3, RTC*
Lead age group coach	4 (27)	8 (62)	2 (20)	0 (0)	*Small: RTC; Moderate: Cat2*
Age group coach	8 (53)	1 (8)	2 (20)	4 (36)	*Small: RTC; Moderate: Cat2, Cat3*
Medical Staff	0 (0)	0 (0)	0 (0)	1 (9)	
Sport Science support staff	1 (7)	2 (15)	1 (10)	0 (0)	
Player	1 (7)	1 (8)	0 (0)	1 (9)	
Other	1 (7)	1 (8)	3 (30)	2 (18)	*Small: Cat3, RTC*
How frequently are training load reports compiled?					
Daily	9 (60)	6 (46)	2 (20)	2 (18)	*Small: Cat2; Moderate: Cat3, RTC*
Weekly	5 (33)	2 (15)	2 (20)	5 (46)	*Small: Cat2, Cat3, RTC*
Monthly	0 (0)	1 (8)	1 (10)	1 (9)	*Small: Cat3*
Quarterly	0 (0)	0 (0)	0 (0)	2 (18)	*Small: RTC*
Bi-annually	0 (0)	0 (0)	1 (10)	0 (0)	
Annually	1 (7)	0 (0)	1 (10)	0 (0)	
Other	0 (0)	4 (31)	3 (30)	1 (9)	*Moderate: Cat2*

*Question permitted multiple responses

Scale of magnitudes: <10%, trivial; 10-30%, small; 30-50%, moderate; 50-70%, large, 70-90%, very large; >90%, huge[22]

Cat1, Category 1 academy; Cat2, Category 2 academy, Cat3, Category 3 academy; RTC, Regional Talent Club.

4.3.2. Training Load

Monitoring training load is deemed *highest* importance for injury prevention (Table 4.3). Player recruitment, retention, parent/guardian and player feedback and legislative purposes were considered *comparatively low* importance. Responses suggest Cat 1 academies *likely* share load monitoring information with parent/guardians less often than other academies.

Resource limitations, staffing numbers, financial budget limitations and limited intervention opportunity were all considered *comparatively high* barriers to training load monitoring (Table 4.3). Cat3 academies *likely* find these barriers more prominent than Cat1. Management and coach support, staff competency and limited opportunity for intervention were *comparatively low* barriers to training load monitoring. A *possible to likely* differences in coach support may infer greater coach buy-in within Cat1 academies than others. Additionally, it is *likely* that RTC academies perceived staff competency as a greater barrier than Cat1 academies.

Moderate differences suggest that Cat1 academies utilise RPE and coach perception less than other academies in preference for external training load measures (Table 4.4). *Small to moderate* differences suggest that Cat1 academies favour customised spreadsheets to the Performance Management Application (PMA), conversely it is worth noting that the PMA is not available for RTC academies which likely influenced between-group comparisons. Training load data was mostly collated by Sport Science support staff with *moderate* differences between Cat1 and RTC academies. *Moderate* differences suggest Cat1 academies report training load data to age group coaches more frequently than other academies, but less to lead age group coaches than Cat2 academies.

4.4 Discussion

This chapter represents the first attempt to establish perceptions of monitoring of maturity and training load in UK soccer academies. Given inherent differences between the two concepts, biological maturation and training load monitoring findings are discussed individually.

4.4.1. Biological Maturation

Practitioners agreed that injury prevention was of *highest* importance for including maturation estimations into their practice. Responses indicate that practitioners recognise associations between maturation and amplified injury risk, and that monitoring maturation positively influences long-term outcomes (A. Johnson et al., 2009). Yet, there is disparity concerning protocols employed to estimate maturation between academies, with indicators of timing (offset) and status (percentage of predicted adult height) prominent. '*Other*' responses may include a maturity ratio, growth velocity curves or skeletally derived methods (e.g., body dimensions) (Malina et al., 2004). Both dominant protocols are advocated by the legislative bodies, however Cat1, Cat3 and RTC academies demonstrated a greater reliance on the prediction of adult height, with Cat2 favouring maturity offset (Table 4.2). Their prevalence is likely attributable to the 'non-invasive' and logistically simple algorithm-based protocols, yet evidence has previously outlined limitations in somatic assessment of maturity in comparison with more invasive skeletal protocols (Malina et al., 2012). Consequently, it is imperative that practitioners are cognisant of the relevant methodological limitations (discussed further in chapter 5) and accommodate for this when informing decision making to ensure appropriate classification and accurate (de)selection evaluations.

Despite being pivotal for categorisation, practitioners unanimously perceived maturation estimation of *comparatively low* importance for biologically classified training and *lowest* for competition. This is perhaps surprising given the recent rise of bio-banded male soccer tournaments supported by the EPPP, in which players are categorised by their current biological maturity status (Cumming et al., 2017). The relative immaturity of the Women's FA Talent Pathway, however, could explain the *comparatively low* importance placed on this by RTC clubs. Bio-banding is largely considered "an alternative method of categorising players, according to maturity status rather than their chronological age category, with the assumption that this will alleviate (de)selection bias associated with earlier and/or later maturing players" (Reeves et al., 2018, p. 13). Bio-banding is a relatively new concept that has until recently traditionally adopted a talent development and selection focus, and therefore the relevance of bio-banding for managing load and injury was possibly overlooked within survey responses. It is reasonable to think that biological constraints within training and match-play would reduce physical variation and help coaches adequately stimulate players to reduce biological variation which may impact the typically high injury incidence around the adolescent growth spurt (Cumming et al., 2017; van der Sluis et al., 2015a). Evidence suggests trends in injury type throughout maturation, with late maturers having more osteochondral disorders and earlier maturers having more tendinopathies (Le Gall, Carling, & Reilly, 2006). These non-traumatic injuries are largely preventable, which supports that biologically appropriate training prescription may help reduce the incidence of certain injuries through more effective manipulation of intensity. Therefore, practitioners are encouraged to consider the wider benefits of biological categorisation to optimise training load to facilitate biologically relevant content (A. Johnson et al., 2009).

Time constraints, resource limitations, staff number and competency were considered as *comparatively high* barriers particularly in lower ranked academies, which could negatively impact validity of maturation estimations (Buchheit & Mendez-Villanueva, 2013). Even when maturation assessments are stringently controlled, prediction equations can vary 0.1 to 0.2 years between weekly measures (Towlson et al., 2017). Therefore, anthropometric data collection requires precise measurements to reduce systematic error, which may be compromised in the absence of adequately trained or experienced staff, equipment, or time. Whether these data are sport science led as prevalent in the survey, or medical staff led, consistency is paramount to reduce systematic error and thus safeguard data fidelity (i.e., inter-rater reliability) (Malina et al., 2004). Importantly, the quality of internal communication between support, medical and technical staff within soccer clubs has been linked with injury rates and match availability (Ekstrand et al., 2019). Therefore, academies that designate responsibility of maturation monitoring to specifically trained staff will likely enhance transfer to positively influence athletic performance and associated caveats (i.e., reduction of injury risk).

There was *moderate* to *very large* differences between the low number of Cat1 respondents reporting maturation data to players and parent/guardians. This is surprising considering Cat1 academies perceive resources as comparatively lower barriers than Cat3 and RTC and therefore likely have better mechanisms to communicate this information effectively. Being transparent with maturation data and informing parent/guardians of the associated transient physical and functional turbulence related to growth, disadvantages (i.e., stress or anxiety) may be alleviated and may even lead to an autonomy supportive bio-psychosocial environment, reducing the likelihood of drop-out or injury (Quested et al., 2013). In contrast, failure to involve stakeholders or providing a clear rationale for decision-making has been termed as '*autonomy-thwarting'* behaviour and linked to failed career progression and behavioural disengagement within soccer (Gledhill et al., 2017).

4.4.2. Training Load monitoring

Injury prevention was perceived to be of *highest* importance for monitoring training load within academies. This is likely influenced by recent associations between training exposure and injury in both adult and adolescent populations (Jaspers et al., 2018; Malone et al., 2017). Despite being of *highest* importance for injury prevention, remarkably almost no medical staff were routinely provided training load data (Table 4.4). This may suggest a reactive approach to injury management, opposed to a proactive approach whereby medical staff are actively involved in load management decisions. By routinely sharing training load data with medical staff (e.g., multidisciplinary team meetings), a more unified approach could better inform the process and help reduce injury incidence (Ekstrand et al., 2019) . This suggests a communication breakdown in lower ranked academies, negating the purpose of monitoring training load and possibly the impact on reducing injury burden (Ekstrand et al., 2019).

In addition, responses suggest coach and player feedback, overall development, systematic progression and individualisation and prescription of future training activities were considered of *comparatively high* importance. Although Cat1 academies reported training load to coaches 80% of the time, other academies reported this data to coaches less. On a positive note, this implies that active engagement in training load monitoring is accepted across all academies, but the communication, interpretation, and application of this appears to be negating impact, likely attributable to the resources available. Although these findings outline reduced impact of monitoring strategies, they correspond with similar conclusions from professional soccer (Akenhead & Nassis, 2016; Weston, 2018). These studies identified coach buy-in and discipline as prominent barriers to the effective impact of training load monitoring, implying that this problem is not an academy-isolated problem. In resolution, academies are encouraged to employ a routine load monitoring strategy enabling consistent collation and interpretation of data in line with context specific and resource appropriate objectives that fit their structure (Gabbett et al., 2017a). This should be combined with an education programme to involve all stakeholders and subsequently establish palatable dissemination strategies to enhance its application (Gabbett et al., 2017a), potentially supported by a local academic institution.

Cat1 academies utilise external training loads more than other academies, which is unsurprising based on the resource investment associated with this. This potentially explains why other academies (Cat3) perceive staff numbers, financial budgets and resource limitations, as *comparatively high* barriers to training load monitoring. Although microelectromechanical systems (MEMS) may provide a wealth of data, it does not automatically result in better monitoring outcomes as some ambiguity exists around the precision of devices and metrics to monitor (Malone et al., 2017). Research suggests combining internal and external loads offer best practice and better dose-response outcomes to appropriately quantify the magnitude of internal response in light of the external stimulus (Jaspers et al., 2018). This is crucial during periods of accelerated growth, considering likely fluctuations of the dose-response within adolescent soccer. In the absence of resources to facilitate MEMS, RPE has been shown to be a suitable and valid surrogate gauge of relative psychophysical training intensity (Impellizzeri et al., 2004). The application of RPE derived training load values is accessible and cost-effective, which may explain the dominant use of this within academies that reported financial and resource barriers (Cat2, Cat3 & RTC). RPE correlates well with physiological, and some MEMS derived metrics, and they can be collated retrospectively with suitable validity in adolescent populations, although an approach utilising multiple markers of training load is preferable if resources permit (Fanchini et al., 2017a; Impellizzeri et al., 2004)

4.4.3. Limitations

Although 49 responses are comparative to other soccer surveys (*n* = 19-41) (Akenhead & Nassis, 2016; Read, Jimenez, et al., 2018; Towlson et al., 2013), it is below that of others (*n* = 182) (Weston, 2018). It is acknowledged responses from the survey represent a portion of the population and the opportunity for multiple responses from academies could lead to clustering (Weston, 2018). The smaller sample size is somewhat negated as responses were from high-performance environments from a finite pool of UK-based academies. From anecdotal estimations, this chapter includes responses from approximately 38% of registered academies, from which a statistically conservative approach to inference was adopted to minimise false positive risk with power and precision results indicated by the 99% compatibility intervals for smallest important effects only. It is also acknowledged that engagement in this survey is more likely from those academies actively engaged in load and maturation monitoring, which may have influenced findings. Finally, it is noted differences between the more established EPPP and developing FA Women's Talent Pathway academies exist, and that legislations for these pathways may influence differences in responses. However, this survey provides the first comparison between the professional practices of male and female adolescent academies and was therefore considered a novel facet to the study.

4.4.4. Practical Applications

Survey responses suggest that routine monitoring of biological maturation and training load is commonplace within adolescent soccer and that clubs adopt monitoring practices to primarily prevent injury. But resource and environmental constraints create natural diversity around the methodologies and success of the monitoring process which may nullify impact. Designating consistent responsibility for data collation to suitably qualified staff may enhance maturation and training load data dependability, engagement and help establish palatable dissemination strategies. Without positively impacting player development or reducing injury risk, the monitoring process is futile. Therefore, practitioners are encouraged to identify a context-specific monitoring system that can be reliably and consistently applied and communicated to players, coaches, and parent/guardians efficiently. Through this, a more effective feedback loop will promote transparency of data and better inform stakeholders of maturity-load relationships leading to enhanced impact at group and individual levels. This interdisciplinary approach will require a more proactive, and targeted style of monitoring, to facilitate early intervention around accelerated growth periods. Finally, practitioners should consider using biological categorisation to help manage load prescription and maturity appropriate dose-response to help reduce non-contact injury risk.

Chapter 5

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Abstract

Purpose: Monitoring maturation facilitates effective talent development. Various methods of maturity estimation exist with limited knowledge of concordance between methods. This study aims to establish agreement between methods of varied constructs to predict maturity status and compare concordance of methods to categorise players using established thresholds.

Methods: This study compared four maturity equations using anthropometrical data from 113 male adolescent soccer players (mean ±SD; age, 14.3 ± 1 years) from two academies. Conservative (±1 year) and less conservative (±0.5 years) circa-PHV thresholds were employed.

Results: Analysis indicates tight (±0.3 year) agreement between maturity offset methods (MO), but broader agreement between MO and predicted adult height methods (–1.5 to 1 year). However, Kappa Cohen *k* suggests moderate to substantial (44%–67%) and fair to moderate (31%–60%) concordance between methods when using the conservative and less conservative circa-PHV thresholds respectively.

Conclusion: Despite MO equation iterations claiming to reduce systematic error, they provide very similar estimations. Additionally, practitioners should not use maturity offset and predicted adult height methods interchangeably and are encouraged to apply either method consistently when looking to estimate maturity status or biologically calssify players.

Keywords

Anthropometry, association football, biological classification, peak height velocity, talent development

Chapter 5: Estimating somatic maturity in adolescent soccer players: A methodological comparison

5.1. Introduction

Identification and development of talented young players is the primary purpose of youth soccer academies. To this end, the holistic and systematic identification and development of the physiological, psychosocial and/or biomechanical attributes that contribute towards success at the adult level, are a primary focus for practitioners working in this field (Bergeron et al., 2015). The composition of these attributes varies between positions and is often determined through the observation and/or assessment of '*elite*' adult athletes. Those individuals who possess or demonstrate the desired attributes are identified, recruited, and then promoted towards excellence. The development of most of these attributes is, however, not linear, and complicated by inter-individual differences which manifest as either strengths or limitations for everyone. This is compounded when adolescent athletes are exposed to rapid variations in both tempo and timing of their development due to biological maturation (Cumming et al., 2017). Biological maturation refers to the process of progress towards full maturation which can vary substantially between individuals of the same chronological age, particularly around the period of peak height velocity (PHV). For example, an individual with a chronological age of 12 years old, could have a biological age anywhere between 9 and 15 years (Borms, 1986; Tanner et al., 1975). This level of diversity in maturation, even within relatively homogenous groups creates uncertainty surrounding relative talent and future potential in young athletes, therefore confounding the talent development process.

Since the inception of the Elite Player Performance Plan (EPPP) (Premier League, 2011) and the associated audit process, UK based soccer academies have fostered a professionalised approach to monitoring and evaluating development trajectories of physical and physiological characteristics. As outlined in chapter 4, academies now track biological maturation which can help inform the coaching process by way of influencing training schedules, activities and the talent selection process (Cumming et al., 2017). There are multiple ways to assess an individual's biological maturation as the process occurs in multiple systems (i.e., somatic, skeletal endocrine, sexual, dental). That said, skeletal age is generally considered the most objective or 'clinical' method for determining biological maturity. Methods such as skeletal age are, however, generally overlooked within academy soccer based on the impractical or invasive process required, compounded by exposure to radiation and associated ethical complications (Fransen et al., 2018; Kozieł & Malina, 2018). Chapter 4 identified that the majority of clubs employ 'non-invasive', somatic equations to estimate biological maturation using known proportionality differences in leg and trunk length alongside longitudinal growth data (Fransen et al., 2018; Khamis & Roche, 1994; Malina & Kozieł, 2014; Moore et al., 2015). Based on the difference in stature, leg length and sitting height and the changing relationship between these variables, these equations can predict the timing and tempo of PHV (Mirwald et al., 2002). These methods predict the years an athlete is removed from the age at which PHV occurs in the form of a 'maturity offset', with the exception of the Khamis & Roche (1994) method which estimates current percentage of adult height. If these measurements are standardised and routinely assessed (3-4 times annually), it is possible to estimate both the timing and tempo within and between individuals (Malina et al., 2019).

The various methods for predicting somatic maturation have received critical appraisal surrounding estimation inaccuracies, which may render them of limited value to practitioners (Mills et al., 2017). The original offset equation (Mirwald et al., 2002) was suggested to predict the timing of PHV to within 1-year 95% of the time which was applicable to individuals aged between 10 and 18 years. Malina and Koziel (2014) longitudinally applied method this to Polish boys in an attempt to re-validate the equation but identified a systematic discrepancy between predicted and observed PHV. The timing of PHV was underestimated at younger ages and overestimated in older age groups, which was supported by Mills et al. (2017) who also added that the equation overestimated the timing of PHV when assessed immediately preceding PHV. Malina and Koziel also noted that the magnitude of the errors tended to be accentuated in early and late maturing males, both of which are of particular concern in youth soccer environments. In light of this Moore et al. (2015) attempted to simplify and externally validate the equations to cater for the overfitting, but still reported an increase in prediction error the further removed from PHV the individual is. A further iteration of this equation has since been validated within academy soccer players (Fransen et al., 2018). The authors suggest that this approach appears to better account for the systematic error by adopting a polynomial model and estimating a maturity ratio rather than an offset to better reflect the non-linear growth process. However, subsequent critique by Nevill and Burton (2018) outlined potential flaws in the equation and the increased likelihood of spurious findings due to chronological age appearing on both sides of the maturity ratio, with concerns over accuracy also reported by Teunissen et al (2020).

In contrast to the maturity offset provided by the above methods, a prediction of adult height (PAH%) developed by Khamis and Roche (1994) is also widely used within academy soccer (Table 4.2). Utilising several of the same anthropometric variables and the addition of birth parental heights to ascertain mid-parent stature the equation can predict the progress towards adult stature as a percentage. If measured accurately the equation is suggested to predict the adult stature to within 2.2 and 5.3 cm for the 50th and 90th percentile respectively, although this error may increase to 5.5-7.2 cm when applied only to the age groups where it relates to the adolescent growth spurt (11-15 years) (Malina et al., 2019). In light of logistical issues around objectively measuring parent height, the equation often uses self-reported parent heights and should therefore be corrected for overestimation (Epstein et al., 1995). Though, in some cases adolescent athletes are not in contact with one or both birth parents, and for whatever reason an accurate stature is not accessible. In such cases the equation suggests using mean national values for male and females, likely reducing the fidelity of the equation via regression to the mean, particularly for those with birth parents with stature significantly different from the national mean. Collectively, these limitations may contribute additional error to the prediction equation, especially in early childhood when mid-parent height contributes more greatly to the prediction equation.

Whichever approach is adopted, these data are often used to identify the period that immediately surrounds PHV, often termed the ‘circa-PHV’ window. This development period has been suggested to coincide with an increased risk and incidence of injury (Bult et al., 2018; D. M. Johnson et al., 2019) and is therefore a period of heightened interest for the practitioner. It is common within literature to di-, or tri-chotomise the maturation cycle into periods, often termed pre-, circa- or post-PHV to categorise individuals (Meyers et al., 2017; Radnor et al., 2020; Ryan et al., 2018; van der Sluis et al., 2015a). In the applied setting, this categorisation may then be utilised to help implement maturity specific interventions, produce reports or inform talent (de)selection decisions (Cumming et al., 2017). Due to inherent error within these regression-based approaches, typical bandwidth thresholds of a conservative ±1-year, or more commonly less conservative ±0.5-years have been utilised in the research to determine whether an individual is circa-PHV or not. For example, if an individual is 13.5 years of age, and the maturity offset indicates -0.4 years, this would suggest they would expect the onset of PHV at 13.9 years and is therefore classified as ‘circa-PHV’ according to both thresholds. Similar conservative (85-96%) and less conservative thresholds (88-93%) exist for the Khamis-Roche approach, based on longitudinal data suggesting PHV typically occurs at approximately 90% PAH with post-PHV considered >93% (Cumming et al., 2017; Malina et al., 2019; Sanders et al., 2017). Despite each method having this categorisation capacity, it is unclear as to the agreement between the various approaches which potentially differs based on the nuances between estimation equations.

Validation of all these methods have generally used large scale reference samples from mostly white-Caucasian, general population backgrounds, which has led to questions surrounding the applicability of this to elite soccer environments. However, chapter 4 of this thesis indicates that these are prominent approaches widely applied within adolescent soccer. Therefore, this chapter has two main aims; a) to observe the agreement of maturity status estimations between methods using the same anthropometric data and b) compare concordance between methods when looking to categorise players as circa-PHV using established thresholds. It is hoped that findings provide a grounding for practitioners to inform the selection of which method to apply in their academy environments to accurately monitor growth and maturation, but also to identify the most appropriate method to employ for the remainder of this thesis.

5.2. Methods

5.2.1. Participants

113 male adolescent academy soccer players (mean ± SD; age, 14.3 ± 1.1 years; stature 170.1 ±10.6 cm; body mass, 58.7 ± 10.5 kg) were recruited from the Youth Development Phase (U13-U16) of two EPPP academies. Anthropometric data from 57 participants was collected from a single assessment point during the 2017-18 season, with the remaining 55 participants providing three repeated measurements during the 2018-19 season (Aug, Jan, and April). Therefore, 222 somatic estimations are included within this chapter. Participants were eligible to take part if they were registered with an EPPP academy and free from injury for the previous month prior to the stratified random recruitment process to ensure a relatively homogenous sample. Ethical approval was granted by the University of Gloucestershire ethics committee, with all parents and players provided sufficient information about the procedures in plain and age-appropriate language. Following a period for further information and opportunity to ask questions, all parents and players completed assent and informed consent respectively and were able to withdraw their data from the research without negatively impacting their relationship with their club or the University.

5.2.2. Procedures

Following International Society for the Advancement of Kinanthropometry (ISAK) recommendations (Stewart et al., 2011) anthropometric measurements were obtained from all participants to facilitate somatic maturity estimations (Fransen et al., 2018; Khamis & Roche, 1994; Mirwald et al., 2002; Moore et al., 2015). A portable stadiometer (Seca© 217, Chino, USA) was used to measure stature when participants stood barefoot with feet together and heels touching the scale, with their head in the Frankfort plane. The stretch stature method was adopted by where the participant was required to take a deep breath and hold their head still whilst duplicate measures of standing stature were recorded to an accuracy of 0.1cm and the mean calculated (Stewart et al., 2011). Following similar procedures, participants seated stature was measured whilst sat on a standardised plinth (40cm high) with feet together and hands rested on thighs (Stewart et al., 2011). Leg length was measured using illiospinale height guidelines (Stewart et al., 2011). The participant stood barefoot with feet together facing cut-out aspect of the standardised plinth (40cm). The base of the segmometer was placed on top of the box and the moving branch positioned at the illiospinale landmark. Leg length was calculated by summing the plinth height and measure to illiospinale landmark. Duplicate readings were taken, and the mean calculated, with a third taken if necessary and the median being employed in such cases. Body-mass was recorded using portable weighing scales (Seca© robusta 813, Chino, USA) whilst participants were stood barefoot wearing normal training attire. Duplicate readings were taken and if measurements varied by 0.2kg a third measure was taken and the median recorded. All measurements were taken by the same researcher to minimise error.

