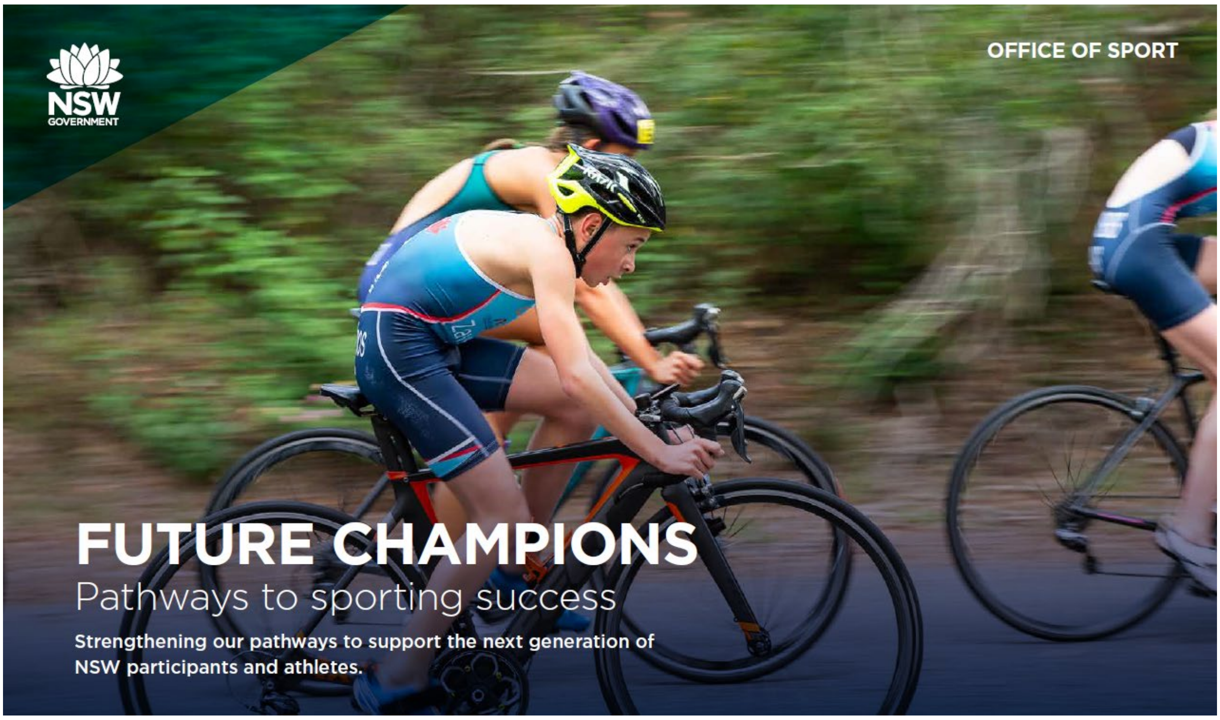

Considering growth and maturation when developing our Future Champions: An educational guide for sporting organisations & practitioners.

NSW GOVERNMENT | THE UNIVERSITY OF SYDNEY

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Resource Background

The *Future Champions* Strategy (NSW Office of Sport, 2019) aims to help emerging NSW youth athletes acquire the appropriate skills and experience to attain future performance success at the senior (adult) level. Guided by the *Foundation, Talent, Elite and Mastery* (FTEM) Framework (Gulbin et al., 2013b; Weissensteiner, 2017a) and specifically *FTEM NSW* (see https://www.sport.nsw.gov.au/pathways-and-development/ftem-nsw) , the *Future Champions* Strategy provides a holistic, best-practice, guide for organisation managers, clubs (and institutes), coaches, practitioners, teachers and parents to ensure participants and athletes 'receive the right support at the right time'. The process of preparing youth athletes for eventual long-term senior-elite performance is complex due to multi-dimensional (e.g., physical, psycho-social, and sport-specific skills) components and are difficult to predict due to changes over time (Cobley, Baker, & Schorer, 2021); overall making the athlete development a challenging process. To assist stakeholders, the *FTEM NSW* framework presents a 'chronology' of eleven progressive levels spanning the lifespan and sports continuum from early foundational to mastery and is inclusive of all outcomes of sport: active lifestyle and pursuits, social, community and high-performance sport. A participant or athlete's movement capability and physical literacy, sporting skills and experience, motivation and ambition, will determine what level they are within *FTEM NSW*, and importantly what opportunities and support they should receive operationally.

Two processes which occur over time and add to the complexity of participant and athlete development are growth and maturation. Growth refers to the increase in size of the body and its systems (e.g., heart, lungs, and muscles), occurring from birth until attainment of full adult state (i.e., 16-18 years in girls and 18-20 years in boys). Meanwhile, maturation describes the developmental progress toward the biologically adult state (Malina et al., 2019) but - more specifically - denotes the period of re-accelerated growth and physical development typically occurring from 11-12 years and 9-10 years in boys and girls, respectively, until the adult state is attained (van der Sluis et al., 2015). With maturation initiating at different chronological age time points (i.e., maturity timing) and with different rates of development occurring (i.e., maturity tempo), there can be substantial variation between individual development. Further, progressive growth and maturation influence body shape as well as technical skill and physical movement development. Related to body shape and size for example, different time-points and rates of acceleration (tempo) of height, body mass, and limb length can occur. Subsequently, technical skill, movement consistency, efficiency and coordination patterns may be affected. The development of physical capabilities, such as cardiorespiratory endurance, muscular strength, and power are also affected (Philippaerts et al., 2006; Till et al., 2014). Therefore, growth and maturation can generate substantial inter-individual differences and impact athlete development, necessitating consideration alongside FTEM application.

Within multiple youth sport contexts (e.g., team sport contexts), performance is being evaluated (and emphasised) at increasingly earlier ages (Winand, 2010). However, it is valuable to recognise that research studies which have tracked youth athletes over time to identify how advanced physical characteristics (e.g., upper, and lower body strength and power) at youth level do not necessarily translate into performance success at senior (adult) level (Cobley & Till, 2017a; Gullich, 2017; Pion et al., 2015). Further, caution is required when exposing youth athletes to adult-like training and competition programs, particularly during growth and maturation. Intensified training at such time points has been associated with an increased likelihood of physical injury and psychological burnout (Bergeron et al., 2015). Exposing youth athletes to adult-like training and competition environments at early ages has also been associated with negative psychological impact, leading to compromised long-term success and sport withdrawal (Cobley et al., 2014; Elferink-Gemser, 2012; Weissensteiner, 2017b).

Another enduring concern is for sporting organisations to potentially miss precocious talent or evaluate youth athletes based on current development. The exclusion or non-selection of ‘later-maturing’ athletes is one common problem. Such athletes are less likely to have developed technical skill and physical capabilities to a level equivalent to their earlier maturing peers, and so are less likely to be identified or selected based on present performance comparisons. In parallel, although less recognised, is the over-selection and subsequent under-development of ‘early maturing’ athletes. ‘Early maturing’ athletes often demonstrate superior physical capabilities at earlier chronological age time points, reflected by accelerated (physical) performance progression relative to their ‘later’ maturing peers. Yet, their all-round holistic development may be neglected, and later exposed as a performance-limiting factor post growth and maturation (Romann, Javet, & Fuchslocher, 2017). As a result, the need to consider and apply strategies that help to either improve the accuracy of athlete evaluation, remove (or reduce) growth and maturational influences upon performance, and/or improve development practices could be necessary for particular sports organisations.

Resource Purposes and Aims

The purpose of this document is to provide an evidence-based practical resource for sporting organisations and schools, administrators (e.g., pathway managers; policymakers), practitioners (e.g., coaches; sport science practitioners), parents and participants (i.e., athletes) about growth and maturation.

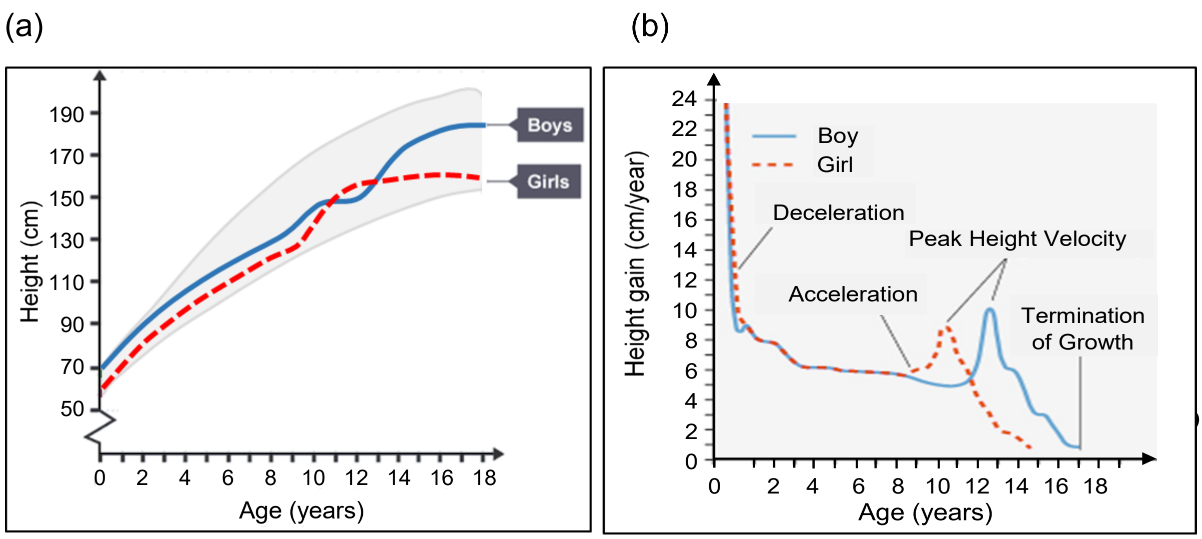
With specific target audiences in mind, this resource aims to:

i. Explain and define growth and maturation.
ii. Explain how growth and maturation affects youth athlete participation, progression, and selection.
iii. Explain how growth and maturation relates to the development of athletic performance indices in youth sports contexts.
iv. Justify why growth and maturation is important to consider in developing athletes.
v. Identify methods sporting organisations, schools, practitioners, and parents can utilise to track growth and maturation alongside athlete development.
vi. Identify and outline strategies for how sporting organisations and their practitioners can better guide their athletes through maturational stages. Strategies include ways to identify and track maturity status, account for or removing the influences of maturational differences, and ways to improve performance evaluation and selection processes.

