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Bio-banding in Youth Sports

Applications in Athlete Development and Injury Prevention in Youth Association Football

Metropolia Ammattikorkeakoulu

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Huolimatta siitä, että lasten ja nuorten urheilusta sekä kasvun ja kehityksen vaikutuksista nuorten urheilulliseen kehitykseen ja loukkaantumisriskiin on tehty lukemattomia tutkimuksia, erilaiset loukkaantumiset ja rasitusvammat ovat lisääntyneet viime vuosina lapsilla ja nuorilla. Tämän opinnäytetyön aiheena on niin kutsuttu bio-banding, eli lasten ja nuorten harjoittelun suunnittelu ja ryhmäjako kronologisen iän sijaan biologisen iän perusteella.

Opinnäytetyö tehtiin yhteistyössä Helsingin Jalkapalloklubin (HJK) kanssa. Opinnäytetyön tarkoituksena oli tehdä laaja kirjallinen katsaus, jonka pohjalta voidaan tulevaisuudessa tuottaa opinnäytetyön aiheesta koulutusmateriaalia ja/tai koulutuksia eri juniorijalkapallon yhteydessä toimiville sidosryhmille. Sekä opinnäytetyön aihe, että tarkoitus ovat erittäin perusteltuja opinnäytetyössä esitetyn tutkimustiedon valossa.

Opinnäytetyö toteutettiin narratiivisena kirjallisuuskatsauksena. Aineiston analyysimenetelmänä käytettiin temaattista sisällönanalyysiä. Bio-bandingiä pyrittiin tarkastelemaan erityisesti juniorijalkapallon näkökulmasta. Teoreettisena viitekehyksenä bio-bandingille toimii tutkittu tieto kasvun ja biologisen iän vaikutuksista lasten ja nuorten kehitykseen ja loukkaantumisriskiin. Teoreettinen viitekehys pyrittiin avaamaan aihealueittain, käyden läpi kasvun eri vaiheet sekä urheilullisen potentiaalin luonnollinen kehittyminen että sen harjoitettavuus biologisen kypsymisen eri vaiheissa. Loukkaantumisriskejä biologisen kypsymisen eri vaiheissa pyrittiin myös avaamaan, pyrkien samalla keskittymään juniorijalkapallolle tyypillisiin vammoihin. Opinnäytetyön lopussa käydään läpi käytännön esimerkkejä siitä, kuinka bio-banding toimii käytännössä.

Opinnäytetyön tuloksena syntyi kattava kirjallisuuskatsaus, jota voidaan käyttää referenssinä järjestettäessä bio-bandingia käsitteleviä koulutustilaisuuksia eri sidosryhmille tai luotaessa aihetta käsittelevää koulutusmateriaalia.

Opinnäytetyössä tehtyjen johtopäätösten perusteella bio-bandingin käyttö on perusteltua lapsi- ja nuorisourheilussa. Työkaluna bio-bandingia ei kuitenkaan ole tarkoitettu korvaamaan tavallista ikäryhmäjaottelua.

Avainsanat	Bio-banding, maturation, youth sports, athlete development, injury prevention, football, soccer

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Despite youth sports and the effect of maturation on youth athletic development and injury risk having been the subject of numerous studies over the years, injury prevalence among youth athletes has lately been on the rise. The topic of this thesis is bio-banding, a recent take on maturity matching players based on biological age instead of chronological age.

The aim of the thesis was to create a comprehensive review of available literature that can, in the future, be used as a reference for stakeholder education on the rationale and application of bio-banding to player development and injury prevention in youth association football. Given the reviewed research outlined in the thesis, the topic and the aim of the thesis are both very much justified. The thesis was written in partnership with Helsingin Jalkapalloklubi (HJK) football club.

The thesis was written as a narrative literature review. The reviewed research was analyzed using thematic content analysis. The thesis attempts to discuss bio-banding in the context of youth association football, with the available research on the effects of growth and biological maturation on youth athletic development and injury risk as the theoretical framework. The thesis attempts to discuss the theoretical framework on a topic to topic basis, shedding light on the different stages of growth and maturation and the natural development of athletic potential and its trainability during different stages of biological maturation. Injury risk factors are discussed in the context of biological maturation, with some focus on maturity-related risk factors in youth association football. Practical applications on how to apply bio-banding are also discussed.

The result of this thesis is a comprehensive review of literature on the theoretical basis of bio-banding and its application to youth sports, specifically association football. The review summarizes key topics needed to put bio-banding into practice and can work as a reference when educating stakeholders or creating educational material.

In light of the reviewed literature, it may be concluded that the use of bio-banding in youth sport may be well justified despite the lack of research on bio-banding itself. However, bio-banding should only be considered an adjunct to traditional training and competition based on chronological age groups.

Keywords	Bio-banding, maturation, youth sports, athlete development, injury prevention, football, soccer

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1 Introduction

Despite the knowledge both the medical and sports science practitioners have on how to prevent sports-related injuries in youth populations, the increasing prevalence of injuries is a cause for concern (Caine – Purcell – Maffulli 2014: 1—10; Arnold – Thigpen – Beattie – Kissenberth – Shanley 2017: 139—147; Friesen – Saul – Kearns – Bachynski – Caplan 2018: 151–169). The growing pressure to win and succeed in sports already at a very early age has made sports practice increasingly repetitive and intensive. Many sports, including team sports such as association football, require early sport specialization and almost daily training from a very early age, exposing children and adolescents to high training loads and increasing the risk of injury (Caine – DiFiori – Maffulli 2006: 749, 757; DiFiori et al. 2014: 287—288 Arnold et al. 2017: 139—147; Friesen et al. 2018: 151–169.)

The topic of this thesis is bio-banding, or matching youth athletes based on maturation instead of traditional grouping by chronological age. While maturity matching is not a new concept and sports science has long known the of effects growth and maturation have athletic development and injury risk, bio-banding is still not very widely used and has been researched relatively little in regards to its applicability to athletic development and injury prevention (Hawkins – Metheny 2001: 1701—1707; DiFiori 2010: 372—378; Ford et al. 2011a: 4; Caine et al. 2014: 1—10; Lloyd et al. 2016a: 1498; Longo – Ciuffreda – Locher – Maffulli – Denaro 2016: 139—159; Cumming – Lloyd – Oliver – Eisenmann – Malina 2017: 34—47; Nguyen – Sheehan – Davis – Gill 2017: 28; Malina et al. 2019: 1671—1685.) While there may be paucity of evidence regarding the efficacy of bio-banding for its intended purposes, evidence regarding the effect of maturation on trainability of athletic performance and injury prevention is abundant (Ford et al. 2011a: 1—12; Ford et al. 2011b: 389-402; Caine, Lloyd – Oliver 2012: 61—72; Caine et al. 2014: 1—10; Cumming et al. 2017: 34—47; Corso 2018 150—160; Friesen et al. 2018: 151–169; Peitz – Behringer – Granacher 2018: 1—44). As such, the choice of bio-banding and its applications to athletic development and injury prevention as the topic of this thesis is solid and well within reason. More specifically, this thesis will attempt to discuss bio-banding and how it relates to athletic development and injury prevention in the context of association football. The thesis was written in partnership with Helsingin Jalkapalloklubi (HJK) football club.

Evidence regarding the efficacy of bio-banding for youth athletic development and injury prevention is currently scarce. However, as Cumming et al. (2017: 34—47) note, this is most likely because of the limited amount of studies that have been carried out the subject. The limited evidence that exists seems to indicate that bio-banding may in fact be a useful tool for talent identification and development and injury prevention, benefitting especially those individuals who are classified as non-average maturers (Cumming et al. 2017: 34—47). Educating stakeholders on the possible benefits of bio-banding may be worthwhile, even with limited evidence of its efficacy, as a lot of the underlying principles regarding maturation, player development and injury mitigation apply even if bio-banding as a tool was proven ineffective. Educating players and their parents may reduce any negative feelings that might raise when a player is made to play up or down an age grade (Meylan – Cronin – Oliver – Hughes 2010: 586). Additionally, coaching should be based on solid knowledge of key factors pertaining long-term athlete development. Educating coaches and practitioners on the effects of maturation on athletic development and injury risk and how to use and apply that knowledge using bio-banding may improve the safety and welfare of the athletes while optimizing their development (Ford et al. 2011a: 4—5; Bergeron et al. 2015: 843—851; Cumming et al. 2017: 34—47; Malina et al. 2019: 1671—1685.) The aim of this thesis is therefore very much justified.

Before discussing the topics included in this thesis, it is first necessary to define recurrent terms. When discussing the target population of bio-banding, the term youth is used to refer to both children and adolescents. The terms child and children refer to youth who have yet to enter puberty. Prepubescent childhood refers to a period when children are close to entering puberty, while early childhood refers to the period between birth and prepubescent childhood. The term adolescent refers to youth who are either experiencing puberty (early, mid- and late puberty) or youth whose puberty has recently ended (post-puberty), while the term adolescence refers to the period ranging from early to post-puberty. The terms athlete and player are used somewhat interchangeably, with a slight difference: while the term athlete refers to youth athletes in general, in this thesis the term player refers to youth football players and is used when attempting to connect the discussed topic to association football.

Biological maturation refers to the process of progressing towards an adult, or mature, state. The term maturation refers to the transitional process from childhood to adulthood as a whole. Growth refers to the increases in body size or that of body dimensions and changes in composition and/or mass that occur as a result of maturation. Development on the other hand refers to physiological and functional changes in different bodily systems and structures as a result of maturation (Beunen – Rogol – Malina 2006: 244; Hakkarainen 2009: 73—75; Malina – Kozieł 2013: 424—437; Lloyd – Oliver – Faigenbaum – Myer – De Ste Croix 2014b: 1454—1455; Malina – Rogol – Cumming – Coelho-e-Silva -- Figueiredo 2015: 852—855; Corso 2018: 150—160; Malina et al. 2019: 1671—1685.)

2 Aims, objectives and process

The aim of this thesis was to create a comprehensive review of available literature that can be used as a reference for stakeholder education on the rationale and application of bio-banding to player development and injury prevention in youth association football. The thesis has several objectives: to give the reader an understanding of changes occurring in the human body as a result of growth and maturation, to give the reader an understanding of how growth and maturation affect athletic development and injury risk, to give the reader an understanding of how to use knowledge of the effects of growth and maturation to optimize athletic development and minimize injury risk specifically in football and finally, to give the reader an understanding of what is bio-banding and how it may be applied to player development and injury prevention in the context of football. To reach these objectives, the following research questions were laid out:

1. Why assess biological maturation and what methods of assessment exist?

2. How do growth and maturation affect development of athletic performance?

3. How do growth and maturation affect injury risk?

4. How to apply bio-banding to player development and injury prevention in football?

To create a theoretical framework for bio-banding and its applications to athletic development and injury prevention, outlining of a number of topics was necessary. The thesis outlines the basics of somatic growth and the effect maturation has on the development and trainability of athletic performance and injury risk. Injury prevention strategies are outlined to allow for more specific recommendations to be made in regards to the application of bio-banding in injury prevention. Finally, some consideration to what bio-banding is and what it isn’t is given, with some practical examples on how to apply it in the context of association football. To create the theoretical framework, and to answer the research questions outlined above, review of literature consisting of a vast range of topics was necessary. Literature was searched using PubMed, Google Scholar, EBSCO-host, EBSCOhost and ProQuest Ebook Central databases. Literature included review articles, academic journals, and books and other literature related to the topics of the thesis. Keywords changed based on topic, which were biological maturation, growth and peak height velocity, assessment of biological maturation, biological maturation and athletic development, biological maturation and injury, injury in youth football, and bio-banding. The literature search was completed in the fall of 2019. The acquired literature was analyzed using thematic content analysis.

The thesis was written as a narrative literature review in an attempt to build an understandable continuum of growth and development from early childhood until late adolescence, with the aim of providing the reader a comprehensive picture of how growth and maturation affect athletic development and injury risk, and how bio-banding may be used to optimize the former and mitigate the latter.

3 Biological maturation and growth

To understand the rationale behind bio-banding, it is necessary to first have some level of understanding of the changes that occur in the human body as a result of maturation. Growth refers to the increases in body size or that of body dimensions and changes in composition and/or mass. The aim of this chapter is to provide insight into mechanisms of growth and the differential growth of various bodily systems, attempting to elucidate the connection between growth, athletic development and injury risk.

3.1 Bone growth

During the prenatal phase, ossification of long bones happens primarily in the diaphysis, or central part of the bone, where hypertrophied chondrocytes degenerate, followed by vascular ingrowth and the ossification of the core of the cartilage model, forming a primary ossification center (Staheli 2007: 4—6). Ossification proceeds at the bone-cartilage junction, and later during infancy and early childhood secondary ossification centers are formed at the cartilaginous ends of the bone. The cartilage that is left between the two ossification centers becomes the growth plate, or physis (Staheli 2007: 4—6; Sarwark – LaBella 2014: 7).

The growth plate pattern varies depending on the bone. There are two physes: the epiphyses and the apophyses. Epiphyses, which form at each end of long bones, are responsible for longitudinal growth of the bones through proliferation and subsequent ossification of cartilage cells in the growth plate; ring epiphyses, on the other hand, are formed around round bones such as the tarsals and the vertebrae and are responsible for circumferential bone growth. Apophyses form at the surface of bones such as the iliac crest, and traction apophyses form at the site where muscle is attached to the bone, such as the tibial tuberosity (Caine – DiFiori – Maffulli 2006: 749; Sarwark – LaBella 2014: 7—8.) Long bones are considered mature when the diaphysis and epiphysis fuse, whereas round and irregular bones are considered mature when they achieve their adult shape (Sarwark – LaBella 2014: 8).

3.2 Muscle and tendon growth

After birth muscle cells differentiate into distinct muscle fiber types, three of which are of importance to the topic of this thesis: type I or slow oxidative fibers, type IIa or fast oxidative fibers and type IIb or fast glycolytic fibers. Due to their slow contraction speed, type I fibers have limited potential for force development, but in turn are generally highly efficient and resistant to fatigue and have a high capacity for aerobic energy supply. Compared to type I fibers, type IIa fibers are inefficient as they contract rapidly and burn through stored adenosine tripsosphate (ATP) quickly. They do, however, have a higher capacity for aerobic energy supply and are more resistant to fatigue compared to type IIb fibers, and as such are often called intermediate fibers. Type IIb fibers contract fast and are have high anaerobic power and potential for rapid force development but fatigue the fastest of the three muscle fiber types as their energy supply is highly dependent on anaerobic metabolism (Hakkarainen 2009: 91—94; Travis 2016: 9.)

At birth, muscle fiber distribution in children is roughly 40% type I, 45% type IIb and 15% type IIa fibers. During the first few months after birth the relative amount of type I and type IIb fibers increases at the expense of type IIa fibers (Hakkarainen 2009: 91—94.) Boys tend to have more type II fibers at adolescence and early adulthood, while girls tend to have more type I fibers. Genetics however play a major role on which muscle fiber type is dominant in each individual, as the ratio of type I to type II fibers is highly dependent one's genetic makeup (Hakkarainen 2009: 91—94.) This has major implications to athletic performance; for example, individuals with high amount of type I fibers tend to excel in endurance events, whereas individuals with majority type IIb fibers fare better in events that require strength and power. (Hakkarainen 2009: 91—94; Travis 2016: 9—11). Genetics play a role in the muscle cells' ability to transition from one fiber type to the other in response to external stimuli. During the first 4—8 postnatal years especially type IIa or intermediate fibers are quick to transition either to fatigue-resistant type I or powerful type IIb fibers depending on exercise stimuli; hence, to ensure optimal muscular development, children's play and involvement in sports should be as diverse as possible during childhood (Hakkarainen 2009: 92—93.)