5.2.3. Maturation Equations

Estimations of age of peak height velocity (APHV), maturity offset (MO) and percentage of predicted adult height (PAH%) were calculated using the anthropometric measures (standing stature, leg length and body-mass) outlined above and decimal age (years). It is outlined at this point, that the Fransen (2018) ($_{FRANSEN}$MO) method requires the calculation of a ratio initially, therefore an additional calculation is outlined below but not analysed in the results as the MO facilitated better comparisons between methods. Estimated APHV and subsequently MO was calculated using equations 5.1-5.4 for males outlined below with PAH% predicted using equation 5.5.

Equation 5.1: (Mirwald et al., 2002) ($_{MIRWALD}$MO)

$$\text{Maturity Offset} = -9.236 + (0.0002708 * (\text{Leg Length} * \text{Sitting Height})) + (-0.001663 * (\text{Age} * \text{Leg length})) + (0.007216 * (\text{Age} * \text{Sitting Height})) + (0.02292 * (\text{Body Mass by stature ratio} * 100))$$

Equation 5.2: (Moore et al., 2015) ($_{MOOORE}$MO)

$$\text{Maturity Offset} = -7.999994 + (0.0036124 * (\text{age} * \text{standing stature}))$$

Equation 5.3: (Fransen et al., 2018) ($_{FRANSEN}$Ratio)

$$\text{Maturity ratio} = 6.986547255416 + (0.115802846632 * \text{Chronological age}) + (0.001450825199 * \text{Chronological age (2)}) + (0.004518400406 * \text{Body mass}) - (0.000034086447 * \text{Body mass (2)}) - (0.151951447289 * \text{Stature}) + (0.000932836659 * \text{Stature (2)}) - (0.000001656585 * \text{Stature (3)}) + (0.032198263733 * \text{Leg length}) - (0.000269025264 * \text{Leg length (2)}) - (0.000760897942 * [\text{Stature} * \text{Chronological age}])$$

Equation 5.4: (Fransen et al., 2018) ($_{FRANSEN}$MO)

$$- \quad \text{Maturity Offset} = \text{Age} / \text{Maturity ratio}$$

-

Equation 5.5: (Khamis & Roche, 1994) (PAH%)

$$\text{Predicated Adult Height} = \beta_o + \text{stature}^* \beta_1 + \text{body mass}^*(\beta_2) + \text{corrected mid-parent stature}^* \beta_3$$

Note: β_o, β_1, β_2, and β_3 are the gender specific intercept and coefficients by which age, stature (in), body mass (lbs) and mid-parent stature (in) respectively should be multiplied from the coefficients table available in Khamis & Roche (1994). Correction factor for self-reported height in males is (Parental Height [cm]*0.955) + 2.316

5.2.4. Data Analysis

Raw data are presented in Table 5.1. Agreement between measures was assessed using Bland-Altman plots with 95% limits of agreement, using Prism 9 software (9.1.0, GraphPad Software LLC). The Mirwald equation (Malina & Kozieł, 2014) was used as a surrogate reference as this is most widely reported in literature. Due to measuring different constructs, both MO (APHV+MO) and PAH% (using growth reference charts (C. Wright, 2002)) were both subsequently converted to represent an estimation of biological age to facilitate analysis. Concordance analysis was conducted using Cohen's Kappa (*k*) coefficients derived from contingency tables. Two evidence informed thresholds to categorise circa-PHV for MO and PAH% were applied, a) conservative ± 1-year and 85-96%; and b) less conservative ±0.5-years or 88-93% (Cumming et al., 2017; Sanders et al., 2017).

Table 5.1. Descriptive comparisons between methods to estimate biological age (years)

Measure	$_{MIRWALD}$MO	$_{MOOORE}$MO	$_{RANSEN}$MO	PAH%
Mean ± SD	14.4 ± 1.9	14.3 ± 1.9	14.3 ± 1.2	14.7 ±1.1
Minimum	11.6	12.1	12.1	11.5
Maximum	16.7	16.6	16.6	18
Range	5.1	4.5	4.5	6.4
SEM	0.08	0.08	0.08	0.08
Variance	1.4	1.4	1.4	1.35

SD: standard deviation; SE: standard error of measurement

5.3 Results

Descriptive analysis indicates minimal variation between all methods, particularly between those that predict MO, with the closest agreement between the Moore and Fransen methods (±0.05 years) (Table 5.1). Bland-Altman analysis indicates that MO methods typically agree within <0.3 years 95% of the time, but Khamis-Roche PAH% offers broader limits of agreement (-1.65-0.87 years) (Figure 5.1). Bias indicates that Khamis-Roche estimates biological age to be ~0.6 years higher than MO methods (Table 5.2).

Concordance between methods is presented in Table 5.3. When conservative (±1 year) there was substantial agreement (64-67%) between MO methods with moderate agreement (44-50%) between MO and PAH% methods. There was a decline to moderate agreement (58-60%) between MO methods and fair-moderate between MO and PAH% (31-43%) when utilising the less conservative threshold.

Table 5.2. Bland-Altman bias (SD) and 95% limits of agreement between biological age estimations

Measure	Mirwald	Moore	Fransen
Moore	0.17	***	***
	−0.31 – 0.37		
Fransen	0.16	0.03	***
	−0.30 – 0.36	−0.05 – 0.05	
Khamis-Roche	0.68	0.61	0.61
	−1.65 – 1.04	−1.53 – 0.87	−1.53 – 0.87

*** N/A

Table 5.3. Concordance (Kappa Cohen *k* coefficient) between maturity status estimation thresholds for circa-PHV

circa-PHV Threshold	Measure	Mirwald	Moore	Fransen
± 1 year 85-96% PAH	Moore	0.67	***	***
	Fransen	0.66	0.64	***
	Khamis-Roche	0.49	0.50	0.44
± 0.5 year 88-93% PAH	Moore	0.60	***	***
	Fransen	0.59	0.58	***
	Khamis-Roche	0.31	0.43	0.39

*** N/A

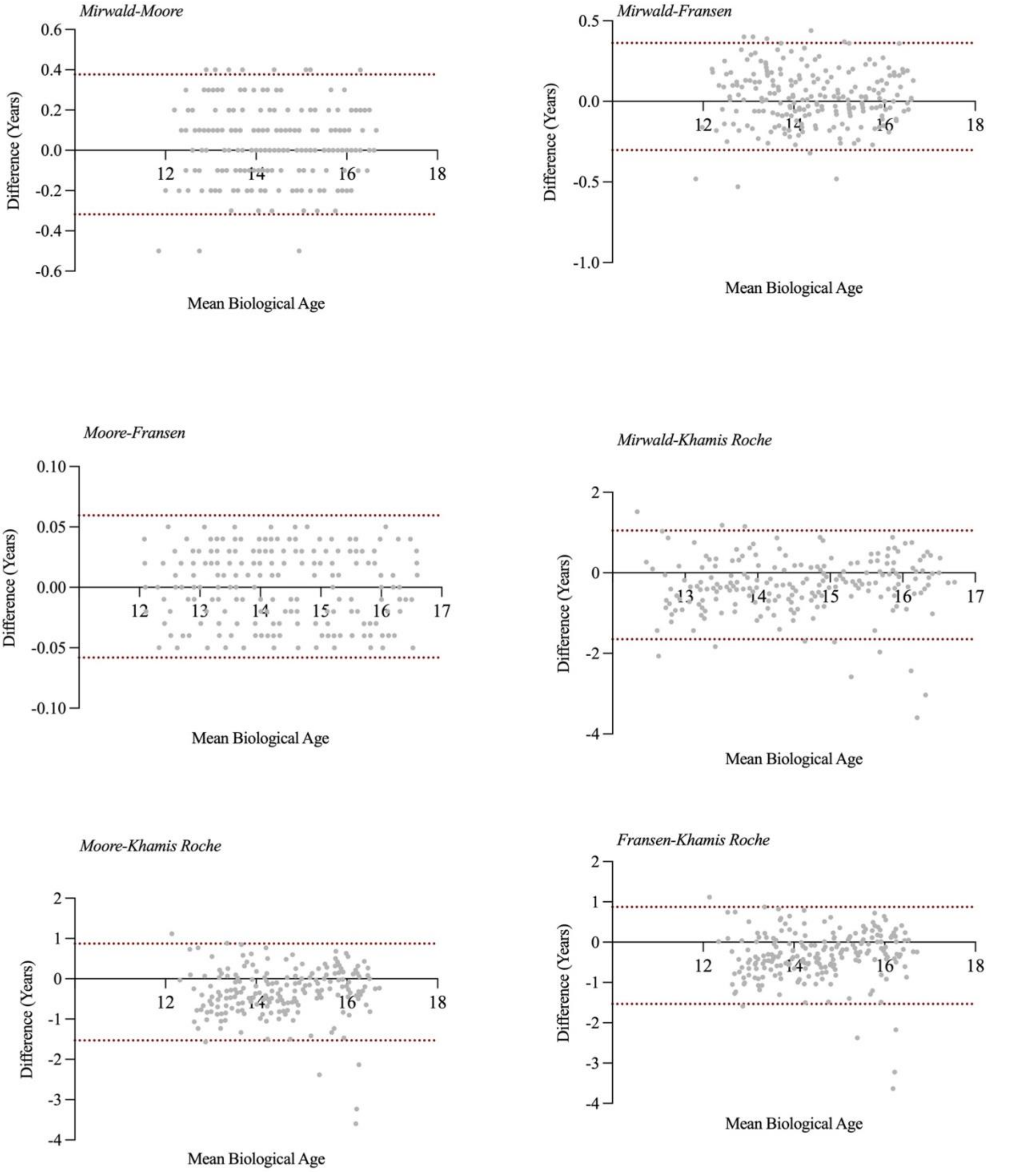

Figure 5.1. Bland-Altman plots (with 95% limits of agreement) for estimated biological age for the different maturity estimation methods

5.4 Discussion

This investigative chapter explored the agreement between various methods of estimating somatic maturity with the aim of informing the remainder of this thesis and practitioners of the differences and interchangeability of the available methods. All methods produced an similar estimate of biological age (14.3–14.7 years). Findings suggest there are tight limits of agreement between MO methods (±0.3 years) despite methodological nuances. However, biological age estimations derived from Khamis-Roche calculations offer much broader agreement window (approx. -1.5 to 1 year) with the MO methods. Unsurprisingly, when looking to identify circa-PHV individuals there is greater concordance when using conservative thresholds (44–67%) than when using more stringent bandwidth thresholds (31–60%).

The tight agreement between thresholds of biological age estimation between MO methods is initially unsurprising based on each being an 'enhanced' iteration of the original regression equation. Moore et al. (2015) attempted to reduce systematic error by removing sitting height from the revised equation. This almost perfect agreement observed here (especially between Moore-Fransen) is therefore interesting based on the technical errors associated with sitting height which tend to be greater than the other anthropometric data required for the equation (Malina et al., 1973). However, the typical error for both seated and standing stature in this chapter was low (0.2%), which is comparable with previously reported error (Massard et al., 2019). This suggests that the inclusion/exclusion of seated stature has little impact on the outcome of the equation if measurement error is adequately controlled. This may alleviate some of the concerns raised by Massard et al. (2019) who indicated that failure to pay close attention to sitting height protocols may influence the outcome for PHV estimation. The lack of significant impact from sitting height measurements suggest that practitioners have flexibility to utilise MO methods with or without sitting height, based on their own logistical constraints.

The $_{\text{FRANSEN}}$MO method demonstrated near perfect agreement with both $_{\text{MIRWALD}}$MO and $_{\text{MOORE}}$MO. This method is the most recent iteration and was devised using a polynomial model to better represent the non-linear process of maturation (Fransen et al., 2018). Authors propose that this model, validated in youth soccer players of mixed ethnicity, yields similar accuracy as previous equations but better accounts for the systematic prediction error (overfitting) for players at either end of the maturity spectrum (i.e., early, or late developers). Specifically, this outcome may be facilitated by the calculation of a maturity ratio (equation 5.3) preceding the maturity offset which enhances the model fit in athletic populations (Fransen et al., 2018). Consequently, for practitioners working in adolescent football the $_{\text{FRANSEN}}$MO likely offers a better alternative to predicting MO with adolescent soccer players than both $_{\text{MIRWALD}}$MO and $_{\text{MOORE}}$MO due to the more suitable validation population and reduced overfitting. There have been claims that $_{\text{FRANSEN}}$MO could well be a potentially flawed equation (Nevill & Burton, 2018) due to chronological age being on both sides of the maturity ratio, and therefore further work to explore this is required before widespread application.

Results indicate that the PAH% equation when corrected for self-reported parental height (Epstein et al., 1995), presented much broader agreement bands with MO estimations (Table 5.2). This may partly be explained by them initially calculating two separate constructs (PAH% and MO) but both can be converted to biological age using known growth trends, as employed in this chapter. The PAH% mean biological age of 14.7 years and Bland-Altman analysis suggest the PAH% offers a ~0.6-year bias compared to MO methods. This bias is more substantial than any of the MO compared with one another., therefore suggesting that practitioners should adopt either a MO or PAH% approach, but not both interchangeably. Recent work from Parr et al. (2020) conducted longitudinal analysis to observe timing of PHV in academy soccer players, and illustrated that PAH% was accurate

96% of the time, with MO accurate 61% of the time. This, combined with other studies (Malina & Kozieł, 2014; Teunissen et al., 2020) highlight the potential limitations of MO methods having a tendency to regress towards the mean, ultimately reducing their efficacy when looking to differentiate between stages of maturation. Data from this thesis chapter would suggest that PAH% is a useful indicator of maturity status in youth football players, however it does provide maturity estimations that differ from MO calculations. Based on the limitations of the MO methods, and in conjunction with previous findings, PAH% may offer increased accuracy for practitioners, but should not be reliably compared to MO estimations. Therefore, practitioners should employ either a MO or PAH% approach to maturity monitoring consistently across the various facts of application (e.g., time to PHV and/or bio-banding). That said, failure to obtain accurate parental heights, or applying appropriate correction of the calculation will ultimately undermine its accuracy and inflate error beyond that reported, reducing the fidelity of predictions and leave MO approaches more efficacious.

Although the MO methods appear to correlate very highly, there is some discrepancy in terms of categorising players as circa-PHV using both thresholds. Despite interpretations suggesting substantial agreement between MO methods, whereby there was 64-67% concordance as either 'circa-PHV' or not. This leaves a disagreement of approximately 30-35% when using the conservative threshold (±1-year) and up to 50% with the more stringent threshold (±0.5-years). Therefore, approximately a third to half of the data would disagree and lead to different categorisation between methods potentially impacting on the practices these individuals are exposed to. For example, a player may be categorised as circa-PHV using one method, but pre-PHV in another, which may potentially expose the player to different training stimulus or reducing/increasing their level of risk inappropriately. Disagreement further increases when we consider MO compared to PAH% to 45-50% and 31-43% for the conservative and less conservative thresholds respectively. McHugh (2012) suggests that kappa values between 0.6-0.7 have approximately 35-63% of data that are reliable and should therefore be considerate moderate agreement at best, with lower values considered weak. A recent study (Parr et al., 2020) conducted a similar analysis but included longitudinal data that observed actual timing of PHV, and illustrated that PAH% observed circa-PHV correctly (i.e., within the 85-96% window) 96% of the time, with MO correct only 61% of the time. The absence of actual PHV data in this thesis prevents such analysis, but based on the work of Parr et al. (2020) and Teunissen et al (2020), it would be reasonable to suggest that the fair-moderate agreement observed here is not surprising and likely a product of reduced accuracy in MO estimation methods. Due to these being the first studies of this nature, further longitudinal work is needed in this field to corroborate these findings with more substantial samples and robust analytical approaches.

5.4.1. Limitations

The absence of a criterion value to compare maturity estimations limits the confidence in the conclusions from this study. As a result, it is not possible to claim with any credibility which approach is more accurate. However, this reasonably large dataset from two EPPP clubs does offer insight into the agreement interchangeability of the approaches whilst using the same anthropometrical data. A similar approach to a recent study (Parr et al., 2020) was adopted to allow comparisons which had utilised a criterion reference but in a smaller sample of individuals. Therefore, the methodological similarities permit some comparisons from which this chapter proposes tentative assessments on the accuracy of the methods employed. It is acknowledged that further work on the accuracy of these somatic estimations of maturity is required, and where possible should include longitudinal data obtained from multi-ethnic groups to facilitate comparisons that enable evaluation of precision for use in adolescent soccer.

5.4.2. Practical Applications

Chapter 4 indicated that academies currently utilise both MO and PAH% methods to estimate maturity status of their players. Findings from this chapter indicate that there is tight agreement between MO approaches but broader agreement thresholds for MO and PAH% methods. Concordance between these methods is moderate at best and may be misleading if multiple methods are applied. Therefore, this chapter indicates that these MO and PAH% methods are not interchangeable and using one approach may provide different biological classification outcomes to the other. Practitioners are encouraged to collect anthropometric data with precision, on a consistent basis by trained individuals and applied to the same equation to obtain a useful indicator of maturation. Previously cited limitations of MO methods (Parr et al., 2020; Teunissen et al., 2020) and the observed bias here would suggest that a PAH% approach may offer enhanced accuracy when looking to monitor status and timing. It is further recommended that practitioners monitor both height and weight velocity and plot their respective growth curves over time. With accurate consideration of these, practitioners can have greater confidence in maturity estimations, leading to appropriate maturity specific development and evaluation of talent.

Chapter 6

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ORIGINAL ARTICLE

The moderating impact of maturation on acute neuromuscular and psycho-physiological responses to simulated soccer activity in academy soccer players

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Abstract
Resource constraints complicate load monitoring practices in some academies, which is problematic based on load-injury associations surrounding periods of rapid non-linear growth. Limited research has explored relationships between maturation and perceived psycho-physiological response to activity and associated neuromuscular performance changes. This study aimed to quantify neuromuscular and psycho-physiological responses to standardised activity and analyse whether dose-responses were moderated by maturation. Fifty-seven male soccer players (age: 14.1 ± 0.9 years; stature: 165 ± 10 cm; body mass, 57 ± 9 kg; percentage of predicted adult height 92.7 ± 5%) from two Elite Player Performance Plan (EPPP) academies completed the youth soccer-specific aerobic fitness test (Y-SAFT^{60}). Countermovement jump (CMJ), reactive strength index (RSI), absolute (ABS) and relative leg stiffness (REL) were measured pre–post the Y-SAFT^{60} with playerload (PL), heart rate (HR), total distance (TD^{ist}) and differential ratings of perceived exertion (dRPE) used as markers of load and intensity. A moderation model was employed to analyse interactions of maturation as a continuous variable. Analysis indicated no significant interaction ($p < 0.05$) between maturation and neuromuscular performance but RPE-Technical demonstrated significant interactions ($p = 0.01$). Slope analysis indicated four variables (PL, RSI, ABS and REL) that demonstrated significance at various stages of maturation, most notably aligning with peak height velocity (~87–96% PAH). Tentatively, we propose that maturational developments in the neuromuscular system offer some mechanistic explanation to the varied dose-responses observed. It is therefore important that maturation is habitually considered within prescription of training programmes and that further empirical studies are completed to determine maturity specific dose-responses.

Keywords: Adolescence, injury & prevention, neuromuscular, team sports, training load

Chapter 6: Acute neuromuscular and psycho-physiological responses to simulated soccer activity

6.1. Introduction

Technological advances have proliferated research around dose-response relationships between load, fatigue, and training prescription to incorporate various internal and external training load metrics (i.e., total distance covered, high-speed running and player load). As a result, quantifying physical demands has become commonplace in elite adult populations, with dose-response markers used to influence athletic outcomes (Hader et al., 2019). Chapter 4 of this thesis indicated that academies faced resource and logistical constraints that sometimes prevent implementation of best practice monitoring strategies. This is problematic for practitioners working with adolescent populations as the temporal, dynamic and non-linear changes in biological development (e.g., hormonal, neural, bone and muscle) likely complicate dose-responses (Bergeron et al., 2015). Barriers to accurate quantification of individual loads make effective manipulation of the training prescription complex and likely inappropriate, particularly for early or late maturing players (approx. 16-40% of academy populations) (M. Hill, Scott, Malina, et al., 2020; A. Johnson et al., 2017).

Injuries are multifactorial, but evidence suggests that inappropriate loading may compound already relatively high incidences during adolescent soccer (D. Johnson et al., 2020; Rommers et al., 2020). Associations between load and injury are noteworthy since the introduction of the Elite Player Performance Plan (EPPP) presented a substantial linear, chronological-age correlated increase in coaching hours from approximately 3,760 to 8,500 (accrued annually between the ages of 8-21) (Premier League, 2011). Subsequent trends suggests increased growth and overuse related injuries particularly in U13-U14 age groups in a distal to proximal nature, with Osgood-Schlatter's and Severs Disease widespread (Read, Oliver, et al., 2018). Additionally, audit methods likely underestimate incidences of overuse injuries as they typically adopt a 'time-loss' definition, when often players do not miss training but need modification (Whalan et al., 2020). Between 46-72% of EPPP injuries are non-contact and 30-43% are moderate in nature with approximately 50% injuries occurring during training sessions (Materne et al., 2020; Read, Oliver, et al., 2018). It is largely considered that non-contact injuries are preventable whereas traumatic contact injuries are unavoidable (Read et al., 2016a). Therefore, better appreciation of dose-responses within these age groups may better mitigate risk and individualise training based on the physical capabilities of individuals.

Rating of Perceived Exertion (RPE) has been extensively applied within soccer and suggested to have acceptable re-call bias and interchangeability between validated scales (CR10 and CR100) (Fanchini et al., 2017b; M. Wright et al., 2020). This versatility and intuitive application proposed by Foster (1998) (RPE multiplied by session duration) make this a robust and accessible method to document training volume and intensity and subsequently inform training prescription. However, despite being common within academy settings, only one empirical study has explored maturity specific responses to subjective psycho-physiological perceptions of intensity (De Ste Croix et al., 2019) and only three studies have observed the age related training response using RPE derived methods in adolescent team sports (Brink, Visscher, et al., 2010; M. Wright et al., 2020; Wrigley et al., 2012). Instead, most maturity related research has focussed on performance markers such as speed, endurance or match performance (Beyer et al., 2020; Buchheit & Mendez-Villanueva, 2014). These studies offer mechanistic explanations regarding changes in performance during the major growth period but offer limited insight as to how individuals perceive dose-controlled activity during this period.

Academy squads are comprised of players within chronological parameters but often present significant variations in physical characteristics including body mass (~50%), stature (~29cm), percentages of predicted adult height (10–15%) and fat free mass (3–8.6kg) (Figueiredo et al., 2010; Hannon et al., 2020; van der Sluis et al., 2015a). These maturation specific components likely influence performance (Buchheit & Mendez-Villanueva, 2014), but limited studies using standardised activity profiles have directly observed this influence (Lehnert et al., 2018). Relationships between maturation related dose-responses have also been performed observing neuromuscular performance around competitive fixtures and/or training (De Ste Croix et al., 2019; Oliver et al., 2015b; Read et al., 2016a). Radnor et al. (2018) suggests that stretch-shortening cycle (SSC) performance increases with age across various neuromuscular tasks such as sprinting, hopping and jumping, therefore it is intuitive to assume maturation influences acute responses in neuromuscular performance. Ambiguously however, findings indicate both significant and non-significant relationships with neuromuscular performance, such as countermovement jump (CMJ), reactive strength index (RSI) and leg stiffness (De Ste Croix et al., 2015, 2019; Lehnert et al., 2017). Most recently De Ste Croix and colleagues (2019) concluded that maturation did not influence responses to match-play in youth soccer despite large changes in RSI, a similar finding was observed by Lehnert et al. (2017). Interestingly, despite sharing many of the same SSC characteristics as RSI, leg stiffness response is less predictable, whereby some individuals experienced acute reductions in leg stiffness with others a state of potentiation with improved stiffness scores post-exercise (De Ste Croix et al., 2019; Oliver et al., 2015b). Yet mechanistic theories suggest an inhibited stretch-reflex and reduced rate-of-force development and golgi-tendon organ (GTO) involvement surrounding peak height velocity (PHV), which likely heightens injury threat and reduces mechanical efficiency (Lehnert et al., 2017).