1. What is Growth and Maturation?

Biological growth refers to the increase in size of the body and its systems (e.g., heart, lungs, and muscles). Growth is a continuous process from birth up until full adult stature is attained at approximately 18-20 years in males and 16-18 years in females (Malina et al., 2019). Figure 1a illustrates how typical increases in height occur over time occur. As part of growth, there is a common adolescent growth spurt period known as maturation. Maturation encapsulates the biological progress toward the adult state, with chronological time points of attainment substantially varied between individuals (Malina et al., 2019). For instance, maturation typically commences from 11-12 years and 9-10 years in boys and girls (van der Sluis et al., 2015), coinciding with re-accelerated growth. Figure 1b illustrates the initiation of the growth spurt period signified by more rapid height gain, accompanied by potentially variable physical development (Hills & Byrne, 2010). During maturation, boys can expect to grow at an average rate of approximately 8-10 cm/yr. Whereas girls can expect to grow at a rate of approximately 6-8 cm/yr. (Granados, Gebremariam, & Lee, 2015; Kelly et al., 2014). The time point when maximal growth rate (i.e., tempo = cm/yr) occurs is called Peak Height Velocity (PHV - van der Sluis et al., 2015).

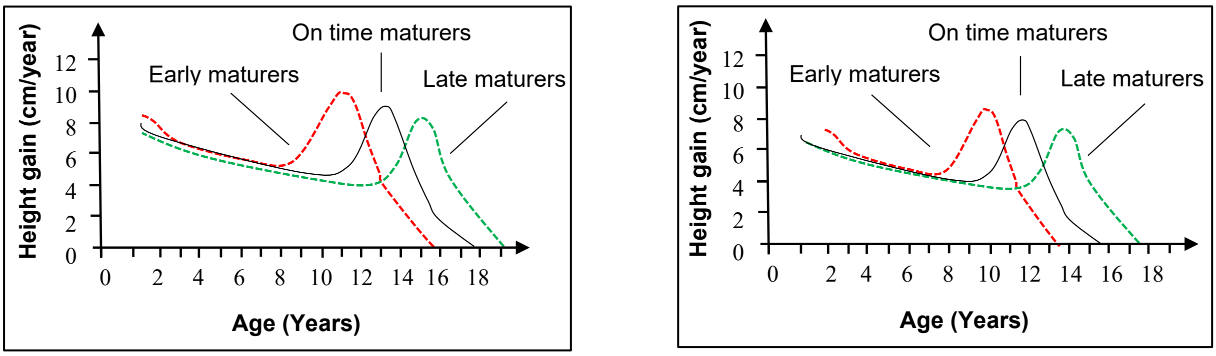
Figure 1: Illustration of normative growth shown by (a) accumulated height (cm) and (b) tempo (cm per year) according to age and sex.



Generally, PHV occurs between 12-14 years in boys and 10-12 years in girls (Granados et al., 2015; Kelly et al., 2014), lasting between one to three years depending on whether the maturational tempo is high (fast over a given unit of time) or low (slow or a given unit of time - Mirwald et al., 2002; Sanders et al., 2017). Figure 2 shows how typical 'On-time' (Normative) PHV attainment in (a) boys is around 13.5-14 years and 11.5-12 years in (b) girls (Kozieł & Malina, 2018). In addition, categorised 'Early' (red line) and 'Late' (green line) maturing adolescents are illustrated, showing how differences in PHV attainment can be up to 3-5 years between adolescents of the same chronological age (Abbott et al., 2020a; Johnson, Farooq, & Whiteley, 2017; Whiteley, Johnson, & Farooq, 2017). For example, 'Early' maturing boys and girls may attain PHV as early as 11-12 and 9-10 years respectively, while 'Late' maturers may not attain PHV until 16-17 and 14-15 years, respectively.

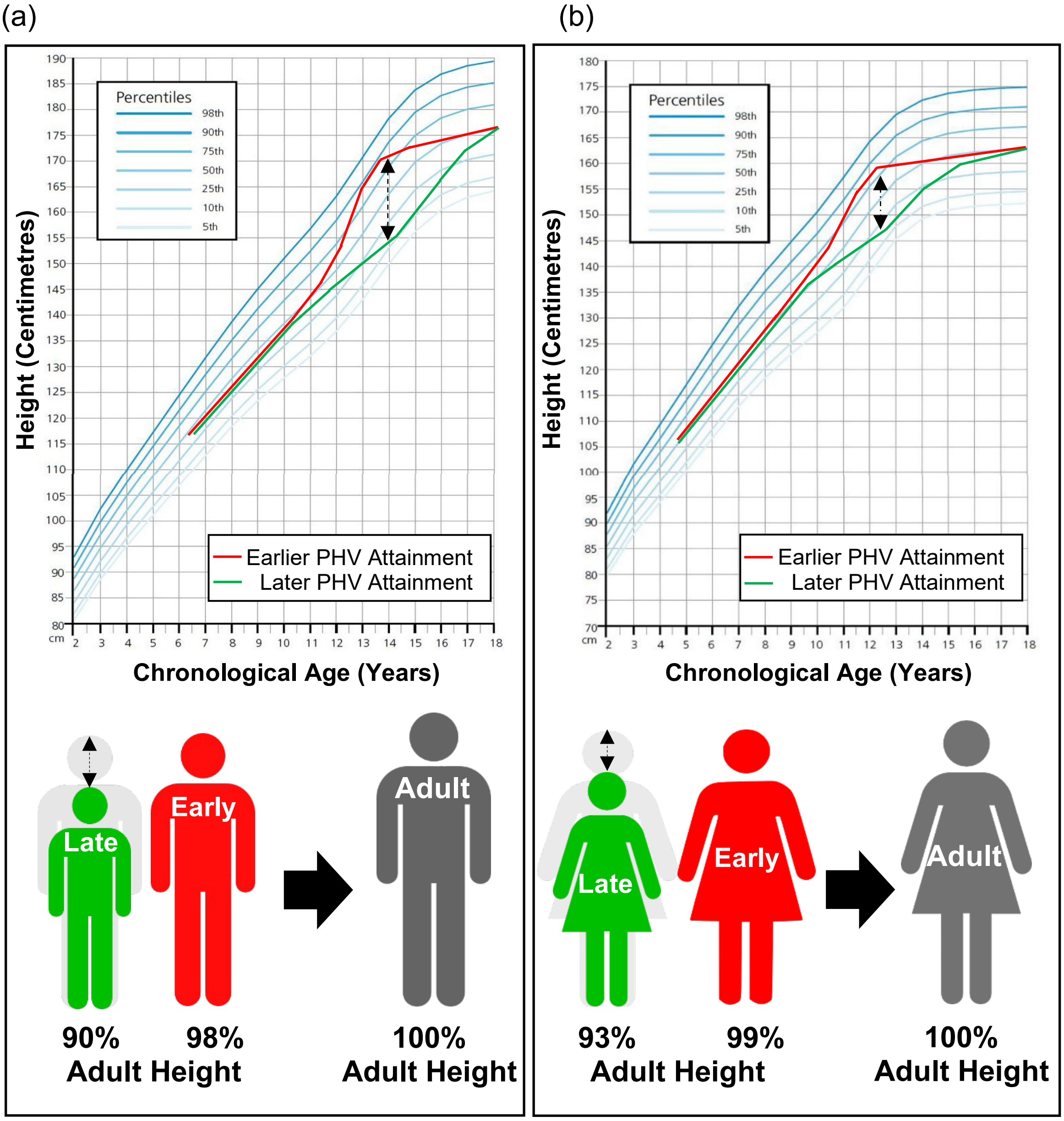
Figure 2: Overview of 'Early', 'On time' and 'Late' maturity status as reflected by accumulated height (cm per year) according to age in (a) boys and (b) girls.

(a) (b)



Differences in maturational timing can also explain how athletes can be further along their maturational journey compared to their age-matched peers, meaning athletes can vary in terms of their different maturity statuses. For example, Figure 3 shows (a) two boys and (b) two girls, with each having different maturational journeys. While both boys and girls follow the same 50th height-for-age percentile, early PHV attainment (red line) is accompanied by a greater growth rate at earlier chronological ages compared to the later maturing boy and girl (green line). Meanwhile, both late maturers experience a delayed and less intense growth spurt period (e.g., PHV). Both figures show how growth patterns can diverge during maturation leading to temporary differences in height (Carrascosa et al., 2018; Mirwald et al., 2002). Figures 3ab also summarise how relative to their chronological age, youth athletes with progressed maturity status are more likely to have completed a larger portion of their genetically determined final adult height. For example, an early maturing 14-year-old boy who is almost two years past PHV has completed 98% of his total adult height gain. Meanwhile, a later maturing 14-year-old boy, still almost one year from attaining PHV, has completed 90% of his total adult height gain. The same can be described in girls with slightly reduced height differences during peak maturation. However, maturity-related differences in growth are only temporary. As seen in Figures 3ab for instance, differences in growth patterns between early and late maturing boys and girls typically converge back toward original pre-adolescent growth curve percentiles (e.g., 50th percentile) when approaching final mature adult stature.

Figure 3: Illustration of different growth patterns over time according to maturity timing (Peak Height Velocity) in (a) boys and (b) girls.