No significant increase in the number of muscle cells occurs after birth, although Hakkarainen et al. (2009: 91) point out that the scientific community is currently somewhat divided on the matter. Instead, muscle growth occurs largely through the enlargement of existing muscle cells due to increases in the cells' functional structures, such as contractile proteins actin and myosin, and other structures such as sarcoplasmic fluid. This results in enlarged muscle fiber cross-sectional area, which eventually leads to muscle hypertrophy, or increases in muscle size, as the fibers of a muscle or a muscle group collectively enlarge (Hakkarainen 2009: 91—92; French 2016: 93—95; Mersmann – Bohm – Arampatzis 2017: 1—18.) Muscle hypertrophy occurs both naturally and in response to exercise stimuli (Hakkarainen et al. 2009: 91—93; Ford et al. 2011: 4—6; Radnor et al. 2018: 57—71).

The role of the tendon in stretch-shortening cycle (SSC) function is crucial, and as such some understanding of its growth and maturation is necessary. Tendon dimensions have a great impact on tendon functional properties: longer tendons have lower stiffness compared to thick tendons (Radnor et al. 2018: 57—71.) Although tendon length increases with maturation, which, in theory, should reduce tendon stiffness, tendon stiffness has in fact been shown to increase with maturation (Mersmann et al. 2017: 1—18; Radnor et al. 2018: 57—71). Differences in dimensional growth have been suggested as a possible explanation: tendon grows both in length and cross-sectional area during maturation, approximately 53% and 93% respectively, suggesting that the more marked increase in tendon cross-sectional area compared to tendon length results in increased tendon stiffness (Corso 2018: 150—160; Radnor et al. 2018: 57—71). The most likely explanation for such a significant difference in dimensional growth is increased chronic loading of the tendon as a due to maturation-related increased body mass and force production, resulting in tendon hypertrophy (Mersmann et al. 2017: 1—18; Corso 2018: 150—160; Radnor et al. 2018: 57—71). Tendon stiffness reaches adult levels by mid-adolescence, around the age at peak height velocity (Radnor et al. 2018: 57—71). Exercise does not have a major impact on tendon structural properties, but it does seem to affect tendon internal properties as it has been shown to increase tendon stiffness (Corso 2018: 150—160; Radnor et al. 2018: 57—71).

3.3 Rate of growth and peak height velocity

Growth patterns in children and youth may vary greatly between individuals, with factors such as genes, hormones and gender impacting both the rate and timing of growth. External factors such as exercise and nutrition may also impact growth (Hakkarainen 2009: 76—79; Ford et al. 2011: 4; Sarwark – LaBella 2014: 3—12). Growth in height is generally fastest during early childhood, slowing down during childhood as the child ages only to increase again after the onset of puberty during what is known as the adolescent growth spurt (Staheli 2007: 8; Hakkarainen 2009: 76—79; Ford et al. 2011: 4; Sarwark – LaBella 2014: 3—6). The adolescent growth spurt begins with a significant acceleration in rate of growth in height. The acceleration in growth rate continues until it reaches a maximum known as peak height velocity (PHV), after which growth decelerates and eventually comes to a halt in late adolescence or early adulthood. Adolescent growth spurt for girls tends to start between the ages of 8 and 10, which on average is roughly 2 years earlier than for boys, who’s growth spurt tends to take off between the ages of 10 and 12. The growth spurt lasts between 2 to 3 years on average. Both boys and girls reach their PHV 2 years after the start of the adolescent growth spurt on average, but girls tend to reach their PHV earlier than boys due to the earlier start of the growth spurt (Hakkarainen 2009: 78; Sarwark – LaBella 2014: 4: Malina et al. 2015: 853.) While the average age at PHV has been shown to be relatively constant in longitudinal studies, it is worth noting that significant inter-individual variation in age at PHV exists, with Malina et al. (2015: 853), for example, reporting an age at PHV range of 9—15 years and 11.5—17.3 years in British, Swiss and Polish girls and boys respectively (Hakkarainen 2009: 78; Sarwark – LaBella 2014: 5; Brown – Patel – Darmawan 2017: 150).

While the rate of growth may vary greatly between individuals, it is worth noting that variation in rate of growth exists between different tissue types in each individual as well (Hawkins – Metheny 2001: 1702—1704; Hakkarainen 2009: 91—95; Ford et al. 2011: 4; Sarwark – LaBella 2014: 3—12). Rate of bone growth varies between the epiphyses. In the lower limbs bone growth is most rapid around the knee joint, just above and below the joint, whereas in the upper limb bone grows fastest at the shoulder and wrist (Staheli 2007: 7.) The trunk grows at its fastest rate during infancy and early childhood, followed by increasing growth of the upper and finally the lower limbs. Lower limb growth is most rapid during early adolescence and coincides with PHV, especially in boys. During the adolescent growth spurt lower limb growth peaks first, followed by upper limbs and finally the trunk, which is the last to cease growth (Sarwark – LaBella 2014: 4, 8.)

Bone mass increases as the child matures and cartilaginous structures ossify. While bone mineral content increases with age, bone mineralization lags behind PHV by approximately one year. This has implications to injury risk, as the adolescent growth spurt and associated rapid longitudinal bone growth temporarily increases bone porousness, thus making them weaker and more susceptible to injury (Caine et al. 2006: 750; Hakkarainen 2009: 94; Lloyd et al. 2016a: 1498; Longo et al. 2016: 141.) Peak bone mineralization occurs during adolescence in both boys and girls, with Bass (2000: 75) reporting up to 50% of total bone mineral accrual occurring during adolescence in girls. Greater than 90% of peak bone mass is generally achieved by age 18 in both boys and girls (Sarwark – LaBella 2014: 8). Exercise during childhood and adolescence has a significant effect on bone health, as it has been shown to increase both bone mineral density and content throughout the maturation process (Bass 2000: 75—76; Burrows 2007: 305—312; Faigenbaum et al. 2009: 66; Hakkarainen 2009: 94; Lloyd et al. 2014a: 499—500). While it is somewhat unclear which developmental period is most opportune when it comes to effect of exercise on bone development (Bass 2000: 77), Burrows (2007: 305—312) and Faigenbaum et al. (2009: 7) suggest that prepubescent boys may benefit more from moderate intensity exercise than prepubescent girls, while both prepubescent boys and girls may benefit from high impact, high intensity exercise such as running and plyometrics. Studies also suggests that high intensity exercise may be especially good at promoting bone health in both adolescent boys and girls, especially during the adolescent growth spurt (Bass 2000: 75; Burrows 2007: 305—312; Zulfarina et al. 2016: 1545—1557). Practitioners should be careful, however, not to overdo such exercise high impact, high intensity exercise during periods of rapid growth, as this may expose the adolescent athlete to injury. This, however, will be covered in more detail in a later chapter.

Lean muscle mass increases significantly with age during childhood and adolescence, with its percentage of total body mass increasing from 42% to 54% in boys and 40% to 45% in girls from age 5 until age 17 (Ford et al. 2011a: 5; Mersmann et al. 2017: 1—18). Rate of muscle growth is similar in boys and girls until the start of puberty, with a relatively linear increase of approximately 0.6% in lean mass per year (Hakkarainen et al. 2009: 93; Ford et al. 2011: 5). While the rate of muscle growth stays relatively linear in girls throughout biological maturation, in boys the rate speeds up markedly around the age of 13 or 14, with increases of roughly 29% in muscle mass per year for two years after the onset of puberty. This gender difference in rate and timing of muscle growth is largely due to the timing of puberty and its associated hormonal changes (Hakkarainen 2009: 93; Ford et al. 2011: 5—6; Sarwark – LaBella 2014: 11; Lloyd – Faigenbaum 2016: 137—138; Brown et al. 2017 2017: 151; Mersmann et al. 2017: 1—18.) Muscles of the lower extremities grow and develop faster than those of the upper extremities due to weight-bearing activities and associated higher workload (Hakkarainen 2009: 92). Longitudinal soft tissue growth, including muscle growth, lags behind longitudinal bone growth (Hakkarainen 2009: 92—93; Ford et al. 2011: 4); this has implications for athletic performance and injury which will be covered later in the thesis.

Exercise does not have a significant effect on muscle growth in prepubescent children. After the onset of puberty, however, the effect of exercise on muscle hypertrophy increases remarkably, with muscle size increasing up to tenfold during adolescence and early adulthood. As such, exercise may affect the rate and magnitude of muscle growth significantly (Hakkarainen 2009: 91—92; Ford et al. 2011: 5—6.) The increased effect exercise has on muscle hypertrophy is attributed to the pubertal hormonal changes mentioned above; similar to natural muscle growth, exercise induced hypertrophy is especially potent in adolescent males due to significantly increased production of testosterone and growth hormones (Hakkarainen 2009: 92; Ford et al. 2011: 5—6). This has major implications for both athletic performance and trainability, but these will be covered later in the thesis.

During growth and maturation, the child’s weight increases as he or she grows in stature, although nutrition and the child’s level of activity can affect weight gain significantly. For normally developing youth, peak weight velocity (PWV), or the maximum rate of weight gain, coincides with or slightly follows PHV in boys, while in girls PWV occurs slightly after PHV (Philippaerts et a. 2006: 221—230; Sarwark – LaBella 2014: 7; Brown et al. 2017 2017: 150). Boys gain more weight on average during puberty than girls. In boys, most of pubertal weight gain comes from the increase in skeletal mass due to height gain and increases in muscle mass. In girls, pubertal weight gain is mostly attributed to increases in fat mass brought on by increased estrogen production (Hakkarainen 2009: 95—96; Ford et al. 2011: 4; Sarwark – LaBella 2014: 7.)

4 Assessment of biological maturation

Practitioners working with youth athletes should have a thorough understanding of growth- and maturity-related changes in athletic development and risk of injury. However, to be able to make full use of the understanding of said topics to optimize long-term athlete development and minimize injury risk, and to understand how bio-banding can be put into practice, it is reasonable to assume that knowledge on how to assess biological maturation is needed (Malina – Kozieł 2013: 424—437; Lloyd et al. 2016a: 1499; Malina et al. 2019: 1671—1685.) Biological maturation refers to the process of progressing towards an adult, or mature, state. Maturation of different systems of the body proceeds at a different rate compared to chronological age, and thus chronological age is a poor indicator of biological maturity. Furthermore, significant interindividual differences in the rate, timing and magnitude of maturation have been observed among children and adolescents of similar chronological ages (Beunen et al. 2006: 244; Hakkarainen 2009: 75—83; Lloyd et al. 2014b: 1454—1455; Malina – Kozieł 2013: 424—437; Malina et al. 2015: 852—855; Malina et al. 2019: 1671—1685.) Despite biological maturation proceeding somewhat independently of chronological age, maturation is assessed in the context of chronological age, in terms of maturity status, or state of maturation at a specific chronological age (for example, prepubertal, early pubertal, postpubertal), and timing, or the chronological age at which specific maturational events occur (for example age at PHV and menarche) (Beunen et al. 2006: 244; Meylan et al. 2010: 572; Malina – Kozieł 2013: 424—437; Malina et al. 2015: 852; Cumming et al. 2017: 34—47; Malina et al. 2019: 1671—1685.) While biological maturation occurs in all parts of the human body, the process occurs at different rates and times depending on the maturing tissues, organs and bodily systems (Beunen et al. 2006: 244; Meylan et al. 2010: 572; Malina et al. 2015: 852). As a result, several methods for assessing biological maturation have been developed, both invasive and non-invasive. The most common methods for the assessment of maturation are the skeletal, physiological and somatic methods (Beunen et al. 2006: 244—294; Meylan et al. 2010: 583—585; Malina et al. 2015: 852—855).

4.1 Assessment of skeletal maturity

Skeletal age is often considered as the gold standard among methods of assessing biological maturity status, and it is perhaps the most extensively used of all assessment methods (Beunen et al. 2006: 244—246; Meylan et al. 2010: 583; Malina – Coelho-e-Silva – Figueiredo – Carling – Beunen 2012: 1705; Lloyd et al. 2014b: 1454–1455;

Sarwark – LaBella 2014: 9). The method is based on assessing skeletal maturation using radiographic imaging as the skeleton transitions from cartilaginous structures of early childhood towards a fully ossified adult skeleton (Beunen et al. 2006: 244—245; Lloyd et al. 2014b: 1454—1455; Sarwark – LaBella 2014: 9). Several methods of assessment exist, most of which are based on comparisons of a left wrist radiograph against predetermined reference criteria (Beunen et al. 2006: 245; Lloyd et al. 2014b: 1455). The three most commonly used methods of assessing skeletal maturity are the Greulich-Pyle method, Tanner-Whitehouse method and Fels method (Beunen et al. 2006: 245; Lloyd et al. 2014b: 1455; Malina et al. 2015: 853).

The Greulich-Pyle method, also known as the atlas technique, involves the comparison of a child’s left wrist radiograph to sex-specific radiographs across different levels of skeletal maturation. The skeletal age is determined as that which most closely resembles one of the standard radiographs of the system; for example, if the radiograph of an 11-year-old most closely resembles that of a 13-year-old of the same sex, he or she is viewed as an early maturer and his or her skeletal age would be determined as 13 (Beunen et al. 2006: 245; Lloyd et al. 2014b: 1455—1456; Malina et al. 2015: 853.)

Unlike the Greulich-Pyle method, which focuses on the hand-wrist complex as a whole, the Tanner-Whitehouse method uses predefined maturity indicators for the bones of the hand, wrist and distal forearm. Each indicator expressed as a stage of maturation and each stage is given a point score. Two versions of the Tanner-Whitehouse method exist: the thirteen-bone assessment, including radius, ulna and phalanges, and the twenty-bone assessment, including radius, ulna, phalanges and carpals. Regardless of the chosen version, the radiographs of the bones are examined and compared with existing maturity indicators, and each bone is given a point score based of their stage of maturation. The point scores are summed and expressed either as a maturity score or a skeletal age (Beunen et al. 2006: 245; Lloyd et al. 2014b: 1456; Malina et al. 2015: 853.)

The Fels method is bone-specific, and uses the radius, ulna, carpals, metacarpals and phalanges to assess skeletal maturation. Each bone is graded according to age and sex, and ratios between length and width of the epiphysis and metaphysis of the long bones are measured. The chronological age and sex of the child or adolescent and the bone rates and ratios are then entered into a software that calculates skeletal age (Beunen et al. 2006: 245; Lloyd et al. 2014b: 1456.)

4.1.1 Criticisms of methods of assessing skeletal maturity

Assessing biological maturity using skeletal indicators, while widely used, has some obvious drawbacks. Irrelevant of the chosen method, assessing skeletal age is relatively expensive, and as such often beyond the economical means of most sports clubs; the assessment is very time consuming and requires specialized equipment and trained professionals to acquire and analyze athlete radiographs (Beunen et al. 2006: 246; Lloyd et al. 2014b: 1456—1457; Malina et al. 2015: 852—853; Romann – Javet – Fuchslocher 2017: 3—13). Children and youth are exposed to radiation, and while the levels of radiation using modern technology are minimal (Meylan et al. 2010: 583; Lloyd et al. 1456—1457; Malina et al. 2015: 852—853; Romann et al. 2017: 3—13), Meylan et al. (2010) note that the assessment is still invasive and as such ethical issues may arise. Additionally, each of the methods mentioned above has their own issues as well. The Greulich-Pyle method fails to take into consideration that the bones in the hand, wrist and distal forearm do not mature in an identical manner, and as such concerns over the accuracy of the method have been raised. What’s more, the original reference radiographs were collected from Caucasian children of high socioeconomic status, making the method’s applicability for assessing skeletal maturation of children of different ethnicities and socioeconomic class questionable (Beunen et al. 2006: 245; Lloyd et al. 2014b: 1455—1456; Cole et al. 2015: 138—143; Malina et al. 2015: 853.) The original data for the Fels method was collected between the 1930s and the 1970s from middle-class American children from south-central Ohio, raising similar questions on the method’s applicability among different ethnicities and socio-economic groups (Beunen et al. 2006: 245; Lloyd et al. 2014b: 1455—1456; Cole et al. 2015: 138—143; Malina et al. 2015: 853). While the most recent version of the Tanner-Whitehouse manages to address these concerns with data collected from European, North and South American and Japanese children (Beunen et al. 2006: 245; Lloyd et al. 2014b: 1456; Malina et al. 2015: 853), Lloyd et al. (2014) note that the method is nevertheless relatively complex, time-consuming and requires a degree of subjective decision making from the assessor, raising the need for quality control and making the method more difficult to apply in youth training environments.