The relative ambiguity and apparent paucity of evidence observing the influence of maturation on neuromuscular performance and psycho-physiological response provides a rationale for further work in this area. These player monitoring methods (i.e., RPE, CMJ and RSI) are commonly used within academy settings to routinely assess development and can therefore provide meaningful data to practitioners regarding maturity related dose-responses. By better understanding this relationship throughout maturation, we can develop approaches to training prescription and recovery. This may, in turn reduce the possible detrimental impact of loading that is associated with non-contact injury within this population (Oliver et al., 2015b). Therefore, this chapter aims to quantify the neuromuscular performance and psycho-physiological responses to a simulated soccer-specific activity profile and analyse whether this dose-response was moderated by maturation in EPPP academy players.

6.2. Method

6.2.1 Participants

Fifty-seven male soccer players (age: 14.1 ± 0.9 years; stature: 165 ± 10 cm; body mass, 57 ± 9 kg; predicted adult height 92.7 ± 5%) from Youth Development Phase (YDP) age groups at two EPPP academies took part in this study. Participants were included if they were part of the YDP (U13-U16 age groups), free from injury and available for all scheduled training sessions and matches for the two-weeks prior to data collection. Participants usually complete three training sessions per week and compete in matches at weekends for approximately forty weeks a year. Participants completed written informed consent and parental assent in line with the declaration of Helsinki following ethical approval from the University of Gloucestershire ethics committee.

6.2.2 Procedures

In line with the general methods (see section 3.2.3), and influenced by findings from chapter 5, maturity status was expressed as a percentage of predicted adult height (PAH%; see equation 2.5) determined by measurement of somatic markers (standing stature, body mass) alongside self-reported parent stature corrected for overestimation (Epstein et al., 1995; Khamis & Roche, 1994). This common approach to estimating maturity status in EPPP academies appears to more accurately predict timing of peak height velocity (PHV) than maturity offset methods (Parr et al., 2020). It is common within maturity research to dichotomise the variable into pre- or post-PHV, or even trichotimise into pre-, circa- and post-PHV for analysis (Radnor et al., 2020; van der Sluis et al., 2015a). Although it is possible to do this using the PAH% approach (PHV occurs at approximately between 88-93% PAH) (Cumming et al., 2017), categorisation of continuous variables limits sensitivity (by consuming variability) of data dramatically reducing statistical power, particularly in smaller sample studies (Altman & Royston, 2006). For example, two individuals at a similar percentage of adult height that fall either side of the cut-off threshold for pre-post PHV will be reported as very different opposed to very similar. Therefore, maturity status (PAH%) was regressed as a continuous variable to protect true variations in the outcomes and maintain statistical power (Altman & Royston, 2006).

To simulate soccer match-play an adapted soccer-specific aerobic field test ($SAFT^{90}$) was used, termed Youth-SAFT (Barrett et al., 2013) as outlined in full within the general methods chapter (see section 3.2.4). This 15-minute fixed-intensity activity profile is based on global-positioning satellite locomotion data from male academy competition and includes acceleration, deceleration, lateral shuffling, jogging, back-pedalling, and sprinting to replicate demands of match-play. The intensity and locomotor activity is controlled by audio cueing which adopts the multidirectional model of the original $SAFT^{90}$ (Small et al. 2009). In groups of four to minimise variation in neuromuscular sampling time, the 15-minute activity profile was repeated a total of four times ($Y\text{-}SAFT^{60}$), interspersed with a 10-minute half-time interval to approximately replicate adolescent competition duration between U13 and U16 (Premier League, 2011). All $Y\text{-}SAFT^{60}$ simulations were completed on 3G pitch whilst participants wore their normal training attire to reduce the variance associated with different surfaces and maintain ecological validity.

Internal and external load was quantified using the methods explained in the general methods sections 3.2.5 and 3.2.6 respectively. Devices were in commercially available vests and sized appropriately for the individual to prevent movement artifact. The mean number of satellites (13.1) and horizontal dilution of precision (HDOP; 0.57) was assessed across all testing sessions to validate data fidelity. Neuromuscular performance was measured (see section 3.2.7) before, at half-time and after the $Y\text{-}SAFT^{60}$.

6.2.3 Data Analysis

To investigate whether PAH% influenced responses in neuromuscular performance, a within-participant repeated measures moderation model was employed. Relationships between the focal predictor (Y_1) and the outcome (Y_2) were examined by testing interactions between these and the stable moderating variable (W_1) utilising a simple moderation model (Montoya, 2019)[1]:

$$Y_{i2} - Y_{i1} = b_{01} + (b_{12} - b_{11})\, W_i + (\varepsilon_{i2} - \varepsilon_{i1})$$
$$Y_{Di} = b_0 + b_1 W_i + \varepsilon_i$$

[1] where $_i$ = individual participant; $_1$ or $_2$ denotes instance; b_0 intercept; b_1 = regression weight; ε = normally distributed residuals with Intercept variance

Ordinary least squares (OLS) regression equations for pre-post changes in neuromuscular performance were conducted using the SPSS macro MEMORE v2.1 (Montoya, 2019). The moderator (PAH%) and focal predictor (e.g., baseline CMJ) were mean centred to eliminate the effects of multicollinearity between variables and to allow the intercept to equal the overall treatment effect (Wu & Zumbo, 2008).

Analysis to explore whether PAH% moderated interactions between mean centred predictor variable (i.e., total distance) and outcome variable (e.g., player load) was conducted using a simple moderator model in the SPSS macro PROCESS v3.4 (Hayes & Rockwood, 2017). Due to the continuous nature of all variables, interactions for both analysis methods were further analysed using the Johnson-Neyman procedure to identify points of transition (i.e., boundaries of significance) across the whole data range, rather than across arbitrarily selected points (Montoya, 2019). If the 95% confidence intervals (CI) did not contain zero, the test was considered significant at the $p < .05$ level.

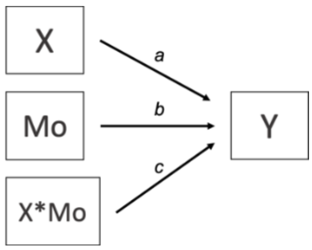

Figure 6.1. Statistical path diagram of the simple moderator model

6.3. Results

The pooled descriptive internal and external load metrics derived from the Y-SAFT[60] are shown in table 6.1 and the descriptive changes in neuromuscular performance are shown in table 6.2. Within-participant moderation analysis indicated that there were no significant interactions between percentage of PAH% and neuromuscular response post Y-SAFT[60]. However, both absolute and relative stiffness indicated that PAH% explained approximately 27-28% of the variance from the model respectively (Table 6.3). Although there was a clear decline in countermovement jump (-4.7%) and a slight improvement in overall RSI performance (3.6%) these were not considered significant. A similar outcome emerged when analysing the interactions between PAH% and load metrics, whereby only RPE-T produced a significant interaction, indicating that approximately 10% (R^2 = 0.10) of the variation explained by PAH% (Table 6.3).

Table 6.1. Pooled internal and external load metrics (mean ± SD) for the Y-SAFT[60]

Internal Load	Mean ± *SD*
sRPE (AU)	65 ± *14*
RPE-B (AU)	55 ± *19*
RPE-L (AU)	67 ± *17*
RPE-T (AU)	43 ± *24*
Heart Rate (bpm)	166 ± *10*
External Load	
Total Distance (m)	5139 ± *226*
Metres per minute (m.min^{-1})	85 ± *4*
Player Load (Au)	651 ± *69*

sRPE; sessional rating of perceived exertion; RPE-B, breathlessness; RPE-L, leg muscle exertion; RPE-T, technical exertion

Johnson-Neyman slope analysis of data identified that specific ranges of four variables (PL, RSI, absolute and relative stiffness) showed some evidence of moderation by PAH% (Figure 6.2). RSI demonstrated a significant slope from 86.3% of PAH% with less mature individuals experiencing smaller changes in RSI over the course of the Y-SAFT[60]. Similarly, smaller changes in absolute leg stiffness were evident in less mature individuals, with slope significance observed from 89.3% PAH% (Figure 6.2). In contrast, this trend reversed for relative stiffness, where there was evidence of slope significance across the PAH% spectrum to ~100%. Additionally, it appears that there is evidence of slope significance between 87.9-96.1 PAH% for PL, but not for other load variables (Figure 6.2).

Table 6.2. Pooled changes (Mean ± SD) in CMJ, RSI and Stiffness (Absolute and Relative) throughout the Y-SAFT[60]

	Pre	HT	% Change	Pre	FT	% Change	HT	FT	% Change
CMJ	25.10 ± 5.0	24.90 ± 6	-0.8%	25.10 ± 5	23.90 ± 6	-4.7%	24.90 ± 5.5	23.90 ± 6.0	-4.1%
RSI	0.55 ± 0.20	0.60 ± 0.2	9.1%	0.55 ± 0.2	0.57 ± 0.2	3.6%	0.60 ± 0.22	0.57 ± 0.2	5.0%
ABS	36.60 ± 11.0	37.60 ± 10	2.7%	36.60 ± 11	35.20 ± 11	-3.8%	37.60 ± 10	35.20 ± 12.0	-6.3%
REL	57.30 ± 17.0	62.20 ± 16	8.5%	57.30 ± 17	58.90 ± 17	2.7%	62.20 ± 16	58.90 ± 17.0	-5.3%

CMJ, countermovement jump; RSI, reactive strength index; ABS; Absolute stiffness; REL, relative stiffness; Pre, before SAFT[60]; HT, half-time; FT, full-time

Table 6.3. Regression model characteristics of training load metrics moderated by percentage of predicted adult height

Estimate	R^2	Coefficient	*SE*	*t* value	*p*-value	*95% CI*
sRPE ~ T^{Dist}	0.06	0.01	0.01	1.19	0.23	−0.01 *to* 0.02
sRPE ~ PAH		−0.51	0.39	−1.31	0.19	−1.29 *to* 0.27
sRPE ~ T^{Dist} x PAH	0.01	−0.01	0.01	−0.72	0.46	−0.01 *to* 0.01
RPE-B ~ T^{Dist}	0.05	−0.00	0.01	−0.07	0.94	−0.02 *to* 0.12
RPE-B ~ PAH		−0.78	0.53	−1.48	0.14	−1.84 *to* 0.27
RPE-B ~ T^{Dist} x PAH	0.01	−0.01	0.01	−0.96	0.33	−0.01 *to* 0.01
RPE-L ~ T^{Dist}	0.07	0.01	0.01	1.65	0.10	−0.01 *to* 0.03
RPE-L ~ PAH		−0.46	0.46	−1.00	0.32	−1.39 *to* 0.46
RPE-L ~ T^{Dist} x PAH	0.01	−0.01	0.01	−0.41	0.68	−0.01 *to* 0.01
RPE-T ~ T^{Dist}	0.13	−0.01	0.01	0.37	0.70	−0.02 *to* 0.03
RPE-T ~ PAH		−1.73	0.62	−2.77	0.00*	−2.99 *to* −0.47
RPE-T ~ T^{Dist} x PAH	0.10	−0.01	0.01	−2.50	0.01*	−0.01 *to* −0.01
HR ~ T^{Dist}	0.02	0.01	0.01	1.18	0.23	−0.01 *to* 0.02
HR ~ PAH		−0.05	0.29	−0.20	0.84	−0.64 *to* 0.2
HR ~ T^{Dist} x PAH	0.01	− 0.01	0.01	−0.08	0.93	−0.01 *to* 0.01
PL ~ T^{Dist}	0.23	0.11	0.04	2.93	0.04*	0.03 *to* 0.19
PL ~ PAH		−4.58	1.7	−2.69	0.00*	−8.00 *to* −1.17
PL ~ T^{Dist} x PAH	0.01	−0.00	0.00	−2.59	0.12	−0.01 *to* −0.00
CMJ	0.01	−0.02	0.36	−0.79	0.42	−0.10 *to* 0.43
RSI	0.01	0.01	0.01	0.23	0.81	−0.04 *to* .01
Absolute Stiffness	0.27	−0.11	0.09	−1.22	0.22	−0.30 *to* 0.07
Relative Stiffness	0.28	−0.20	0.16	−1.25	0.27	−0.52 *to* 0.12

sRPE, sessional rating of perceived exertion; RPE-B, breathlessness; RPE-L, leg muscle exertion; RPE-T, cognitive/technical demand; HR, heart rate; PL, player load; T^{Dist}, total distance; PAH, predicted adult height; CMJ, countermovement jump; RSI, reactive strength index
SE, standard error; CI, confidence interval

6.4. Discussion

This chapter aimed to quantify neuromuscular performance and psycho-physiological responses to a soccer-specific activity profile and the influence of maturation in EPPP academy players. Firstly, T^{Dist}, HR and sRPE during the Y-SAFT^{60} were comparable with data previously reported from U12 to U16 age-competition, however the intensity of 85 m.min^{-1} was below data previously reported (98-118 m.min^{-1}) (Harley et al., 2010; Wrigley et al., 2012). Despite this slight reduced intensity, the Y-SAFT^{60} provided a locomotive stimulus comparable to previously reported activity (Table 6.2). Primary findings from these data illustrate a significant interaction between perceived psycho-physiological load (RPE-T) and maturation, with absolute stiffness, relative stiffness and PL showing slope significance across various stages of maturation (~88-96% PAH). Combined, these data illustrate that various components of neuromuscular performance are more substantially impeded during the adolescent growth spurt, and that locomotion and therefore movement efficiency may alter load-response mechanisms. These interactions suggest that psycho-physiological dose responses are influenced by maturation and should be considered for training prescription purposes, to minimise the likelihood of injury predisposition based on maturation.

Mean pooled data (Table 6.1) illustrates RSI performance improved by >3% during the activity, which is likely a potentiation effect and one that opposes previous findings (De Ste Croix et al., 2019; Lehnert et al., 2018). These studies utilised actual game-play (De Ste Croix et al., 2019) and the SAFT^{90} (Lehnert et al., 2018) which provided greater stimulus duration, possibly explaining the differences. However, slope analysis indicated a linear trend whereby more mature individuals experienced greater potentiation than less mature individuals. Radnor et al. (2018) explained that SSC function develops during maturation through increased elastic energy utilisation, neural potentiation and more efficient stretch-reflex combined with a higher force production propensity. The improved tendon stiffness, motor unit-recruitment and electro-mechanical delay may result in more mature individuals coping better with activity demands and therefore demonstrating more positive responses to the same stimulus. Less mature individuals may experience greater inhibition of SSC function, in turn elevating stress on contractile components and resisting limb deformation during the spring-mass model. This places a greater emphasis on strength characteristics of muscle (compliance) leading to longer propulsive contact times (explained via less efficient RSI illustrated in Figure 6.2) (De Ste Croix et al., 2019; Lehnert et al., 2017). Therefore, with tendon cross-sectional area (CSA) having large influences on its function and CSA increasing with growth, it is unsurprising that more mature individuals demonstrate efficient SSC function (Radnor et al., 2018) and, therefore, more favourable RSI responses from the standardised activity.

This inhibition of SSC function in less mature individuals can partly explain the responses to CMJ, absolute and relative leg stiffness. Pooled means indicate reduced CMJ of 4.1% and leg stiffness of 5.3-6.3% respectively with evidence of a significant slope from ~89% PAH for absolute stiffness and across maturation for relative stiffness (Figure 6.2). Mechanically this translates to increased yielding in the less mature individuals, with greater ground contact times, centre of mass (CoM) displacement and reduced movement efficiency (Radnor et al., 2018). Yielding is caused by the tendon being stiffer than the contractile element of the musculotendinous unit reducing the ability to utilise the elastic storage potential of the tendon. Therefore, less mature individuals fail to generate sufficient muscle stiffness through adequate recruitment of motor units and correct activation strategies (Radnor et al., 2018). This scenario may increase injury risk in the less mature individuals, via increased relative biomechanical load due to increased absorption of shear stress and greater reliance on the knee compared to more mature counterparts (Lloyd et al., 2012). This notion is similar to that reported in other sports, namely ballet where characteristically training loads associate closely with chronological age and where later maturing individuals experience crucial training periods in conjunction with PHV, often resulting in negative injury outcomes (Bradshaw et al., 2014; S. B. Mitchell et al., 2020). Findings relating to stiffness are similar to those proposed by De Ste Croix et al. (2017b) in adolescent female soccer, whereby the negative impact of soccer activity on leg stiffness reduced as the maturation increased, with prepubescent individuals having the most substantial performance decrements and heightened risk of knee injury. In general, the lack of model significance supports assertions by Oliver et al. (2014) and De Ste Croix et al. (2019) in that leg stiffness responses are highly individualised and improvements in one neuromuscular component are not necessarily mirrored in others, despite sharing many SSC characteristics (Lloyd et al., 2012).

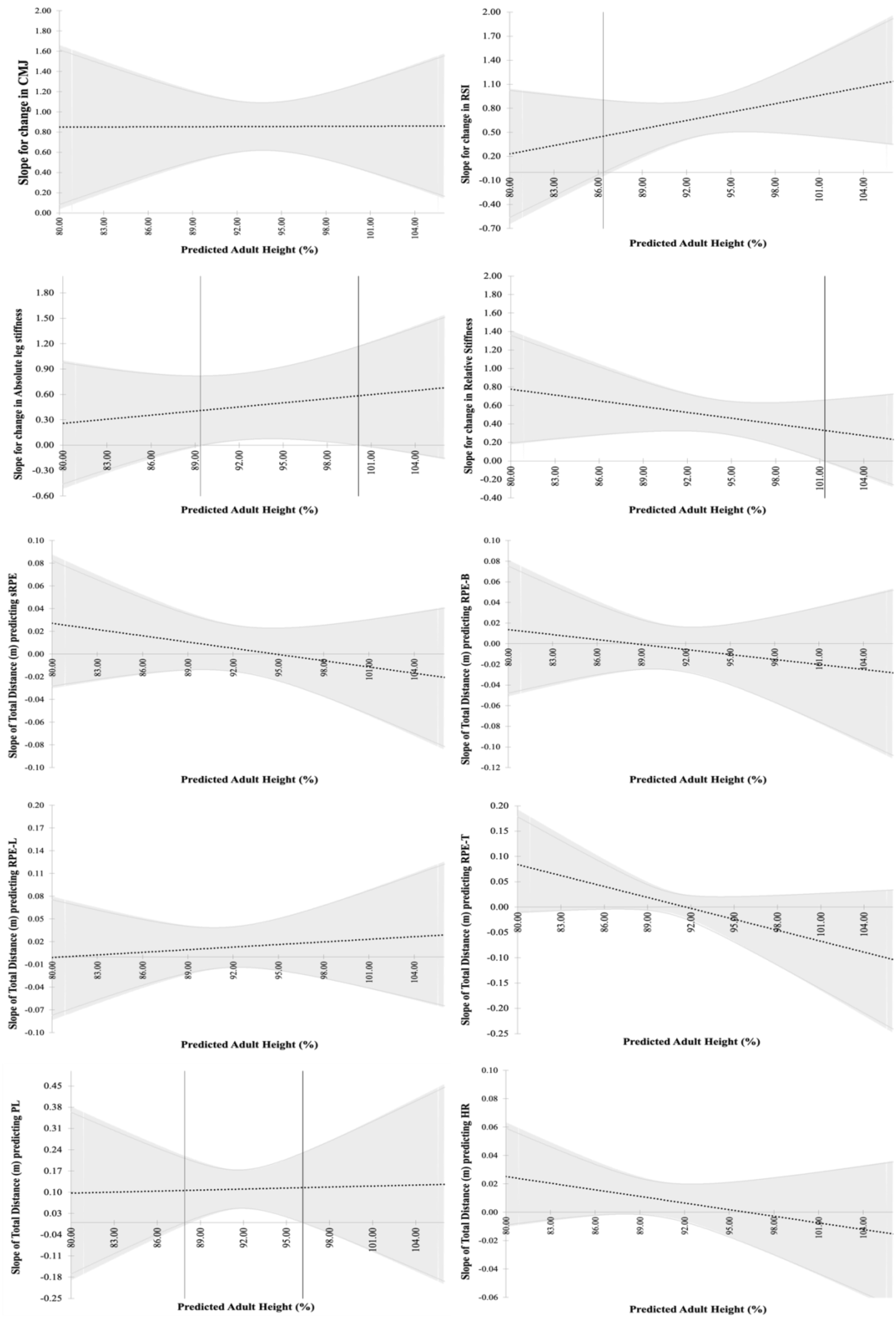

Figure 6.2. Johnson-Neyman slope analysis illustrating responses of neuromuscular performance and training load variables with predicted adult height (%) as the moderator, with thin vertical lines illustrating regions of significance.

Variations in locomotive movement patterns may be linked to interactions observed between PL and PAH% highlighted in Figure 6.2. Although PL appeared consistent through the PAH% range, slope analysis suggests there is greater dose-response variation at the tails of maturation (considered pre- or post-PHV) with a significant slope identified almost exactly aligned with PHV (87.9-96.1% PAH; Figure 6.2). Tentatively, this may suggest that load-response patterns are influenced around PHV from a single exercise bout, which could represent a causal pathway of injury due to the relative increased multidimensional load during the same movement profile. Admittedly, the likely larger variation in anthropometric and physical properties at the tails of maturation could have also influenced the variation observed either side of the significant slope (Figueiredo et al., 2010). PL is a measure of the instantaneous rate of change in acceleration in each of the three vectors and can infer biomechanical load, though its accuracy for assessing load-response pathways at a structural level is yet to be determined (Verheul et al., 2020). However, a similar response that aligned with PHV (88-93% PAH) was observed in both absolute and relative stiffness. Combined, these findings would suggest altered movement patterns circa-PHV and may present a causal mechanism for injury based on the seemingly increased relative cost of activity. However, considering the small sample size, interpretations should be cautious and treated as an informed possibility that whole-body load-response pathways are influenced by PAH% with further empirical investigation required. More frequent use of accelerometery within academy soccer will permit this work on which has the potential to provide valuable insights for injury prevention within youth soccer and more widely youth sport.

In general, internal load metrics were not moderated by PAH%, but analysis indicated an interaction with RPE-T and Figure 6.2 illustrates a progressive reduction in perceived RPE-T as PAH% increases. In line with other research (McLaren et al., 2017b) RPE-T was perceived to be lower than other RPE metrics, likely because the Y-SAFT^{60} is a repetitive audio-controlled activity profile requiring minimal cognitive strain in comparison to training and match activities. Why less mature individuals perceive the Y-SAFT^{60} more technically demanding remains unclear, although one theory is linked to the relative physical shortcomings explained previously. Lloyd et al. (2012) suggested that changes in SSC during growth are associated with improvements in anaerobic performance such as sprinting and change of direction, which may have indirectly influenced perceptions of technical effort. For example, Y-SAFT^{60} audio cues such as 'stride' or 'sprint' require maximal effort. A highly intense period during the Y-SAFT^{60} could be perceived more cognitively demanding for less mature individuals endeavouring to maintain pace with the audio. An alternative theory is that less mature individuals experienced greater training monotony during the repetitive activity profile or non-linear differences in physical and cognitive maturation could have influenced perceptions (Brink, Visscher, et al., 2010; M. Wright et al., 2020). Despite no interaction, other dimensions of intensity (sRPE, RPE-B and HR) followed a similar trend whereby more mature individuals found the activity less intense (Figure 6.2). This would confirm the intuitive hypotheses, but lack of statistical significance prevents this conclusion; again, suggesting the need for more work in this area. It would also appear that perceptions of exertion during adolescence are influenced by the specific protocol and training mode which may have contributed to these findings (McLaren et al., 2017b).