In addition to height gain, maturation is also marked by observed increases in body mass (or weight) in boys and girls. Peak weight gain typically occurs 2-6 months after PHV attainment (Bozzola & Meazza, 2012; Guimarães et al., 2021). In boys, weight gain mostly comprises of increases in fat, muscle, and bone mass up until 14-15 years (Hills & Byrne, 2010). Post 14-15 years, increases in muscle and bone take over as the main contributors to maturational weight gain. In girls, weight gain mostly comprises of increasing fat (adipose tissue), muscle and bone mass up until 13-14 years during maturation (Martinho et al., 2021). Post 13-14 years, weight gain is typically associated with increases in fat (adipose tissue) and bone mass with some increases in muscle mass.

Several other important biological milestones signify stages of maturational development. In girls, for example, the first menstrual cycle period, termed ‘menarche,’ occurs most commonly around 12-13 years of age, or approximately within one year following PHV (Granados et al., 2015). Interestingly, around 70% of girls have usually attained PHV by menarche (Granados et al., 2015). Like maturity initiation, menarche can occur early (e.g., 10 years) or later (e.g., 14 years), depending on maturation timing and tempo (Carvalho et al., 2019). Age at menarche can also be used to indicate ‘physiological’ (reproductive) maturity along with sexual characteristic development, such as pubic hair development in boys and girls, breast development stage in girls and genital development (e.g., increased testicular volume) in boys (Onat, 1975; Tanner et al., 1975). In fact, various methods have been developed to assess maturation stage.

Radiographs of the hand wrist (carpals and epiphyses) are considered the gold standard for identifying ‘anatomic’ or ‘skeletal’ age (Johnson et al., 2017; Rotch, 1908). Within youth sports contexts, more practical and ethical maturation assessments have become common, involving height and weight measures (Sherar, Baxter-Jones, & Mirwald, 2004; Mirwald et al., 2002; Khamis & Roche 1994). Using height, sitting height, and weight, PHV can be estimated. With the addition of measuring both (biological) parents’ height, the percentage of attained adult height (%PAH) can also be estimated (Carrascosa et al., 2018; Khamis & Roche, 1994; Mirwald et al., 2002; Sherar et al., 2005). Further information on how to conduct PHV and %PAH assessment is described in Section 4.1.2. Assessing PHV as a strategy for identifying athlete maturation status is a first step toward understanding an athletes' stage of growth and maturational development, and for considering potentially identifying appropriate strategies to account for different developmental journeys youth athletes may take over time. Understanding individual athlete maturation status also highlights why chronological age-grouping during and across adolescence may be of limited value in youth sport. With this in mind, how chronological age and maturational differences affect athlete participation and selection across multiple youth sporting contexts is discussed next.

2. How are Growth and Maturational Differences a Problem in Youth Sports?

The highly individualised process of growth and maturation contributes, in part, to the wide-ranging developmental paths athletes follow over time (Burant, 2016). Accounting for such individuality is challenging for sporting organisations, including administrators, practitioners, and coaches, particularly at stages where athlete evaluation, participation and (de-) selection decision-making processes are occurring (Cobley et al., 2009; Tierney et al., 2016). The common practice of placing children into annual age groups for logistical/planning purposes does attempt to help equalise competition experience scan also unintentionally work against the objectives of policymakers and administrators. One consequence birth date or age cut-off criteria (i.e., age at the day of competition/ or start of the season) is the Relative Age Effect (RAEs – Barnsley et al., 1985). In youth sports contexts, RAEs refer to an overrepresentation of older athletes within a given age group. In other words, there are more participating athletes born closer to the cut-off date. Simultaneously, there is an underrepresentation of younger athletes within given age groups; that is athletes born further away from the cut-off date (Wattie, Cobley, & Baker, 2008). Generally speaking, amongst the multiple explanations, the most supported account for RAEs in youth sports relates to the observation that relatively older athletes are more likely to have progressed further in growth and maturational terms compared to their relatively younger peers (Cobley et al., 2009; Helsen, Starkes, & Van Winckel, 1998; Lovell et al., 2015). Figure 4 illustrates how relative age differences within one-year age group associate with growth and maturation variation. A relatively older and more mature athlete with accompanying greater body size and mass may gain certain performance advantages, such as superior cardiorespiratory endurance, muscular strength, and speed (Malina et al., 2007; Viru et al., 1999). Meanwhile, a relatively younger and less mature athlete relative to their peers may experience short-term performance disadvantages related to endurance, strength, and speed.

Figure 4: Illustration of the Relative Age Effect visualised using normative growth differences within 12-year-old female swimmers.

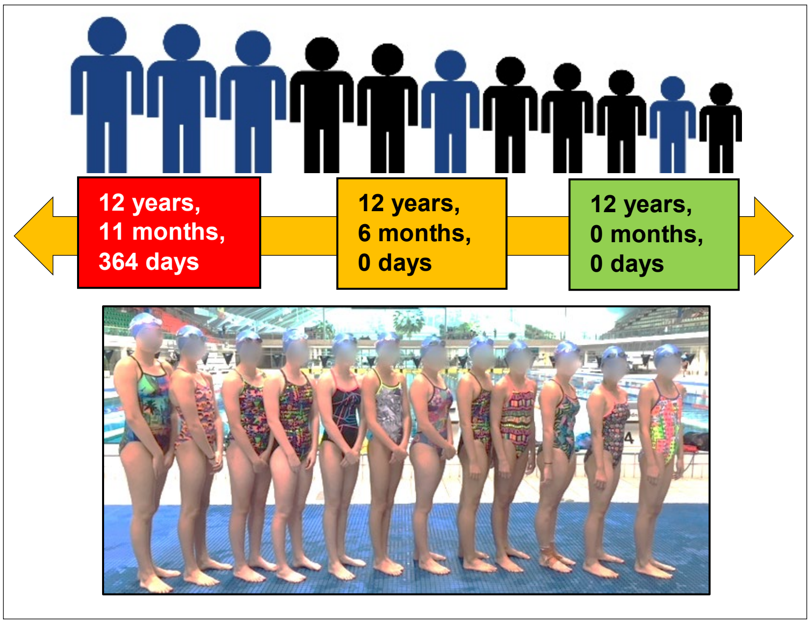


Figure Note: Image (top) adapted from Irish Youth Football; image (bottom) courtesy of Swimming NSW

An important distinction to make between (relative) age and maturation is that, unlike chronological age, maturation does not strictly follow a 'straight linear' passage over time (Khamis & Roche, 1994; Moore et al., 2015). This means it is possible for an athlete to be the oldest in their respective age group yet may still be the least physically mature. Likewise, an athlete may attain PHV early while also being the relatively youngest in their age group. While relatively older athletes are more likely to be – on average – more progressed in growth and maturation, the impact of maturation can magnify growth differences during particular time points before subsiding later (post-maturation – Johnson et al., 2017). To illustrate, Figure 5 shows how growth differences are present between the relatively oldest and youngest (orange), and at the same time, the most and least mature male athletes within one-year age groups (green). During maturation, relative age may account for approximately 10-12% of growth differences within age groups whereas maturity status may account for approximately 20-40% of growth differences within age groups. Although relative age-related differences in growth are smaller than maturational differences in growth, the impact of maturation doesn't emerge until ages 9-10 years in boys and 8-9 years in girls. Peaking around the time point of PHV, maturity-related differences in growth within age groups subside as full maturity is approached at approximately 17-18 years in males and 15-16 years in females (Cobley et al., 2009; Smith et al., 2018). Persisting relative age differences which sit separately from maturation indicate the presence of some performance indices less influenced by growth yet are still important when considering athlete participation and selection such as technical and social- and perceptual-cognitive skills (e.g., experience, practice - Cumming et al., 2018b).

Figure 5: Conceptual illustration of how Relative Age (RA) and Maturity (PHV) related differences in body size and shape progress per year in boys.

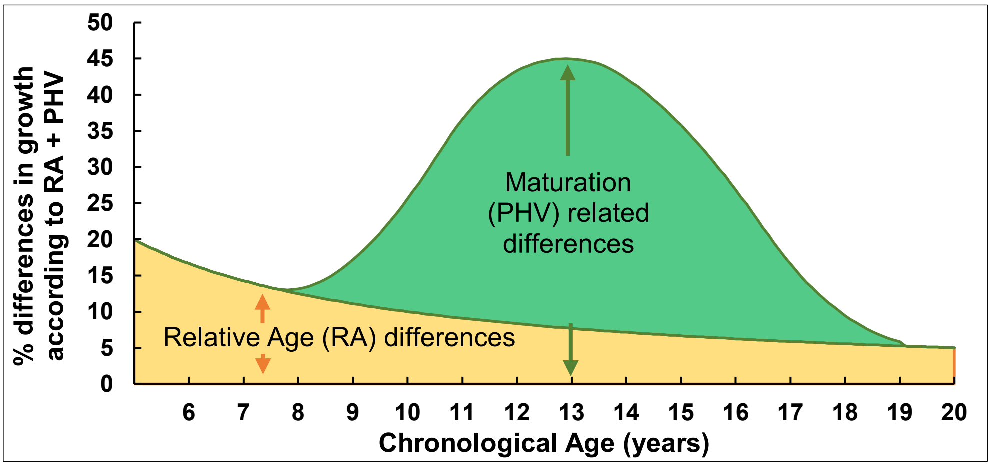


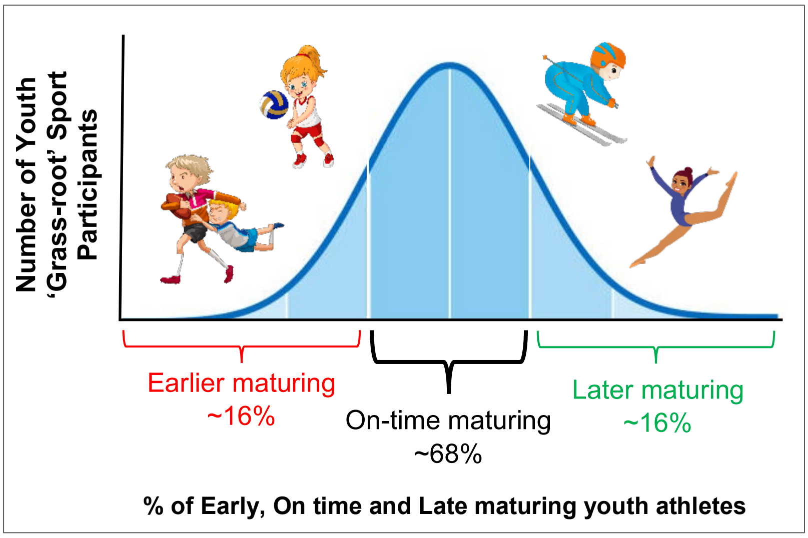
Figure Note: Figure adapted from Cobley et al. (2021) – Talent Identification and Development in Sport