4.2 Assessment of physiological maturity

Different physiological indicators have been widely used when assessing biological maturation in children and youth. Assessment of biological maturity using physiological indicators is based on the idea that while there may be large interindividual differences in the changes brought on by biological maturation, certain physiological changes take place at certain stages of the maturation process as the human body develops toward full reproductive maturity (Beunen et al. 2006: 246; Lloyd et al. 2014b: 1457). Indicators of physiological maturation can be divided into sexual and hormonal indicators.

Methods of assessing sexual maturation are largely based on observation of secondary sex characteristics, such as pubic hair in both sexes, breasts in girls and genitalia (penis, testes) in boys, and subsequent comparison of said characteristics against five reference stages commonly known as the Tanner stages 1-5 (or Tanner criteria) (Beunen et al. 2006: 246; Lloyd et al. 2014b: 1457; Malina et al. 2015: 852—853; Romann et al. 2017: 3—13). It is worth noting that the stages are not interchangeable between characteristics, as the maturation of each secondary sex characteristic can occur at different rates and magnitudes and can vary in timing of maturation (Beunen et al. 2006: 246; Lloyd et al. 2014b: 1458).

In addition to the Tanner criteria, there are other ways of assessing sexual maturation in both boys and girls. Observation of axillary hair in both boys and girls, and facial hair and voice change in boys can used to assess sexual maturation. Beunen et al. (2006: 246) and Malina et al. (2015: 852) note, however, that because these indicators develop late in the maturation process, they may not be good indicators of sexual maturation before or during early puberty, and as such they are not widely used in studies. Genital maturation can be assessed in boys by evaluating testicular volume, although this requires a qualified and experienced medical professional. Age at menarche, or first menstruation, can be used to assess maturity timing in girls (Beunen et al. 2006: 246; Lloyd et al. 2014b: 1458; Malina et al. 2015: 852—853.) While the method is commonly used with girls, Lloyd et al. (2014) note that because age at menarche is typically a retrospective measure of biological/sexual maturation, its use in sport- and exercise-related settings may be limited.

Significant hormonal changes occur during adolescence, and hormonal indicators have often been used to assess biological maturation and its timing (Beunen et al. 2006: 247—

248; Meylan et al. 2010: 584). As the child matures, increases in levels of hormones such as dehydroepiandrosterone and androstenedione (precursors to androgen testosterone and estrogen estradiol) are observed. When children reach puberty, the levels of circulating androgen hormones (especially testosterone) in boys and estrogen hormones (especially estriadol) in girls increase significantly. The production of growth hormone and insulin-like growth factor I (IGF-1) increases remarkably during puberty and is especially high around peak height velocity (Beunen et al. 2006: 247—248; Hakkarainen 2009: 85—87; Meylan et al. 2010: 584.) Changes in hormonal levels can be measured using either blood or saliva sampling, and they provide relatively accurate evidence of the maturation of specific bodily systems (Beunen et al. 2006: 248; Meylan et al. 2010: 584).

4.2.1 Criticisms of assessment of physiological maturity

The methods of physiological maturity assessment outlined above have their limitations and are deserving of some criticism. Assessment of physiological indicators of maturation can be relatively expensive, requiring access to trained clinicians, up-to-date background checks on assessors when observing secondary sex characteristics and expensive laboratory facilities and equipment when using hormonal indicators to assess maturation (Beunen et al. 2006: 248; Hakkarainen 2009: 89—91; Meylan et al. 2010: 584; Lloyd et al. 2014b: 1457; Romann et al. 2017: 3—13). The so-called Tanner stages have been criticized as being somewhat arbitrary and having limitations when it comes to differentiating children within stages, being unable to assess rate of maturation and being tied to the period of puberty, making them unusable with children outside of puberty (Beunen et al. 2006: 247; Lloyd et al. 2014b: 1458; Romann et al. 2017: 3—13). While secondary sex characteristics are relatively easy to determine, and are closely linked to hormonal indicators of maturity, assessing characteristics such as pubic hair, genitalia and breasts is very invasive and may be viewed as a breach of personal privacy. Moreover, assessing secondary sexual characteristics in children poses very real ethical challenges such as child protection issues, assent and consent of both the child and his/her parent and assurance of confidentiality and anonymity (Beunen et al. 2006: 247; Meylan et al. 2010: 584; Lloyd et al. 2014b; 1457.) Beunen et al. (2006: 247) do well to also note that assessing secondary sex characteristics may not be viewed as acceptable among some cultural groups. While some of these problems have been eliminated by using different self-assessment protocols, studies have shown the reliability of self-assessment of secondary sexual characteristics to be questionable (Beunen et al. 2006: 246; Meylan et al. 2010: 584; Lloyd et al. 2014b; 1458).

When assessing physiological maturity using hormonal indicators, Meylan et al. (2010) recommend using saliva sampling due to the ethical issues related to blood sampling in children. While hormonal indicators may provide direct insight into the maturation of certain bodily systems, neither methods using blood nor saliva sampling come without problems; the hormones related to maturation are produced in pulses, causing their levels to change throughout the day, making accurate assessment require a series of blood or saliva samples over a prolonged period of time (Beunen et al. 2006: 248; Hakkarainen 2009: 89—91). Additionally, accurate testing requires further considerations, such as management of stress levels and nutrition prior to sampling (Meylan 2010: 584).

4.3 Assessment of somatic maturity

Somatic maturity refers to the level growth in overall stature and that of body dimensions. Body size alone, however, is a poor indicator of biological maturity, and as such assessment of somatic maturity requires more, often longitudinal data that can be used to put body height, weight and dimensions in the context of chronological age and biological maturity (Beunen et al. 2006: 244—256; Meylan et al. 2010: 584—585; Lloyd et al. 2014b: 1454—1464; Malina et al. 2015: 852—859). Assessing somatic maturity is considered non-invasive and it can be done in terms of both status and timing. A common way of estimating maturity using somatic indicators is estimating age at PHV. Estimating age at PHV requires the regular measurement of height preferably from middle childhood and until late adolescence. Height should be measured at least twice, preferably four times annually to increase the accuracy of the method. Longitudinal growth data allows for the analysis of growth curves and enables the estimation of age the onset of the adolescent growth spurt and age at PHV by revealing changes in rate of growth; the longer the period of time over which data is collected, the more accurate the estimate (Beunen et al. 2006: 244—256; Lloyd et al. 2014b: 1454—1464; Malina et al. 2015: 852—859.) Collecting other data such as body weight and skin fold measurements to measure body fat percentage may help in estimating maturity as changes in weight and body composition tend to occur at certain stages of maturation (Lloyd et al. 2014b: 1454—1464). Growth curve assessment can only be used retrospectively to identify PHV, however, meaning that if age at PHV is to be predicted, mathematical modelling is necessary. A commonly used mathematical model is that developed by Mirwald and colleagues. (Mirwald – Baxter-Jones – Bailey – Beunen 2002: 689–694). The model uses chronological age (years and months), body mass, standing height, sitting height and leg length to estimate years from or after PHV (maturity offset) and, in turn, predict age at PHV. Boys and girls have different equations (Mirwald et al. 2002: 689—694; Malina – Kozieł 2013: 424—437; Kozieł – Malina 2018: 221—236):

$$\text{Boys: Maturity offset (years)} =$$
$$-9.236 + 0.0002708 \text{ x } (\text{leg length x sitting height}) + (-0.001663) \text{ x } (\text{age x leg length})$$
$$+ 0.007216 \text{ x } (\text{age x sitting height})) + 0.02292 \text{ x } (\text{body mass / standing height}) \text{ x } 100)$$

$$\text{Girls: Maturity offset (years)} =$$
$$-9.376 + 0.0001882 \text{ x } (\text{leg length x sitting height}) + 0.0022 \text{ x } (\text{age x leg length})$$
$$+ 0.005841 \text{ x } (\text{age x sitting height}) - 0.002658 \text{ x } (\text{age + body mass}) + 0.07693$$
$$\text{x } (\text{body mass / standing height x } 100)$$

Alternative, more simplified equations were developed by Moore et al. (2015: 1755—1764):

$$\text{Boys: Maturity offset (years)} = -7.999994 + (0.0036124 \text{ x age x height})$$

$$\text{Girls: Maturity offset (years)} = -7.709133 + (0.0042232 \text{ x age x height})$$

Age at PHV can be predicted by looking at the difference between chronological age and maturity offset using either equation. For example, using the equation by Moore et al. (2015), a boy who is 13 years and 6 months old and 145cm tall would have a maturity offset of:

$$-7999994 + (0.0036124 \text{ x } 13.5 \text{ x } 145) = -0.929$$

This would then be interpreted as the boy being 0.929 years, or slightly over 11 months (~11.15) from his predicted age at PHV.

The equations by Mirwald et al. (2002) and Moore et al. (2015) have been validated with European and North American boys and girls (Mirwald et al. 2002: 689—694; Malina – Kozieł 2013: 424—437; Moore et al. 2015: 1755—1764; Kozieł – Malina 2018: 221—

236). Mirwald et al. (2002: 689—694) reported that using their equation they were able to estimate maturity offset (and subsequently predict age at PHV) within ±1 year 95% of the time in children between aged between 4 years from average PHV to 3 years post-PHV. Based on an average chronological age of 14 at PHV, they recommended that the equation is applicable between the ages of 10—18 (Mirwald et al. 2002: 689—694; Malina – Kozieł 2013: 424—437). Moore et al. (2015: 1755—1764) noted, however, that the equations by Mirwald et al. (2002) only had a predictive ability of only 80—85%, while their revised equations managed to raise the accuracy to 90%.

Another method of assessing biological maturity using somatic indicators is by estimating percentage of predicted adult height. The estimate requires the measurement of an individual's current height and a prediction of adult height obtained by calculating midparental height and using a sex-specific equation to estimate predicted adult height (Meylan et al. 2010: 585; Malina et al. 2012: 1705—1717; Lloyd et al. 2014b: 1454—1464; Bergeron et al. 2015: 843—851; Malina et al. 2015: 852—859.) The equations for boys and girls by Tanner et al. can be seen below (Faigenbaum, Lloyd – Oliver 2019: 60):

$$\text{Midparental height (cm)} = (\text{mother's height} + \text{father's height}) / 2$$

$$\text{Boys' predicted adult height (cm)} = (\text{midparental height}) + 6.5$$

$$\text{Girls' predicted adult height (cm)} = (\text{midparental height}) - 6.5$$

The equation by Tanner et al. has been criticized for having the predictive error increase in cases where one or both parents' height is non-average, i.e. he or she is either very tall or very short. To address this, other equations have been developed. The equation by Luo et al. managed to get the standard to about 5cm using the following equation (Faigenbaum, Lloyd – Oliver 2019: 60):

$$\text{Boys' predicted adult height (cm)} = (0.78 \times \text{midparental height}) + 45.99$$

$$\text{Girls' predicted adult height (cm)} = (0.75 \times \text{midparental height}) + 37.85$$

A popular, if somewhat complex, method of estimating predicted adult height in youth aged 4—17.5 years is the Khamis-Roche method. Using midparental height and the child's current height and weight, multiplying each with a coefficient that depends on the child’s current age and adding the gained values to a sex- and age-specific intercept, the method is able to estimate predicted adult height accurately with a relatively small measurement error (Khamis – Roche 1994: 504—507; Malina – Cumming – Morano – Barron – Miller 2005: 1044—1052; Faigenbaum, Lloyd – Oliver 2019: 60.) An example of using the Khamis-Roche method to predict the age of a female 7-year-old who is 95.5cm tall, weighs 40.8kg and has a midparental height of 154.95cm can be seen below:

$$\text{Predicted adult height (cm)} = (-2.87645) + 95.5 \times 1.11342 + 40.8 \times (-0.013184)$$
$$+ 61 \times 0.31748 = {\sim}152\text{cm}$$

As is evident from the above, the Khamis-Roche method may be somewhat complicated due to the age- and sex-dependent intercept and coefficients. Online calculators, however, are widely available, making the method easier to use.

No matter what the chosen method to estimate predicted adult height, to estimate an individual’s maturity status the individual’s current height is expressed as a percentage of the predicted adult height. Maturity status can then be estimated by examining the percentage of predicted adult height at the time of observation: the closer the individual is to their predicted adult height, the further along the maturational process they are. Although percentage of predicted adult height cannot be used to estimate rate of growth, studies using longitudinal data have been able to show that PHV occurs at approximately 91—92% of adult height. Based on evidence from longitudinal data showing that the adolescent growth spurt generally lasts approximately 24—26 months, Cumming et al. (2017: 34—47) suggested applying a 1-year period before and after the estimated percentage of adult height at PHV to get a 88—95% percentage range for the adolescent growth spurt. By using this criteria, estimated percentage of predicted adult height can be used to categorize players as pre- (PAH < 88%), circa- (PAH = 88—95%) and post-PHV (PAH ≥ 96%). Data from earlier longitudinal studies, such as the Fels longitudinal study, Worclaw growth study or the Guidance study of the University of California, Berkeley, may be used to classify the individual as early, on-time or late maturing based on his or her percentage of adult height at a given chronological age compared to standardized data of the same chronological age (Khamis – Roche 1994: 504—507; Malina et al. 2005: 1044—1052; Malina et al. 2012: 1705—1717).

Using percentage of predicted adult height to assess somatic maturity status has been validated with European and North American boys and girls, and the method has been found to have moderate concordance with status classifications based on skeletal age (Meylan et al. 2010: 585; Malina et al. 2012: 1705—1717; Lloyd et al. 2014b: 1454—1464; Bergeron et al. 2015: 843—851; Malina et al. 2015: 852—859; Myburgh – Cumming – Malina 2019: 1—9.)

Like other methods of assessing biological maturity, the somatic methods are not without failings, and such are deserving of some criticism. Collection of longitudinal data required for the maturity offset method may prove difficult, especially in team sports settings at lower levels. What’s more, because both staff and players come and go, increasing the risk of not having any growth-related data before a relatively old age, making it impossible to identify past changes in growth (Lloyd et a.l 2014b: 1454—1464). Malina et al. (2012: 1705—1717), Malina – Kozieł (2013: 424—437) and Kozieł – Malina (2018: 221—236) found that when comparing maturity offset prediction, percentage of predicted adult height, skeletal age assessment and stage of puberty, correlation between the maturity offset and the other methods of assessing maturity was poor or moderate at best. Predicted maturity offset and age at PHV were found to be greatly affected by chronological age, with age at PHV being underestimated at younger ages and overestimated at older ages with the largest differences in predicted and actual age at PHV at ages 8—11 and 16—18. Mean predicted age at PHV was also shown to increase with chronological age (Malina et al. 2012: 1705—1717; Malina – Kozieł 2013: 424—437; Bergeron et al. 2015: 843—851; Malina et al. 2015: 852—859.) Additionally, standard deviation was found to be small across age groups, raising questions of the method’s ability to differentiate between early, on-time and late maturing individuals. In fact, prediction of maturity offset and age at PHV has been found to classify majority of individuals as being on time in maturation, limiting its use with early and late maturing athletes (Malina et al. 2012: 1705—1717; Malina – Kozieł 2013: 424—437; Bergeron et al. 2015: 843—851; Malina et al. 2015: 852—859; Kozieł – Malina 2018: 221—236.) Thus, it has been suggested that instead of being used as a continuous measurement of maturity (years from PHV), maturity offset could be used as a categorical value to define maturity status: any below 0 value would classify individuals as pre-PHV, while any above 0 value would classify individuals as post-PHV. It has also been recommended that maturity offset be used with youth between the ages of 13—15 to lower the chance of prediction error (Mirwald et al. 2002: 689—694; Bergeron et al. 2015: 843—851; Malina et al. 2015: 852—859.)