6.4.1 Limitations

Whilst the standardised Y-SAFT^{60} facilitated a dose-response comparison, it is conceded that it disregards many reactive soccer-specific actions (e.g., responding to opponents, jumping, and kicking). Consequently, although comparative from a locomotive perspective, the Y-SAFT^{60} may underrepresent true anatomical, physiological, and biomechanical stresses placed on adolescent players during actual training and/or competition. This may explain why some individuals experienced a level of potentiation in neuromuscular performance as the demands were insufficient to elicit detrimental performance changes. However, the large positional and individual variability of external loads from competitive matches and training activities make more ecologically valid dose-response protocols highly complex for research. In addition, it is appreciated that baseline markers of physical fitness (e.g., aerobic fitness, strength, speed) may influence individual responses to the standardised activity profile and therefore should not be discounted when considering the moderating impact of PAH%.

This acute study suggests that a single soccer specific activity bout can elicit maturation specific dose-responses (RSI, RPE-T, Stiffness), which are likely magnified when combined with repeated activities each week (see chapter 7). The notion that a single-bout of sub-maximal activity can create significant maturity-specific variations in load-response are a possible explanation to the heighted incidence of injury risk in this population. Therefore, practitioners are urged to consider the maturational load-response variation in an attempt to reduce injury incidence from inappropriate levels of physical and cognitive stress (Brink, Visscher, et al., 2010). Based on tentative findings, it would be irresponsible to make robust recommendations regarding how to change training practices, but the authors would encourage practitioners to be mindful of dose-response variations across maturation in the following ways. Firstly, activities high in biomechanical load characterised by short, intense intervals with frequent accelerations, decelerations, and changes of direction, often over small to moderate pitch-dimensions may accentuate variations in response. Therefore, it may be prudent to restrict the frequency and volume of exposure to such load across the training week, particularly in those approaching peak-height velocities. Secondly, practitioners are encouraged to adapt their prescription processes and routinely consider maturation specific load management strategies whenever possible, for example utilising existing maturity-categorised strategies such as bio-banded training or competitions (Cumming, Brown, et al., 2018). Although this does not automatically reduce the load on those deemed vulnerable, it provides opportunity for the coach to better manage the frequency and volume of exposure to stressful activities on a group level and therefore reduce large variations in inter-individual response attributed to maturity. Finally, this would facilitate the inclusion of activities that required less unpredictable, reactive strength (typified by deceleration or COD) actions in favour of more structured 'technical' practices that built on key movement competencies such as acceleration, deceleration, change of direction and strength development as suggested by the Youth Physical Development (YPD) model (Lloyd & Oliver, 2012). It is not recommended that practitioners reduce training exposure per se or remove any activities completely, but more that the emphasis of training shifts to allow smart prescription of loads that are directed at the individual appropriately.

6.4.2 Practical Applications

Collectively, these findings provide evidence of the moderating effect of maturation to perceptions and responses to standardised activity. Therefore, the findings suggest that failure to consider maturity-related responses may elevate the predisposition to injury of some athletes. Both psycho- and physiological responses are altered during maturation which must be considered by practitioners within their training prescription to avoid negative consequences on their players. Strategies already exist within research and practice to facilitate maturity specific training interventions which may help coaches manage the individual dose-response smartly and practically within a group environment. More work is needed to corroborate these findings and provide exact mechanisms of the causes; however, tentative inferences suggest that repeated high-velocity biomechanical loads may contribute to the observed differences in neuromuscular response across maturation and should be managed considerately.

Chapter 7

Maturity status, not tempo influences training load and neuromuscular performance during an academy soccer season

Chapter 7: Maturity status, not tempo influences training load and neuromuscular performance during an academy soccer season

7.1 Introduction

Extensive research has explored associations between training load, injury and performance in adult sport (Kalkhoven et al., 2021). Although injury risk is multifactorial and nuanced in many ways, it is now widely accepted that with adequate manipulation of training load, practitioners can mitigate injury risk to some degree (Impellizzeri, Marcora, et al., 2019a; C. Williams et al., 2017). Chapter 6 identified maturity-specific differences in dose-response to an acute training session in adolescent players. Typically, players experience between 3-4 acute bouts of specific training on a weekly basis, proposing that the differences observed in the previous chapter may be exacerbated over the course of a season. Obtaining the optimal fitness-fatigue balance is a complicated, multi-faceted but entirely possible priority within elite sport through proactive prescription and effective recovery (Thorpe et al., 2017). This is often a data-informed process that combines measures of internal and external load to advise coaching and support staff on micro-cycle development (Impellizzeri, Marcora, et al., 2019a). Such a comfort is rarely afforded respective coaching and support staff working with adolescent athletes, who often have training load superimposed onto other physical exertions from school and recreational based settings (Phibbs et al., 2018b).

The Elite Player Performance Plan (EPPP) provides recommendations on the quantity of coaching hours that players are exposed to, which systematically increases with age (Premier League, 2011). These legislative guidelines exist to provide criteria upon which academies are then audited and subsequently form a mechanism to uphold talent development standards. Therefore, it is the responsibility of each academy to navigate within these guidelines and strive for optimal fitness-fatigue balance for its players in a bid to achieve long-term success. Although there is some precedent of workloads in adolescent soccer (Arazi et al., 2020; Coutinho et al., 2015; Wrigley et al., 2012), there is a relative paucity in comparison with adult populations. This is likely caused by logistical and environmental complexities associated with collecting, interpreting, and utilising reliable training load data in these environments (i.e., staffing and resources), as outlined in (as outlined in chapter 4), further complicated by the non-linear changes in physical and physiological development through maturation.

Studies exploring adolescent workloads within soccer have primarily adopted a chronological age-group approach, whereby they observe differences or similarities between specified chronological age-groups (Arazi et al., 2020; Coutinho et al., 2015; Wrigley et al., 2012). Granted, this approach aligns with systematic increases in coaching hours and related exposure durations outlined previously (Premier League, 2011), however it potentially oversimplifies the magnitude of individual variability associated with this period of development. It is common to see large within-age-group variations in physical characteristics such as body mass (~50%), stature (~29cm), percentages of predicted adult height (PAH: 10-15%) and fat free mass (3-8.6kg) (Figueiredo et al., 2010; Hannon et al., 2020). Such variations infer that exposing all individuals of a similar chronological age to age-specified workloads is a flawed strategy and is reasonable to expect that early- and late-maturers will experience a different dose-response, as demonstrated in chapter 6. Evidence suggests that maturation interacts with various components of physical performance including sprint speed (Meyers et al., 2017), match running performance (Buchheit & Mendez-Villanueva, 2014), strength and muscle architecture (Radnor et al., 2020). These interactions indicate variable maturity-related adaptations, and it is therefore unrealistic to expect all players within a given chronological age-group to cope with prescribed loads equally.

Age-related dose-responses may have small implications for between-session recovery, however over prolonged periods, this broad brush approach to load prescription may well contribute to the relatively high injury incidence observed across adolescent age groups (Read, Oliver, et al., 2018; Rommers et al., 2020; Tears et al., 2018). For example, academies generally divide the on-the-pitch coaching across 2-3 evenings per week plus matches, over 40-weeks of the year (Premier League, 2011). Mechanistically this confines recovery time and emphasises the need for appropriate load management as consistently performing with residual fatigue may result in non-functional overreaching (NFOR). NFOR has been reported in up to 27% of male academy players (C. Williams et al., 2017) with symptoms of athletic burnout also being common (25%) (A. Hill, 2013). Additionally, several empirical studies have presented the apparent relationship between maturation and injury incidence with up to 62% of Youth Development Phase (YDP) injuries described as non-contact (Read, Oliver, et al., 2018), indicating various significant negative consequences associated with not managing load during this turbulent period of development proactively.

Methods to track training loads vary between senior and academy settings, with academy environments often reverting to cost-effective and easily administrable surrogates of more objective but expensive equipment (chapter 4). Sessional ratings of perceived exertion (sRPE) are a valid way to monitor the psycho-physiological perceptions of intensity within soccer, that is commonly used within academy settings to quantify perceived training intensity (Fanchini et al., 2016; Wrigley et al., 2012). The traditional all-encompassing sRPE approach offers a convenient global marker of training intensity, but may lack sensitivity towards the specific contributing facets of exercise intensity and has been modified to differentiate specific psycho-physiological mediators (M. Wright et al., 2020). These differentiated ratings of perceived exertion might help to distinguish between physiological and mechanical load adaptation pathways and provide richer insight into the individual response to training loads (Vanrenterghem et al., 2017). In addition to self-reported indicators of load, markers of physical performance routinely collected as part of the EPPP benchmarking process (e.g., countermovement jump) offer valuable insight into how players are coping with training loads. Therefore, combining subjective, self-report loads and accessible objective markers of performance can offer a robust mechanism through which to observe within-participant variations in load-adaptation over time.

The relative paucity of evidence surrounding the role of maturation tempo (cm/year) and status (PAH%) and the responses to acute load (chapter 6) provide an important rationale for this relative longitudinal experimental chapter. It is anticipated that players of different maturity status will perceive the training intensity differently and that their neuromuscular performance over the course of the season will vary because of maturation. The overarching aim of this chapter was to establish the impact of biological maturation to routinely prescribed training loads over an extended period (1-season) from an elite performance environment and be able to provide recommendations for practitioners to manage this proactively going forward.

7.2 Methods

7.2.1 Participants

Fifty-five male soccer players (age 14.5 ± 1.2 years; stature 172 ± 10 cm; body mass 59.8 ± 10 kg) from a Category 2 EPPP academy participated in this chapter during the 2018-19 season. Participants were included if they were registered for a Youth Development Phase (YDP) age group squad (U13-U16 years) at the academy. To maintain data fidelity, participants were excluded from analysis if they failed to report self-reported perception of intensity for >75% of training sessions during the season, which may have resulted from injury/illness, poor adoption, or de-selection from the academy. In addition, due to the position specific nuances associated with goalkeepers and the likely variations in load this design excluded goalkeepers.

Typically, players were required to attend three scheduled 90-minute training sessions and one competitive match each week, however due to logistical limitations self-reported perceptions of intensity were not routinely recorded for competitive matches. Ethical approval in line with the declaration of Helsinki was sought and granted from the University of Gloucestershire ethics committee.

7.2.2 Procedure

Maturity status was expressed as a current percentage of predicted adult height (PAH%) determined by measurement of somatic markers (stature and body mass) combined with self-reported parental stature adjusted for overestimation (Epstein et al., 1995; Khamis & Roche, 1994) as explained in the general methods (equation 2.5). Maturation tempo was expressed as the change in stature per year (cm/year) which was measured at three time points during the study, separated by approximately 3-4 months (Malina et al., 2004).

Self-reported perceptions of psycho-physiological intensity were collected approximately 15-minutes after each training session for a period of 40-weeks (September to May). Players used a touch-screen tablet (Acer Iconia One 8 B1-850, Taipei, Taiwan; Acer Inc) to record their perceptions of intensity using a customised application (McLaren et al., 2017a). The application utilised the CR100® centi-Max scale that was numerically blinded but employed verbal anchors to provide confidential responses free from conformation bias (McLaren et al., 2017a; M. Wright et al., 2020). Ratings of global (sRPE) and differential (RPE-B, breathlessness; RPE-L, leg muscle; RPE-T, technical/cognitive) perceptions of exertion were provided in arbitrary units (AU) for each training session. This load monitoring procedure was introduced approximately 1-year prior to the start of the data collection, allowing significant opportunity for players to become habituated and experience the full range of sensations associated with the CR100® scale permitting valid responses. Mean weekly RPE for each participant was calculated and utilised for analysis.

Neuromuscular (NM) performance was measured using countermovement jump (CMJ), reactive strength index (RSI), absolute (ABS) and relative leg (REL) stiffness at the specific timepoints across the season coinciding with EPPP benchmark testing dates (September, January, April). Participants had opportunity to familiarise themselves with the protocol after a standardised 5-minute dynamic warm-up consisting of bodyweight activities designed to mobilise and activate muscles. After sufficient rest (3-5 mins) participants completed two attempts of each protocol using the Optojump photocell system (Microgate, Bolzano, Italy) with the best result taken for analysis. CMJ and RSI were calculated from five consecutive, maximal bilateral jumps. Participants started in an upright, standing position with hands on hips and then squatted to a self-selected depth and without pausing jumped maximally five times. Participants were encouraged to perform the eccentric phase as quickly as possible to maximise vertical jump height and minimise ground contact time. Jump height (cm) was calculated from the first maximal jump using flight time from the following equation (equation 3.1) (De Ste Croix et al., 2015). Jump height and ground contact time were averaged across the five rebound maximal bilateral jumps to calculate RSI using the following equation (equation 3.2).

Equation 3.1.

$$\text{Jump height} = (\text{Flight time}^2 * \text{gravity}) / 8$$

Equation 3.2.

$$\text{RSI} = \text{jump height (m)} / \text{ground contact time (s)}$$

ABS and REL stiffness were measured from contact time and flight time during 20 consecutive bilateral sub-maximal hops at a frequency of 2.5 Hz. This tempo was deemed to have the highest reliability of leg stiffness measured in adolescent populations (CV 7.2%) (De Ste Croix et al., 2015). Participants were asked to place hands on their hips to minimise upper body interference; rebound for height and land within the photocell gates; landing with legs fully extended and looking forwards. ABS stiffness ($kN \cdot m^{-1}$) was calculated using equation 3.3 where K_{leg} refers to leg stiffness, M is total body mass, Tc refers to ground contact time and Tf is equal to flight time (Lloyd et al., 2009). To account for the influence of mass on leg stiffness and leg length on mechanical properties of locomotion between participants, absolute values of leg stiffness were divided by body mass and leg length to provide a dimensionless value of relative leg stiffness (De Ste Croix et al., 2015).

Equation 3.3.

$$K_{leg} = [M*\pi\ (T_f+T_c)]\ /\ T_{c2}\ [T_f+T_c/\pi) - (T_c/4)]$$

7.2.3 Data Analysis

Visual inspection of raw data distribution was conducted using Q-Q plots, with statistical normality assessed through Shapiro-Wilk test with no considerable deviation from normal. Differences in differential RPE (sRPE, RPE-B, RPE-L and RPE-T) and NM performance (CMJ, RSI, ABS and REL) across maturation (status and tempo) were examined using linear mixed modelling (SPSS Statistics v.25, Armonk, NY: IBM Corp). The model investigated differences between fixed effects (Squad; PAH% or cm/year) while using a random effect for player and PAH% or cm/year (intercept; unstructured) to account for repeated-within athlete observations for each dependant variable. To protect against increased risk of a type 1 error due to multiple comparisons, Bonferroni adjusted *p*-values were reported. Prior to analysis PAH% was mean centred to reflect variance of the intercepts specific to the sample mean and contextualise interpretations. PAH% was also scaled to allow more meaningful interpretations, whereby the model illustrates the estimates for a 5% and 10% deviation in PAH% from the mean. These deviations are important as they signify meaningful variations commonly seen within chronological age-groups in academy football. For example, Figueiredo et al. (2010) reported a range in skeletal age of 13.1 to 16.8 years and stature of 146.7 to 177.3 cm in players aged 13-14. As a worst case scenario, this corresponds to a range between 82-99% of predicted adult height within chronological age-groups (Royal College of Pediatrics and Child Health, 2012). Additionally, contemporary methods to biologically categorise players (i.e. bio-banding) commonly utilises 5% thresholds for determine groupings (Malina et al., 2019).

To facilitate practical applications, subsequent non-clinical magnitude based decisions (MBD) were applied to offer qualitative inferences of the difference magnitudes (Hopkins, 2019). Without empirical anchors for minimum practically important differences (MPID) in differential-RPE variables, a difference of 8 AU was used as this represents the shift required to move a players rating beyond halfway to, or from, the next effort category on the scale (CR100® centi-Max) (M. Wright et al., 2020). Similarly, a distribution-based approach (between-player SD multiplied by 0.20) to calculating MPID, otherwise known as smallest worthwhile change (SWC), was applied to NM performance data in the absence of empirical anchors for adolescent athletes. Probabilities of effects being substantial and effect sizes were reported using standardised thresholds (Hopkins, 2019). Uncertainty for all estimates was expressed using 95% confidence intervals (90% CI).

7.3 Results

In accordance with our data exclusion criteria (>75% response rate), 18 participants were removed prior to analysis, resulting in 37 participants generating data from 3,996 individual training sessions with >350,000 training minutes over the 40-week season. Descriptive data (mean ± SD) for baseline within-age-group physical characteristics, NM performance and mean weekly differential-RPE ratings are presented in Table 7.1. On average, within age-groups, players consistently rated training sessions as 'Strong' or 'Heavy' across all differential-RPE domains (Figure 7.1). Analysis indicates there was a most likely trivial impact of maturation tempo (cm/year) on all variables across the study (Table 7.2). There were very likely to most likely trivial differences in maturity status for perceptions of intensity for all domains except for sRPE. Analysis indicates that for sRPE, a 5% increase in maturity status (PAH%), results in players rating sessions 6.9 AU lower and 13.9 AU lower for a 10% maturity shift (Table 7.2). All aspects of NM performance were influenced by maturity status and identified likely to most likely differences, except for relative stiffness (unclear), but no such influence was observed for maturation tempo (Table 7.2). Both 5% and 10% changes in maturity status (PAH%) most likely resulted in higher CMJ, with likely to very likely differences observed for RSI and ABS. In line with probability distribution interpretations, REL data was unclear and therefore deemed not influenced by maturation (status or tempo).

Table 7.1: Descriptive statistics of anthropometric and neuromuscular characteristics (mean ± SD) according to age category at the start of the season, and mean ± SD weekly differential-RPE (AU) values over the season

	U13 (n = 12)	U14 (n = 9)	U15 (n = 9)	U16 (n = 7)
Age (y)	12.6 ± 0.3	13.5 ± 0.6	14.8 ± 0.1	15.7 ± 0.2
Stature (m)	160.0 ± 7	166.0 ± 7	177.0 ± 5	179.0 ± 9
Body mass (kg)	49.9 ± 8	56.5 ± 9	63.4 ± 4	65.2 ± 9
Status (PAH%)	88.7 ± 2	92.2 ± 2.7	97.0 ± 1	98.6 ± 1
Tempo (cm/year)	12.1 ± 6	8.7 ± 7	7.4 ± 10	7.1 ± 4
sRPE	52.1 ± 15	50.8 ± 14	45.9 ± 12	43.2 ± 12
RPE-B	48.0 ± 13	50.5 ± 14	48.0 ± 12	45.5 ± 12
RPE-L	51.3 ± 15	52.8 ± 15	46.2 ± 10	46.4 ±12
RPE-T	45.2 ± 13	49.3 ± 15	43.6 ± 11	41.2 ± 11
CMJ	22.0 ± 3	29.7 ± 4	33.1 ± 6	33.9 ± 4
RSI	0.6 ± 0.2	0.7 ± 0.2	0.56 ± 0.2	0.6 ± 0.1
ABS	15.4 ± 6	18.6 ± 8	18.9 ± 5	19.7 ± 5
REL	26.2 ± 12	25.6 ± 12	25.4 ± 7	24.9 ± 6

PAH%, percentage of predicted adult height; sRPE, sessional rating of perceived exertion; RPE-B, RPE breathlessness; RPE-L, RPE-leg exertion; RPE-T, RPE-technical exertion; CMJ, countermovement jump; RSI, reactive strength index; ABS, absolute stiffness; REL, relative stiffness

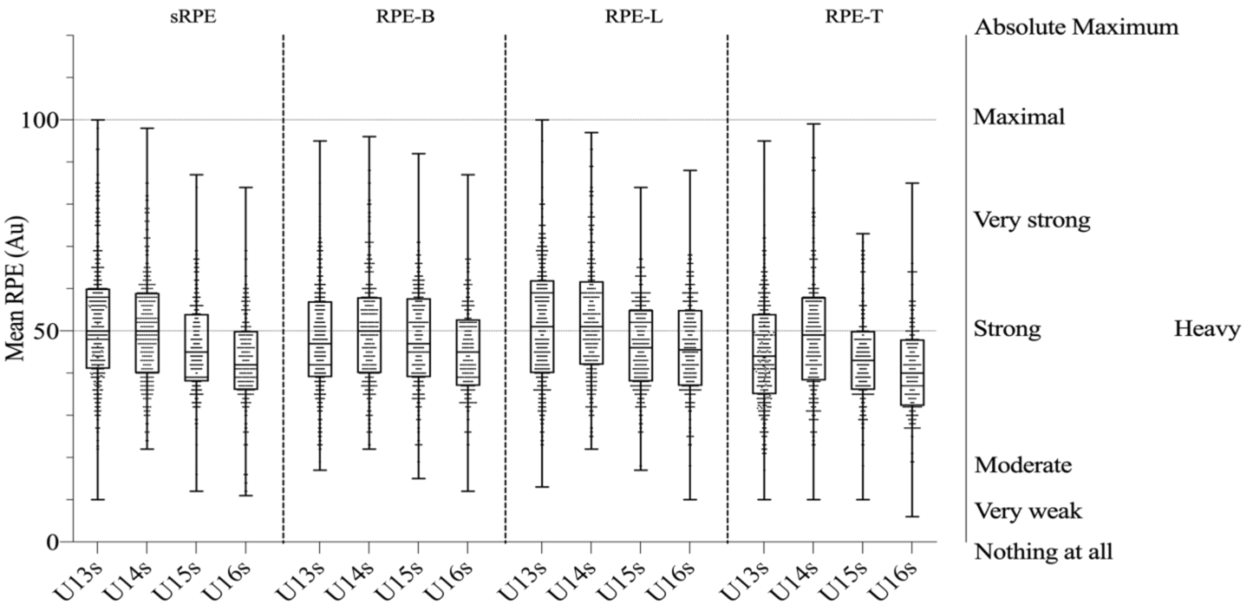

Figure 7.1. Box (25th to 75th percentile) and whisker (minimum and maximum) ratings of each differential-RPE across chronological age-groups for the full season aligned to the verbal anchors of the Borg CR-100 centi-MAX scale

Table 7.2. Slope, mean difference (95% confidence interval), effect size (d) and non-clinical practical inferences (probabilities) for 5% and 10% increments in PAH

Variable	±PAH%	*df*	*t*	*P*	Difference (95% CI)	*d*	Non-clinical inference
sRPE	cm/year	36	5.61	0.115	0.3 (−0.1 to 0.9)	0.02	*Most likely trivial (0/100/0)*
	5%	65	−3.33	0.002*	−6.9 (−11.1 to −2.7)	0.75	*Likely trivial (0/71/29)*
	10%	51	−3.33	0.002*	−13.9 (−22.3 to −5.5)	1.01	***More mature likely lower (0/7/93)***
RPE-B	cm/year	15	1.41	0.182	0.4 (−0.2 to 1.0)	0.03	*Most likely trivial (0/100/0)*
	5%	30	0.81	0.423	1.3 (−1.9 to 4.5)	0.24	*Most likely trivial (0/100/0)*
	10%	30	0.81	0.423	2.6 (−3.9 to 9.1)	0.42	*Very likely trivial (5/95/0)*
RPE-L	cm/year	18	0.52	0.606	0.2 (−0.5 to 0.8)	0.01	*Most likely trivial (0/100/0)*
	5%	23	−0.31	0.755	−0.6 (−4.5 to 3.3)	0.10	*Most likely trivial (0/100/0)*
	10%	23	−0.31	0.755	−1.2 (−9.1 to 6.7)	0.13	*Very likely trivial (1/95/4)*
RPE-T	cm/year	64	1.31	0.192	0.3 (−0.2 to 0.8)	0.03	*Most likely trivial (0/100/0)*
	5%	8	−0.63	0.529	−1.1 (−4.6 to 2.3)	0.16	*Most likely trivial (0/100/0)*
	10%	8	−0.65	0.532	−2.1 (−9.4 to 5.2)	0.29	*Very likely trivial (0/95/5)*
CMJ	cm/year	19	−0.96	0.348	−0.1 (−0.2 to 0.1)	0.03	*Most likely trivial (0/100/0)*
	5%	58	4.89	0.001*	4.3 (2.5 to 6.1)	1.72	***More mature most likely higher (99/1/0)***
	10%	58	4.89	0.001*	8.6 (5.1 to 12.1)	3.03	***More mature most likely higher (100/0/0)***
RSI	cm/year	60	0.42	0.674	0.1 (−0.1 to 0.1)	0.02	*Most likely trivial (0/100/0)*
	5%	75	2.1	0.038*	0.1 (0.1 to 0.2)	1.44	***More mature likely higher (90/10/0)***
	10%	65	1.98	0.052	0.2 (−0.1 to 0.4)	3.06	***More mature very likely higher (95/4/1)***
ABS	cm/year	9	−1.16	0.463	−0.3 (−4.3 to 3.7)	0.27	*Most likely trivial (0/100/0)*
	5%	67	2.10	*	2.8 (0.9 to 5.5)	0.58	***More mature likely higher (90/10/0)***
	10%	84	2.10	0.043	5.6 (0.2 to 11.1)	1.53	***More mature very likely higher ((95/4/1)***
REL	cm/year	29	−0.67	0.507	−0.17 (−0.7 to 0.4)	0.02	*Most likely trivial (0/100/0)*
	5%	57	1.1	0.285	2.7 (−2.3 to 7.7)	0.57	*Unclear (65/30/5)*
	10%	48	1.1	0.255	6.1 (−4.5 to 16.8)	1.73	*Unclear (80/14/6)*

Abbreviations: RPE, rating of perceived exertion; sRPE, sessional-RPE; RPE-B, breathlessness; RPE-L, leg muscle exertion; RPE-T, Technical/cognitive exertion; CMJ, countermovement jump; RSI, reactive strength index; ABS, absolute stiffness; REL, relative stiffness; cm/year, maturation tempo; PAH%, percentage of adult height; *df*, degrees of freedom; *t*, t-statistic; *P*, p-value

7.4 Discussion

The aim of this cross-sectional chapter was to establish whether biological maturation (status and/or tempo) influenced perceived psycho-physiological response and NM performance in response to typical training loads over an extended period within an academy environment. Primary findings are two-fold, in that a) overall session intensity (sRPE) was substantially influenced by maturity status, but not tempo; and that b) maturity status (not tempo) substantially influences NM performance over the course of a season. Whilst the latter is less surprising, the former is novel and may provide practical insight for managing training load prescription in academy settings.