Given being relatively older and more physically mature are linked to increased physical performance indices depending on the sports context, it may not be such a surprise that maturity-related differences in performance are more noticeable during peak maturational years. While RAEs can describe physical development and performance differences up to one (annual) year, maturity-related differences can be far greater and range up to 3-4 biological years within one (annual) year during 13–15-year annual age groups in boys, and 11-13 year annual age-groups in girls (Kelly et al., 2014; Whiteley et al., 2017). Thus, being relatively older and more mature is related to consistent athletic performance and selection advantages in numerous male and female sporting contexts which may negatively impact the long-term participation of many relatively younger and later maturing athletes (Cobley & Till, 2017b; Delorme, Boiché, & Raspaud, 2009; Lemez, MacMahon, & Weir, 2016).

2.1 Impact on Participation

At lower organised youth sporting levels, the majority of youth athletes tend to enter maturation at similar time points to those boys and girls observed in the general wider population (e.g., ages 13-15 years in boys and 11-13 in girls). Such trends have been identified at lower ('grass-roots') participation levels across multiple youth sporting contexts including, Australian Rules Football (Tribolet et al., 2018), Baseball (Baxter-Jones et al., 2020), Basketball (Guimarães et al., 2021), Handball (Hammami et al., 2019), Hockey (Baxter-Jones et al., 2020), Judo (Giudicelli et al., 2020), Rowing (Thiele et al., 2021), Sprint Running (Meyers et al., 2015), Soccer (Martinho et al., 2021; Müller et al., 2018; Philippaerts et al., 2006), Alpine Skiing (Müller et al., 2017), Swimming (Abbott et al., 2020a), Tennis (Fernandez-Fernandez et al., 2019; Myburgh et al., 2016) and Volleyball (Albaladejo-Saura et al., 2022). Figure 6 illustrates how most boys and girls (approx. 68%) participating in youth sport at a grass-roots level attain PHV within normative age ranges (i.e., 13-15 years in boys and 11-13 years in girls). Boys and girls who are early or late maturing are less represented relative to on-time maturers and each makes up approximately 16% of the total participant numbers, respectively.

Figure 6: Conceptual illustration of maturity timing distributions in youth sport participants at 'grassroots' level.



Typically, biases towards earlier or late maturing athletes, depending on the youth sport context emerge when performance emphasis and selection increases. At the lower ('grass-root') sporting level however, the normal distribution of early (approx.

16%), on-time (approx. 68%) and late maturing (approx. 16%) athletes can be explained by policymaker-encouragement of participation without performance emphasis or selection (Côté, Lidor, & Hackfort, 2009). Youth athletes are not being evaluated based on physical characteristics which may be influenced by growth and maturation. Without performance expectations, there is reduced demand for developed physical fitness characteristics subsequently facilitating more inclusive participation opportunities. Some youth sport contexts which function using measurable indices such as centimetres (e.g., long jump), grams (e.g., boxing, judo) or seconds (e.g., athletics, swimming), also referred to as 'cgs sports' (Gulbin et al., 2013a), may find de-emphasising performance particularly challenging and potentially deterring late maturing athletes from early stages. Thus, maturation biases may emerge at lower participation levels (Abbott et al., 2020a). For instance, de-emphasising performance in youth swimming, athletics may require event organisers to re-think competition formatting altogether to retain late maturing athletes. Whereas sports such as soccer and rugby can modify team composition (e.g., mixed gender, small-sided) or playing rules (e.g., non-tackle, removed scorekeeping) (Póvoas et al., 2018).

RAEs have been found at lower ('grass-roots') sporting levels. Relatively older athletes are more likely to participate in sports such as Track & Field (Nakata & Sakamoto, 2012; Romann & Cobley, 2015), Tennis (Gerdin, Hedberg, & Hageskog, 2018), Swimming (Cobley et al., 2018), Soccer (Brustio et al., 2018; Helsen, van Winckel, & Williams, 2005), Basketball (López de Subijana & Lorenzo, 2018) and Rugby (Till et al., 2010) compared to relatively younger athletes. Here, the impact of normative growth and developmental differences (e.g., social, cognitive) associated with being relatively older is influential upon participation. In youth sports contexts requiring high technical skill-related qualities such as golf and gymnastics, differences between the number of relatively older athletes participating compared to relatively younger athletes are comparatively less, particularly at later chronological time points (e.g., 15-16 years - Erlandson et al., 2008; Patel et al., 2020). These findings indicate reduced, and potentially counteracting influences of progressed growth (anthropometrics) and physical development. While emerging RAEs have been identified, growth and maturation influences may not be as extensive at lower sporting participation levels. However, when performance demands are increased growth and maturation differences between individuals are exposed.

2.2 Impact on Selection

In boys and girls, maturation marks the time point of heightened anthropometric (e.g., height, weight, limb lengths and breadths) and muscle growth which are positively associated with improved cardiorespiratory endurance, muscular strength and power, speed and agility (Almeida-Neto et al., 2021a; Armstrong & Welsman, 2019; Carvalho et al., 2019). Depending on the sports context, such physical gains contribute to improved performance. Thus, sporting organisations, their administrators, and coaches should consider growth and maturation when evaluating athlete performances and making selection decisions (Cripps, Hopper, & Joyce, 2016; Hill et al., 2019). Studies suggest pathway managers and selectors understand athlete evaluations (e.g., selection, identification) may be difficult if growth and maturation influences on performance are not considered (Bergkamp et al., 2022; Gullich, 2017). However, studies also suggest selection decision-making within certain youth sports contexts between ages 10-15 years (e.g., Soccer, Rugby) still commonly interpret progressed growth and maturity status for superior technical skill and long-term performance potential (Hill et al., 2021; Romann et al., 2017). Therefore, depending on the youth sport context, early maturing athletes are more likely to be selected for higher-tier participation levels and high-performance opportunities relative to their late maturing peers (Lovell et al., 2015; Müller et al., 2015). On the other hand, later maturing age-group athletes with temporarily delayed growth and physiological capabilities are not afforded the same physical performance advantages. This means that relatively younger and later maturing athletes may be under-represented at competitive youth sporting levels and are less likely to be selected into higher youth performance tiers (Abbott et al., 2020a; Cobley & Till, 2017b). At ages 10-15 years, later developing athletes who are do not meet performance-based selection criteria are more likely to change sports or exit from participating altogether (Hill et al., 2021; Moulds et al., 2020).

While a selection-bias favouring earlier maturing athletes exists in certain sports, a reversal effect has been reported in youth sport contexts where performance is less dependent upon increased body size and physicality and more reliant upon technical skill. Sports such as Ballet (Hamilton et al., 1997), Gymnastics (Erlandson et al., 2008; Patel et al., 2020) and certain swimming events (e.g., Female 100-m Freestyle - Hogan et al., 2022) indicate a ‘swing’ toward improved selection likelihood in later maturing compared to earlier maturing youth athletes during and post-maturational time points (i.e., PHV). Findings suggest later maturational onset (i.e., PHV attainment) is associated with less intensive growth and weight gain during maturation (Malina, Bouchard, & Bar-Or, 2004; Thomis et al., 2005). Such increases in anthropometrics (e.g., height, weight, limb lengths and breadths) may correspond to similar continuous gains in physical performance development. This allows late maturing athletes more time to adjust to physiological gains in movement coordination, joint range of motion, bodyweight strength and technical skill development (Thomis et al., 2005).

Depending on the youth sport context, maturation-selection biases may ‘weed out’ early or late maturing athletes if differences in maturity status and timing are not considered (Hill et al., 2021; Moulds et al., 2020). Figure 7a shows how early maturers are more likely to be represented in higher selection levels as physical performance demands increase (e.g., higher qualifying standards, physical performance benchmarks). Meanwhile, Figure 7b illustrates how late maturers may be over-represented at higher selection levels in sports with increased aesthetic and technical skill components. While maturity timing differences may reflect physical characteristics associated with improved performance, they should not necessarily preclude participation or be used to evaluate future athletic potential. Research studies suggest that later maturing athletes who persist within sport with high physical performance demands may actually catch up to their earlier maturing peer’s post-maturation (Cobley et al., 2018; Deaner, Lowen, & Cobley, 2013). Accounting for maturation when evaluating performance and making selection decisions, therefore, is vitally important to retaining youth athletes, promoting long-term development, and maximising athletic depth by later adolescence (e.g., accommodating late-bloomers).

Figure 7: Conceptual illustration of maturity timing distributions of youth participants in sports with high (a) physical characteristics and (b) technical skill and aesthetic contributions at state/national age-group performance-selection level.