When it comes to estimating predicted adult height, it is worth noting that equations using midparental height have been shown to have a relatively large standard error (3—5cm), but the error decreases with age (Lloyd et al. 2014b: 1454—1464; Malina et al. 2015: 852—859). For more accurate prediction, Beunen et al. (2006: 249) recommend using the percentage of predicted adult height with skeletal age assessment. It should be noted, however, that while using skeletal age assessment with final adult height predictions could make the latter more accurate, is not absolutely necessary when using the prediction of adult method (Lloyd et al. 2014b: 1454—1464). Because the intercepts and coefficients are only determined for half-year intervals in the original study by Khamis and Roche (1994: 504—507), questions can be raised regarding about the method's accuracy for youth who fall between the intervals, for example someone aged 13 years and 9 months, or 13.75 years, as use of intercepts and coefficients requires rounding of ages either up or down. Furthermore, Meylan et al. (2010: 585) urge caution when using the adult height prediction models, as they often fail to differentiate between late maturers and those who simply end up not becoming as tall as the normative data would suggest. Using Z-scores to classify youth as early, on time or late maturing may be difficult, as access to longitudinal data may be limited. Additionally, calculating Z-scores may require the use of complex software or algorithms as calculating them by hand is very arduous and time consuming (Faigenbaum, Lloyd – Oliver 2019: 60).

Finally, most studies validating either the maturity-offset method or the equations for predicted adult height have been done with youth of European or North American ancestry, raising questions of either method's applicability to children and adolescents of other ethnicities (Beunen et al. 2006: 249; Meylan et al. 2010: 585; Malina et al. 2012: 1705—1717; Bergeron et al. 2015: 843—851; Malina et al. 2015: 852—859; Moore et al. 2015: 1755—1764; Myburgh et al. 2019: 1—9).

5 Biological maturation and athletic development

Much like tissue, different components of athletic performance (strength, speed, motor control etc.) develop at different rates and times during the maturational process. What's more, components of athletic performance seem to have so called 'windows of opportunity', periods of time during which the potential for developing certain components through exercise is at its highest (Ford et al. 2011: 7—10; Lloyd – Oliver 2012: 61—67.) To optimize athletic development during youth it is imperative that practitioners involved with youth athletes are aware of different periods of accelerated development and 'windows of opportunity' for increased trainability during the maturational process. While bio-banding may be of most use during adolescence and around PHV, development of athletic performance during preadolescent childhood is discussed as well to give the reader a more comprehensive understanding of the continuum of athletic development throughout maturation. The following chapters will cover the natural development of different components of athletic performance and their trainability at different stages of maturation.

5.1 Motor development

Participation in active play and a variety of sporting activities are vital for motor development and the learning fundamental movement skills. In normally developing children, motor development and learning of fundamental movement skills occurs largely in early and prepubescent childhood, between the ages of 0—12, due to the high neural plasticity associated with those stages of maturation (Ford et al. 2011a: 5; Ford et al. 2011b: 390—392; Lloyd et al. 2016a: 1494.) Children generally learn rudimentary locomotive, stabilizing and manipulating movement skills during very early childhood, between the ages of 0—2, after which they start learning more advanced fundamental movement skills such as running, kicking, jumping, throwing, striking and catching (Jaakkola 2009: 204—242; Lloyd et al. 2016a: 1494—1495). Several studies have identified periods of accelerated brain maturation in children between the ages of 6—8 and 10—12 in both boys and girls. These periods seem to coincide somewhat with the 'windows of opportunity' for motor development proposed by Balyi and Hamilton in their Long-term athlete development model (Ford et al. 2011a: 5; Ford et al. 2011b: 392.) Although it seems there may be increased potential for training-induced motor skill development during childhood (Ford et al. 2011a: 5; Ford et al. 2011b: 392; Lloyd et al. 2016a: 1494, 1497), Ford et al. (2011b: 392) and Lloyd et al. (2016: 1498) among others note that while studies may highlight periods of accelerated motor development during early and preadolescent childhood, there seems to be no evidence of clearly defined ‘windows of opportunity’ for increased motor skill trainability during these periods.

While there seem to be some indicators for increased potential for motor skill trainability in early and prepubescent childhood, it does not mean that later motor development does not occur. Fundamental movement skills learned during childhood may serve as a basis for more complex, sport- or task-specific movement skills that the child or adolescent may later need (Ford et al. 2011b: 392; Lloyd et al. 2016a: 1494—1495). Ford et al. (2011a: 5) cited a study by Viru et al. (1999), where the authors found that girls aged 11—12 and 13—14 learned more precise foot and hand movements the fastest, suggesting that periods of enhanced motor development may occur during the adolescent years as well. Adolescent advances in motor development are further supported by Lloyd et al. (2016: 1498), who note that both children and adolescents can make significant improvements in motor performance. What’s more, as strength is an important part of motor competence, increases in strength have been shown to complement motor development and the execution motor skills. While the effect of strength development on motor skill performance is generally larger in pre- and early-pubertal children compared to adolescents, training-induced increases in strength have been shown to improve motor skill performance in adolescents as well, highlighting that motor development does take place during later stages of maturation (Faigenbaum et al 2009: 8; Jaakkola 2009: 241—242; Behringer – Vom Heede – Matthews – Mester 2011: 186—206; Ford et al. 2011a: 5; Ford et al. 2011b: 392—393, 396; Lloyd et al. 2014a: 499, 503; Lloyd et al. 2016a: 1494—1495.) Practitioners would do well to remember, however, that some individuals go through a period of decreased motor performance during the adolescent growth spurt. This period, also called a period of ‘adolescent awkwardness’, generally occurs about 6 months before PHV, and is characterized by decreased motor control and coordination mainly as a result of rapid rate of limb growth and changes in body center of mass. Disruption in motor competence during adolescent awkwardness may affect adolescent sports performance and increase the risk of injury (Ford et al. 2011b: 395; Lloyd – Oliver 2012: 66; Lloyd et al. 2014b: 1461; Lloyd et al. 2016a: 1498, 1501.) Thus, it is recommended that training is adjusted to reflect the changes in motor competence during this period, and individuals affected by adolescent awkwardness take a step back from more complex motor skill training and instead focus on relearning previous motor control patterns (Lloyd – Oliver 2012: 66; Lloyd et al. 2014b: 1461; Lloyd et al. 2016a: 1501). Motor skill training should be a part of the training programme throughout the maturational process, with the focus changing according to an individual's level of maturation. Based on the studies cited above, it is recommended that motor skill development should focus on rudimentary and fundamental movement patterns during early and prepubescent childhood. Training should move on to more complex, sport- or task-specific skills as the child and adolescent becomes more mature, while being adjusted in case an individual shows signs of pre-PHV adolescent awkwardness (Faigenbaum et al 2009: 8; Jaakkola 2009: 240—242; Behringer et al. 2011: 186—206; Ford et al. 2011a: 5; Ford et al. 2011b: 392—395; Lloyd – Oliver 2012: 66; Lloyd et al. 2014a: 499, 503; Lloyd et al. 2014b: 1461; Lloyd et al. 2016a: 1494—1495, 1501.)

5.2 Energy systems' development

Biological maturity has been shown to have a significant effect on both aerobic and anaerobic capacity and power (Carvalho et al. 2011: 721—727; Carvalho – Coelho-e-Silva – Eisenmann – Malina 2012: 428—434; Ford et al. 2011a: 8; Ford et al. 2011b: 393; Lloyd et al. 2014b: 1461; Bergeron et al. 2015: 844). While children generally have a well-developed aerobic capacity from a very early age onwards, evidence suggests that both absolute and relative aerobic capacity increases with maturity as a result of physical and physiological changes in the body (Riski 2009: 279; Ford et al. 2011a: 8; For et al. 2011b: 393; Bergeron et al. 2015: 844). Increases in aerobic capacity seem to be relatively linear throughout both childhood and adolescence, although several studies have suggested that there may exist periods of accelerated development in both boys and girls. However, evidence for these periods is somewhat equivocal; Viru et al. (1999), for example, identified periods of accelerated development between the ages of 12—16 in both boys and girls using data from longitudinal studies, while reporting that cross-sectional data indicates that the periods take place between the ages of 10—16 in boys and 7—13 in girls (Ford et al. 2011a: 8; For et al. 2011b: 393; Bergeron et al. 2015: 844.)

Results regarding periods of increased trainability of aerobic capacity have been similarly inconsistent. 'Windows of opportunity' for aerobic training have been suggested to exist pre-, circa- and post-PHV, and children and adolescents have been shown to be able to make improvements in aerobic performance in all stages of maturation (Ford et al. 2011a: 8; Ford et al. 2011b: 393—394; Lloyd – Oliver 2012: 66.) Ford et al. (2011a: 8) note that while in theory aerobic performance may be further enhanced through training during the 'windows of opportunity', there is no evidence that suggests that individuals will be unable to achieve their full genetic potential for aerobic performance during adulthood if training does not occur during these periods of accelerated development. In fact, Lloyd – Oliver (2012: 66—67) go as far as suggesting that while aerobic exercise should be carried out throughout childhood and adolescence and could be emphasized more as the individual gets closer to adulthood, it should not be the main focus of training at any point in youth who do sports or are otherwise active. They argue that sport-specific training may be enough to improve sport-specific endurance, and that because many sports do not require high levels of aerobic endurance, sport-specific training will elicit a high enough stimulus to improve aerobic capacity to an adequate level. Their argument is supported by Vamvakoudis et al. (2007: 930—936), Carvalho et al. (2012: 428—434) and Mandroukas and Heller (2019: 21—31) and many others who have shown that participation in sport-specific training improves aerobic performance in young and adolescent team sport athletes. Furthermore, a study by Faigenbaum et al. (2011: 573—583) showed that children and adolescents may be able to improve aerobic performance through training that is not energy system-specific, such as strength training, plyometrics and movement skill practice. Thus, the need for separate aerobic conditioning may be questioned, especially in sports such as association football that have an inherent aerobic component.

Young children’s anaerobic performance capabilities are generally poor compared to adults. While children recover from high intensity exercise faster and are more resistant to fatigue than adults, this is largely attributed to their higher muscle oxidative activity and aerobic ATP production (Ratel – Tonson – Cozzone – Bendahan 2010: 1562—1564; Ford et al. 2011a: 9; Bergeron et al. 2015: 844.) Young children rely largely on the aerobic energy system for energy production, and its been shown that children have reduced potential for rephosphorylation of used ATP (or adenosine diphosphate ADP) through the anaerobic pathways (Armstrong – Welsman – Chia 2001: 118—124; Ratel et al. 2010: 1562—1564; Bergeron et al. 2015: 844). The reliance on the aerobic energy system reduces as the individual matures, however, and the anaerobic-aerobic ratio increases as the body becomes better at utilizing the anaerobic pathways for energy. While the increased reliance on the anaerobic energy system causes the individual to become less resistant to fatigue, both anaerobic capacity and power increase as trade-off as the individual matures (Armstrong et al. 2001: 118—124; Ratel et al. 2010: 1562—1564; Bergeron et al. 2015: 844.) Anaerobic performance increases relatively linearly with maturation in both boys and girls throughout early and prepubertal childhood. Girls generally outperform boys in high intensity efforts until the age of 12 due to their earlier maturation.

After the onset of puberty, however, boys tend to experience a marked increase in anaerobic performance and subsequently outperform girls. In girls, anaerobic performance development stays relatively linear even after the onset of puberty (Armstrong et al. 2001: 118—124; Philippaerts et al. 2006: 221—230; Bergeron et al. 2015: 844.) It is worth noting, however, that although the anaerobic-aerobic ratio changes with maturation, this does not mean that aerobic performance decreases. Instead, as Bergeron et al. (2015: 844) point out, both anaerobic and aerobic performance capabilities increase with maturation, only at differing rates: peak power and mean power as measured by Wingate Anaerobic Test was shown to increase by approximately 120% and 113% in boys and 65% and 60% in girls between the ages of 12—17, while peak oxygen uptake increased by 70% and 50% between the same ages in boys and girls respectively (Armstrong et al. 2001: 118—124; Bergeron et al. 2015: 844.)

Although anaerobic performance capabilities are discussed above as a whole, it may be practical to cover the alactic (or phosphagen) and lactic (or glycolytic) anaerobic energy systems somewhat separately even if the development of the two systems is similar. Where the anaerobic alactic energy system provides energy for short, intense efforts lasting no more than 10 seconds, the anaerobic lactic energy system can supply the body with energy during high intensity exercise for up to 2—3 minutes (Herda – Cramer 2016: 53—55). Where peak anaerobic power relies largely on the alactic system, anaerobic capacity relies on both alactic and lactic systems (Herda – Cramer 2016: 53—55). To fully comprehend anaerobic performance and its development it is necessary to discuss the different components of anaerobic performance separately. The following chapter 5.3 will outline the natural and training-related development of strength, power, plyometric ability and speed throughout the maturational process.

5.3 Development of strength, power, plyometric ability and speed

5.3.1 Strength

Strength development during childhood and adolescence occurs both naturally as the individual matures and through adaptation to exercise stimuli. Strength development is multifactorial and increases through neural and structural (hypertrophy, muscle pennation angle, motor unit differentiation etc.) factors. Natural increases in strength during childhood are largely attributed to the maturation of the central nervous system and subsequent improvements in the ability to recruit more motor units (Hakkarainen 2009: 197;

Sarwark – LaBella 2014: 11; Lloyd et al. 2014a: 499; Bergeron et al. 2015: 844; Brown et al. 2017 2017: 155; Radnor et al. 2018: 57—71.) During childhood strength increases naturally at a relatively linear rate, with only minor differences between boys and girls before puberty. It is after the onset of puberty that major differences in natural strength gain between boys and girls start to become evident. While girls tend to continue gaining strength in a relatively linear fashion throughout childhood and adolescence, boys, on the other hand, experience a rapid increase in strength as a result of increased testosterone and growth hormone levels brought on by puberty and the adolescent growth spurt (Hakkarainen 2009: 197; Lloyd et al. 2014a: 499; Sarwark – LaBella 2014: 11; Lloyd et al. 2014a: 499; Bergeron et al. 2015: 844; Lloyd – Faigenbaum 2016: 138—140; Brown et al. 2017 2017: 152—155.) Naturally occurring pubertal strength gains in boys may largely be attributed to increases in muscle mass and other structural changes, as the rapid increase in strength during adolescence coincides with the period of accelerated muscle growth associated with puberty. (Hakkarainen 2009: 197; Lloyd et al. 2014a: 499; Sarwark – LaBella 2014: 11; Radnor et al. 2018: 57—71.)

Increases in strength as a result of exercise can occur at a very early age. Studies have shown that children as young as 5 years old are able increase their muscular strength through exercise, provided exercise is done regularly and that the exercise programme is well planned and completed over a prolonged period off time (Faigenbaum 2009: 4; Hakkarainen 2009:197—198; Ford et al. 2011b: 396; Lloyd – Oliver 2012: 63—64; Lloyd et al. 2014a: 500; Lloyd et al. 2014b: 1460—1461; Lloyd – Faigenbaum 2016: 140; Brown et al. 2017 2017: 151; Peitz et al. 2018: 1—44). Exercise induced increases in strength before the adolescent growth spurt are largely attributed to neural adaptations such as increased motor unit activation and improved motor control; in fact, training for hypertrophy in prepubescent children has generally been viewed as ineffective due to the low levels of circulating testosterone and human growth hormones (Faigenbaum et al. 2009: 64—65; Hakkarainen 2009: 198, 203—205; Lloyd – Oliver 2012: 63—64; Lloyd et al. 2014a: 502 Lloyd et al. 2014b: 1461; Bergeron et al. 2015: 844; Lloyd – Faigenbaum 2016: 140; Myers – Beam – Fakhoury 2017: 138—139; Peitz et al. 2018: 1—44.) Strength trainability increases with age, especially in boys who benefit from the hormonal changes brought on by puberty. While neural adaptations to exercise continue during adolescence in both boys and girls, exercise induced increases in strength during puberty are greatly enhanced by hypertrophic factors in boys. In girls, exercise induced strength gains are generally not of the same magnitude as in boys due to lower levels of circulating testosterone. (Faigenbaum et al. 2009: 65; Hakkarainen 2009: 197—198, 203—206; Lloyd et al. 2014a: 499, 502; Bergeron et al. 2015: 844; Lloyd – Faigenbaum 2016: 138—140; Myers et al. 2017: 139—140; Peitz et al. 2018: 1—44.)