Mean pooled sRPE ratings were 49.2 AU which compares to previous studies involving players of similar age groups that have used either the CR-100 (M. Wright et al., 2020) or CR-10 scale which can be subsequently converted to facilitate CR-100 comparisons (Clemente et al., 2019). Figure 7.1 illustrates a progressive negative trend in mean sRPE values through the YDP age-groups, which is likely explained by an increased distribution of more biologically advanced players reporting lower sRPE values in older age-groups. Analysis indicates that a 5% increase in PAH, resulted in a reduction of ~7AU per session, with a ~14AU difference for a 10% difference in PAH (Table 7.2). On face value, these findings may appear trivial as within-session inter-individual differences of 7-14AU are common (T. Lovell et al., 2013; McLaren, 2017). However, these values represent perceived intensity across the full season, comprising of approximately three sessions and a competitive match each week (matches not recorded in this chapter). Therefore, players less biologically developed are consistently working harder just to compete with more biologically advanced teammates of a similar age. When accrued, these small inter-individual differences may become a substantial variation in training load over prolonged periods (e.g., week, month, term).

The big picture is, that less biologically advanced players report accumulated loads that far exceed more advanced counterparts, despite experiencing the ‘same’ prescription, likely elevating their risk of non-functional overreaching, injury and possibly ‘burnout’ (A. Hill, 2013; C. Williams et al., 2017). This is a noteworthy finding based on evidence suggesting chronological age-groups within this range are comprised of players varying in PAH by 10-15% (Figueiredo et al., 2010) with injury incidence also peaking at the same time (Rommers et al., 2020). Although very much depicted as a ‘worst case scenario’, figure 7.2 illustrates the potential self-reported load differences between players of different maturity status using the intensity multiplied by duration method (Foster, 1998). The general consensus from training load research is that doing too much, or too little is associated with increased injury risk (Kalkhoven et al., 2021). The omission of injury data in the current study prevents interpreting which of the extremes depicted are more ‘at risk’ (i.e., over-cooking or under-cooking), but recent findings indicate increased injury burden post-PHV (i.e. >96% PAH) (Monasterio et al., 2020). Although tentative, this may suggest that more biologically advanced players may actually be underprepared for the demands of the game (i.e., undercooked), that in turn contributes to the ~35% of all injuries that occur within matches (Tears et al., 2018).

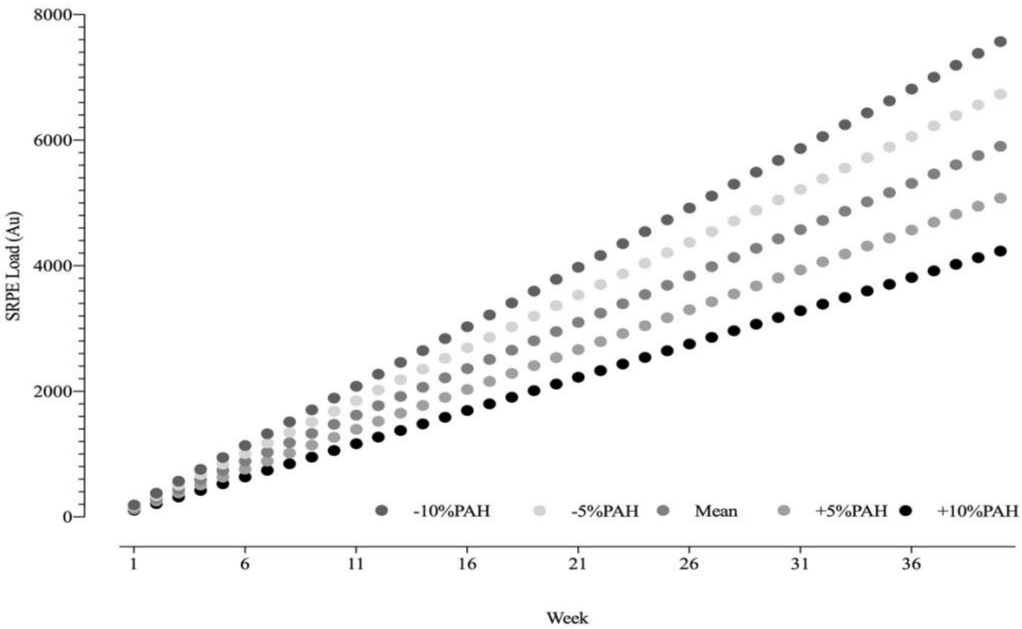

Figure 7.2. Forecasted accumulated training load differences in sRPE over a typical season for players of varied maturation

No such substantial differences were observed when independent psycho-physiological mediators were observed using differential-RPE variables (Table 7.2). There is a paucity of research exploring the use of differential-RPE within adolescent soccer with only one study showing moderate to large (*r*. .59-.69) associations between sRPE and differential mediators (M. Wright et al., 2020). Evidence from adult populations indicates that training mode influences the differential response as they align with various internal constructs (McLaren et al., 2017a), and it is possible that this approach may have been over-complicated for the adolescent population within current study solely reporting total training loads. This population are considered to have the cognitive ability to understand and accurately rate sRPE, however the relationship between RPE and the specific internal constructs (i.e., heart rate) is less pronounced at this age and somewhat influenced by the training mode (Groslambert & Mahon, 2006) which may confound differential-RPE measures. Perhaps if the study split sessions into their various training modes (e.g., repeated high-intensity efforts or skill-based conditioning) differential-RPE may offer more sensitive quantification of psycho-physiological response, but more work is needed to explore this notion. Therefore, we are satisfied that the substantial differences observed in sRPE across maturation result in meaningful findings for the applied practitioner, who in most cases adopt sRPE rather than differential-RPE to monitor internal training loads in academy settings (Wrigley et al., 2012).

A 5% increase in PAH would likely improve CMJ performance by approximately 4.3cm with similar relative magnitudes of performance improvement for RSI and ABS (Table 7.2). Inferences for REL were unclear, however this equation accounts for changes in body dimension by including mass and leg length, therefore this finding is not surprising. This progressive improvement in NM performance aligned to maturity status is not novel and has been highlighted in previous work (Lloyd, Oliver, Radnor, et al., 2015) and is thought to result in the development of musculotendinous properties that enhance the stretch-shortening cycle and utilisation of elastic energy (Radnor et al., 2020). Previous work had suggested that changes in leg stiffness were individualised (De Ste Croix et al., 2019), though the strength of relationship observed here would indicate this is more predictable than previously inferred. A notable result from this chapter indicates that maturation tempo was not substantially associated with NM performance. There is a paucity of research that observes rate of growth and its interaction with performance characteristics, but findings here would suggest that this is negligible and in fact we may gleam more information by using maturity status than tempo to analyse performance progression. Admittedly, these are secondary findings from this experimental chapter and longitudinal work from diverse populations would be required to confirm this assertion.

7.4.1 Limitations

Although informative, it is accepted that the cross-sectional nature of this chapter comprised of data from one academy limits its application. To some degree, the relatively large sample size and data fidelity negate this, but maturation and load monitoring strategies vary between organisations (as illustrated in chapter 4). Additionally, including competitive match and injury data, recorded in a manner sensitive to overuse type injuries would help complete the picture outlined in this study. It is therefore, proposed that the large majority of EPPP academies already routinely possess data resembling that presented here and consequently could use the premise of this research design to explore trends within their own talent development environments to facilitate application of these findings. This combined with competitive match and injury data could drive powerful internal action to remedy any similar observations and promote more positive experiences for young players.

7.4.2 Practical Applications

This chapter employed routine methods adopted by EPPP clubs to monitor training load and NM performance to facilitate practical application. Findings illustrate that less mature individuals consistently perceive training to be substantially more intense than more biologically advanced peers. Short-term this should at least be a concern for practitioners involved with training prescription. However, over extended periods this has the potential to undermine the whole developmental pathway, as the assumption that players of a similar chronological age are experiencing similar load-responses is precarious. Failure to act, by adopting more maturity sensitive ways of working for example, will result in a 'survival of the fittest' environment, rather than the systematic, considered, and individualised approach to optimal loading proposed in policy documents and literature. It is this exact scenario that injury incidence, non-functional overreaching and burnout research has been condemning for several years and without adapting our practice will continue to condemn for years to come. To do this, we should monitor and utilise maturity status opposed to maturation tempo to inform training prescription and reduce the potential void in accumulated load over the course of the development cycle.

Chapter 8

Maturity-related changes in neuromuscular movement profile, perceived exertion, and the impact of biological classification of training

Chapter 8: Maturity-related changes in neuromuscular movement profile, perceived exertion, and the impact of biological classification of training

8.1. Introduction

Chapters 6 and 7 indicated that maturity status can influence both the acute and chronic responses to training loads respectively. The Elite Player Performance Plan (EPPP) is designed that players of chronological age compete alongside each other (with individual exceptions), until the Professional Development Phase (PDP) where multiple age-groups can compete together (U17-U23) (Premier League, 2011). Although this approach is logistically preferable due to its alignment with the school system and behavioral and cognitive development trajectories (Groslambert & Mahon, 2006; Malina et al., 2004), adolescent injury incidence data (Materne et al., 2020; Read, Oliver, et al., 2018; Rommers et al., 2020) would indicate this is a maladaptive approach for the physical and psychological development of players. Although positional differences exist, generally players within the same youth training sessions complete relatively similar external loads (i.e., distance covered, sprint distance, accelerations and decelerations) as a result of developmental practices employed by coaches (Maughan et al., 2021; Riboli et al., 2021; Wrigley et al., 2012). Although external training loads may be similar, chapter 6 revealed that dose-responses vary between players of different biological maturation, which over the course of a season may manifest into a large training load discrepancy between players of varied maturation (chapter 7).

All injuries are multifactorial (Bittencourt et al., 2016), but the inconsistent load-response pathway across players of a similar chronological age may be a significant contributory factor to increased injury incidence during this stage of development (Kalkhoven et al., 2021). As mentioned previously (chapter 6), the period surrounding peak height velocity (PHV) exposes potentially ‘fragile’ individuals to systematic, age-related increases in training loads (Premier League, 2011; van der Sluis et al., 2015c). The individuals response to load is influenced by several factors such as tissue morphology, cross-sectional area, density and stiffness properties (Kalkhoven et al., 2021) resulting in highly varied individual dose-responses in pubertal populations. Furthermore, the frequency and intensity of EPPP schedules often result in minimal recovery time between training sessions (i.e., <72 hours) with adolescent training loads often superimposed on top of academic and recreational activities (Phibbs et al., 2018c). Reduced recovery time and additional ‘stressors’ (i.e., exams, academic pressure) have been shown to contribute to injury incidence and may predispose athletes to amplified risk (Carling et al., 2016; Gustafsson et al., 2017; Nobari, Fani, et al., 2021). Additionally, in some academies (e.g., Category 2 and 3), often only internal training loads are measured (i.e., ratings of perceived exertion) (chapter 4) which can have poor agreement between coach and player rated intensity, (Macpherson et al., 2019) and may consequently complicate understanding of dose-responses. Combined, these issues make ‘managing’ adolescent workloads complex in comparison to elite adult environments, where often training prescription is wholly controlled by experienced support staff utilising a combination of internal and external markers of training intensity (West et al., 2020), with players of a greater anatomical, biological and physiological stability.

Small sided games (SSGs) are commonly used within academy settings to simulate competitive situations and develop physical and game-related qualities (Hill-Haas et al., 2009). SSGs are considered to be an efficient method to combine technical proficiency, tactical and spatial awareness, speed, agility whilst offering a conditioning stimulus (Riboli et al., 2020), and are therefore used across all ages for various performance related outcomes across football. The composition of the SSG can be altered by manipulating the pitch-size, number of players per team, duration of game, technical rules and goalkeeper presence to suit the aims of the session (Riboli et al., 2020). Therefore, coaches can up- or down-regulate movement profiles to suit the outcome of the session and the physiological consequence desired in the micro cycle (i.e., larger pitch-size increases distance covered and high-speed running). FA Guidelines (Football Association, 2012) stipulate recommended pitch sizes for academy fixtures, with 11-a-side area per player (m^2) ranging from 187 (U13-14) to 292 m^2 (>U16) across the Youth Development Phase (YDP). Naturally, SSGs utilise a much tighter area per player, with studies ranging from 52 to 128 m^2 (Fenner et al., 2016; Guard et al., 2021; Riboli et al., 2020), which significantly influences both internal and external markers of load. Typically, larger area sizes are associated with higher physiological and perceptual responses and a concomitant increase in accelerative and high magnitude decelerative loads, but reduce high velocity running exposure due to boundary constraints (Guard et al., 2021; Rampinini et al., 2007; Riboli et al., 2020). As a result, it is common for SSGs to be performed using multiple bouts (e.g., 4-6) of shorter durations (e.g., 4-5 minutes) with regular recovery (i.e., 2-3 minutes) to facilitate the maintenance of the required intensity (Fenner et al., 2016; Guard et al., 2021; Rampinini et al., 2007; Riboli et al., 2020). Therefore, standardizing the duration, dimensions, rules and number of players offer practitioners a valid and useful tool to reduce variation in external loads to facilitate quantification of acute changes in neuromuscular performance (Rowell et al., 2018).

The dimension, area per player and rules of the SSG may influence the exposure to external movement profiles, but it still permits variations in internal response. Transient temporal changes in soft and hard tissue during maturation, stimulated by hormonal and anthropometrical development combined with exposure to mechanical load produce an individual stress-response matrix for each athlete (Malina et al., 2004; Radnor et al., 2018; Waugh et al., 2012). Tendon mechanical load-adaptation profiles respond to changes in loads, which is also influenced by maturity related changes in body mass and force production capabilities (i.e., muscle mass and motor unit recruitment) (Waugh et al., 2012). Maturational adaptations such as fibre type composition, pennation angle, tendon size and stiffness and co-contraction directly influence the kinetic ability of adolescent athletes (Radnor et al., 2018) which ultimately governs their ability to a) complete dynamic sporting activities successfully, and b) reduce injury risk. Although the sequential development of these musculo-tendinous properties is known, their timing and tempo are not and therefore individuals may be competing with peers more (or less) capable of utilising the stretch-shortening cycle (SSC) and producing/absorbing higher force (Radnor et al., 2018). Naturally, this has implications for talent identification, development, performance, and injury risk and should therefore be monitored and load exposure coordinated appropriately.

Quantifying the magnitude of impact on neuromuscular performance of a given training exposure would help practitioners appreciate the stress-response of their athletes. Whilst injury risk profiles are highly individualised, maturity specific trends exist in injury epidemiology and prevalence (Materne et al., 2020; Read, Oliver, et al., 2018), which are linked with neuromuscular developments throughout maturation (Pedley et al., 2021; Radnor et al., 2018; Tumkur Anil Kumar et al., 2021). Evidence suggests that the metabolic profile of pre-pubescent individuals could lead to reduced peripheral fatigue through limited depletion of phosphocreatine, accumulation of inorganic phosphates and hydrogen ions during exercise (Ratel, 2016). This, coupled with a relatively reduced force/power capacity and higher percentage of fatigue resistant slow-twitch fibers reduce the afferent inhibitory feedback to the central nervous system (CNS), which reduces central fatigue. Conversely, the central governor theory proposes that increased central fatigue acts as a protective safety mechanism which increases central fatigue to deliberately reduce force/power output (by restricting motor unit recruitment) and maintain homeostasis to limit the peripheral fatigue (Amann et al., 2011; Streckis et al., 2007). This is linked to musculotendinous stiffness in that compliant tissues may act also as a mechanical buffer to reduce damage and fatigue. Greater tendon compliance would result in greater shortening of the contractile muscle and therefore work at shorter relative fiber lengths, reducing peripheral fatigue but increasing central fatigue (Amann et al., 2011; Streckis et al., 2007). This notion is ambiguous and may be attributable to the increased sensitivity of the central nervous system (CNS) in children and why when matching exhaustion levels of less and more mature individuals, it is likely the less mature will experience greater central fatigue (Ratel, 2016). This has implications for the nature and magnitude of the stress-response between players of different biological maturity and requires careful physiological consideration.

It has become increasingly common to utilise standardised sub-maximal activity to detect performance change, variation in movement profile and/or recovery status in adult sport (Altmann et al., 2021; Leduc et al., 2020; Schneider et al., 2020). Utilising standardised running activity as part of a training session (i.e., start and end) using contemporary micro-electrical mechanical systems (MEMS) devices offers practitioners the ability to objectively assess changes in neuromuscular activity locomotor movement profiles of athletes (Altmann et al., 2021; Leduc et al., 2020). As this equipment is often expensive and logistically impractical for many academies, as well as being a sign of a well-rounded load management approach (Gabbett et al., 2017b), it is important to corroborate these data with more accessible self-reported perceptions of intensity. Sessional ratings of perceived exertion (sRPE) are a valid and common way to monitor the psycho-physiological perceptions of intensity within soccer (Fanchini et al., 2016; Wrigley et al., 2012), and widely used in academy settings (chapter 4) and this thesis previously (chapters 6 and 7). More recently applied differentiated-RPE (i.e., breathlessness, leg muscle and cognitive/technical) may help to distinguish between physiological and mechanical load adaptation pathways and provide insight into the individual response (Vanrenterghem et al., 2017). By collating such data, coaches and practitioners can begin to recognise how the composition of training sessions can influence the stress-response and ultimately performance and injury risk across maturation, whilst offering potential to detect central versus peripheral perceptions of fatigue.

One method that has been used to potentially coordinate the maturational differences we are already aware of is bio-banding. Bio-banding has been utilised across sport as a method to group individuals based on biological maturation rather than chronological age, primarily for talent identification and development purposes (Cumming, 2018; Cumming et al., 2017). Typically, players falling within established maturity thresholds (e.g., 88-96% of predicted adult height percentage (PAH%) are grouped together for training sessions and/or competition, irrespective of their chronological age. This approach reduces the biological inequality between players and allows individuals that are either pre-, mid- or post-PHV to compete against each other, reducing the physical advantage of more mature individuals (Cumming et al., 2017). Traditionally, this strategy has been used to allow players (particularly less mature) to demonstrate a more holistic array of technical and tactical capabilities by removing physical emphasis, however it also offers an enhanced psycho-social challenge for players (Cumming, Brown, et al., 2018). Naturally, reducing the physical diversity within sessions should consequently smooth the magnitude of inter-individual differences due to players possessing similar physical and physiological make up. Therefore, supplementing the chronological programme with bio-banded activities, may offer practitioners a practical method to better control load exposure and ultimately mechanical load related injury risk. As a result, this study has two primary outcomes, a) to explore the within-session impact of maturity status on neuromuscular performance and psycho-physiological response; and b) to observe the effect of standardised chronological and bio-banded training sessions on neuromuscular performance and psycho-physiological perceptions of intensity. It is hypothesized that biologically categorising training reduces variations in response and perception of intensity which may allow coaches to use this as a method of load management.

8.2. Methods

8.2.1. Participants

Fifty-five male soccer players (mean ± SD; age 13.8 ± 1.4 years; stature 164.3 ± 11.5 cm; body mass 52.7 ± 10.3 kg; PAH% 91.3 ± 5.3) were recruited from the U12-U16 age-groups of a single academy (Category 3). Percentage of predicted adult height (PAH%) (Khamis & Roche, 1994) was used to determine maturity status of all players (see equation 2.5), using self-reported parent stature corrected for over-estimation (Epstein et al., 1995). Participants were subsequently categorised as either pre-PHV (<88%; *n* = 20), circa-PHV (88-93%; *n* = 19) or post-PHV (>93%; *n* =16). Participants were eligible to take part if they were registered with the academy, free from injury and available to take part in full training. Participants typically completed three training sessions (90 mins) and one competitive match each week. Due to the difference in movement profiles, goalkeepers were excluded from the analysis, but were permitted to participate in the sessions alongside outfield players. All participants provided written consent with parents providing written assent following ethical approval from the University of Gloucestershire ethics panel in accordance with the Declaration of Helsinki.

Table 8.1. Mean ± SD anthropometrical and predicted adult height data for U12-U16 age groups

Characteristic	U12 (n = 14)	U13 (n = 14)	U14 (n = 13)	U15 (n = 7)	U16 (n = 7)
Age (years)	12.1 ± 0.3	13.2 ± 0.2	14.0 ± 0.3	15.2 ± 0.3	16.3 ± 0.1
Stature (cm)	153.6 ± 6.8	157.7 ± 6.2	169.2 ± 7.6	175.1 ± 6.5	177.9 ± 8.1
Body Mass (kg)	45.6 ± 7.2	45.6 ± 5.1	54.1 ± 7.4	61.7 ± 5.6	67.7 ± 7.6
Sitting Height (cm)	77.1 ± 3.3	78.8 ± 2.9	84.3 ± 4.1	88.9 ± 3.0	100.7 ± 18.5
PAH (%)	85.6 ± 19.9	88.1 ± 1.9	93.0 ± 2.4	97.2 ± 0.8	99.2 ± 1.2

8.2.2. Procedures

Data for each group was collected over a 6-week (first summer half term [April to May]) period during normal training sessions for the academy, separated by 7-days (i.e., once weekly) to reduce the impact on the coaching schedule. Following an initial familiarisation session to introduce equipment, test timing schedules and pitch-dimensions, three consecutive weeks of chronologically derived SSGs were followed by three consecutive weeks of bio-banded SSGs. All data were collected at the same time of day (evening) at the same training venue using natural grass pitches in weather condition between 13 and 21 °C. Figure 8.1 illustrates the format for all sessions (once per week for six-weeks), with the composition of the SSGs (i.e., chronological, or bio-banded) being the only variation.