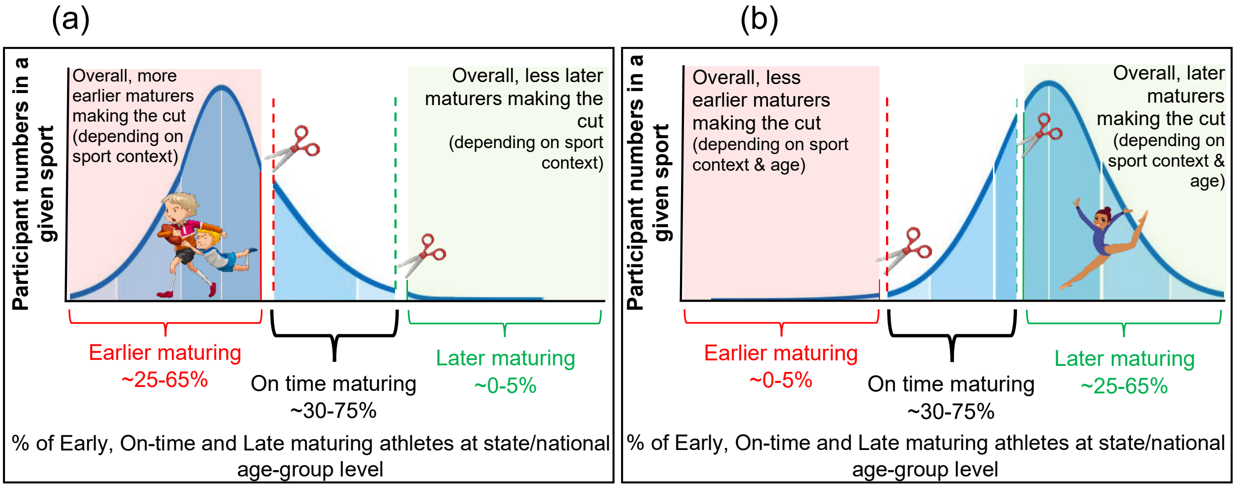


Figure Note: Adapted from youth male and female age-group swimmer populations (Abbott et al., 2020; Hogan et al., 2022)

3. How do Growth and Maturation influence Youth Athletic Performance?

Across multiple youth sporting contexts, growth and maturation influence numerous physical performance indices, including the relative rate of their development over time (Cobley et al., 2021). The types of performance indices affected include (although not an exhaustive list): cardiorespiratory endurance, muscular strength, power, flexibility, technical skill, and movement coordination. Exactly how, and the extent of growth and maturational influences varies according to the type of performance capability assessed, pre-existing athlete physiology (e.g., hormonal, neuronal, bone and muscle development - Malina et al., 2004; Malina, Bouchard, & Beunen, 1988) and the nature of the physical task within the sport context (e.g., reach, throw, jump, sprint, pass). Thus, it is important for sporting organisations, managers, coaches, supporting practitioners and parents to understand how growth and maturation influence such performance indices, so as to understand present capabilities in individual athletes; the potential reasons for between-athlete differences; the likely developmental trajectories for individual athletes; and identify appropriate intervention steps to optimise development.

3.1 Cardiorespiratory Endurance

To perform movement tasks with high physical exertion for an extended period, the efficient transport of oxygen to the working muscles by the heart and lungs is necessary. Cardiorespiratory endurance is the capacity for the heart and lungs to transport oxygen to the muscles needed during exercise (Hawkins et al., 2007). Before maturation onset, boys and girls share similar cardiorespiratory endurance levels and relative rates of improvement (Geithner et al., 2004). However, between 10-16 years of age, maturational-based differences in cardiorespiratory endurance development emerge (Armstrong & Welsman, 2019). Figure 8a illustrates how in boys' cardiorespiratory endurance increases continuously across maturation, with full maturational gains not finalised until adulthood (i.e., > +3 years PHV). Meanwhile, Figure 8b demonstrates how cardiorespiratory endurance development in girls similarly progresses across maturation. However, unlike boys, the influence of maturation tends to accelerate and diminish at earlier chronological ages (i.e., -2 years PHV and +1 years PHV respectively - Chamari et al., 2005). With maturational progress, particular maturity time points mark occasions where there is a likely prominent increase in cardiorespiratory endurance (Geithner et al., 2004). Figure 8a illustrates how boys experience a pronounced acceleration in cardiorespiratory endurance just prior or during PHV. For girls, Figure 8b identifies accelerated cardiorespiratory development prior to PHV (around -2 years PHV), with accelerated gains up to PHV. One explanation for the difference in cardiorespiratory endurance gains and absolute differences between boys and girls across PHV stages is that larger amounts of muscle mass are gained during and post-PHV in boys compared to girls (Armstong & McNarry, 2016). Larger muscle size helps utilise more oxygen during exercise which assists with improved cardiorespiratory endurance (Landgraff et al., 2021).

Figure 8: Changing relationships over time between Maturity Status (Years to/from Peak Height Velocity) and Cardiorespiratory Endurance (% of VO2) in youth athletic boys (a) and girls (b).

(a) **(b)**

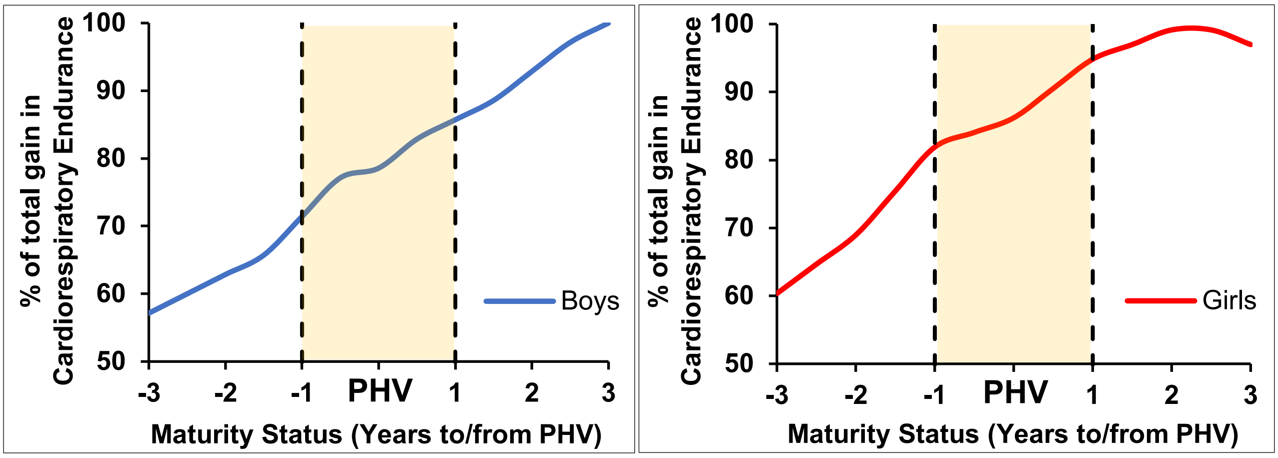


Figure Note: Adapted from youth male and female active general and athletic (soccer) populations (Saward et al., 2020; Geithner et al., 2004); VO_2 refers to the body's capability to utilise oxygen.

In a practical setting, such developmental patterns may lead to observations where youth athletes advancing earlier into, and through PHV, may experience earlier more rapid improvements in cardiorespiratory-based sports performance, including field-based assessments such as Multi-Stage Fitness Tests (e.g., Beep tests). For later maturing youth athletes, they may experience more gradual rates of acceleration and deceleration at later time points.

3.2 Muscular Strength

As youth athletes progress through maturation, hormonal (androgenic) and skeletal (anthropometric) changes contribute to increases in muscle size and strength (Brown, Patel, & Darmawan, 2017; Jones et al., 2008; Myer et al., 2013). During maturation, the patterns of muscular strength development tend to be similar between upper and lower body muscles (Beunen & Malina, 1988; Lloyd & Oliver, 2012). To highlight in relation to upper-body strength, Figure 9 shows gradual strength accumulation leading to the point of PHV in boys (Figure 9a) and girls as measured during seated medicine ball throwing in Basketballers and shoulder (internal rotation) push strength in swimmers (Figure 9b). However, for boys and girls, muscular strength gains accelerate at 0.5-1.5 years after PHV (Philippaerts et al., 2006; Wild, Steele, & Munro, 2013). While boys and girls follow similar maturational related strength-gains, it is important to remember maturational onset occurs two chronological years earlier in girls on average. Thus, girls are more likely to have attained a greater percentage of their total maturational strength for a given chronological age.

Figure 9: Changing relationships over time between Maturity Status (Years to/from Peak Height Velocity) and Muscular Strength in youth athletic (a) boys and (b) girls.

(a) (b)

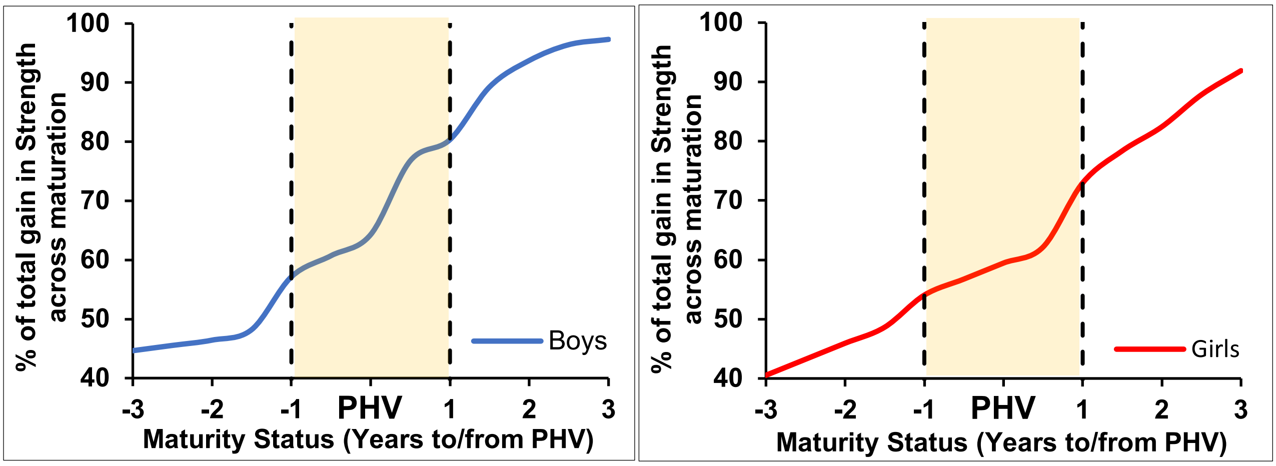


Figure Note: Adapted from youth male and female upper-body strength trends in athletic (basketball and swimming) populations (Guimaraes et al., 2021; Abbott et al. *unpublished*).