Peak strength gain occurs generally between the ages of 13—16 in boys and 11—15 in girls (Ford et al. 2011a: 9; Brown et al. 2017 2017: 152—155). In boys, peak strength gain occurs approximately 12—18 months after PHV, following PWV and its associated muscle growth by about a year, while in girls peak strength gain seems to occur immediately after PHV (Ford et al. 2011b: 396; Sarwark – LaBella 2014: 11; Lloyd – Faigenbaum 2016: 138; Brown et al. 2017 2017: 151). However, because the factors related to exercise induced strength gains change as children mature, strength training cannot be said to have one clear ‘window of opportunity’ (Ford et al. 2011b: 396; Lloyd – Oliver 2012: 63—65; ; Lloyd et al. 2016a: 1494—1495, 1498—1499; Lloyd – Faigenbaum 2016: 140). Lloyd and Oliver (2012: 63—65;) and Lloyd et al. (2016: 1498—1499) among others suggest that strength training should be an integral part of youth athletic development throughout the maturational process, as it can be viewed as having several windows of opportunity depending on the factors influencing increases in strength related to the stage of biological maturation. Thus, strength training should focus on neural adaptations before and after the adolescent growth spurt, while taking advantage of the increased potential for hypertrophy during and after puberty and PHV (Ford et al. 2011a: 9—10; Ford et al. 2011b: 396, 398; Lloyd – Oliver 2012: 63—65; Lloyd et al. 2014a: 502; Lloyd et al. 2016a: 1494—1495, 1498—1499; Lloyd – Faigenbaum 2016: 140; Peitz et al. 2018: 1—44.)

5.3.2 Power and plyometric ability

Like strength, the ability to produce power improves naturally as children progress in maturation (Philippaerts et al. 2006: 221—230; Carvalho et al. 2011: 721—727; Ford et al. 2011a: 9; Ford et al. 2011b: 396—397; Lloyd – Oliver – Hugher – Williams 2011: 1889—1897; Sahrom – Cronin – Harris 2014). Power is the product of force and velocity, and as such strength, or the ability to produce force, has major implications for the development of power. Muscular power, both absolute and relative, is generally very poor in young children. It is generally accepted that the reduced capacity for power production in children is most likely due to underdeveloped neuromuscular and hormonal factors (Ford et al. 2011a: 9; Lloyd et al. 2016a: 1495.) Natural development of muscular power occurs on a somewhat similar trajectory with strength. Power development is relatively linear in early and prepubescent childhood. Boys tend to perform better than girls when maturation is accounted for. The gender difference in performance increases with maturation, indicating a more marked increase in power occurs in after the onset of puberty in boys, while in girls the development stays relatively linear (Ford et al. 2011b: 397; Lloyd – Meyers – Oliver 2011: 24; Sahrom et al. 2014.) Albeit inconclusive, studies have identified two possible periods of accelerated power development during the maturation, with the first period occurring during prepubescent childhood, between the ages of 7—11 and 6—9 in boys and girls respectively, and the second one taking place around and after PHV, between the ages of 13—16 and 10—12 in boys and girls, respectively (Philippaerts et al. 2006: 221—230; Carvalho et al. 2011: 721—727; Ford et al. 2011a: 9; Ford et al. 2011b: 396—397; Lloyd et al. 2011b: 1889—1897). Power development during prepubescent childhood is largely the result of neural adaptations and motor skill development, while adolescent power development is more due to a combination of hormonal, neuromuscular and mechanical factors (Ford et al. 2011b: 397; Sahrom et al. 2014).

Studies have shown that increases in body fat free mass and dimensions correlate highly with increases in power. Peak power development seems to coincide with PWV when measured using the counter-movement jump (CMJ), squat jump (SJ) or the cycle ergometer protocols, with accelerated development continuing up to 1 year after PHV (Armstrong et al. 2001: 118—124; Carvalho et al. 2011: 721—727; Ford et al. 2011b: 397; Lloyd et al. 2011b: 1889—1897; Sahrom et al. 2014; Deprez et al. 2015: 1—8.) Interestingly, several studies have shown a decrease in CMJ-SJ ratio with maturation. While the exact reason is unclear, several explanations have been suggested for this phenomenon, such as increase in contractile element length and contraction velocity in the musculotendinous unit (Temfemo – Hugues – Chardon – Mandengue – Ahmaidi 2009: 457—464; Sahrom et al. 2014), imbalances in muscle and tendon development (Mersmann et al. 2017: 1—18), changes in the elastic properties (compliance, stiffness etc.) of the musculotendinous unit (Sahrom et al. 2014) and stretch-shortening cycle (SSC) function and associated movement variability (Sahrom et al. 2014; Suchomel – Sands – McNeal 2016: 15—30). Lloyd et al. (2011: 1889—1897) and Sahrom et al. (2014), however, suggested that the decrease in ratio is most likely due to differences in the development of eccentric and concentric strength and power, as maturation seems to have a more marked positive effect on concentric strength and power compared to eccentric strength and power. Sahrom et al. (2014) even suggest that eccentric capability seems to decrease with maturation, especially in girls. This may have implications to power trainability which are covered later in the chapter.

Because the SJ does not use the stretch reflex and the CMJ is categorized as a slow SSC action (ground contact time GCT>500ms), and because both are so highly reliant on strength and muscular power, they may not provide enough insight regarding plyometric ability and fast SSC (GCT<250ms) function (Lloyd et al. 2011b: 1889—1897; Sahrom et al. 2014). Plyometric ability, however, is an important part of athletic performance and rapid force and power production and as such its development and trainability should be covered in this thesis. Plyometric ability is dependent on the function of stretch-shortening cycle (SSC), a sequential pattern of eccentric, isometric and concentric muscle actions that relies on elastic energy and reflex muscle activity to produce faster and stronger, i.e. more powerful, concentric force output (Lloyd et al. 2011a: 23). Fast SSC performance has been shown to increase with maturation when measured using maximal and submaximal hopping tests to assess reactive strength and leg stiffness (Lloyd et al. 2011b: 1889—1897; Laffaye – Choukou – Benguigui – Padulo 2016: 29—35; Radnor et al. 2018: 57—71). Plyometric development is highly dependent on the same neuromuscular adaptations associated with other components of performance (strength and motor skill, for example) and maturation. Efficient SSC function, both fast and slow, requires sufficient interaction between the neural and muscular systems and the musculotendinous unit, meaning SSC development is strongly linked with both structural and neural factors, such as muscle and tendon size and stiffness, muscle strength and motor unit recruitment, reflex control etc. (Lloyd et al. 2011b: 1889—1897; Lloyd et al. 2011a: 24; Sahrom et al. 2014; Radnor et al. 2018: 57—71.)

Laffaye et al. (2016: 29—35) found that reactive-strength index (RSI) and jump height improved significantly between the ages of 13—20 in boys, with a more marked increase between the ages of 13—16. In girls, RSI improved between the ages of 13—16 and 19—20 while jump height increased from age 13 until age 16. In both categories the increases in performance were much higher in boys than in girls. In boys, leg stiffness was found to increase progressively from age 11 until age 20, while in girls leg stiffness fluctuated, with two distinct peaks between the ages of 15—16 and 19—20. It may be worth noting that in girls, RSI and leg stiffness performance decreased between the ages of 17—18 when compared with the 15—16 age group while jump height decreased from age 17 onwards (Laffaye et al. 2016: 29—35.) The authors postulate that the most likely explanation is the increase in body mass, and especially fat mass, most girls experience during adolescence (Laffaye et al. 2016: 29—35); this has implications to training prescription and injury risk, both of which will be discussed in more detail later in the thesis.

While periods of accelerated development for plyometric ability may be difficult to accurately identify, based on the study by Laffaye et al. (2016: 29—35) cited above they could be suggested to exist roughly between the chronological ages of 13—16 for both boys and girls, with girls experiencing another accelerated period for reactive strength and leg stiffness around the ages of 19—20 after a period of decreased performance. For boys, this is supported by a study by Lloyd et al. (2011: 1889—1897) who identified one ‘almost certain’ and another ‘very likely’ period of accelerated development between the ages of 10,5—12 and 13—14 and possibly 15—17. Put in terms of maturity and PHV, it seems there exist periods of accelerated development for plyometric ability pre- and post-PHV, with some individuals experiencing a period of decreased performance circa-PHV (Lloyd et al. 2011b: 1889—1897). These periods coincide somewhat with those of strength, power and motor skill performance as noted by Lloyd et al. (2011: 1889—1897) when discussing improvements in CMJ and SJ, highlighting the multifactorial nature of plyometric ability.

Evidence regarding periods of increased trainability for both power and plyometric ability is equivocal. While it seems there may exist periods of accelerated natural development for power and plyometric ability, Lloyd et al. (2011: 1889—1897), Ford et al. (2011a: 9) and Ford et al. (2011b: 397) among others note that the existence of periods of accelerated natural development does not mean that periods of increased trainability exist. Ford et al. (2011b: 397) suggest that a possible explanation to the uncertainty of the existence of ‘windows of opportunity’ for power and plyometric training is the fact that since power is the result of force and velocity, or strength and speed, periods of increased trainability are strongly linked with those of strength and speed and as such have already been accounted for. Evidence does, in fact, show that improving power and plyometric performance is possible throughout maturation, with both children and adolescents having shown worthwhile training-related improvements in power and plyometric performance (Faigenbaum et al. 2011: 573—584; Lloyd et al. 2011a: 24; Lloyd – Oliver 2012: 65; Lloyd – Radnor – De Ste Croix – Cronin – Oliver 2016b: 1239—1247; Behm et al. 2017: 1—37.) However, there seems to be maturation-related variation on the most appropriate training methods for improving power and plyometric performance. Studies that have compared the training effect of plyometric-only, resistance-only, power-only (Olympic weightlifting) and combined resistance, power and plyometric training in children and adolescents have found that youth in the pre-PHV stage of maturation seem to have a more favourable training response to plyometric-only training compared to their circa- and post-PHV counterparts, while also benefitting more from plyometric-only and power-only training compared to resistance-only or combined resistance and plyometric training (Lloyd et al. 2016b: 1239—1247; Peitz et al. 2018: 1—44; Radnor et al. 2018: 57—71.) A possible explanation to the increased training response can be found in the increased potential for neural adaptation associated with early and prepubescent childhood: training induced improvements in muscular power, plyometric ability and SSC function are most likely due to motor learning and neural adaptations, such as improved motor unit recruitment and contraction velocity, pre-activation and stretch reflex (Lloyd et al. 2011a: 24; Lloyd et al. 2016b: 1239—1247; Radnor et al. 2018: 57—71). On the other hand, youth in the circa- and post-PHV phases seem to benefit most from combined resistance and plyometric training when compared to plyometric- and resistance-only training. This has been attributed to the periods of accelerated natural development and concurrent period of increased strength trainability occurring in circa- and post-PHV adolescence (Lloyd et al. 2011b: 1889—1897; Lloyd et al. 2016b: 1239—1247; Behm et al. 2017: 1—37; Peitz et al. 2018: 1—44; Radnor et al. 2018: 57—71.) Because maturation seems to influence concentric strength and power more than eccentric strength and power as mentioned above, circa- and post-PHV youth seem to have decreased eccentric capability and thus decreased potential for increasing concentric strength/power using the SSC. Focusing more on resistance training to increase strength and muscle stiffness may enable circa- and post-PHV youth to better utilize the SSC, as increased strength may help the athlete absorb high impact forces in shorter time, thus improving SSC fuction (Potach – Chu 2016: 472—474; Behm et al. 2017: 1—37; Radnor et al. 2018: 57—71.)

To sum up, power and plyometric training should focus more on plyometric training before PHV, while increasing the emphasis on strength and power training as children mature and enter puberty. Key words here are focus and emphasis, however, as no training modality should be used as a stand-alone training programme for performance improvement despite the studies above using programmes consisting only of one training modality. Resistance, power and plyometric training should be part of a well-rounded and varied training programme that is periodized to change focus when developmentally appropriate to ensure optimal long-term athlete development (Lloyd et al. 2016b: 1239—1247; Behm et al. 2017: 1—37.) A prolonged period of strength motor skill training may be necessary before commencing more complex power and plyometric training to establish an adequate base of strength and motor competency for power production and SSC function (Deprez et al. 2015: 1—8; Potach – Chu 2016: 478—479; Behm et al. 2017: 1—37; Peitz et al. 2018: 1—44). Care should be taken to ensure that plyometric training is not overdone, especially during PHV, as this may increase the risk of injury. Training should progress from simple to complex, taking into account the significant role motor learning and competence has on power production and plyometric ability (Lloyd et al. 2011a: 23—32; Lloyd – Oliver 2012: 61—72; Potach – Chu 2016: 478—479; Mersmann et al. 2017: 1—18.) While boys can progress into more challenging power and plyometric training, care should be taken when programming plyometric training for girls after around the age of 15, when power and plyometric performance tends to decrease (Laffaye et al. 2016: 29—35).

5.3.3 Speed

Speed, like other components of performance, has been shown to increase naturally with maturation. Speed develops naturally at similar rates in both boys and girls during early and prepubescent childhood, with an early period of accelerated development suggested to take place between the ages of 5—7 in both sexes. Accelerated speed development during this period is largely attributed to the significant development of the central nervous system and motor coordination during childhood (Philippaerts et al. 2006: 221—230; Ford et al. 2011a: 9; Ford et al. 2011b: 394—395; Meyers et al. 2015: 85—94.) Another period of accelerated development is suggested to occur during puberty around the age at PHV, or chronological ages of 12—15 in boys and 11—13 in girls. This is where peak speed development tends to occur (Philippaerts et al. 2006: 221—230; Ford et al. 2011a: 9; Ford et al. 2011b: 394—395; Meyers et al. 2015: 85—94). Body dimensions have been shown to greatly affect speed performance in both sexes; the rapid changes in leg length associated with the adolescent growth spurt have been shown to increase stride length, positively affecting sprint speed (Meyers et al. 2015: 85—94). It is worth noting that stride frequency tends to decrease, and ground contact time tends to increase in pre-PHV youths, and that speed performance may, in fact, decline during this period, at least in some individuals. This is most likely due to the loss of motor coordination associated with adolescent awkwardness (Philippaerts et al. 2006: 221—230; Ford et al. 2011b: 395; Meyers et al. 2015: 85—94.)

In addition to neural development and somatic growth, increase in speed performance during the adolescent growth spurt is suggested to result from structural and hormonal changes in the musculotendinous unit, such muscle cross-sectional area and length, selective type IIb fiber hypertrophy, muscle-tendon stiffness and the size of the musculotendinous junction (Ford et al. 2011b: 394—395; Meyers et al. 2015: 85—94.) This is especially true for adolescent boys, who benefit significantly more from hormonal changes associated with puberty compared to girls and, as a consequence, tend to outgain girls in strength, power and lean mass during adolescence, while girls' performance is hindered by increased fat mass (Ford et al. 2011b: 394).

Periods of increased speed trainability are difficult to identify due to the multifactorial nature of speed; speed is, after all, build on a foundation strength, explosive power, efficient SSC function and motor competency. Given that all the other components of performance seem to be trainable throughout childhood and adolescence, it is not inconceivable that speed should be trainable throughout maturation as well. Although one clear 'window of opportunity' for speed development cannot be said to exist with certainty, speed has, in fact, been shown to be trainable throughout childhood and adolescence. However, like with power, there seems to be variance in the most appropriate method of training depending on maturation (Philippaerts et al. 2006: 221—230; Ford et al. 2011a: 8—9; Ford et al. 2011b: 394—395; Lloyd – Oliver 2012: 66—67; Meyers et al. 2015: 85—94; Behm et al. 2017: 1—37; Radnor et al. 2018: 57—71: Peitz et al. 2018: 1—44.)