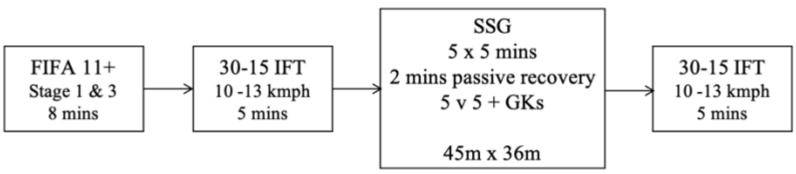

Figure 8.1. Schematic example of the weekly session structure

At the start of each session all players participated in a standardised incremental warm up, the FIFA11+ (Stage 1 and 3) (Bizzini & Dvorak, 2015). Players were familiar with this as part of their normal warm-up routine, which was standardised to facilitate accurate observation of the SSG intervention. Following this, players performed a standardised sub-maximal run using the audio controlled 30-15^{IFT}, with starting velocity set at 10 km·h^{-1} (Buchheit, 2008). Each 30-second shuttle across the 40 m area was separated by 15 second passive recovery with the velocity increasing by 0.5 km·h^{-1} each shuttle up to and including 12.5 km·h^{-1}. It is acknowledged that from a relative intensity perspective, these speeds are different for U12 and U16 players, however 12.5 km·h^{-1} represents 79-89% maximal aerobic speed (MAS) in these age-groups respectively (Mendez-Villanueva et al., 2012), which results in all players performing sufficiently sub-maximally and at a similar intensity even at the fastest speed required. Participants were instructed to run at a consistent pace throughout and to keep in time with the audio signal. Players then competed in five bouts of 5-minute 6v6 (including GK) SSG on a playing area 45 x 36 m (135m^2 per player), each bout separated by 2-minutes passive recovery. It is acknowledged that the area per player changes for competitive matches between U12 (187m^2) and U16 (292m^2) and that this study deliberately confined play to a tighter relative space (Football Association, 2012). These dimensions align with previous research utilising SSG type-activity (Fenner et al., 2016; Guard et al., 2021; Riboli et al., 2020, 2021) and it was deemed important to fix the area size to investigate the maturity-specific research question, rather than be confined by chronologically informed pitch dimensions from The FA. SSGs were supervised by age-group coaches who were informed they could verbally coach and encourage throughout. Corners and throw-ins were replaced by short passes by the nearest player and a multi-ball system was employed to quickly replace balls and keep intensity high. Where there were more than 6 players per team, these players were included as 'bounce' players on the periphery of the playing area for both chronological and bio-banded SSGs, with rolling subs utilised throughout to keep non-playing time minimal. Every attempt to keep bounce players to a minimum was made, but in some cases, there were varying numbers of bounce players (between 1-5) which may have accordingly influenced the loads experienced by players within that SSG (i.e., more bounce players result in slightly less playing time per player). Chronological (week 1-3) and bio-banded (week 4-6) teams were selected by coaches using data provided by the research team where needed (i.e., PAH%) to ensure that an even distribution of playing positions and quality across the 6-a-side teams. The U15 and U16 teams routinely trained together due to the squads carrying lower numbers of players, therefore this was maintained for the SSGs. Following the SSGs, same sub-maximal running protocol was repeated to measure acute changes in neuromuscular movement patterns.

To examine changes in neuromuscular movement profiles a foot-mounted inertial measurement unit (IMU) housed within custom silicone straps was used (PlayerMaker™, Tel Aviv, Israel). The device, located on the lateral aspect of the calcanei, includes 1000 Hz IMU microprocessor and comprises of a 3-axis 16 g accelerometer and 3-axis gyroscope (MPU-9150, InvenSense, California, USA) (Waldron et al., 2020). The PlayerMaker™ system calculates whole-body velocity-based metrics which permits detection of the orientation and translation of the participants limbs during gait cycles and through algorithms can detect heel strike, toe-off, zero-velocity and non-gait patterns (e.g., ball contact). This is then computed through a Kalman filter to provide locomotor specific metrics. Previously, locomotion data has been limited to laboratory based research through the use of 3-D movement analysis or force plate assessments but the contemporary and sophisticated IMU with the PlayerMaker™ device has facilitated much needed applied insights to locomotor movement (Verheul et al., 2020). As a result, mean ground contact time, flight time, stride length and cadence were calculated for each component of the session (i.e., pre-session sub-maximal 30-15) and interpreted to examine adaptations in locomotion owing to neuromuscular responses. Data is subsequently synchronised to the manufactures cloud-based software system and exported to Excel (Microsoft, Redmond, USA) for analysis (Marris et al., 2021; Waldron et al., 2020). Reactive Strength Index (RSI) was calculated using equation 3.2 from data derived from PlayerMaker™ units during the sub-maximal 30-15 IFT. Additionally, absolute, and relative leg stiffness were then measured from contact times and flight times during the sub-maximal 30-15 IFT (pre and post). Absolute leg stiffness ($kN·m^{-1}$) was calculated using equation 3.3 where K_{leg} refers to leg stiffness, M is total body mass, Tc refers to ground contact time and Tf is equal to flight time. To account for the influence of mass on leg stiffness and leg length on mechanical properties of locomotion between participants, absolute values of leg stiffness were divided by body mass and leg length to provide a dimensionless value of relative leg stiffness (De Ste Croix et al., 2017b).

Equation 3.2

$$RSI = \text{jump height (m)} / \text{ground contact time (s)}$$

Equation 3.3

$$K_{leg} = [M*\pi (T_f+T_c)] / T_{c2} [T_f+T_c/\pi) - (T_c/4)]$$

To ascertain internal load, psycho-physiological perceptions of intensity were measured using sessional rating of perceived exertion (sRPE) alongside differential rating of perceived exertion (dRPE) for breathlessness (RPE-B), leg muscle exertion (RPE-L) and cognitive/technical (RPE-T) demands, as highlighted in chapter 3. Players individually provided their rating in arbitrary units (Au) using the centiMax scale (CR100®; see figure 2.4) (E. Borg & Borg, 2002) with verbal anchors to provide confidential responses free from conformation bias within 15-minutes post-session (McLaren et al., 2017b; M. Wright et al., 2020).

8.2.3 Data Analysis

Baseline data was visually inspected through Q-Q plots of the raw data. All data were approximately normal except for flight time which showed a slight deviation at each tail. To analyse the impact of maturation (model 1) and then chronological age or biologically categorised matches (model 2) mixed linear modelling (SPSS v25 IBM Corp) was used to examine differences between fixed effects (model 1: maturity status; model 2: categorisation), with player identity included as a random effect (intercept; variance components) to account for repeated observations within players. Raw change scores (i.e., post session RSI – pre session RSI) of each variable were computed and used the dependant variable, with mean centred baseline pre-session values used as a covariate to account for individual difference and regression to the mean. Secondly, to determine the differences in psycho-physiological perceptions (i.e., sRPE) of intensity between maturity groups and categorised SSGs a between-groups ANOVA was conducted. Effects were deemed to be statistically significant at a Bonferroni adjusted alpha level of $P < 0.05$ with data presented as means (± SD) with 95% confidence intervals (CI) (Hopkins et al., 2009), alongside Cohens d effect sizes (i.e., psycho-physiological perceptions) using standard published thresholds (Cohen, 1992).

8.3. Results

Participant anthropometric characteristics related to estimation of maturity status are provided in Table 8.1. Sub-group analysis of the chronologically categorised SSGs demonstrates that there are moderate to large increases in absolute stiffness across all maturity groups during the session (Table 8.2). Additionally, the pre-PHV and Circa-PHV groups experience a small reduction in stride length with Circa-PHV having a simultaneous small reduction in cadence. Although not statistically significant, there are between-group differences of note. For example, both the pre-PHV and Circa-PHV reduce their stride length post session by ~4.3cm whilst the post-PHV group increase theirs by 0.69cm, indicating a between-group difference of >5cm. A similar outcome is observed between Circa-PHV cadence reduction (-3.93 s/m) and post-PHV cadence increase (1.53 s/m), resulting in a between-group difference of 5.4 s/m (Table 8.2). Additionally, the post-session increase in absolute stiffness for post-PHV (12.16 kN·m^{-1}) is approximately a third of the pre- (18.6 kN·m^{-1}) and circa-PHV groups (18.6 kN·m^{-1}), with relative stiffness reducing in pre-PHV (-1.07 kN·m^{-1}) but increasing post-PHV (0.83 kN·m^{-1}).

Table 8.2. Pre-post differences (95% confidence interval) in neuromuscular markers for each maturity group with significance (P) and effect size (d)

Variable	Pre- PHV			Circa-PHV			Post-PHV		
	Pre-Post Diff (95% CI)	*P-value*	Cohens *d*	Pre-Post Diff (95% CI)	*P-value*	Cohens *d*	Pre-Post Diff (95% CI)	*P-value*	Cohens *d*
RSI	−0.029 (−0.18 to 0.12)	0.99	−0.05	−0.087 (−0.29 to 0.11)	0.99	−0.12	−0.06 (−0.19 to 0.07)	0.99	−0.13
Contact Time (s)	0.028 (−0.03 to 0.09)	0.99	0.15	0.001 (−0.07 to 0.07)	0.99	0.01	0.01 (−0.04 to 0.06)	0.99	0.06
Flight Time (s)	−0.02 (−0.05 to 0.01)	0.76	−0.19	0.001 (−0.03 to 0.03)	0.99	0.01	−0.02 (−0.04 to 0.01)	0.58	−0.21^{S}
Absolute Stiffness (K_{leg})	18.69 (12.8 to 24.5)	<0.001	1.01^{L}	18.65 (11.14 to 26.2)	<0.001	0.78^{M}	12.16 (6.72 to 17.62)	<0.001	0.71^{M}
Relative Stiffness (R_{leg})	-1.07 (-6.87 to 4.74)	0.99	-0.06	0.02 (-7.44 to 7.48)	0.99	0.001	0.83 (-4.57 to 6.25)	0.99	0.05
Stride Length (cm)	-4.32 (-8.12 to -0.51)	0.01	-0.31^{S}	-4.31 (-8.66 to 0.05)	0.055	-0.27^{S}	0.69 (-3.88 to 2.50)	0.99	-0.06
Cadence (s/m)	2.63 (-1.32 to 6.59)	0.72	0.18	-3.93 (-7.29 to 1.14)	0.40	-0.20^{S}	1.53 (-1.79 to 4.85)	0.99	0.12

^{S}, small effect size; ^{M}, moderate effect size, ^{L}, large effect size

Table 8.3 illustrates noteworthy (small to moderate) differences between chronologically and bio-banded SSGs for several neuromuscular variables, including RSI, contact time, absolute stiffness, stride length and cadence. In general (except for cadence and relative stiffness) bio-banded categorization reduced the magnitude of within-session change in neuromuscular performance. Although effect sizes illustrate small to large differences in several markers of performance, only absolute stiffness, stride length and cadence produced statistically significant differences (P = <0.05) (Table 8.3). Players almost unanimously perceived bio-banded training sessions to be less intense across both sRPE and all dRPE constructs, but only RPE-T (post-PHV) showed a significant statistical difference (Table 8.4), with all responses being categorised as 'Moderate' or 'Heavy' on the centiMAX CR100 scale. There were consistently small to moderate reductions in sRPE, RPE-B, RPE-L and RPE-T for the pre-PHV and post-PHV with the circa-PHV group reporting trivial differences or a small increase in RPE-L.

Table 8.3. Within participant pre-post change values (Mean ± SD) for chronological and bio-banded training sessions with mean difference presented with 95% confidence intervals and effect size (*d*) for neuromuscular markers

Variable	Chronological SSG	Bio-banded SSG	Mean Difference *(95% CI)*	*P*-value	Cohens *d*
RSI	−0.54 ± 0.30	−0.43 ± 0.23	−0.11 *(−0.10 to 0.79)*	0.818	0.39[S]
Contact Time (s)	0.17 ± 0.11	−0.02 ± 0.33	*0.02* *(−0.01 to 0.05)*	0.189	0.88[L]
Flight Time (s)	−0.00 ± 0.08	−0.00 ± 0.05	*−0.00* *(−0.02 to −0.02)*	0.677	0.01
Absolute Stiffness (K_{leg})	14.41 ± 19.72	−1.66 ± 4.86	*16.07* *(10.94 to 21.21)*	0.000*	1.01[L]
Relative Stiffness (R_{leg})	−0.26 ± 21.4	−2.29 ± 7.46	2.03 (−3.65 to 7.71)	0.481	0.11
Stride Length (cm)	−2.69 ± 7.97	1.96 ± 14.57	−4.66 (−7.93 to −1.39)	0.005*	0.43[M]
Cadence (s/m)	0.69 ± 8.41	−2.84 ± 7.02	3.54 (1.03 to 6.05)	0.006*	0.44[M]

[S], small effect size; [M], moderate effect size, [L], large effect size

Table 8.4. Ratings of perceived exertion (Au) for chronological and bio-banded SSG sessions with mean difference and 95% confidence intervals (95% CI) and effect size (*d*)

Variable	Maturity Group	Chronological SSG (Mean ± SD)	Bio-banded SSG (Mean ± SD)	Mean Difference [AU] *(95% CI)*	*P*-value	Cohens *d*
sRPE	Pre-PHV	47.1 ± 12.3	40.5 ± 10.3	6.6 *(−0.7 to 13.6)*	0.139	0.56[M]
	Circa-PHV	44.1 ± 16.1	40.7 ± 10.5	3.4 *(−5.3 to 11.9)*	0.993	0.23[S]
	Post-PHV	50.9 ± 12.2	46.9 ± 11.2	3.95 *(−3.4 to 11.3)*	0.863	0.33[S]
RPE-B	Pre-PHV	43.5 ± 13.7	37.5 ± 12.5	5.9 *(−1.5 to 13.4)*	0.292	0.45[S]
	Circa-PHV	37.5 ± 15	37.6 ± 14.2	−0.1 *(−9.1 to 8.9)*	0.999	0.01
	Post-PHV	46.1 ± 11.1	43.1 ± 11.6	2.84 *(−4.7 to 10.4)*	0.994	0.26[S]
RPE-L	Pre-PHV	45.4 ± 15.4	38.3 ± 11.7	7.1 *(−0.2 to 14.2)*	0.078	0.51[M]
	Circa-PHV	39.8 ± 10.9	43.1 ± 10.9	−3.2 *(−11.9 to 5.44)*	0.993	0.30[S]
	Post-PHV	47.6 ± 10.1	44.4 ± 11.2	3.1 *(−4.2 to 10.6)*	0.975	0.31[S]
RPE-T	Pre-PHV	39.3 ± 11.9	35.3 ± 14.5	4.1 *(−3.3 to 11.3)*	0.826	0.31[S]
	Circa-PHV	37.6 ± 12.5	36.7 ± 14.8	0.9 *(−7.8 to 9.7)*	0.999	0.07
	Post-PHV	43.8 ± 11.5	35.2 ± 13.4	8.6 *(1.14 to 16.1)*	0.016*	0.71[M]

SD, standard deviation; 90% CI, 90% confidence intervals; PHV, peak height velocity; sRPE, sessional rating of perceived exertion; RPE-B, breathlessness; RPE-L, leg muscle exertion; RPE-T, technical/cognitive exertion

*Denotes significance $p < 0.05$; [S], small effect size; [M], moderate effect size

8.4. Discussion

This study intended to explore the within-session impact of maturity status on neuromuscular performance and psycho-physiological response, whilst observing the effect of standardizing both chronological and bio-banded training sessions. It was hypothesized that the introduction of biologically categorised training sessions reduced the neuromuscular and psycho-physical impact of sessions and ultimately the stress-response. Findings indicate that to some extent this notion is true, and that the introduction of bio-banded training sessions does minimize the decrement in neuromuscular and locomotor markers and ratings of perceived intensity for players across the maturation spectrum.

Traditionally, academy training is divided into chronological age-groups comprising of players from various stages of maturation. Findings here (Table 8.2) indicate that despite being exposed to the same training session, players may adopt differing stress-response according to their maturity status. For example, all groups experienced a moderate (pre-PHV) or large (mid and post-PHV) within-session increase in absolute stiffness. Yet the post-PHV group saw an increase only two-thirds that of pre- and circa-PHV. The elevated but comparatively smaller pre-post session change in absolute stiffness in post-PHV players is likely explained by tendon stiffness maturity, as tendons reach adult values around the PHV (Radnor et al., 2018; Tumkur Anil Kumar et al., 2021) suggesting that post-PHV players may tolerate mechanical loads better than less mature counterparts. These moderate (pre-PHV) to large (circa-PHV) changes in post-session stiffness values support the notion that less mature individuals have limited 'energy-saving' mechanisms and therefore experience greater reductions in performance which may heighten injury risk (Tumkur Anil Kumar et al., 2021). Additionally, less mature individuals may not have the ability to create optimal tendon stiffness via appropriate muscle activation or motor unit recruitment, causing the muscle to yield under force (Radnor et al., 2018). Combined, muscle yielding and elevated levels of lower limb stiffness are speculated to be associated with an higher risk of overuse, bone-related injuries which aligns with injury epidemiology for adolescent athletes (Butler et al., 2003; Read, Oliver, et al., 2018). Mechanistically, it is proposed that increased stiffness leads to amplified loading rates and peak forces and subsequently augmented shock to the lower extremity, which ultimately increases the mechanical stress on bony structures and musculotendinous unit, initiating a causal pathway for injury (Kalkhoven et al., 2021). This mechanistic theory links to the work of Ratel (2016) discussed in section 8.1 whereby less mature individuals may experience more central fatigue which compromises the neuromuscular system to a greater extent than peripheral fatigue. Although tentative findings, this may offer potential insight into the higher relative prevalence of musculotendinous and apophyseal injuries observed during maturation in academy soccer, particularly in the U12-U14 age-groups (Read, Oliver, et al., 2018). The changes in stiffness outlined above, may also contribute to the post-session stride length reduction for pre- and circa-PHV players (~4.3 cm) and increased (~0.7 cm) for post-PHV players. Higher levels of stiffness are associated with a more efficient stretch-reflex, which can lead to shorter contact times (although not observed in the present study) and better force production capabilities (Radnor et al., 2018). This may explain why post-PHV players slightly increased stride length, whilst pre- and circa-PHV reduced theirs, likely owing to a greater post-session decrement in force production capacity. The trivial changes in contact and flight times for all groups limit this notion to speculation, with further exploration required to confidently support claims.

Biologically categorising training sessions produced significant differences in pre-post response for absolute stiffness, stride length and cadence, whilst offering small to large changes in RSI and contact time (Table 8.3). The only marker to offer greater change (trivial) in the biologically categorised condition was relative stiffness, which considers both limb length and body mass within the calculation, thus catering for maturation to some extent (De Ste Croix et al., 2017b). In the context of this chapter, and from a load management point of view, these relatively smaller pre-post changes offer promising early indications that biologically categorising training may help to stabilise the negative stress-response for players across maturity groups. Of all markers, the impact on absolute stiffness was most notable, which may have indirectly (positively) impacted contact time, RSI and stride length to stimulate less 'shock' to the athletes and therefore ultimately reducing injury risk. Not only do these changes indicate that acute changes in neuromuscular performance are stabilised, but they also surmise that reduced pre-post change performance requires less recovery time ahead of the next session (Kellmann et al., 2018). Theoretically, these differences could be attributable to the changes in technical demands during bio-banded activity (Abbott et al., 2019; Lüdin et al., 2021), whereby players were more evenly matched physically and therefore able to express themselves technically without the large biological diversity apparent in chronological SSGs. Evidence indicates that bio-banded activity involves less long range passing (particularly for pre- and circa-PHV) and dribbling, and more shots on goal with limited differences in external load profiles between chronological and bio-banded games (Abbott et al., 2019; Lüdin et al., 2021). This may result in less emphasis on physical attributes and offer a reduced dose-response – which may be advantageous in some, but not all sessions as exposure to match-specific loads are important for injury prevention. Although these findings are novel, and therefore conscious of overstating findings, but this could potentially reduce the likelihood of accumulative fatigue, which is associated with the high prevalence of gradual onset overuse type injury within the adolescent soccer population (C. Williams et al., 2017). Thus, the inclusion of biologically categorised training sessions may offer coaches a useful tool to help moderate the stress-response of players in varying stages of maturation simultaneously.

RPE was generally considered to be less intense when biologically categorised training sessions were implemented (Table 8.4), which opposes previous work in this area (Abbott et al., 2019; Lüdin et al., 2021). Pre- and post-PHV players rated all components of differential RPE less intense (small or moderate) when bio-banded SSGs were used, versus chronologically aged SSGs who reported less homogenic perceptions of intensity. Circa-PHV players showed a similar trend for sRPE and RPE-T, but rated RPE-L more intense (small) in bio-banded SSGs. These differences are likely influenced by the reduced biological diversity within these sessions resulting in a perceived lower relative intensity. For example, the pre-PHV group rated every RPE construct lower in bio-banded sessions, likely because this approach eases the emphasis on physical characteristics and offers opportunity for individuals to flourish technically and tactically (Abbott et al., 2019; Cumming, Brown, et al., 2018; Cumming et al., 2017; Lüdin et al., 2021). Similarly, the post-PHV group rated the bio-banded sessions relatively lower intensity than chronologically categorised sessions, but comparatively higher than both the pre- and circa-PHV groups for all constructs (Table 8.4). Therefore, although grouping the most physically mature players together reduces perceived intensity, players still consistently rate these sessions higher than pre- circa-PHV players. Again, from a load management perspective these data illustrate that using biologically categorised training sessions can reduce the perceived stress-response for players of all maturities and offer a mechanism by which coaches can modify training stimulus, which may be a useful addition into the training week to manage chronic training loads. Importantly, these self-reported markers of internal load concur with more objective data provided by the PlayerMaker™ IMUs, in that locomotor and neuromuscular responses align with perceptions of intensity. This is important based on the limited availability of these IMU devices to academy settings due to cost and resource implications (chapter 4) and thus offer insightful additions to the research which needs to be explored further using similar contemporary methods.

8.4.1. Limitations

Although the findings from this study identify a possible mechanism to control load-adaptations in adolescent soccer, these conclusions need to be considered in-line with its limitations. Firstly, all players were from the same soccer academy which limit the generalisation of these findings to the wider soccer network, particularly those with a differing socio-economic and ethnic diversity. Additionally, using this single academy reduced the initial sample size which due to various reasons (i.e., illness, injury, non-attendance, covid-19 isolation) meant there were less total training sessions observed than initially intended. For example, the intention was to collate data from a total of six sessions per player (approx. 330 total sessions) but few players attended all six sessions, which combined with the data cleaning process to maintain fidelity (i.e., removal of outliers and spurious data), reduced the number of sessions observed by approximately 50% (165 total session observations). The research design (multiple repetitions of each condition) was intended to accommodate some missed sessions; however, these were slightly more prevalent than envisaged which may have limited the outcomes of the study. Unfortunately, this is one of the primary limitations to applied adolescent research and therefore these conclusions should be considered exploratory findings, with follow-up work on this line required.

Practically, it was sometimes difficult to maintain the 135 m^2 area per player specified in the methodology. Due to the number of players at each session, coaching needs, and logistics this did vary slightly on occasions, although this was minimal and not deemed to have significant impact on the outcomes explained. For example, instances when limited goalkeepers were available, or an uneven number of players per group, coaches slightly adapted the pitch-dimensions to accommodate all players without impacting area per player significantly. Finally, it is acknowledged that the use of natural turf instead of artificial pitches may have influenced ground contact quality in variable weather conditions and therefore neuromuscular metrics discussed in the results may have been influenced. Whilst increasing ecological validity, we accept that changes in ground condition may impact reliability of neuromuscular values and impact self-reported perceptions of intensity. However, it was not logistically possible to collect such data on artificial turf due to the training schedule of the club.