While muscular strength gains occur continuously across maturation, boys and girls may experience periods of stagnated progression (Guimarães et al., 2021). Figures 9ab also show how the rate of change in muscular strength gains per year may be temporarily reduced leading into PHV for boys and at early mid-PHV stages for girls. Once PHV has been attained, however, boys demonstrate much quicker accumulations in muscular strength (i.e., from +1 years PHV - Viru et al., 1999). Generally speaking, more rapid increases in male strength levels post-PHV help explain how boys eventually catch up to and exceed female strength levels during adolescence.

Understanding how maturation impacts muscular strength development in youth athletes is particularly important in sports where upper and lower limb muscular activity need to propel, displace, or lift the body (Jaric, 2002). In swimming, for example, sufficient force (i.e., strength) is necessary to propel through the water (Morais et al., 2020). However, boys and girls can also experience increases in lean and fat mass accumulation during maturation which affect strength capability, and therefore, performance (Taeymans et al., 2009). In girls, for example, early maturity timing (e.g., PHV < 11 years) is associated with sharper increases in weight gain via subcutaneous adipose (fat) tissue relative to muscle mass accumulation (Malina et al., 2004). Increased fat mass, specifically, may partially counteract improved strength capabilities required in movements to propel, displace, or lift the body in specific movement tasks. For instance, early maturing females with increased body fat accumulation, compared to later maturers, may be unable to meet necessary strength-related demands and associated technical requirements necessary for continued progression (Hamilton et al., 1997) in contexts such as Ballet (Mitchell, Haase, & Cumming, 2020). Therefore, greater strength relative to later maturational attainment (PHV) may be advantageous in the longer-term (Gay et al., 2014; Mitchell et al., 2018). Meanwhile, for boys, body mass gains are predominantly due to accumulating muscle mass (with less fat mass accumulation), thereby helping positively translate into muscular strength without potential performance detriment (Jones et al., 2008).

3.3 Muscular Power

Muscular power refers to the capacity of muscles to produce force over a given (typically short) period (Thiele et al., 2021). Muscle power is needed when performance requires displacement of mass which could take the form of an object (e.g., ball, discus, javelin) or the athlete themselves (e.g., lifting, running, jumping, swimming - Barreiros, Cote, & Fonseca, 2014; Korff et al., 2009; Waugh et al., 2013). Sports tasks requiring speed (e.g., 20-m shuttle run, 100-m sprint), and agility (change of direction - Saward et al., 2020) by the athlete, therefore, depend on muscular power. During maturation, upper and lower body muscular power increases continuously until adulthood in boys (Figure 10a) and girls (Figure 10b - Almeida-Neto et al., 2022). Boys experience faster biological gains in muscular power during PHV compared to girls; however, such differences reduce as maturity-related improvements in muscular power begin 'levelling off' following peak growth (i.e., > 1-1.5 YPHV).

Figure 10: Changing relationships over time between Maturity Status (Years to/from Peak Height Velocity) and Leg Power in youth athletic boys (a) and girls (b).

(a) (b)

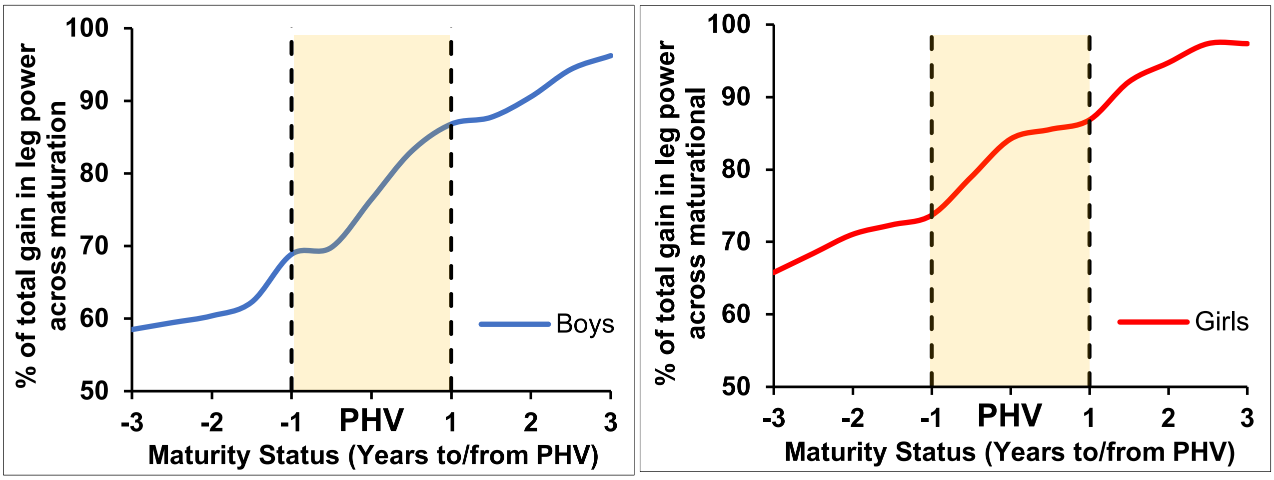


Figure Note: Adapted countermovement jump trends in active youths and verified in athletic (rowing [ergometer] and swimming [vertical jump]) populations (Almeida-Neto et al., 2022; Almeida-Neto et al., 2021; Abbott et al. *unpublished*).

Like muscular strength gains across maturation, boys and girls may experience time points of increased muscular power improvements followed by periods of stagnated progression rates during PHV (Rumpf et al., 2013). As shown in Figures 10ab, temporary reductions in rates of maturity-related leg power improvements have been observed, during for example a vertical jump test, immediately pre-PHV in boys (approx. -1 to -0.5 from PHV) and girls (approx. -1.5 to -1.0 years from PHV). In boys, potentially reduced improvement rates in leg power may be seen around -1 years from PHV when the femur and tibia bones are typically growing at their maximum rate (Almeida-Neto et al., 2021b). Rapid lower limb growth may contribute to compromised force-generating capabilities of leg muscles involved in power-based movements at these particular time points in both boys and girls (Abbott et al. 2023). Following further rapid gains in muscle power at PHV, youth athletes may again experience reduced rates of muscular power improvements around +1 year from PHV - Almeida-Neto et al., 2022). On this occasion, the later PHV stage aligns with expected increases in torso growth. While similar patterns in muscular power gain occur in girls, changes appear more varied during PHV which may be explained by differences in growth and maturation (Almeida-Neto et al., 2021a). In girls, time points characterised by rapid increases in lower-limb growth (pre-PHV) and weight gain (post-PHV) correspond with reduced muscular power improvement (Figure 10b). Despite improvement rates in girls re-accelerating again around +1 year after PHV, maturity-related increases in body mass which also occur at this time may explain more modest progression in muscular power compared to boys (Mitchell et al., 2018).

3.4 Flexibility

Flexibility refers to the range of motion (ROM) available around a joint (Magnusson & Renström, 2006). As some sports require greater ROM than others, the capability to move through greater joint ROM is important for performance and injury prevention (Donti et al., 2022). For example, gymnasts, divers, and dancers require heightened ROM along with fine motor control to complete technical skills (e.g., repetitive, and rotational movements, point work - Poggini, Losasso, & Iannone, 1999). As maturation is associated with changes in bone shape, increased muscle mass and nerve tissue development, ROM is also affected (Storm et al., 2018). Depending on the joint examined, ROM may increase and decrease at maturational time points. Figure 11 illustrates how in boys immediately prior to PHV, trunk (lower-back) and leg ROM are negatively affected by re-accelerated growth. Following PHV however, trunk (lower-back) and leg ROM improves as growth decelerates. The reason for these trends in boys and girls has been associated with the rapid lengthening of the femur and tibia (Xu et al., 2009). Such lengthening applies stretch-like tension to the underdeveloped leg muscles, giving rise to tendon and muscle tightness and growth-related injury (e.g., Osgood-Schlatter Disease - Nakase et al., 2014). Improvements in ROM are more likely to occur outside peak growth time points. Thus, individuals experiencing periods of rapid growth are more vulnerable to ROM loss and potential injury. For those experiencing heightened growth (e.g., mid-PHV), regular lower-intensity stretching may temporarily alleviate ROM-associated symptoms (e.g., tightness - Behm et al., 2016).

Figure 11: Changing relationships over time between Maturity Status (Years to/from Peak Height Velocity) and Upper-Leg Range of Motion in Male Soccer Players during a Sit & Reach Test.

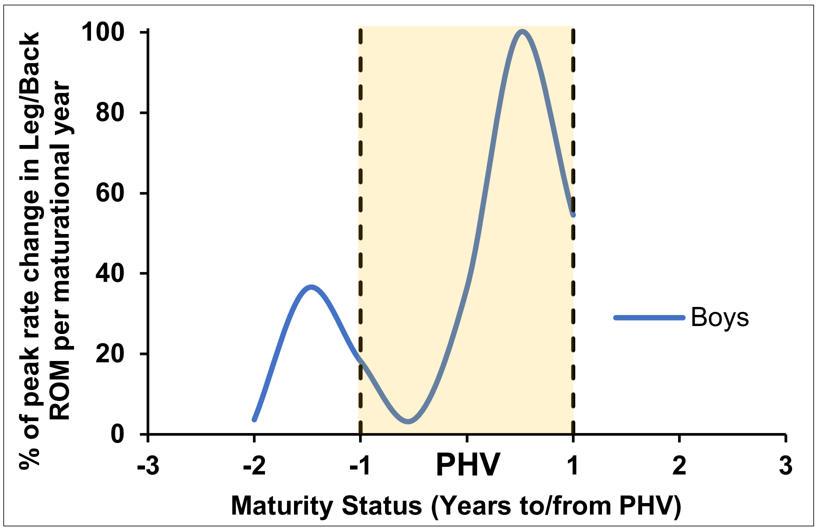


Figure Note: Adapted from Philippaerts et al., (2007) during Sit & Reach Test in youth male soccer players and verified in youth athletes from Guimaraes et al. (2020).