Speed trainability follows that of power and plyometric ability quite closely. Young children and children in the pre-PHV stage seem gain the biggest speed-related benefits from training that emphasizes motor skill and plyometric training due to the increased potential for neural adaptations associated with earlier stages of maturation (Philippaerts et al. 2006: 221—230; Ford et al. 2011b: 394—395; Meyers et al. 2015: 85—94). Training for speed pre-PHV should focus on improving SSC function and motor skills such as running technique and balance to build technical competency on which to build upon at later stages of maturation, with the aim of reducing ground contact time and improving stride frequency (Lloyd – Oliver 2012: 65; Meyers et al. 2015: 85—94; Behm et al. 2017: 1—37; Peitz et al. 2018: 1—44). While simpler plyometrics and motor skill training may be necessary for some circa-PHV youth, neural training should continue to progress throughout adolescence, from simple and less intense to complex and more intense drills and movements (Lloyd – Oliver 2012: 65; Meyers et al. 2015: 85—94). From PHV onwards, strength and rate of force development should be emphasized in training to fully take advantage of the increased potential for strength and muscle mass, as improving strength will enable better force application and absorption, thus improving SSC function and running speed (Philippaerts et al. 2006: 221—230; Lloyd – Oliver 2012: 65; Meyers et al. 2015: 85—94; Behm et al. 2017: 1—37; Peitz et al. 2018: 1—44.)

6 Biological maturation and injury

Increased prevalence of both acute and overuse has been associated with biological maturation. Differential growth rates of bone, muscle and tendon during maturation expose children and adolescents to varying kinds of injury during the maturational process. Maturation-related changes in bone, muscle and tendon structural and functional properties, body mass and body dimensions, as well as the developmental changes in strength and motor skill, all influence the risk of injury to a varying degree (Ford et al. 2011a: 4; Bergeron et al. 2015: 845—846; Lloyd et al. 2016a: 1498; Johnson et al. 2019: 1—9.) The adolescent growth spurt has been strongly linked to increased risk of injury, and injury incidence does seem to peak during this period in the youth athletic population. It is during the adolescent growth spurt that the changes in body structures and function tend to occur most rapidly. As added stressors, training and competition demands tend to increase with chronological age, resulting in increased total workload and reduced time for recovery during adolescence (Hawkins – Metheny 2001: 1701—1707; Caine et al. 2014 1—10; DiFiori 2010: 372—378; Ford et al. 2011a: 4; DiFiori et al. 2014: 287—288; Bergeron et al. 2015: 845; Lloyd et al. 2016a: 1498; Longo et al. 2016: 139—159; Johnson et al. 2019: 1—9.) The early demand for single sport specialization even in team sports such as association football results in increased homogeneous, repetitive stress, increasing the risk of injury in youth (Lloyd et al. 2014b: 1454—1464; Bergeron et al. 2015: 845; Lloyd et al. 2016a: 1495; Arnold et al. 2017: 139—147; Read – Oliver – Myer – De Ste Croix – Lloyd 2018a: 168—175). Because practitioners in youth sport have such a huge influence on injury mitigating or aggravating factors, it is imperative that they understand the risk factors concerning the maturing athlete.

Maturity status and timing should be considered when discussing injury risk factors. While maturity status may affect risk factors interindividual size difference, maturity timing affects injury risk factors that are dependent on the timing of different maturational changes in body structure and function, such as differential growth and changes in motor competency. Early maturing athletes may be at an increased risk of injury, as they tend to experience a more intense growth spurt. On the other hand, late maturing athletes go through a period of rapid growth at a chronological age where intensity of training and competition tend to increase markedly, raising the risk of both acute and overuse injuries (Cumming et al. 2017: 34—47; Johnson et al. 2019: 1—9.) Circa-PHV athletes have been shown to be at a higher risk of both acute and overuse injury compared to pre- and post-PHV athletes, and injury risk has been shown to peak during the adolescent growth spurt around the age at PHV. (Caine et al. 2006: 750; Malina et al. 2006: 214—222; Caine et al. 2008: 21, 29; DiFiori 2010: 372—378; Caine et al. 2014: 1—10; DiFiori et al. 2014: 287—288; Lloyd et al. 2016a: 1498; Longo et al. 2016: 141; Nguyen et al. 2017: 29; Corso 2018: 156; Read et al. 2018a: 168—175; Read et al. 2018b: 48—53; Johnson et al. 2019: 1—9; Malina et al. 2019: 1671—1685.) Thus, when discussing maturity-related injury risk, the following chapters 6.1 and 6.2 will discuss them mostly in the context of maturity timing, more specifically in relation to age at and around PHV. Acute and overuse injuries will be discussed in separate chapters, because while the maturity-related risk factors are similar, difference in injury mechanism merits them being discussed separately. Where acute injuries are caused by a sudden, often traumatic incident that is clearly identifiable, overuse injuries are caused gradually by inadequate recovery from repetitive exercise induced microtrauma and as such they do not have a clearly identifiable beginning (Pfirrmann – Herbst – Ingelfinger – Simon -- Tug 2016: 410—424; O'Kane et al. 2017: 1).

6.1 Maturation and acute injuries

The differential growth of tissues and body dimensions exposes the maturing athlete to acute injuries that are rarely seen in the adult athlete. The physes and articular cartilage of children and adolescents is more vulnerable to fractures and apophyseal avulsions related to traction forces than the mature adult bone (Hawkins – Metheny 2001: 1701—1707; DiFiori 2010: 372—378; Ford et al. 2011a: 4; Caine et al. 2014: 1—10; Lloyd et al. 2016a: 1498; Longo et al. 2016: 139—159; Nguyen et al. 2017: 28). Due to their role and placement in bones, epiphyseal and apophyseal growth plates in the lower extremities are especially susceptible to injury, as they are subject high axial and traction forces during locomotion. During growth and maturation, the physis seems to be the weakest structure in the growing body, with up to 15% of all fractures involving the physis (Caine et al. 2006: 750—751; Sarwark – LaBella 2014: 7—8; Longo et al. 2016: 139—159; Nguyen et al. 2017: 28.) The risk of acute injuries to the physes becomes especially pronounced during the adolescent growth spurt and age at PHV, when bone growth is at its fastest and the growth plates grow thicker and weaker. Apophyseal growth plate stress is increased by longitudinal soft tissue growth lagging behind that of bone, which results in increased musculotendinous tension and subsequently exposes the apophyses to higher traction forces (Hawkins – Metheny 2001: 1701—1707; Caine – Maffulli – Caine 2008: 21, 29; DiFiori 2010: 372—378; Ford et al. 2011a: Caine et al. 2014: 1—10; 4; Nguyen et al. 2017: 29—30; Johnson et al. 2019: 1—9.) Changes in musculotendinous structure and functional properties result in decreased flexibility with maturation. Although evidence is inconsistent regarding the relationship between flexibility and injury risk, decreased flexibility reduces joint range of motion which, in turn, has been linked to increased risk of acute musculoskeletal injury (Cejudo et al. 2019.) Growth in limb length and weight increases limb moment of inertia, requiring higher muscle forces for movements about the joints. The maturing muscles may adapt relatively quickly to increased force demands, but the apophyses may not, increasing the stress caused by increased muscle force on the apophyses (Hawkins – Metheny 2001: 1701—1707; Caine et al. 2006: 750; DiFiori 2010: 372—378; Read et al. 2018b: 48—53.) With the above combined with high eccentric forces and high intensity explosive movements common in many sports, significant increase in the risk of apophyseal avulsion fractures occur in the maturing athlete because the physis tends to give before muscle or tendon. Indeed, mechanisms that typically cause sprained ligaments, muscle strains or torn tendons in adults commonly result in avulsion fractures in youth (Caine et al. 2006: 750; Caine et al. 2014: 1—10; Longo et al. 2016: 139—159; Nguyen et al. 2017: 30.) While the onset of acute apophyseal fractures is generally traumatic, it should be noted that chronic traction injuries such as apophysitis due to repetitive stress increase the risk of and can also result in an avulsion fracture (Longo et al. 2016: 139—159).

The risk of acute, traumatic injuries more commonly seen in the adult population also increases with maturation. Rapid growth in bone length together with lagging bone mineralization causes the bones to become more porous and weak, significantly increasing the risk of fractures around the age at PHV (Caine et al. 2006: 750; Caine et al. 2008: 21, 29; DiFiori 2010: 372—378; Caine et al. 2014: 1—10; Lloyd et al. 2016a: 1498; Longo et al. 2016: 141; Nguyen et al. 2017: 29). While rare among younger youth athletes, risk of musculotendinous injury increases with maturation, especially in the lower limbs (Nguyen et al. 2017: 34). Altered neuromuscular properties, such as decrease in motor performance during the period of adolescent awkwardness, leg dominance, muscle asymmetries and joint malalignment may increase the risk of knee or ankle ligamentous injury and fracture in adolescents (DiFiori et al. 2014: 287—288; Read – Oliver – De Ste Croix – Myer – Lloyd 2016a: 1059—1066; Lloyd et al. 2016a: 1497; Read – Oliver – De Ste Croix – Myer – Lloyd 2018c: 372—378). Adolescent gains in body mass increase the risk of lower body injury. The effect of weight gain on injury risk is more pronounced in girls, as they tend to gain weight faster than their strength increases. Adolescent girls seem to be at especially high risk of suffering anterior cruciate ligament (ACL) injuries during adolescence due to the combination weight gain, hormonal changes and joint laxity and the neuromuscular factors mentioned above (Caine et al. 2014: 1—10; Lloyd et al. 2014b: 1458; Lloyd et al. 2016a: 1498; Sabato – Walch – Caine 2016: 99—113; O'Kane et al. 2017: 1—8.)

6.2 Maturation and overuse injuries

Repetitive, submaximal stress from sports practice exposes the maturing athlete to stress-related overuse injury. The effect of repetitive stress due to sports practice tends to increase with age, as training becomes more homogenous due to sport specialization and training volume is increased at the expense of recovery; in fact, disproportionate training volume combined with repetitive and unvarying movement patterns and inadequate time for rest and recovery is the most significant individual risk factor for overuse injury in children and adolescents (Caine et al. 2006: 753—757; DiFiori et al. 2014: 287—288; Bergeron et al. 2015: 845; Longo et al. 2016: 139—159; O'Kane et al. 2017: 7.) Maturation, however, brings other factors to the table that predispose the young athlete to overuse injuries seldom seen in mature athletes.

Risk factors of overuse injuries related to maturation are much like those of acute injuries. Increased musculotendinous tension due to differential longitudinal bone and soft tissue growth increases stress in the osteotendinous junctions, predisposing the growing athlete to overuse-related traction apophysitis, which may eventually lead to avulsion fracture (Ford et al. 2011: 4; Bergeron et al. 2015: 845; Longo et al. 2016: 139—159; Nguyen et al. 2017: 36; Corso 2018: 156.) Differential changes in the structural and muscular properties combined with differential tissue adaptation to exercise expose the maturing athlete to overuse soft tissue injury, such as tendonitis due to increased stress in the musculotendinous junction (Hawkins – Metheny 2001: 1701—1707; Mersmann et al. 2017: 1—18). Growth-related increases in body dimensions, mass and limb moments of inertia increase the risk of stress fractures in the physes and joint surfaces of the spine and the extremities, osteochondral lesions in the joints and stress-related overuse injuries in the tendons (Hawkins – Metheny 2001: 1701—1707; DiFiori 2010: 373; Bergeron et al. 2015: 845; Launay 2015: 139—147; Nguyen et al. 2017: 37—38). The risk of overuse injury in youth athletes increases significantly during the adolescent growth spurt and, like mentioned above, injury incidence seems to peak in athletes who are circa-PHV (DiFiori et al. 2014: 287—288; Johnson et al. 2019: 1—9).

6.3 Common injuries and injury risk factors in association football

Considering the sport-specific demands and commonly occurring movements patterns in association football, it is no surprise that lower body is the most prominent site of injury in youth football players. Lower body injuries in youth association football account for up to 70—80% of all injuries (Koutures et al. 2010: 410—414; Read et al. 2016a: 1059—1066). Acute injuries account for roughly two thirds of all injuries, with overuse injuries accounting for roughly a third (Pfirrmann et al. 2016: 410—424).

The most common acute injuries seem to be different types of strains, sprains and contusions with the upper leg, knee and the ankle being the most common areas of injury (Koutures et al. 2010: 410—414; Pfirrmann et al. 2016: 410—424; Read et al. 2016a: 1059—1066). There are several risk factors for acute injury to the lower limb that are inherent to association football. While some of them are injury risk factors even with maturity is accounted for, maturation may play a part in their significance and mitigation. Read et al. (2016a: 1059—1066) suggested that football predisposes players to altered neuromuscular performance and control during common, sport-specific dynamic activities which, in turn, makes the players more susceptible to injury. The authors noted that movements that require rapid deceleration increase quadriceps dominance due to their high eccentric demands on knee extensors. The quadriceps adapt to the demands of practice and competition and subsequently increase in strength, while the hamstrings are left without similar stimuli, increasing the imbalance between the muscle groups. Quadriceps dominance has been linked with increased risk of ligamentous injury at the knee, especially that of the ACL due to higher ground contact and shear forces (Read et al. 2016aa: 1059—1066; Read et al. 2018b: 48—53; O'Kane et al. 2017: 6.) Reduced knee flexion due to quadriceps dominant landing strategies has been linked with increased knee valgus during landing and deceleration (Walsh – Boling – McGrath – Blackburn – Padua 2012: 406—413; Read et al. 2018b: 48—53). Increased knee valgus alignment during movements that require hip and knee flexion has been noted in youth footballers, indicating joint malalignment as a risk factor inherent to the sport. Increased knee valgus has been linked to altered landing kinematics, predisposing players to acute injuries in the knee, specifically injuries to the ACL and the MCL (medial collateral ligament) and the meniscus (Read et al. 2016a: 1059—1066; Read et al. 2018b: 48—53; O'Kane et al. 2017: 6.) Read et al. (2018b: 48—53) showed increased landing forces (both absolute and normalized to bodyweight) in circa-PHV male football players, indicating that quadriceps dominance may be a more significant injury risk factor for lower body injuries during PHV. In another study (Read et al. 2018c: 372—378), the same authors found knee valgus moment to be more prominent in pre- and circa-PHV footballers compared to their post-PHV counterparts, indicating it as a more significant injury risk factor during earlier stages of adolescence.

Leg dominance is another risk factor inherent to association football. Leg dominance has been found to be evident already in early childhood in youth footballers, but seems to increase around the age at PHV, suggesting leg dominance to be a more significant injury risk factor close to PHV. Interlimb asymmetries, however, seem to be task-specific. The non-preferred limb seems to perform better in tasks requiring stability and force absorption; this is most likely explained by the demand to stabilize on the stance leg repeatedly during kicking in practice and games, resulting in asymmetrical training adaptation between the limbs. The preferred limb, on the other hand, seems to perform better in task requiring coordination and sub-maximal high velocity movements, such as kicking the ball (Read et al. 2016a: 1059—1066; Read et al. 2018a: 168—175; DeLang – Rouissi – Bragazzi – Chamari – Salamh 2019: 551—562.) A difference of 15% in interlimb performance has been linked with increased risk of acute knee injury, especially in the weaker limb as it is subjected to increased stress during common sport-specific movements such as sprinting and cutting (Read et al. 2016a: 1059—1066; Read et al. 2018a: 168—175). Interestingly, Read et al. (2018c: 372—378) found knee valgus interlimb asymmetry to increase markedly in circa-PHV football players, suggesting a link between leg dominance and knee valgus.

Poor dynamic balance and trunk control due to the core musculature’s inability to meet the inertial demands of the limbs and the trunk have been shown to increase risk of injury in youth football players. The inability to resist trunk and limb motion seems to peak in post-PHV adolescence. Maturity-related factors predisposing players to poor balance and trunk control include rapid growth in limb length and body mass and subsequent changes in the center of mass (Read et al. 2016a: 1059—1066; Pappas – Shiyko – Ford – Myer – Hewett 2016: 107—113; Read et al. 2018b: 48—53.) Excessive ipsilateral trunk lean has been observed in youth football players during movements that require stabilization of the body on a single lower extremity, such as cutting, landing and kicking the ball; excessive lateral trunk flexion has also been suggested to be a compensatory movement pattern to reduce the demand on hip and trunk stabilizers, suggesting a connection may exist between leg dominance and excessive ipsilateral trunk lean. Lateral trunk lean has been shown to increase knee valgus, increasing risk of acute ligamentous injury to the knee. It may also contribute to overuse injuries such as patellofemoral pain syndrome because of the resultant shift of the ground reaction force vector more laterally to the knee (Read et al. 2016a: 1059—1066; Pappas et al. 2016: 107—113; Read et al. 2018b: 48—53.) Poor trunk control seems to be a significant risk factor especially in female football players and it has been linked with increased risk of ACL injury (Pappas et al. 2016: 107—113).