8.4.2. Practical Applications

Current chronologically categorised development pathways permit significant within-session biological diversity, which harvests complexity around the management of individual stress-responses. Based on the high relative prevalence of non-contact, growth-related injuries within this population, it is important that technical, medical and support staff adopt a proactive approach to load management for all players. Although tentative based on study limitations, this chapter illustrates the potential positive impact that biologically categorised training activity may have on load management for players in adolescent environments. Bio-banded sessions elicited a smaller pre-post decrement in neuromuscular performance, particularly on metrics associated with injury risk with similar reduced ratings of perceived exertion from the same bio-banded condition. Findings also identify that there were small to moderate differences in the way in which maturity groups responded to the sessions, which advocates a maturity-specific approach to load exposure. Based on this, practitioners should actively seek opportunities to integrate biologically classified training activity alongside chronologically categorised sessions within their training schedules. In doing so they may alleviate the consistent stress placed on less mature players as part of standard chronologically categorised sessions without compromising the development of those more mature and able to tolerate greater workloads. In doing so, coaches can up- or down-regulate bio-banded session composition and intensities as desired to help ease the turbulent period through maturation for talented young soccer players.

Chapter 9

General Discussion

Chapter 9: General Discussion

The overall purpose of this thesis was to investigate maturity-specific dose-responses to training loads in adolescent football players. Prior to this thesis, information in this area was sporadic and lacked consistency in approach and as a result available knowledge was tenuous. Furthermore, there was no recognised and cohesive approach to using maturation data to guide and inform training load prescription in adolescent football. Therefore, an important and novel aspect of this thesis was to utilise a consistent approach to monitoring training loads and offer practitioners some evidence from which to inform maturity-specific load prescription decisions for their academy players. The primary findings offer insight into the maturity-specific load-responses from acute and chronic workloads and illustrate that a 'one size fits all' approach to load exposure is inadequate when looking to effectively develop adolescent football players. Players of variable maturity status respond to loads in different ways which appears to be linked with neuromuscular changes that occur during the adolescent growth spurt, and that biologically categorising activities may offer a mechanism to mitigate the maturational variability in dose-responses. Therefore, practitioners can use this method to appropriately stimulate players of differing maturity status in the anticipation that this may more appropriately challenge players, whilst reducing injury risk and enhancing long-term outcomes.

This discussion chapter intends to synthesise the findings from the various experimental studies within this thesis in relation to the stated aims and objectives, whilst outlining how and where the aims have been achieved. Each aim and outcome will be discussed sequentially for clarity, with more holistic findings critically discussed in conjunction with current literature to highlight the addition this thesis makes to the existing body of research. Whilst interpreting findings, the major limitations of the work involved in this thesis will be explained to help outline the practical application of these findings, whether locally (i.e., study participants) or more generalised. It is anticipated that following this chapter, practitioners will be able to successfully integrate the findings of this doctorial work into their practice to enhance the athletic development environments for their youth athletes. For convenience, the thesis aims, and objectives are repeated below:

Thesis Aims

1. Establish the current practices for monitoring growth, maturation, and training load in academy football
2. Establish the dose-responses to soccer-specific activity between players of different stages of biological maturation
3. Provide maturity-specific guidelines around load management to optimise development and minimise injury risk

Research Objectives

1. Investigate the current growth, maturation and training load monitoring strategies employed in academy football
2. Measure and compare the acute psycho-physical and neuromuscular responses to a fixed soccer-specific activity profile across maturation
3. Quantify and compare the psycho-physical response and neuromuscular performance to 'typical' football activity across maturation over an academy season
4. Ascertain dose-response comparisons between chronological-age categorised activities to those of maturity-categorised (bio-banded) activities
5. Provide maturity-specific guidelines to advance training prescription for academy practitioners

9.1 General Discussion

9.1.1. Aim 1, objective 1

Firstly, it was deemed important to establish the current growth, maturation, and training load monitoring practices in academy soccer (Aim 1). In doing so, this would provide context to inform subsequent chapters, whereby the routinely applied methods to monitor growth, maturation and load in Academy environments were employed into subsequent studies to provide contemporary context of the real-world environment and facilitate better application of the research. Aim and objective 1 were primary outcomes of Chapter 4 where this cross-sectional study canvassed responses from ~40% of the academy pool during the early part of the 2017-18 season regarding growth, maturation, and load monitoring activity in their clubs. The relative ambiguous and non-prescriptive nature of EPPP guidance (Premier League, 2011) around maturation (i.e., 'anthropometric assessments') and load monitoring (i.e., 'monitoring physical exertion') compared to the more prescriptive facility and/or training hour stipulations in EPPP documentation, permits variable degrees of engagement between academies, hence this being the initial objective of the thesis.

Chapter 4 was the first study of its kind to specifically explore the current practices of academies towards monitoring growth, maturation, and load monitoring in adolescent soccer. Previous studies have been specifically focussed on load monitoring in adult populations (Akenhead & Nassis, 2016; Weston, 2018) identified limited congruency between methods of collating and disseminating data between clubs and exposed several communication-based limitations in applied practice. General findings from chapter 4 revealed similar conclusions, in that all academies are routinely monitoring training loads to some extent, with the primary purposes stated as injury prevention, load management, coach and player feedback and ultimately enhancing player development. Higher ranked academies (Category 1) used resource intensive GPS devices more than lower ranked academies, with RPE's being widely utilised across all academy classifications (Table 4.4). Whilst this suggests that academies have good intentions and have a load monitoring strategy in place, there were clear practical barriers that prevented the efficiency and efficacy of these systems being optimised. There was a clear gulf between academies of different categories, with lower ranked academies (Category 2 and 3) ranking staff and resource limitations for all types of monitoring as higher barriers, which negatively influenced the communication of the findings to key stakeholders (i.e., parents, players medical staff). In some cases, this is due to lack of specified responsibility, but in other cases this suggests a communication breakdown and therefore negates the purpose of load monitoring (Gabbett et al., 2017a). This was most evident as training load data was not reported to medical staff, despite often being involved in the decision making for the prevention of, or returning from injury, particularly in lower ranked academies with fewer staff. Therefore, it seems that academies are collating data but not systematically utilising it effectively to inform practice and enhance the player development pathway, questioning the value placed on this process. Anecdotally, it implies that academies collect this data because they believe they should (i.e., EPPP legislation) but lack either the infrastructure or conviction to fully integrate the data within their development decisions (i.e., training prescription, injury prevention). This communication breakdown supports findings outlined in previous surveys (Akenhead & Nassis, 2016; Weston, 2018), and indicates that there is a need to better disseminate data through multi-disciplinary internal feedback loops, which has shown to be an effective way to increase player availability (Ekstrand et al., 2019). Chapter 2 (section 2.1.2) outlined the prevalence of non-contact, load related injuries within adolescent soccer cohorts and potentially by adopting more effective feedback strategies, academies could enhance the impact of the collected data within a more proactive approach to load monitoring. This can then lead to reducing injury incidence, which is the primary reason clubs collate such data (see table 4.1 and 4.3), which will be discussed further when reviewing aims 2 and 3.

From a biological maturation perspective, academies primarily collected somatic maturity data to reduce injury risk, manage training loads and improve player development but were impeded by limited staff (number and competency) and financial resources (Table 4.1). From the outside, these responses would suggest that academies would routinely adopt biologically categorised training interventions to manage the prescription of training activity to help manage 'at-risk' players, yet biologically categorised training was also deemed a comparatively low purpose for collecting this data. Although a deeper exploration into these views is warranted, it is considered a perceived lack of knowledge and/or skillset (e.g., competency) related to growth and maturation which may inhibit the application of maturity-specific interventions such as bio-banding. Like training load data above, this outlines the importance of this thesis in illustrating the potentially positive impact biologically categorised training can have on the management of load and non-contact, growth-related injury risk within this population and the need for knowledge exchange from experts in this field. Further discussion of this is inked with aims 2 and 3 later in the discussion. Another finding from chapter 4, that significantly influenced the rest of the thesis was the clear split in the methods used to estimate maturation across academies, with either maturity offset or predicted adult height used almost exclusively (Table 4.2). Significant debate exists regarding the accuracy, reliability and usefulness of these somatic estimations of biological maturity within adolescent soccer (Fransen et al., 2018; Mills et al., 2017; Teunissen et al., 2020) and the error associated with them, which is important to consider when looking to adapt practice based on estimations. Although uniformity in approaches does not assure quality, it does facilitate consistency and therefore comparison between academies and allow the development of recognised guidance for academies (Aim 3). Currently the national Player Management Application (PMA) used by academies calculates both methods, however having clubs adopting a single method reduces complexity when developing guidance criteria and/or research studies and allows for comparison across national benchmarks (for talent identification and/or selection). An argument for and against a comparative model of athletic development exists, and is beyond the scope of this thesis, but a consistent approach would help to avoid the grey area surrounding magnitude of error based on methodological approaches used to determine maturity status.

Somatic estimates of biological maturation were a fundamental aspect of this thesis and the various analyses involved in experimental chapters. Based on the varying methodological approaches adopted in practice observed in chapter 4 it was deemed critical to the rigour of this thesis that comparative analysis between commonly applied methods of maturation estimation was conducted as a standalone chapter. Using data derived from chapter 6 and 7 and in conjunction with recommendations from contemporary research (Parr et al., 2020; Teunissen et al., 2020) a concordance and agreement analysis was performed (chapter 5). Elements of this thesis have used maturity status as a continuous variable (e.g., 88% PAH; chapter 6 and 7), whereas other components (chapter 8) grouped players based on a trichotomy of their current maturity status (i.e., pre-, mid-, or post-PHV), therefore it was important to assess concordance between methods using both continuous and grouped methods. It is acknowledged that these somatic measures of maturation estimation have methodological flaws and error in comparison with gold-standard skeletal measurements (Chumela et al., 1989; Mills et al., 2017). However, these approaches accurately represent routine methods employed by academy practitioners and as such offered ecological validity and greater practical transfer for the research outcomes, free from ethical constraints associated with radiative exposure. Due to the cross-sectional nature of the studies involved with this thesis, it was not possible to obtain a criterion reference (i.e., actual age of PHV) from the sample. Therefore, the Mirwald et al (2002) equation was employed as a reference due to this being more widely utilised in previous research studies than other equations (Fransen et al., 2018; Khamis & Roche, 1994; Moore et al., 2015). To enable comparison between measures of different constructs (i.e., MO and PAH%) all data was converted into biological age using growth reference charts (C. Wright, 2002), which emerged from this chapter as an excellent method to communicate maturation information practically to coaches and/or parents. This method converts estimations of biological maturity and clearly identifies the difference between chronological and biological age (for example chronologically a player may be 14.2 but biologically they may be 16.1 years). This appears to be much better received to those less informed in this area than a PAH% (i.e., 90%) or MO (i.e., +0.6 years) value. Based on all the MO equations being an iteration of each other, it was unsurprising these illustrated close agreement, with APHV falling within 0.3 years 95% of the time, with PAH% ~0.6 years higher (Figure 5.1). This initial finding has significant implications for practitioners who may be looking to implement biologically categorised training interventions as there may potentially be ~6 months difference based on the method employed, which may negate their impact. This becomes more important when looking to group players into biologically categorised groups. Previous studies have used conservative (±1 year) and less conservative (±0.5 year) thresholds to group players, but concordance between methods was fair to moderate for both thresholds (Table 5.3), except for when using an iteration of MO against each other (substantial agreement).

Therefore, practitioners are advised to adopt a consistent method to estimate maturation and avoid using multiple methods interchangeably for different purposes (i.e., reporting APHV and bio-banding), as facilitated by the PMA system if desired. The limitation of chapter 5 as mentioned is the lack of a criterion reference which makes it challenging to claim which method offers better accuracy, however two contemporary studies (Parr et al., 2020; Teunissen et al., 2020) elude that PAH% offers best predictions (96% v 61%) when tracking actual APHV. The broader range, reduced tendency to converge on the mean and preferred choice of previous EPPP bio-banded events (Cumming, Brown, et al., 2018; Cumming, Searle, et al., 2018) would indicate that if practitioners were to select between MO or PAH% methods, then PAH% methods likely offer more holistic value. However, it should also be noted that reference samples for all maturity estimation methods used predominantly middle-class, white Caucasian samples and therefore there are questions around the application of these methods to the more diverse ethnic population of academy soccer (Fransen et al., 2018). Thus, there is a need for a further work using longitudinal approaches to establish accurate and valid somatic maturation estimations in soccer populations. Considering this, practitioners are encouraged to measure relevant anthropometric characteristics quarterly to plot growth velocity curves (i.e., stature and body mass), which facilitates visual and objective trajectories of timing and tempo of individual change throughout maturation. This is an important process as evidence (Wik, Martínez-Silván, et al., 2020) has outlined a relationships between the tempo of maturation and injury risk, although this thesis identified tempo was of less importance than status (see chapter 7).

9.1.2. Aim 2, objective 2

Chapter 5 offered justification into a consistent and informed approach to somatic estimation that could be applied for analysis in latter chapters of this thesis and contribute to the development of maturity specific guidelines (Aim 3). Combined, chapter 4 and 5 achieved aim and outcome 1, illustrating current practices whilst outlining some of the issues experienced in monitoring of growth, maturation and training loads in academy soccer. These findings were considered within the design of chapter 6 which explored aim and outcome 2 and looked at the acute dose-responses of players across maturation. As mentioned in chapter 2, typical injury epidemiology within the adolescent population in question suggests a high prevalence of non-contact, growth, or overuse related injuries (Read, Oliver, et al., 2018). Mechanistically, these injuries often occur as a result of frequent, repetitive movements of the same nature with inadequate recovery time between bouts, often termed accumulated fatigue (C.

Williams et al., 2017), and are often associated more with early specialisation sports such as soccer (Materne et al., 2016; Read et al., 2016b). Before observing the long-term impact of repeated loads (chapter 7), it was important to establish maturity-specific dose-responses to a standardised load, to identify if a single bout of activity impacted the objective and subjective response.

Typically in academy settings players are categorised into groups by chronological age, which results in a large within-group biological diversity including players that may be 10-15% different in PAH% (Figueiredo et al., 2010; Hannon et al., 2020). Without active consideration, the assumption is that all players would respond to the given load of the session equally and therefore the same session is prescribed for all players within the group, without maturity-specific adaptation. Evidence suggests that significant neuromuscular changes occur during maturation that impact the individual response and ultimately performance of the stretch-shortening cycle and related force producing components (Radnor et al., 2018; Tumkur Anil Kumar et al., 2021), which may result in maturity-specific degrees of performance change. Additionally, due to physical but also psychological and behavioural changes, players perceptions of intensity may also change as a result of their increased body awareness (Brink, Nederhof, et al., 2010; Lloyd & Oliver, 2012). Therefore, the aim of chapter 6 was to quantify acute responses to a standardised activity profile and establish whether maturity status moderated this response, aligning with aim 2 and objective 2 of the thesis.

The research design employed an audio-controlled movement profile but omitted reactive soccer-specific actions and ball involvement (Barrett et al., 2013; Harley et al., 2010). Consequently, it offered a highly controlled mechanism to ensure that all players conducted a standardised external load free from extraneous variables such as positional demands and/or reactive involvements with or without the ball. Previous studies observing load-response in adolescent soccer have utilised regular training (M. Wright et al., 2020; Wrigley et al., 2012) or SSG match-play (Hauer et al., 2021; Köklü et al., 2011; Nunes et al., 2021; Rowell et al., 2018), which may have increased the variables that influence external loads and thus the standardised dose. Using PAH% as a continuous variable allowed visualisation of where true points of transition (i.e., significance) occurred across the full maturity spectrum, rather than trichotomising into arbitrary points of interest (e.g., pre-, mid- and post-PHV) (Montoya, 2019). This approach yielded significant interactions between neuromuscular change (pre vs. post Y-SAFT^{60}), which aligned with peak-height velocity for several neuromuscular components (i.e., absolute, and relative stiffness, RSI and PlayerLoad; Figure 6.2). It was clear that the onset of PHV (i.e., 86-88% PAH) coincided with significant interactions in neuromuscular performance, most likely as result of limited movement efficiency and increased deformation of the musculotendinous unit (MTU) experienced by less mature individuals (Radnor et al., 2018; Tumkur Anil Kumar et al., 2021), negatively impacting their neuromuscular performance post activity (Ratel, 2016; Read et al., 2016a). Contrary to previous research (De Ste Croix et al., 2019; Lehnert et al., 2018), the Y-SAFT^{60} actually stimulated small potentiation effects in RSI, whilst showing smaller changes in less mature individuals for RSI and absolute leg stiffness (i.e., reduced potentiation). Relative stiffness incorporates body mass and limb length within the equation, thus considering key components of maturation-based algorithms, therefore it is expected to offer an alternative picture to absolute values. This apparent potentiation is likely related to the Y-SAFT^{60} being shorter duration than competitive YDP matches to facilitate data collection within a single training session (including pre-post tests and half-time period) and therefore may have temporarily enhanced performance in more mature individuals whilst being an insufficient stimulus to generate significant reduction in these neuromuscular markers of performance for less mature individuals (Table 6.1). Reduced efficiency of the elastic storage potential and greater yielding of the MTU with inadequate recruitment of motor units at, or shortly before PHV may accentuate injury risk through increased relative biomechanical loads and reliance on absorption of shear stress through the knee (Lloyd & Oliver, 2012; Read et al., 2016a). This may link to the significant interaction with PlayerLoad during the PHV period (i.e., 87.9–96.1% PAH; Figure 6.2), which may then relate more broadly to contemporary theory around the relationship between mechanical load-adaptation and injury (Kalkhoven et al., 2021). The nature of the findings and the lack of injury data attached to this chapter reduce these conclusions to inferences and although more work in required to corroborate these findings, they present potential mechanistic associations.

Despite some clear interaction with neuromuscular markers of performance, psycho-physiological perceptions of intensity were less clearly impacted by maturity status, with RPE-T the only domain of differential-RPE moderated by PAH% (Figure 6.2). As predicted, perceptions of intensity (i.e., sRPE, RPE-B and RPE-L) decreased as PAH% increased, indicating that the Y-SAFT[60] offered a progressively lower relative intensity for more mature individuals, except for RPE-T. Although unclear, the mechanistic explanation for this is that potentially the relative physical shortcomings of less mature individuals explained above influences their perceptions of technical intensity. For example, changes in SSC performance also impact anaerobic performance such as speed and change of direction (Lloyd & Oliver, 2012), which may mean that less mature individual perceive these tasks (i.e., imposed by Y-SAFT[60]) more technically challenging, or potentially that their greater training age presents a relatively lower perceived intensity. However, there is debate around the ability of adolescent athletes to effectively distinguish the various pyscho-physiological mediators when using differential-RPE in soccer specific activity, with only a single study reporting moderate to large (r = .59–.69) associations (M. Wright et al., 2020). It is possible that the differential-RPE approach over complicated the subjective reporting due to their cognitive ability. This population are considered to have the cognitive ability to understand and accurately rate global perceptions of intensity (i.e., sRPE), however the relationship between RPE and the specific internal constructs (i.e. heart rate) is less pronounced at this age and somewhat influenced by the training mode (McLaren, 2017) which may confound differential-RPE sensitivity. This may also relate to developmental change in the pre-frontal brain cortex which occurs during early adolescence and has been thought to lead to significant cognitive control, which likely alters perceptions of intensity (Moura et al., 2017). Similar observations emerged from the psycho-physiological perceptions of intensity over a 40-week season in chapter 7, which suggests that further work around the validity and reliability of differential-RPE in adolescent players is required before this can be applied with high-confidence.

9.1.3. Aim 2, objective 3

Understanding acute maturity-specific responses to soccer activity is a useful process, however the chronic implications of dose-responses offer greater applied relevance for practitioners. Chapter 7 aimed to explore the maturity-specific impact of typical training patterns across an entire 40-week season, which contributed to thesis aim 2 and objective 3. Chapter 6 identified that players of different stages of maturation responded to loads in different ways, therefore it was predicted that this would be exacerbated over a prolonged period. Using methods employed by clubs (as identified in chapter 4), this study estimated maturation (i.e., PAH%) and measured neuromuscular performance (i.e., countermovement jump, stiffness and RSI) at three specified time points during the season and collated RPE scores from all YDP players for each training session. By repeating maturity estimations throughout the year, it was possible to analyse changes in tempo rather than just maturity status. Some evidence (Buchheit & Mendez-Villanueva, 2014; Radnor et al., 2018) suggests that the stage of development is less important that the rate of change in the individual and that it may be the tempo which is associated with disturbance to movement efficiency. Mixed modelling was used to assess the dose-responses of players at 5% intervals of maturation (e.g., 85% v 90% v

95%) as this represents typical thresholds for biologically categorised activity and is representative of typical differences within chronological age-groups (Figueiredo et al., 2010). This study incorporated data from almost 4000 individual training sessions and indicated that maturity status clearly influenced the perception of intensity of players, however maturity tempo was not an influencing factor. Maturity tempo has been linked with injury risk (Wik, Martínez-Silván, et al., 2020), but this evidence suggests that it is less informative than maturity status when looking to quantify training loads. Findings indicated that a 5% increase in PAH translated into a ~7 Au difference in sRPE per session, and ~14 Au difference for a 10% PAH difference. Therefore, less mature players could be rating the session between 7 and 14 Au more intense based on their maturity status, despite participating in the same session as more mature individuals. As a standalone session, this figure would not be concerning, however over the course of the season (average 108 sessions per player) this equates to a significant difference (~40%) in subjective workloads between players (Figure 7.2). This is turn may contribute to the maturity specific increase in injury trends discussed in chapter 2 and possibly non-functional overreaching and athletic burnout (A. Hill, 2013; C. Williams et al., 2017) and emphasises the importance of adapting training prescription in conjunction with the individual maturity status. These findings are novel and although only representative of a single academy, offer the clearest insight into the highly differentiated maturity-specific dose-response in adolescent athletes so far.

Chapter 7 also highlighted that maturity status impacted the neuromuscular response over the course of a season, in that performance generally improves with maturity status (Table 7.2). An increase of 5% PAH translates to a CMJ improvement of around 4.3cm with a similar trend in both RSI (0.1) and absolute stiffness (2.8 $kN \cdot m^{-1}$) qualities. The lack of interaction between maturity status and relative stiffness indicates the importance of converting absolute values to relative values and not using absolute values in solitude for effective interpretations. These changes in neuromuscular performance align with previous discussion from chapter 6 and primarily surround the natural development of the stretch-shortening cycle and musculotendinous characteristics as a result of maturation (Radnor et al., 2018; Tumkur Anil Kumar et al., 2021). Although these neuromuscular related findings support those previously reported there is a paucity of research that observes the rate of growth and its interaction with performance characteristics. Results here would indicate an element of novelty in that maturity tempo is less informative than maturity status when observing associations with both neuromuscular and self-reported psycho-physiological perceptions of intensity in adolescent players. Therefore, maturity-tempo data more be more may informative when observing injury risk and/or incidence (Monasterio et al., 2020; Rommers et al., 2020; Wik, Martínez-Silván, et al., 2020), and maturity status more appropriate when observing load-response patterns.