Depending on the joint, increased growth and hormonal activity during maturation may lead to joint instability and increased ROM at undesirable ranges (Hewett et al., 2015; Meyers et al., 2015; Wild et al., 2013). For example, increased knee laxity during PHV may place unwanted loading on the connective tissue (e.g., ligaments) when performing at extreme ROM or changes in direction tasks (e.g., turn, twist, side-step – see Figure 12). Particularly in girls, increases in leg length and upper-body mass during PHV are likely to demand greater muscular knee strength for similar knee stability. Without such stability, which may not develop until post-PHV, there is possibility of heightened injury risk (Hewett et al., 2015; Meyers et al., 2015; Wild et al., 2013).

Figure 12: Changing relationships over time between Maturity Status (Years to/from Peak Height Velocity) with Knee Range of Motion (knee abduction from the midline) during landing in a jump task.

(a) (b)

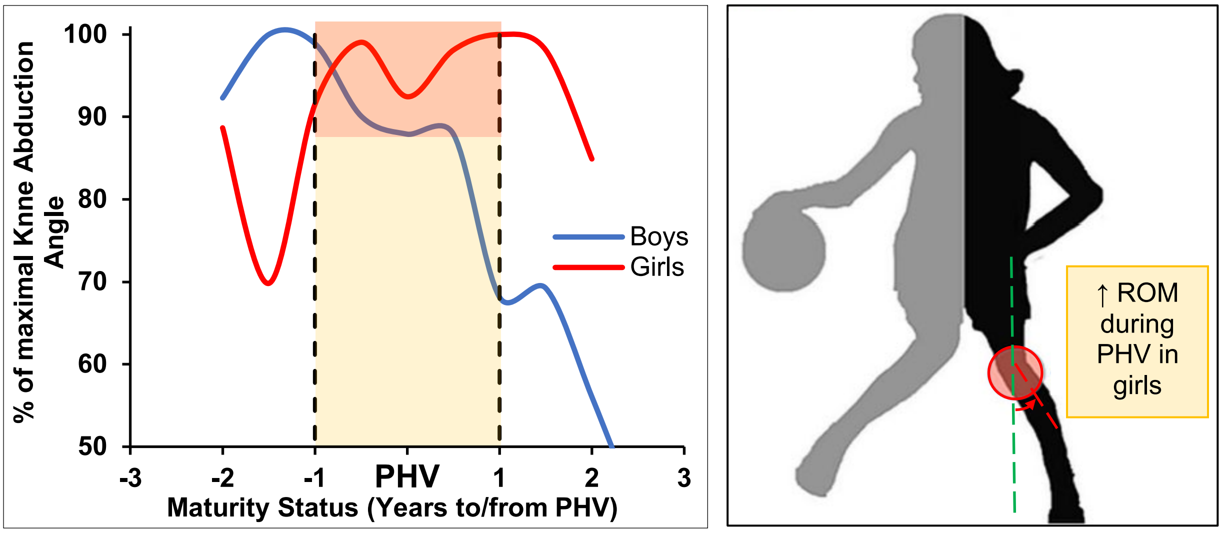


Figure Note: Adapted from Hewitt (2015) in male and female youth Soccer and Basketball players and Figure 12b adapted from Myers et al., (2015).

3.5 Technical Skill

The capability to move the body to coordinate required sport-specific actions with (bio-)mechanical and energetic efficiency can be collectively referred to as technical skill. Examples of some technical skills in sports such as Australian Rules Football, Rugby, Rugby League, and Soccer include handling (or dribbling), passing and shooting. Meanwhile, other sports with technical emphases such as gymnastics, diving and dancing include complex acrobatic-style movements require heightened balance (stability) and limb control (e.g., minimal leg separation and joint angle deviations). During adolescence, technical skills may develop at different rates and according to the type of skill assessed (Abbott et al., 2021; Valente-dos-Santos et al., 2012). To help illustrate, Figure 13 shows how as maturation is influential upon ball shooting accuracy and dribbling speed in male youth soccer players (Valente-dos-Santos et al., 2012). Marginal changes in ball shooting accuracy can be seen between -2 YPHV and +3 YPHV. Meanwhile, ball dribbling speed improves at a steeper rate immediately pre- and mid-PHV compared to ball shooting accuracy indicating how maturation can influence each technical skill differently. The trends in Figure 13 also suggests that the magnitude of maturational influence on technical skills may also depend on how much physiologic input is involved (e.g., skeletal growth, muscular strength, and power). For instance, ball shooting accuracy may rely less upon physical growth and maturation. This is possible because the distance from the shooting mark to the goal targets were kept constant over time in the study where Figure 13 was generated (Valente-dos-Santos et al., 2012). Ball shooting accuracy performance may be more reliant on other factors associated with the (linear) passage of time such as learning and practice (e.g., training, experience). Dribbling skill performance which includes fitness components of sprinting and agility may thus be more influenced by growth and maturation.

Figure 13: Changing relationships over time between Maturity Status (Years to/from Peak Height Velocity) and Technical Skills in youth soccer players.

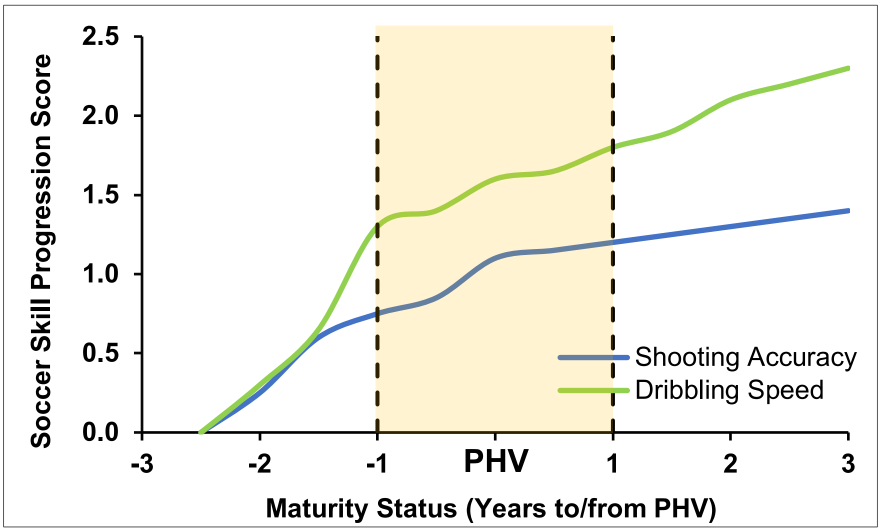


Figure Note: Adapted from annually repeated Soccer-Specific skills assessments in males aged 11-17 years (Valente-dos-Santos et al., 2012).

Technical skill is important for athletic performance and can be developed over time without substantial impact of growth and maturity status (Abbott et al., 2021;

Segers et al., 2008). In other words, how an athlete uses (and coordinates) their limbs is consistently important for performance over time irrespective of how big (or long) their body proportions are (e.g., muscle mass, limbs, breadths), depending on the sports context. Figure 14 shows that as boys and girls mature over time, their swim efficiency generally improves. The blue dotted line shows how increases in age and associated accumulated training hours over time is associated with consistent improvements in swim efficiency. Meanwhile, increases in maturity status indicate marginal improvements in swim efficiency over time (Abbott et al., 2021). This suggests that despite positive influences of growth and maturation upon physical characteristics of performance such as strength, power and cardiorespiratory endurance, youth athletes can develop technical skill proficiency at any time. Improved technical skills are positively associated with performance across age group sporting years. Findings have particular significance for late maturing athletes who may be physically disadvantaged relative to their early maturing peers yet can still focus on developing technical skill level to improve performance until increased growth and maturation occur. In addition to competitive youth swimming, similar trends have also been observed in other youth sports contexts. During running for example, late-maturing athletes have been shown to make technical adjustments (e.g., longer relative stride length, reduced knee, and ankle bend during swing phase) in order to match the running efficiency of earlier maturing athletes of similar chronological age (Segers et al., 2008). Therefore, it is critical practitioners and coaches developing youth athletes emphasise technical skill development and understand the appropriate technical skill requirements according to maturity status.

Figure 14: Relationships between Maturity Status (Years to/from Peak Height Velocity) and Technical Skill in youth swimmers.

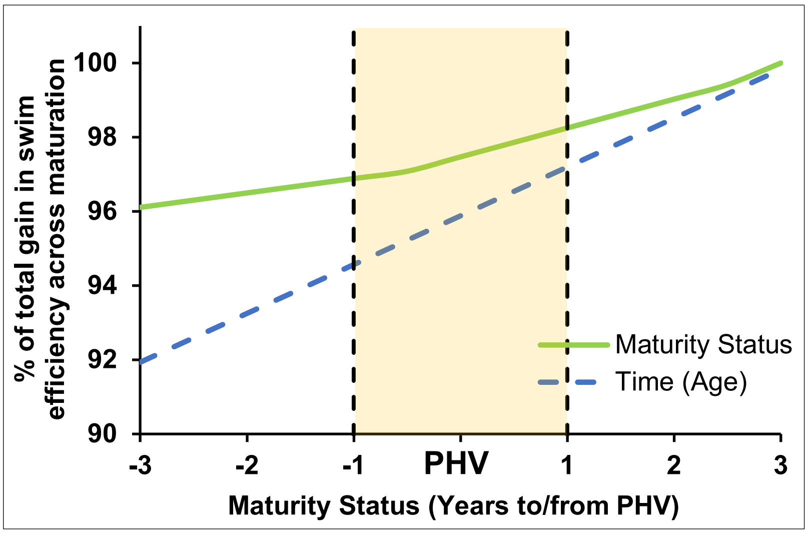


Figure Note: Adapted from 2-year tracking of youth male and female swimmers aged 10-15 years (Abbott et al., 2021).