While fractures seem to account for only a small fraction of acute injuries in youth association football (Pfirrmann et al. 2016: 410—424), it should be noted that Longo et al. (2016: 148) found that acute apophyseal injuries may account for up to 16% of all injuries in some sports. As such, apophyseal fractures merit some consideration. Apophyseal avulsion fractures tend to occur around the hip or the upper leg area, at sites such as the iliac spines (spinae iliacae) and ischial tuberosity (tuber ischiadicum) due their narrow tendon insertions. Sprinting at practice or during games exposes the anterior superior iliac spine and ischial tuberosity to high traction forces may cause an acute avulsion fracture at either site. The prevalence of high intensity kicking predisposes the anterior inferior iliac spine to avulsion fracture due to intense traction caused by the strong rectus femoris muscle during hip flexion (Launay 2015: 142.) The most common overuse injuries in youth association football involve the physes. In younger players Sever's disease seems to be the most common overuse injury, resulting from repetitive traction of the Achilles tendon on the calcaneal apophysis (Launay 2015: 143—145; Nakase et al. 2015: 1277—1281; Malina et al. 2019: 1671—1685.) Osgood-Schlatter's disease in the knee is seen in football players during the adolescent growth spurt, resulting from a combination of maturity-related risk factors, such as differential longitudinal growth and increased musculotendinous tension, weight gain and decreased flexibility, and football-related risk factors, such as chronic repetitive traction of the patellar tendon, quadriceps dominance (Suzue et al. 2014: 369—373; Launay 2015: 143—145; Nakase et al. 2015: 1277—1281; O'Kane et al. 2017: 6; Malina et al. 2019: 1671—1685). Especially worrisome are overuse injuries to the spine. Sakai – Sairyo – Suzue – Kosaka – Yasui (2010: 281—288) reported lumbar spondylolysis rates of up to 30% of youth athletes across sports, although they did note that prevalence varies depending on the sport. While prevalence may not be as high as 30% in youth association football, lumbar spondylolysis does still occur in the sport. Sakai et al. (2010: 281—288) reporting rates of approximately 9% in Japanese adolescent football players, while Shah and colleagues (Shah – Cloke – Rushton – Shirley – Deeha 2014: 1—9), reported 4% of players with lower back pain as having lumbar spondylolysis. Suzue et al. (2014: 369—373) noted that the injury seems to be more common during adolescence compared to prepubescent childhood, indicating rapid growth as a risk factor for spondylolysis. Lumbar spondylolysis risk factors such as repetitive hyperextension, hyperflexion, and axial rotation in the lumbar spine during movements such as kicking the ball are common in football, predisposing the players to spinal injury (Sakai et al. 2010: 281—288; Shah et al. 2014: 1—9; Plais et al. 2019: 367—373).

A worrying overuse injury occurring in youth football players due to morphological adaptation to repetitive stress is the Cam-type femoroacetabular impingement. Repetitive movement patterns such as kicking in football may cause a cam-type deformity to form on the femoral head, causing abnormal contact between the femoral head and the hip bone, pain and preventing normal, fluid movement and full range of motion. Early sport specialization and resultant frequent (≥4 per week) participation in football activities especially during the adolescent growth spurt have been shown to increase the risk of Cam-type femoroacetabular impingement (Agricola et al. 2014: 798—806; Read – Oliver – De Ste Croix – Myer – Lloyd 2016b: 2295—2302.)

6.4 Injury prevention strategies

Injury prevention in youth sports should be a multifaceted, continuous process involving coaches and other staff, the players, and their parents. Stakeholder education on the effect of maturation on injury risk should be a part of any injury prevention programme. Staff education may help with injury prevention by improving athlete monitoring. The knowledgeable practitioner will be able to identify changes in neuromuscular performance and address individual deficiencies in movement skill and athletic performance, helping to reduce injury risk (DiFiori 2010: 377; Bergeron et al. 2015: 843—851; Launay 2015: 146.) Education of staff, parents and players may aid early identification of signs of overuse injury, enabling early intervention and helping prevent more serious injury (DiFiori 2010: 377; Myer et al. 2011: 155—166; Shah et al. 2014: 1—9; Lloyd et al. 2016a: 1499; O’Kane et al. 2017: 6). Parents and players should be educated on good habits that help reduce injury risk, such as balanced diet and adequate hydration and sleep. Educating the players on injury prevention strategies may improve compliance to the injury prevention programme, enhancing its effectiveness (Pfirrmann et al. 2014: 410—424; Launay 2015: 146; Lloyd et al. 2016a: 1499; Longo et al. 2016: 139—159.)

Frequent monitoring growth and maturation during childhood and adolescence should be a priority in injury prevention because many of the risk factors associated with injury during youth are related to maturation. Risk of both acute and overuse injury seems to peak during the adolescent growth spurt and PHV, meaning training should be adjusted based on growth and maturation. Knowledge on how to assess maturity and how make training adjustments based on maturity status and timing is vital to injury prevention, highlighting the importance of staff education (Caine et al. 2006: 757—758; DiFiori 2010: 377; Launay 2015: 146; Lloyd et al. 2016a: 1499 Longo et al. 2016: 139—159.)

Injury prevention during childhood and early adolescence should focus on building a robust base of movement skills through free play and participation in varied structured activities, such as organized sports. Participation in multiple sports can help reduce training repetitiveness and add variance to training, exposing children and adolescents to a wider range of movements and reducing the risk of overuse injury. Early participation in strength and conditioning activities has been shown to decrease injury risk by improving motor control and competence, reducing training repetitiveness and by helping meet the demands of the sport as the child or adolescent progresses to higher level training and competition (Myer et al. 2011: 155—166; Bergeron et al. 2015: 843—851; Launay 2015: 146; Lloyd et al. 2016a: 1497; Longo et al. 2016: 139—159; Read et al. 2016b: 2295—2302; Arnold et al. 2017: 139—147.) Targeted actions can be taken to mitigate risk of injury. Training during preadolescence and pre-PHV should include unilateral strength training to reduce limb dominance and interlimb asymmetry, as it has been shown that both risk factors are established during preadolescence. Interventions consisting of unilateral strength, plyometric and dynamic balance training combined with sport-specific skill practice using both lower limbs have been shown to be effective (Lloyd et al. 2016a: 1497; Pappas et al. 2016: 107—113; Read et al. 2016a: 1059—1066; Read et al. 2018a: 168—175.) Participation in multiple sports may reduce the magnitude of injury risk factors inherent to football, such as leg and quadriceps dominance through more varied training stimuli and more balanced training adaptation (Myer et al. 2011: 155—166; Launay 2015: 146; Read et al. 2016b: 2295—2302; Arnold et al. 2017: 139—147). Integrative neuromuscular training consisting of landing exercises, strength and motor control training should be done in conjunction with other forms of training, for example during the warmup prior to sport-specific practice, to target neuromuscular deficiencies such as reduce knee valgus alignment (Faigenbaum et al. 2011: 573—584; Myer et al. 2011: 155—166; Read et al. 2016a: 1059—1066).

Because most injury risk factors seem to peak close to PHV, targeted injury risk mitigating interventions are necessary during the adolescent growth spurt. Training load should be reduced during periods of rapid growth to reduce the stress on physes and tendons and lower the risk of acute and overuse injury (Caine et al. 2006: 757—758; Myer et al. 2011: 155—166; Shah et al. 2014: 1—9; Read et al. 2016b: 2295—2302; Arnold et al. 2017: 139—147.) Adjusting training frequency should be considered to allow more time for rest and recovery. It should be noted, however, that training should not completely cease in favor of recovery, as this may cause spikes in acute workload; instead, sport-specific training could be substituted with activities that provide different stimuli, such as strength and conditioning, corrective exercise or other sports (Myer et al. 2011: 155—166; Shah et al. 2014: 1—9; Launay 2015: 146; Arnold et al. 2017: 139—147.) Motor skill practice should be emphasized in circa-PHV adolescents, with a larger emphasis with those going through periods of decreased motor competency. Motor skill practice may be used help mitigate the effects of knee valgus alignment and decreased balance, limb and trunk control commonly seen in circa-PHV youth (Caine et al. 2008: 33; Myer et al. 2011: 155—166; Read et al. 2016a: 1059—1066; Longo et al. 2016: 139—159; Read et al. 2018b: 48—53.) Monitoring the players’ motor competency should be done frequently during the adolescent growth spurt to identify individuals going through adolescent awkwardness and enable more individualized programming of training (Myer et al. 2011: 155—166; Longo et al. 2016: 139—159; Read et al. 2018b: 48—53).

Strength and conditioning activities should be an integral part of any injury prevention programme during adolescence. A well implemented strength and conditioning programme may help meet the increased demands placed on the body by increased body dimensions and weight, thus helping with limb and trunk control. Additionally, strength training has been shown to enhance motor skill, helping mitigate effects of decreased balance and motor competency (Caine et al. 2008: 33; Myer et al. 2011: 155—166; Longo et al. 2016: 139—159; Read et al. 2016b: 2295—2302; Read et al. 2018b: 48—53.) Special emphasis should be put on strengthening the muscles of the trunk and core to prevent overuse injuries in the lumbar spine (Plais et al. 2019: 367—373). Inclusion of unilateral exercises and landing drills should continue from childhood to adolescence to mitigate leg dominance, knee valgus alignment and quadriceps-dominant landing strategies. Posterior chain work, especially hamstrings, should be emphasized to counteract quadriceps dominance inherent to football and reducing the associated risk of ACL injury (Caine et al. 2008: 33; Pappas et al. 2016: 107—113; Read et al. 2016a: 1059—1066; O’Kane et al. 2017: 6; Read et al. 2018a: 168—175; Read et al. 2018b: 48—53.) Tendon-specific interventions combining strength training with maturity-appropriate plyometric training may help induce positive structural and functional adaptations in the tendons, reducing the risk of tendinous overuse injury in older circa- and post-PHV adolescents (Mersmann et al. 2017: 1—18).

7 Bio-banding: the concept, the rationale and the application

The need for grouping youth athletes based on their level of maturation instead of chronological age stems from evidenced interindividual differences in the rate growth and maturation. While grouping athletes based on their level of maturation is not a new concept in team sports, it has rarely been applied systematically on a large scale. The most recent effort of matching athletes based on maturity status and/or timing is called bio-banding. Bio-banding attempts to group players in bands based on biological maturity for specific bio-banded training or competition, instead of grouping them based on chronological age. The underlying idea is that by leveling the playing field through the elimination of maturity-related interindividual differences such as size, strength and speed, all athletes may have equal opportunity to participate, develop and be given consideration during team selection (Lloyd et al. 2014b s. 1461—1463; Malina et al. 2015: 855—859; Lloyd et al. 2016a: 1499; Cumming et al. 2017: 34—47; Malina et al. 2019: 1671—1685.) Leveling the playing field by having the players play up or down an age grade and having similarly maturing youth play together may allow non-average maturing youth more appropriate training environments: early maturing players may have to rely less on their physicality and more on their skill, whereas late maturing players may get more significant playing time and opportunities to show and develop their sport-specific skills (Malina et al. 2015: 855—859; Cumming et al. 2017: 34—47; Malina et al. 2019: 1671—1685.) Bio-banding may also help with athlete assessment for talent identification and monitoring of athletic development (Meylan et al. 2010: 585—586; Malina et al. 2012: 1715; Lloyd et al. 2014b s. 1461—1463; Lloyd et al. 2016a: 1499; Cumming et al. 2017: 34—47; Malina et al. 2019: 1671—1685).

Given that maturation has a significant effect on the development of different components of athletic performance and injury risk, it is not surprising that bio-banding has also been suggested as a tool to optimize athletic development and injury prevention in youth athletes (Lloyd et al. 2014b s. 1460—1461; Lloyd et al. 2016a: 1499; Cumming et al. 2017: 34—47). In team sports settings, where a mere handful of practitioners may be responsible for the safe training of dozens, if not hundreds of youth, bio-banding may help provide more individualized training to the players. By grouping youth who are at similar stages of maturation into smaller maturity bands, practitioners will be able to prescribe maturity-appropriate exercises for each band, enabling them to make use of maturity-related changes in trainability of different components of athletic performance outlined in chapter 5 (Lloyd et al. 2014b s. 1460—1461; Lloyd et al. 2016a: 1499; Cumming et al. 2017: 34—47.) The same applies to injury prevention. By banding together those who are at a higher risk of injury, for example circa-PHV players, targeted reduction in training and competition workload can be applied, reducing risk of injury significantly. At the same time, individuals at other stages of maturation are able to better take advantage of their higher tolerance of training by continuing to train at a higher volume and intensity, again enabling more optimal development of athletic performance and sport-specific skill compared to everyone at a specific chronological age having their workload reduced (Read et al. 2016a: 1059—1066; Lloyd et al. 2016a: 1499; Cumming et al. 2017: 34—47.) By observing banded training and competition, practitioners may be able to identify individuals at lesser/heightened risk of injury, allowing more individualized training prescription based on individual movement competency and injury risk factors. In situations where players far outnumber the practitioners, banding players by maturity may help manage the training programmes of larger player populations, as preventive and corrective exercises may be prescribed for each maturity band based on the risk factor data outlined earlier in chapter 6 (Lloyd et al. 2014b s. 1461; Bergeron et al. 2015: 843—851; Read et al. 2016a: 1059—1066; Lloyd et al. 2016a: 1499—1500; Cumming et al. 2017: 34—47.) While this type of ‘one size fits all’ group programming for strength and conditioning activities and injury prevention may be far from ideal, it may be justified due to necessity in settings where players outnumber the practitioners by a large margin.

Evidence regarding the efficacy of bio-banding for youth athletic development and injury prevention is currently scarce. However, as Cumming et al. (2017: 34—47) note, this is most likely because of the limited amount of studies that have been carried out the subject. The limited evidence that exists seems to indicate that bio-banding may in fact be a useful tool for talent identification and development and injury prevention, benefitting especially those individuals who are classified as non-average maturers (Cumming et al. 2017: 34—47.) It is, thus, worthwhile to look into the possible benefits and practical applications of bio-banding in football context.

7.1 How to implement bio-banding?

Given that bio-banding is based on stages of maturation, it is natural to assume that maturity assessment is where application of bio-banding should start. Practitioners should choose the most appropriate method of maturity assessment based on the resources available to them; however, considering the high cost, need for trained medical professionals and invasiveness of skeletal and physiological methods of assessment, it may be warranted to give somatic assessment methods preference over the first two (Lloyd et al. 2014b: 1460; Sarwark – LaBella 2014: 10; Lloyd et al. 2016b: 1499; Cumming et al. 2017: 34—47). Of the two somatic methods of maturity assessment, percentage of predicted adult height seems to have a smaller margin of error and better concordance with other methods of assessing maturity than the maturity offset method (Myburgh et al. 2019: 1—9). Additionally, the maturity offset method seems to discriminate against early and late maturing individuals, classifying an overwhelming maturity as maturing on time. The method has also been suggested to have a very narrow chronological age range when it can be reliably used, between 13—15 years (Mirwald et al. 2002: 689—694; Bergeron et al. 2015: 843—851; Malina et al. 2015: 852—859), and so it may be a poor choice in a football academy environment. Based on the above, percentage of predicted adult height is recommended in this thesis as the method of choice for bio-banding.

Practitioners would do well to remember, however, that estimated percentage of predicted adult height does not give offer insight to the rate of growth of the players, and as such, regular, preferably quarterly monitoring of growth in height, weight and body dimensions is recommended. Measurement should always take place at the same time of day, preferably in the morning, and always before any training has been done (Caine et al. 2006: 757—758; Lloyd et al. 2014b: 1460; Lloyd et al. 2016b: 1499; Longo et al. 2016: 139—159; Malina et al. 2019: 1671—1685).