9.1.4. Aim 2, objective 4

Based on both acute (chapter 6) and chronic (chapter 7) studies indicating maturity-specific responses to training activity, the final experimental chapter of the thesis was aimed at offering a solution to the problem for practitioners (aim 3 and outcome 4 and 5). Chapter 8 explored the dose-responses between traditional chronologically versus biologically categorised training activities (outcome 4) in the hope of providing guidelines for practitioners (outcome 5). Typically, bio-banding has been used as a talent identification tool (Cumming, Brown, et al., 2018; Cumming et al., 2017), but findings from this thesis indicate that using biological classification for load management purposes might serve as a useful mechanism to alleviate large differences in dose-response between biologically diverse individuals. By separating players into their respective stages of maturational development using PAH%, practitioners may be able to control the prescription and thus exposure to load to mitigate risk for 'at risk' players, whilst allowing those at relatively lower risk to flourish. Therefore, to detect the impact biologically classifying training activity on dose-response, a standardised training activity was devised which included the FIFA 11+ Stage 1 and 3 before a sub-maximal 30-15 intermittent fitness test (IFT) either side of five small-sided games (SSGs) of five outfield players plus a goalkeeper on a standardised pitch (45 x 36 m) (Chapter 8). By standardising the warm-up and assessing neuromuscular characteristics in a similar way to chapter 6, the design facilitated clear comparisons between chronologically and biologically categorised SSGs. Utilising contemporary equipment (PlayerMaker™, Tel Aviv, Israel) that was unavailable at the time of chapter 6, the inclusion of the sub-maximal 30-15 IFT facilitated measurement of RSI, stiffness (absolute and relative) locomotive characteristics such as stride length and cadence for comparison pre-post session, with the addition of sRPE for consistency with other chapters. The distal (foot mounted) location of the PlayerMaker™ compared with scapula mounted MEMS devices facilitated more detailed lower limb locomotor investigation versus more global body loads, which offers informed links to load-adaptation pathways and lower limb injury mechanics.

Chapter 8 revealed that when looking at players of differing maturity status (i.e., pre-, mid-, and post-PHV) within chronologically categorised sessions, it was evident that as also reported in chapter 6 and 7, there was a maturity specific response. All three groups demonstrated a moderate to large pre-post session change in absolute stiffness, but this was relatively smaller in the post-PHV suggesting that they 'coped' with the load better. This indicates that progressive and well-managed increments in load exposure are feasible and would help develop robustness and resilience to injury as a result orf progressive exposure to sport-specific demands (Gabbett, 2016a; Gabbett et al., 2014; Jayanthi et al., 2021) Again, as mentioned in previous chapters this is likely attributed to developmental changes in tendon maturity as the individuals experience PHV (Radnor et al., 2018; Tumkur Anil Kumar et al., 2021), resulting in post-PHV players having better 'energy saving' mechanisms as a result of improved SSC function. Increased stiffness leads to amplified loading rates and augments shock within the lower body, ultimately increasing mechanical stress which can elevate injury risk (Kalkhoven et al., 2021) and may partially explain the increased incidence surrounding PHV in adolescent players. Additionally, these change in stiffness may also relate to the post-session stride length reductions (~4.3cm) for pre- and circa-PHV players, and the increased (0.7cm) stride length for post-PHV players. Stride length is associated with force production capability and the pre-post session change illustrates that the less mature players (pre- and circa-PHV) were more susceptible to reduced force production at the end of their chronologically categorised sessions (Table 8.2).

These heterogenic maturity specific responses observed from chronologically aged sessions were minimised to some extent when training was biologically classified (Table 8.3). There were smaller pre-post changes in neuromuscular response for all markers except for relative stiffness and cadence, which can be partly explained in by relative stiffness including anthropometrical measurements (i.e., leg length and body mass) within the equation as outlined previously. Using relative stiffness indicated that values had reduced across both interventions, but more so from biologically banded activity. This was also reported almost unanimously from psycho-physiological perceptions of intensity (Table 8.4), whereby players rated bio-banded sessions lower intensity with statistically small to moderate differences. This is an important finding considering the substantial maturity-specific differences in load reported over the course of a season observed in chapter 7, whereby using bio-banded activity may stabilise the diversity in load-response. Combined, bio-banded activity may offer practitioners a practical and logistically feasible method to reduce the dose-responses of their players, or at least facilitate a method whereby they can better manage the load-response of their group on a sessional and consequently periodised basis. By scheduling bio-banded sessions at suitable times, coaches can stabilise the dose-response of their players and provoke less maladaptation to 'at risk' players, who may subsequently reduce injury risk and incidence. Reduced depreciation of neuromuscular performance and lower ratings of RPE post-session will naturally reduce recovery times between sessions and therefore reduce the likelihood of accumulated fatigue and non-functional overreaching in this population (C. Williams et al., 2017). In turn, this may allow players to perform in a more adaptative and recovered state which can only positively influence the quality of future sessions and technical, tactical and psycho-social performance (Brink et al., 2012; Brink, Nederhof, et al., 2010). However, it is important to note that reducing training loads too much may also elevate injury risk, therefore, more work to clarify these initial guidelines for practitioners on how they can train smarter around the maturity-specific responses to training activity are needed.

9.1.5. Aim 3, objective 5

A key aim of this thesis was to provide guidance to practitioners on how to manage the maturity-specific variations in dose-response and ensure appropriate training across maturation. Due to the nature of the discussion above, many of the guidelines derived from the studies have emerged in previous sections of the discussion but a clarifying summary is provided here. Although the thesis does not provide explicit load benchmarks such as those (i.e., ACWR) initially theorised by Gabbett et al (2010), the various chapters offer insight into the likely responses of, and approaches to managing players of varied maturity status. For example, chapter 5 offers guidance on the most appropriate method to monitor maturation in adolescent footballers' whist critiquing the error associated with various others. Simultaneously chapter 5 presents the issues around using estimation methods interchangeably for different purposes (i.e., APHV estimation and bio-banding) and the apparent lack of agreement between methods (Table 5.2). By adopting a single and reliable approach to estimating maturity, practitioners can intervene early with confidence, and consciously consider equation error when informing training practices. Additionally, chapters 6 and 7 illustrated the maturity specific responses to acute and chronic training loads respectively which can help guide practitioners on what load-responses to expect with players at either end of the pre-post PHV spectrum (and those in-between). The findings from these chapters offer initial guidelines to the variation in perceived response (i.e., ~7Au per 5% change in PAH), locomotion (e.g., >5cm stride length) and neuromuscular performance (e.g., 4.3cm per 5% change in PAH) from single training sessions and that perceived training load can vary approximately 40% between maturity groups over a 40-week season (chapter 7). Therefore, combined practitioners should be advised that producing sessions that fail to consider biological maturity are sub-optimal and will ultimately increase the likelihood of injury. Finally, chapter 8 offers guidance to practitioners on a feasible and practical method to provide maturity-specific load prescription in the form of bio-banded sessions. Table 8.4 clearly illustrates that bio-banded activity produces relatively lower perceived intensities and regulates the variation in the neuromuscular response, allowing coaches to stimulate maturity groups at the appropriate level. These bio-banded approaches should not replace chronological activity but supplement the training structure. Coaches could utilise the approach to act as a 'stitch in time' to tactically reduce the intensity and/or composition of sessions to decrease the repeated exposure to high-intensity mechanical load.

9.2 Limitations

With any research, there are methodological and practical limitations within this thesis, and it is important to recognise these and the difficulties they present when looking to generalise findings. The key limitations have been outlined below:

9.2.1. Accuracy of biological maturity data

Although this thesis has taken several years to complete, each experimental chapter has used a different academy and/or academy cohort. Therefore, it has been impossible to obtain longitudinal (i.e., over more than 1-season) measurements of anthropometrical data which can then be used to objectively determine maturity timing/tempo of participants (e.g., growth curves for actual timing of PHV). This results in ambiguity around the accuracy of the maturity estimations included within the various chapters of this thesis and open to the error associated with each equation (Fransen et al., 2021), despite a chapter explicitly discussing the various equations and justifying the approach adopted (chapter 5). Where possible, the adopted Khamis-Roche (1994) method has been supported with longitudinal work (Parr et al., 2020; Teunissen et al., 2020) that outlines its enhanced accuracy over methods, but ultimately this thesis lacks an objective criterion reference to corroborate estimations which limits wider generalisation of the findings. It was deemed logistically and ethically unrealistic to conduct more objective maturation assessment (e.g., skeletal assessment) based on the data provided in chapter 4 where academies utilise somatic methods routinely within their practice. Clubs should therefore seek to employ robust measurements of anthropometrical data and utilise objective criterion reference methods (i.e., longitudinal growth-curve modelling), if possible, within their respective environments.

9.2.2. Participant sample

Most of the experimental studies in this thesis (chapters 5-8) were resource and time intensive, which often required repeated or time-consuming data collection for each player. This made utilising multiple academies unrealistic and difficult, both logistically and practically. Two chapters (chapter 5 and 6) utilised players from two separate academies, with both being based in heavily white Caucasian ethic regions of Yorkshire whilst the remaining data was collated from a single academy in Yorkshire. This reduces the generalisability of the findings as there could be environmental bias or processes that have influenced outcomes, which may not relate to academies across the UK or further afield, particularly those with players of more diverse ethnic backgrounds. Additionally, the nature of academy football means that most chronological age groups consist of 15-16 players, resulting in the absolute maximum sample size being ~75 from any academy, notwithstanding injuries or absence. Although power calculations were completed a priori, samples sizes were ultimately influenced by player availability and accessibility within each academy setting. This is one of the major difficulties of conducting applied research and although limits the strength of statistical interpretations, likely offers greater ecological validity for practitioners.

9.2.3. Injury Data

The absence of meaningful injury data within this thesis limits any injury risk discussion to inference rather than interpretation. It was planned that chapter 7 collated overuse injury trends using the Oslo Sports Trauma Research Centre Overuse Injury Questionnaire (OSTRC-Q) (Clarsen et al., 2020), however inconsistent, incomplete and missing responses made this of little value to the chapter. Therefore, conclusions have focussed predominantly on the mechanistic changes that have occurred that may, in theory, contribute to injury risk. Further work is required to ascertain whether these mechanistic adaptations have a clear association with injury risk in this population.

9.2.4. Measuring biomechanical loads

A key focus of this thesis was the subsequent practical application and as a result much of the methodological strategy was designed around using methods routinely employed by academies in practice (i.e., somatic maturity estimation, RPE and neuromuscular performance markers). However, quantification of biomechanical and tissue specific loads *in-vivo* as discussed in this thesis are complicated and often more informative when conducted in laboratory-based environments. Precise inferences from indirect estimates of in-vivo loads acting on structures including bone, stiffness and muscle-tendon forces are possible, but generally require musculoskeletal modelling techniques and as a result become laborious and time-consuming (Verheul et al., 2020), reducing the applicability for the practitioner. Additionally, whole body accelerometery data using contemporary MEMS devices (as in this thesis) may provide an indication of the accumulated external impacts acting on the body, but this premise suggests that these whole-body monitoring devices accurately represent loads acting on structures or tissues, which is yet to be determined (Nedergaard et al., 2017; Verheul et al., 2020). Therefore, explanations around the underlying mechanism of injuries informed by data collected in this way need to be tentative and with follow-up in-vitro studies where possible.

9.2.5. Complexities in adolescent research

This thesis has observed load-responses through a maturity-specific perspective, observing how maturation may impact the perceptions of and objective markers of neuromuscular performance. It is however important to state that there are several other factors which may also contribute to variations in load-response and neuromuscular performance in this population, which complicates interpretations in this research field. For example, contextual factors such as exposure to supervised strength and conditioning sessions, training age and academy philosophy can all influence the athletic competency, physiological development, and movement efficiency of players, which may masquerade as maturity related differences. It is therefore not the intention of this thesis to suggest that maturation alone is responsible for the changes in load-response during adolescence but is a contributing factor alongside several others. Future work could explore the interaction between contributing factors such as maturity, training age, exposure to structured strength and conditioning and period in EPPP environments to unravel the complex intertwining relationship between such variables.

9.3 Practical Applications

The overarching aim of this thesis was to enhance the quality of training load management within youth football to help practitioners reduce the incidence of injury risk and promote more positive outcomes for young athletes. Below are a series of recommendations derived from the findings of this thesis that may, if applied, be useful in the development of the quality of provision to youth footballers with the EPPP.

9.3.1. EPPP policy reformation

The EPPP policy document first published in 2012 has standardised and professionalised academy football in many ways. The clear and non-negotiable stipulations for staffing, facilities, coaching hours, and games programme offer a mechanism by which clubs are audited in relation to their category, with clubs improving their category rating if they enhance provision across various areas. As a result, clubs employ sufficient staff, invest in appropriate equipment and facilities, and deliver the appropriate coaching hours to ensure they adhere to audit requirements and maintain or improve their status. The current lack of detail and relative ambiguity of stipulations within the EPPP relating to monitoring of biological maturation and/or training load monitoring results in academies, even higher category academies, demonstrating mixed practice which may well undermine other areas of the academy structure. The current the ambiguity around the importance of and uses for maturation data may result in academies offering maladaptive training activities to their young players, despite having qualified staff and top-class facilities. Having category specific requirements for minimum standards relating to biological maturation and training load in a similar way to staff and facility requirements, we can better direct clubs to 'best practice' and more positive long-term outcomes for players. This maturity-nuanced guidance could have holistic advantages for academies, players, and football in general. This recommendation is timely based on the EPPP approaching its tenth year and the field of biological maturation and training load monitoring having developed significantly over this period. It is now feasible for policy to indicate informed monitoring strategies appropriate for each category academy and facilitate the interpretation and reporting of this through the PMA. Subsequently, revised guidelines should formalise the monitoring process within academies and therefore promote better communication and interpretation of data for the overall development of talented players. This process could be initiated through better communication (based on findings from chapter 4) between multidisciplinary teams within academies to help identify smarter approaches to prescribing and managing loads for adolescent players. Specialist support staff working closer with technical coaches to prepare session content and maturity-specific mitigations where relevant is an achievable and affordable first step.

9.3.2. Estimating biological maturity

Chapter 4 highlighted the routine estimation of somatic maturity of academy athletes, using either maturity offset (MO) or predicted adult height (PAH%) primarily. Whilst all methods have limitations, standardising the estimation method and frequency would facilitate the development of national guidelines to inform wider practice. Definitive thresholds for key developmental periods including pre-, mid-, and post-PHV groups could be provided using the inherent error in a single methodological approach, which allows practitioners to recognise and cater for this in their application. Although it could be argued that these exist already, the fact that some clubs employ a MO and some PAH% means that technically the players could be banded differently purely based on the methodological approach used. Therefore, there is some ambiguity and error when looking to employ multi-academy maturity events (see point 3 below), which may undermine the process somewhat and the experience had by players. Additionally, it is anticipated that with further research in the not-too-distant future that we can provide guidelines for load management strategies at various stages as indicated within this thesis. For example, those players 88–96% PAH who can be termed 'circa-PHV' may want to reduce the training exposures, particularly high mechanical load activity to alleviate musculotendinous stress associated with SSC development through PHV. This may in turn offer a more adaptive condition and reduce growth and/or non-functional overreaching injuries in this population. From a recommendation perspective, this is much easier to communicate to players, parents and coaching staff if all academies are utilising the same approach where specific guidelines are applicable (i.e., 88–96%), rather than ambiguous term 'circa-PHV' with poor concordance between methods as illustrated in chapter 5. By adopting a single method and being consciously aware of the error associated with this, clubs could streamline their practice and make more informed decisions in line with national guidelines free from clouded judgement impacted by mathematical calculations.

9.3.3. Maturity specific interventions

This thesis has highlighted maturity specific responses to both acute and chronic training activity and illustrated a potential way for practitioners to moderate this response. It is therefore suggested that academies look to replace some of the chronological age programme with supplementary but regular and deliberate bio-banded activity, through informal training activities or more deliberate events (as previously coordinated by the Premier League). The chronological classification system works for many young players, likely the 'on-time' developers, but it is not appropriate for all. Therefore, by supplementing the chronological programme we can offer stratified and deliberate alternative learning experiences for those who need it most. For example, weekly bio-banded training sessions may offer coaches an opportunity to up- or down-regulate the composition of the session, offering a maturity-specific stimulus. This may involve using a larger area for 'at risk' players to reduce the frequency of rapid accelerations and decelerations associated with mechanical stress or reduce on-pitch activity by top and tailing the session with movement, coordination and/or physical development work (e.g., yoga or gymnastics). In doing so, this may act as a 'stitch in time' to preserve players and reduce the likelihood of load related injury, specifically around peak height velocity. This would require a holistic academy approach and require investment from coaching, medical, sport science and potentially pastoral staff to ensure the communication and implementation of this was well received. Players and parents will need to be educated on the opportunities and challenges associated with bio-banding and how this may inform long-term athlete development. The holistic nature of this approach would certainly be aided by the fruition of practical application point 1 above. It is acknowledged that some education for players would be required to help alleviate any psycho-social fears as a result of playing with either older or younger players, but it is reported that biologically categorised interventions are generally well received (Cumming, Brown, et al., 2018; M. Hill, Scott, McGee, et al., 2020).

9.3.4. Monitoring load

Similarly with biological maturity estimation, chapter 4 illustrated that clubs routinely collate training load data, often in the form of sessional ratings of perceived exertions (sRPE). This thesis then adopted a differentiated approach to (dRPE) to detect responses from the various psycho-physiological mediators of performance within across maturation, with some success. Although there is more work to be completed around the validity of dRPE within adolescent soccer, this thesis demonstrated that sRPE offers a mechanism to sensitively detect maturity specific load-responses, which often align with objective markers of (neuromuscular) performance. Therefore, it is recommended that academies at all levels incorporate a structured system for collating sRPE, if possible, in conjunction with external markers of training load, which is then interpreted to inform training prescription. Although much of this data is collated routinely already, greater communication and intervention alongside biological maturity data to intervene early and prevent large discrepancies in accumulated load over the course of a season is needed (as indicated in chapter 7). sRPE monitoring is accessible and cheap to implement within academy-specific constraints and may simply involve the coach collating verbal perceptions from players against validated scales (e.g., CR100) after each session, or more advanced customised applications. Either way, longitudinal tracking and analysis of this load data will offer greater insight and likely impact on player development. Clubs indicated time and staffing as major barriers to implementing such as formalised process, but this is an ideal opportunity to establish links with a local University. The development of a load monitoring database and collation of sRPE data is well within the realms of student/internship skill set and may offer academies an affordable but impactful strategy to manage loads and prepare players, whilst offering valuable applied experience to future practitioners in a financially viable manner.

Chapter 10

Future Research

Chapter 10: Future Research

This thesis has generated novel findings, but as a result has raised more questions. There is a considerable amount of work to do within the field of load management in adolescent football, the impact of biological maturation and their relationship with injury before we can make any conclusive recommendations for coaches and practitioners. The undertaking of this thesis has identified some clear areas in need of further research, of which the most prominent are outlined below to stimulate the progression of the field:

10.1. Estimating somatic maturity

Based on the mixed methods used to estimate biological maturity and the associated error within academy football, and the increasing ethnic diversity of academy players, there is a great need for longitudinal, multi-centre studies that investigate the accuracy of somatic methods. Studies that collect appropriate anthropometric data from players regularly (quarterly) over the course of 3-5 years spanning PHV will provide important information about the most applicable method. If possible, these studies should include an objective measurement in the form of skeletal assessment which is regarded as 'gold-standard' in the field and can act as a criterion reference. It is anticipated that such work will breed confidence in the identified method and facilitate national guidelines and benchmarks as outlined in the practical applications section above.

10.2. Bio-banding and injury trends

As outlined within the thesis, traditionally bio-banding has been used primarily for talent identification and development purposes, however there is an opportunity to observe the impact of bio-banded activity on injury incidence. Biologically classifying training and/or match activity is practical and logistically feasible with good somatic maturity processes and would not require additional resources or equipment. Therefore, there is opportunity to further investigate the impact of supplementing bio-banded activity within the academy structure, with a specific emphasis on overuse and/or non-contact injury spanning PHV. There is a growing body of work around the association of maturation and injury, but very few studies collect overuse injury data specifically (i.e., OSTRC-Q) or assess the influence of biologically classified intervention. These studies would add real value to the field and enable coaches a framework to prescribe training activity.

10.3. Laboratory based studies

Much of the data investigating the impact of maturation of performance and/or dose-response is field based, typically because of resources and equipment accessibility leading to enhanced ecological validity. However, despite the emergence of contemporary accelerometery equipment (i.e., PlayerMaker™) there is still 'noise' within *in-vivo* studies that are compounded by relatively small sample sizes, constrained by academy structures. Therefore, there is a need for some studies to prioritise data reliability and precise mechanical observations at a structural and tissue level over ecological validity and utilise more controlled laboratory-based methods to investigate the mechanistic changes in locomotion and movement during maturation and their relative impact on injury risk. The addition of force platform, isokinetic dynamometry and 3D motion analysis may offer more detailed explorations of musculotendinous changes and better explore the causal pathways of injury proposed by Kalkhoven et al (2021).

10.4. Understanding session composition

This thesis explored the impact of load through standardised and traditional training patterns in players, using a differentiated (dRPE) and gestalt (sRPE) approach. However, obtaining a better understanding of training session composition and its impact on load-response across maturation would be highly informative for practitioners. For example, do training sessions comprised of higher total distance elicit different responses to sessions comprised of less distance but higher accelerative and decelerative loads. There is premise of this work in adult populations (Castillo et al., 2021; Ispirlidis, 2021) and there are links with associated neuromuscular damage as a result of eccentric actions (Satkunskiene, 2021), but no research explores this in relation to biological maturity. This work is important based on many academies sharing a full-size pitch in academy training sessions to reduce hire costs, but this may indirectly contribute to injury incidence as training sessions are constrained by pitch-dimension, which ultimately influences movement patterns and thus, mechanical loading. Establishing the causal links between this could help offer academies a strategy to reduce injury incidence purely because of playing area size.

Chapter 11

References

Chapter 11: References

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Chapter 12

Appendix

Appendix 12.1: Smoothed values of the intercepts and (β_0) and regression coefficients for white males (Khamis & Roche, 1994)

Chronological Age	β_0	Stature (in)	Weight (lb)	Midparent Stature (in)
4.0	−10.2567	1.23812	−0.0087235	0.50286
4.5	−10.7190	1.15964	−0.0074454	0.52887
5.0	−11.0213	1.10674	−0.0064778	0.53919
5.5	−11.1556	1.07480	−0.0057760	0.53691
6.0	−11.1138	1.05923	−0.0052947	0.52513
6.5	−11.0221	1.05542	−0.0049892	0.50692
7.0	−10.9984	1.05877	−0.0048144	0.48538
7.5	−11.0214	1.06467	−0.0047256	0.46361
8.0	−11.0696	1.06853	−0.0046778	0.44469
8.5	−11.1220	1.06572	−0.0046261	0.43171
9.0	−11.1571	1.05166	−0.0045254	0.42776
9.5	−11.1405	1.02174	−0.0043311	0.43593
10.0	−11.0380	0.97135	−0.0039981	0.45932
10.5	−10.8286	0.89589	−0.0034814	0.50101
11.0	−10.4917	0.81239	−0.0029050	0.54781
11.5	−10.0065	0.74134	−0.0024167	0.58409
12.0	−9.3522	0.68325	−0.0020076	0.60927
12.5	−8.6055	0.63869	−0.0016681	0.62279
13.0	−7.8632	0.60818	−0.0013895	0.62407
13.5	−7.1348	0.59228	−0.0011624	0.61253
14.0	−6.4299	0.59151	−0.0009776	0.58762
14.5	−5.7578	0.60643	−0.0008261	0.54875
15.0	−5.1282	0.63757	−0.0006988	0.49536
15.5	−4.5092	0.68548	−0.0005863	0.42687
16.0	−3.9292	0.75069	−0.0004795	0.34271
16.5	−3.4873	0.83375	−0.0003695	0.24231
17.0	−3.2830	0.93520	−0.0002470	0.12510
17.5	−3.4156	1.05558	−0.0001027	−0.00950