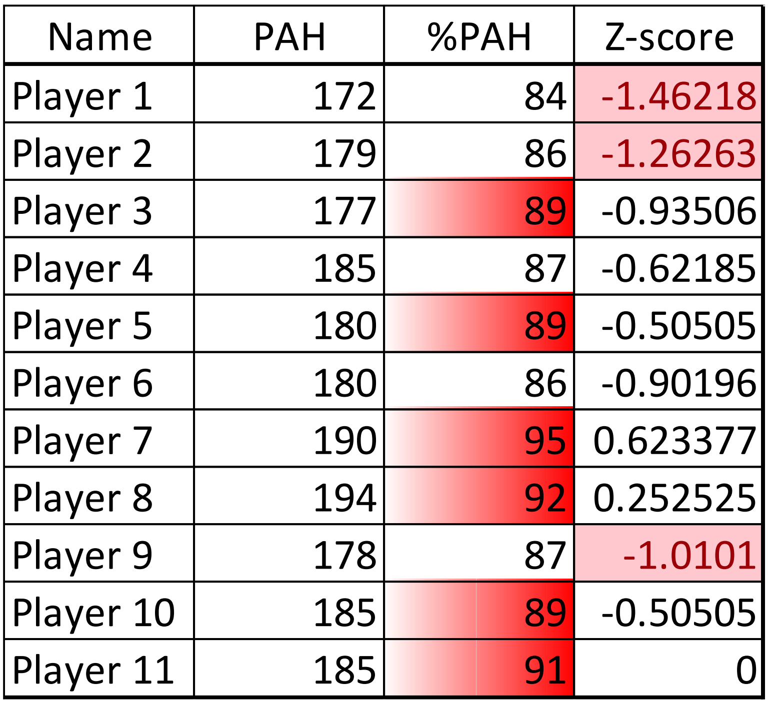
Using the percentage of predicted adult height method recommended above, the practitioner should decide which equation to use. Using the Khamis-Roche equation outlined in chapter 4 is recommended in this thesis, provided the necessary tools (spreadsheet or software) are available. To give an example on how to apply bio-banding, a hypothetical scenario is used in this thesis. Table 1 below outlines data of a hypothetical boys' 2006 age group football team with 11 players. In this scenario, the measurements were taken on the 23rd of April 2020.

Name	Date of birth (dd/mm/yyyy)	Rounded age (years)	Height (cm)	Weight (kg)	Mother’s height (cm)	Father’s height (cm)
Player 1	05/10/2006	13.5	145	40	164	177
Player 2	01/04/2006	14	155	45	170	184
Player 3	20/01/2006	14.5	158	52	169	180
Player 4	10/08/2006	13.5	160	50	165	188
Player 5	20/04/2006	14	160	52	172	175
Player 6	15/11/2006	13.5	155	47	169	178
Player 7	02/01/2006	14.5	180	71	167	181
Player 8	04/07/2006	14	178	67	168	190
Player 9	17/02/2006	14	155	49	172	177
Player 10	20/05/2006	14	165	54	165	188
Player 11	25/03/2006	14	168	60	168	179

Table 1: Data of hypothetical boys’ 2006 age group

The percentage of predicted adult height for each player can be estimated using the data above. In this hypothetical scenario, the predicted adult height for each player was estimated using the Khamis-Roche method. For the sake of this example, the percentage of predicted adult height for each player was given a Z-score to classify maturity status. Z-scores were calculated using age-specific means and standard deviations used in the Guidance Study by the University of California, Berkeley in vein of by Malina et al. (2005: 1044—1052) and Malina et al. (2012: 1705—1717). It should be noted, however, that when applying bio-banding to practice, team values can be gathered over a prolonged period of time to use as team-specific standardized data. This data can then be used to calculate individual z-scores for maturity status in comparison to other players that have played or still play for the club (Meylan et al. 2010: 585.) If no retrospective growth data is available, however, this may take some time.

Table 2 below outlines the estimates of predicted adult height, percentage of predicted adult height and the z-score for the players in the hypothetical scenario.



Name	PAH	%PAH	Z-score
Player 1	172	84	-1.46218
Player 2	179	86	-1.26263
Player 3	177	89	-0.93506
Player 4	185	87	-0.62185
Player 5	180	89	-0.50505
Player 6	180	86	-0.90196
Player 7	190	95	0.623377
Player 8	194	92	0.252525
Player 9	178	87	-1.0101
Player 10	185	89	-0.50505
Player 11	185	91	0

Table 2: predicted adult height (PAH), percentage of predicted adult height (%PAH) and Z-scores for a hypothetical boys' 2006 age group

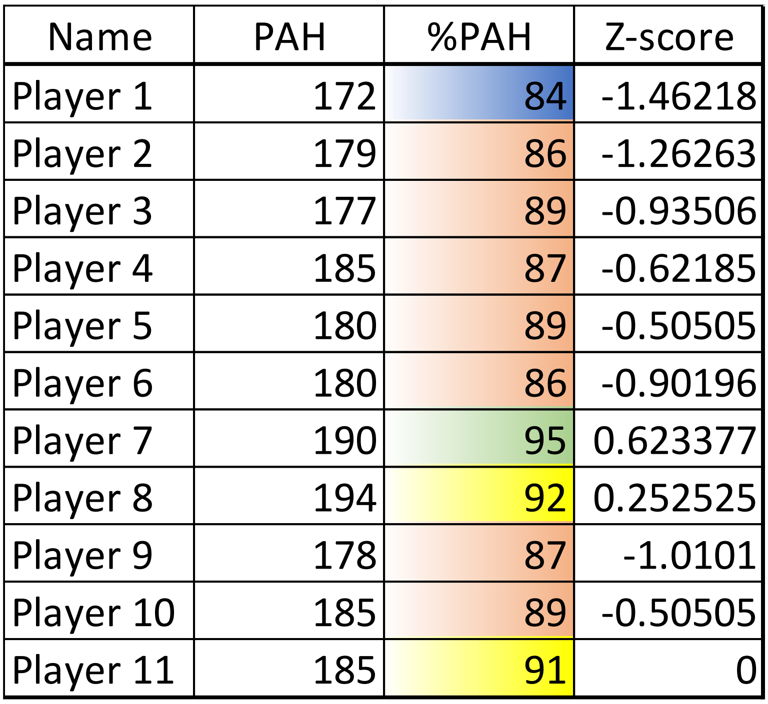
Analyzing the data in table 2, some important observations can be made. Based on the suggested range of 88—95% by Cumming et al. (2017: 34—47), players 3, 5, 7, 8, 1 and 11 can be categorized as circa-PHV. At the same time, using a Z-score range of -1 to +1, with the former indicating late and the latter indicating early maturation, it is evident that while most players in the group can be classified as maturing on time, players 1, 2 and 9 are maturing late compared to the average percentage of predicted adult height at their age (Malina et al. 2005: 2005: 1044—1052; Malina et al. 2012: 1705—1717). Both of these observations have value in regards to athletic development of the players and injury prevention. Using the data from table 2 and the training recommendations outlined in chapter 5, the circa-PHV players can be programmed training that focuses more on taking advantage of increased potential for hypertrophy, putting some emphasis on eccentric strength and while focusing movement skill practice, simpler plyometrics, balance and range of motion exercises to counteract adolescent awkwardness and loss of flexibility during the adolescent growth spurt. Being categorized as pre-PHV, players 1, 2, 4, 6 and 9 on the other hand can be prescribed more plyometrics, movement skill practice and strength training that emphasizes neural adaptations. Using the data from table 2, and the recommendations in chapter 6, injury prevention for the pre-PHV group should consist of movement skill acquisition, for example using weekly or biweekly sport sampling sessions, and inclusion of unilateral strength exercises to counteract interlimb asymmetry and improve balance. For the circa-PHV group, training load should be reduced to lower the risk of injury associated with PHV, either by reducing training frequency or session workload; in the latter case, the circa-PHV group could end sports practice earlier than the pre-PHV group to go through their preventive exercises, for example, consisting of unilateral work and strengthening of the core, trunk and the posterior chain muscles, as per recommendations outlined in chapter 6. Assessment of physical competency should also increase for the circa-PHV group to identify players experiencing decreased motor competency.

Consideration should also be given to later maturing individuals: as mentioned in chapter 6, late maturing individuals may be at an increased risk of injury as they tend to go through a period of rapid growth at the same time as training and competition intensity increases markedly. With regular measurement of body anthropometrics, the growth of players 1, 2 and 9 can be monitored and training load can be adjusted to their rate of growth (Lloyd et al. 2016b: 1499; Longo et al. 2016: 139—159).

In the example above, the players were grouped based their proximity to estimated PHV. Cumming et al. (2017: 34—47), however, suggested using smaller bands based on pubertal status. Cross-referencing with stages of pubic hair to match percentage of predicted adult height with stages of puberty, the authors suggested the following maturity bands:

PAH < 85% = prepubertal
PAH ≥ 85% to < 90% = early pubertal
PAH ≥ 90% to 95% = mid-pubertal
PAH ≥ 95% = late pubertal

Using the same hypothetical 2006 age group as above, bands according to the suggestion by Cumming et al. (2017: 34—47) are outlined in table 3.



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Player 1	172	84	-1.46218
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Player 8	194	92	0.252525
Player 9	178	87	-1.0101
Player 10	185	89	-0.50505
Player 11	185	91	0

Table 3: hypothetical 2006 age group players banded by estimated pubertal status based on %PAH.

Grouping players using the bands suggested by Cumming et al. (2017: 34—47) above, it becomes evident that intragroup differences in pubertal status can be significant. By using narrower bands to organize maturity appropriate training and competition, talent identification and development may be optimized, while simultaneously lowering the injury risk of those who are less mature skills (Meylan et al. 2010: 585—586; Malina et al. 2012: 1715; Lloyd et al. 2014b s. 1461—1463; Malina et al. 2015: 852—859; Lloyd et al. 2016a: 1499; Cumming et al. 2017: 34—47; Malina et al. 2019: 1671—1685.). For example, in the hypothetical 2006 age group, player 1 could play down an age grade to train or compete with players who are close to his maturational level, while the more mature players 7, 8 and 11 play up an age grade; this would allow player 1 more chances to play meaningful minutes and not get ‘run over’ by physically more mature players, while making players 7, 8 and 11 rely less on their physicality due to having play against players of similar physicality.

To make use of bio-banding in player assessment, using common tests such as the counter-movement jump tests or 10m sprint test to assess players in bio-banded groups may give more appropriate insight into the players’ levels of athletic performance. Given the impact puberty has on all components of performance, it would not be unreasonable to expect player 7 of the hypothetical 2006 group to outperform player 1 in most tasks requiring strength, power, or speed, for example. While this may make player 1 seem inferior in regards to athletic performance, instead of comparing the players to each other, their performance could be compared to those of same maturity status or band-specific normative data, allowing for more appropriate assessment of performance (Cumming et al. 2017: 34--47.) From an athletic development standpoint, banding players based on pubertal status estimated from percentage of predicted adult height may be used for more individualized programming of strength and conditioning. Based on the recommendations made in chapter 5, player 1 should be programmed training more focused on neural adaptations, while the rest of the group should focus on both neural and hypertrophic adaptations, with player 7 focusing mostly on hypertrophic adaptations.

It should be noted that bio-banding is not mean to replace traditional age group practice and competition. Bio-banding fails to take into account the technical, tactical, psychological and social development of individuals (Lloyd et al. 2014b: 1462—1463; Cumming et al. 2017: 34—47; Malina et al. 2019: 1671—1685.) Banding children and adolescents into constantly changing maturity groups may cause feelings of isolation and loss of team camaraderie, deteriorating the nature of team sport (Reeves – Enright – Dowling 2018: 1—13). Bio-banding should be used as part of a holistic player development pathway, assisting in exposing the players to varying stimuli and supporting their long-term athletic development. A good way of utilizing narrower bands used above is by organizing club-wide or interclub bio-banded trainings, games, and tournaments. These can be done on a weekly, biweekly, or monthly basis. The underlying idea is that by having players train and compete with less familiar teammates and coaches, they get exposed to different playing and coaching styles, allowing for more robust sport-specific development (Cumming et al. 2017: 34—47; Malina et al. 2019: 1671—1685.) This may also reduce any negative feelings players (or their parents) may have regarding playing down or up an age grade (Meylan et al. 2010: 586; Malina et al. 2012: 1715; Reeves et al. 2018: 8—9), as instead of having to join a specific age group, the players would join groups that have very little to do with age grades. Bio-banded training and competition has generally been received very well by both players and coaches, making them an excellent way of introducing new challenges to both groups (Cumming et al. 2017: 34—47; Cumming et al. 2018: 757–765; Malina et al. 2019: 1671—1685).

8 Conclusions

The thesis aimed to answer several research questions in order to meet the its aim and objectives. The processes of somatic growth were outlined to give the reader a framework to better understand assessment of biological maturation. The thesis then outlined and critiqued the most common methods of assessing biological maturity in an attempt to gauge the best solution for maturity assessment in an association football setting and to give the reader an understanding of different classifications of maturity status and timing. Building on reader's the familiarity of maturity status and timing classifications, the thesis then outlined the effect maturation has on athletic development and injury risk. Finally, bringing it all together, practical examples were outlined on how to apply the knowledge on growth, maturation and its assessment, athletic development and injury prevention to practice using bio-banding as a tool.

The present thesis attempted to build a continuum between maturation, athletic development and injury risk that justifies the use of bio-banding in sport. While direct evidence of the tool's efficacy may be scarce, evidence regarding the effect maturation has on development of athletic performance and injury risk is unquestionable. Using knowledge of maturity assessment and how maturation affects athletic development, practitioners should, in theory, be able to programme training and expose their athletes to training stimuli that enable adaptations that are complimented by the athletes' stage of maturation. Using band-based programming, bio-banding allows this to be done in larger settings, where athletes outnumber the practitioners and individualization of training may be difficult. In theory, the same applies to injury prevention, where targeted preventive measures can be programmed to individuals at a heightened risk of injury. If carried out well, bio-banding enables sports clubs and practitioners to create a safe training environment where each individual can be programmed maturity-appropriate training regardless of their maturity status or timing.

Bio-banding is not meant to replace traditional chronological age groups in football, but it can be a valuable tool in the practitioner's player development and protection toolkit. Education of players, parents, coaches and other practitioners is warranted, however, as the tool is not well known and as such may cause feelings of confusion or frustration. The present thesis has summarized a lot of the needed information for educating stakeholders on the possible benefits of bio-banding, while also giving tools and practical suggestions on how to put bio-banding into practice.

A few limitations of this thesis should be brought to attention. Research on bio-banding itself is very limited, with most research on potential benefits occurring in sports such as combat sports that have a long history of categorizing athletes by size and weight. While the underlying theoretical basis is very well researched, the possible benefits of bio-banding and its the efficacy on athlete development, injury prevention and talent identification merit more research, especially in a team sports settings (Cumming et al. 2017: 34—47; Malina et al. 2019: 1671—1685). The mitigating effect bio-banding may or may not have on the phenomenon known as relative age effect was omitted from this thesis due to not being related to athletic development or injury prevention. Although it was omitted, readers are encouraged to familiarize themselves with the phenomenon, as it is a very real issue inherent to all youth sports.

Detailed description of the cardiovascular system was omitted from the thesis due to the focus on musculoskeletal injury and and the development strength- and power-related components of athletic performance. To fully understand the theoretical rationale of bio-banding and its application to athlete development, it is recommended that practitioners familiarize themselves with cardiovascular growth and development as well.

The section outlining the methods of assessing maturity in this thesis failed to clarify whether or not the use of some methods might not be allowed in some countries, for example Finland where the thesis partnership club HJK is located. Regarding the Khamis-Roche method used for bio-banding in this thesis, it is unclear how suited the reported parental height that have been adjusted for tendency to overestimate are for the equation (Cumming et al. 2017: 36), and as such the question merits further study. Furthermore, the Khamis-Roche equation has been validated using North American and European youth, warranting further validation with different ethnicities.

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