3.6 Movement Coordination

Athlete movement control systems generally improve from childhood to adulthood (Abarghoueinejad et al., 2021). Even though athletes experience natural biological gains in muscular strength, power and agility during maturation (Duarte et al., 2018; Freitas et al., 2016; Philippaerts et al., 2006; Sokołowski & Chrzanowska, 2012), athletes undergoing rapid increases in growth within short periods, particularly the leg bones (femur and tibia), may experience temporary disruptions in movement coordination (Quatman-Yates et al., 2012). Growth-related impairments in movement (motor) control during balancing, sprinting, and jumping tasks (Ford, Myer, & Hewett, 2010; Wik et al., 2020) can translate into short-term reductions in performance (Dos Santos et al., 2019) and increased injury risk (Monasterio et al., 2021). The disruptive changes in athlete coordination, mobility and skill execution that occur during maturational growth can also be referred to as 'adolescent awkwardness' (Wachholz et al., 2020). Using sports which require the lower limbs to land and rebound quickly as an example, Figures 15 ab shows how boys and girls undergoing rapid growth may have difficulty coordinating efficient hop, jump, step, or change of direction type movements. Depending on the movement control system, boys may experience a temporary 7-11% reduction in leg coordination during PHV, whereas girls undergo more modest growth increases compared to boys during PHV and may experience similar but reduced coordination impairments (Quatman et al., 2006; Abbott et al., 2023). Following PHV, Figures 15 ab also show how movement control capabilities increase quickly before 'levelling off' later in adolescence.

Figure 15: Changing relationships over time between Maturity Status (Years to/from Peak Height Velocity) and Movement Coordination in youth athletic (a) boys and (b) girls.

(a) (b)

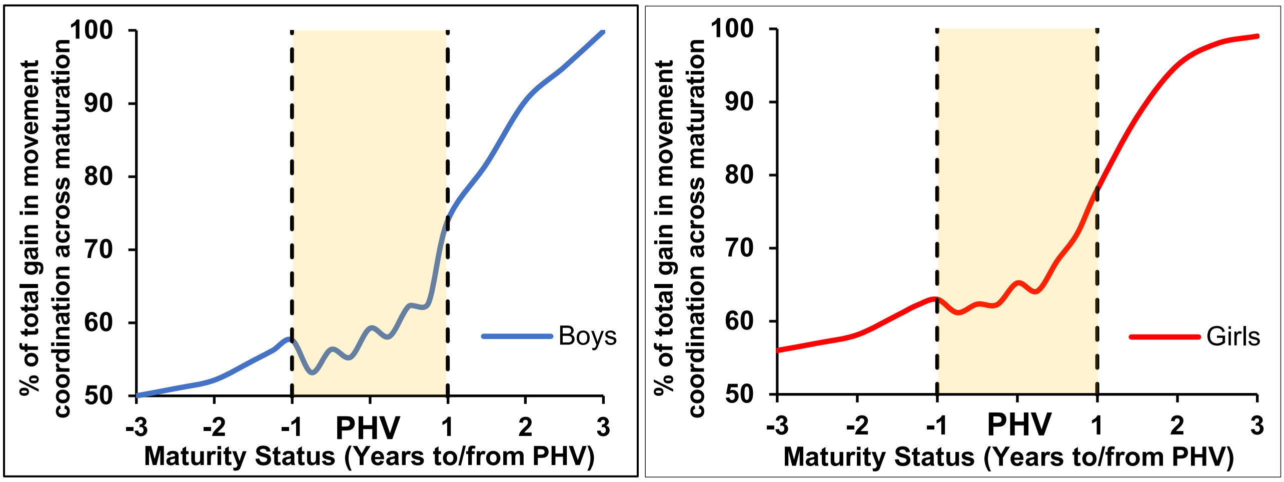


Figure Note: Adapted from 3-year tracking of youth male and female swimmers aged 10-15 years (Abbott et al., 2023).

4. What can you do to account for Growth and Maturation in Athlete Development?

How far an athlete has progressed along their maturational journey at particular time points (i.e., maturity status) can tell you a lot about their physical and technical skill performance. Understanding this, provides a rationale for why sporting organisations should emphasise to practitioners and coaches that growth and maturation information be used as part of athlete tracking and evaluation. It is recommended that parents track growth and maturation from 11-12 years in boys and 9-10 years in girls and share this information with their youth sport practitioners and coaches. To help, this section will provide detailed instructions for parents measuring growth and assessing maturation. These procedures can be utilised across various sporting contexts.

4.1 Tracking Growth and Maturation

4.1.1 Growth

To accurately capture changes in height, the initiation of the growth spurt ('take-off') and PHV attainment, periodic body height measurements are recommended every 4-6 months between the ages of 10-18 years.

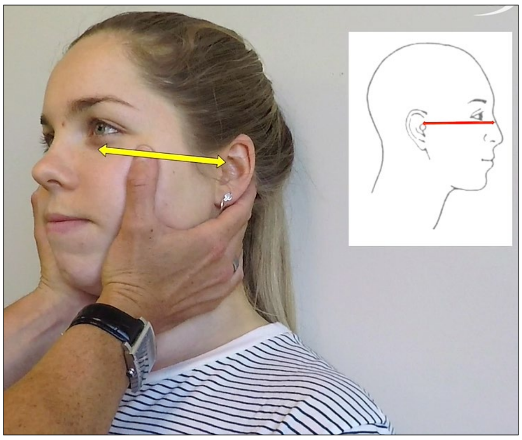
Measuring Height

To measure height accurately, shoes should be removed, and measures taken with the subject standing on a hard, level surface (e.g., concrete, tiled, timber flooring).

1. Have the athlete stand with their back, hips, and heels against a stadiometer (or wall) with feet together and flat on the floor.
2. Adjust the athlete's head to ensure the eyes and ears are level – also called the Frankfort plane - as seen in Figures 16. Place your hands far enough along the

line of the athlete’s jaw so that the hands cover the area of the skull just below and behind the ear and along the jaw line and cheek.

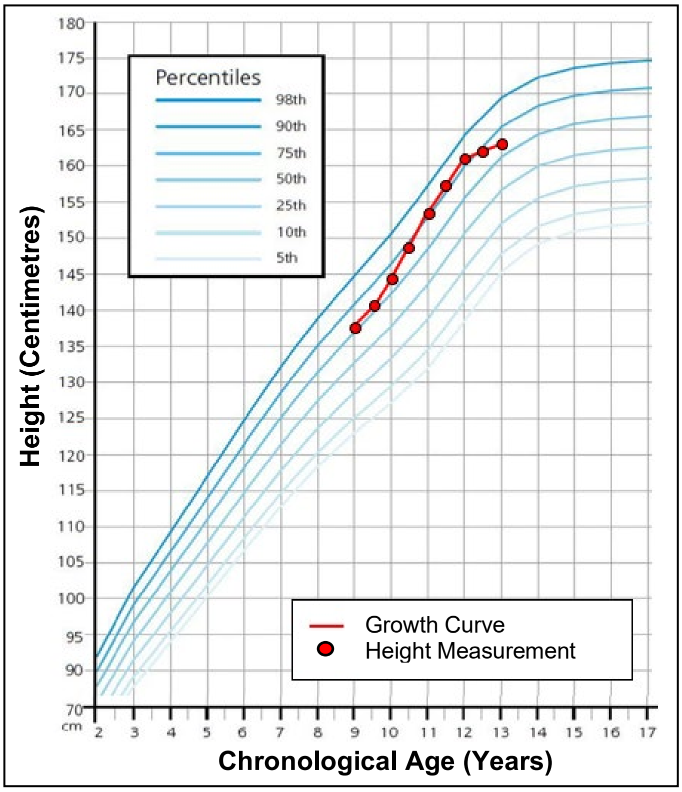
Figure 16: Illustration of head positioning in the Frankfurt plane during height measurement.



3. Instruct athlete to take and hold a deep breath while keeping the head level (in the Frankfort plane). At the same time, place the headboard (e.g., clipboard, ruler, or hard cover book) firmly down on the top of the head, crushing the hair as much as possible. Ensure that the athlete does not lift their heels off the ground and that the position of the head remains level.
4. Mark the point on the wall at the end of the deep inward breath – measure and record height to the nearest 0.1 centimetres.
5. Repeat steps 1 to 4
6. If the two measurements differ by more than 0.4 cm then a third measure is required (i.e., repeat steps 1 to 4)
7. If two measurements, record the average value. If three measurements, record the median (middle) value.

Parents and coaches can use athlete height measures to plot growth over time. One strategy is to plot height measurements onto Australian reference growth curves for boys or girls. Height for age growth charts for boys and girls between 2-18 are freely accessible from here. Figure 17 provides an example of a female athlete with 6-monthly growth measurements recorded and plotted (in red) between 9-13 years. At ages 9-9.5 years, height measures follow just above the 75th percentile until growth begins to deviate above the expected 75th percentile growth curve between 10-13 years. During adolescence, an increased growth curve gradient in line with, or exceeding, the expected percentile curve as seen in Figure 17 signifies the beginning of the peak growth period. Meanwhile, the chronological age at which the growth curve is steepest indicates PHV attainment. In the example of Figure 17, the initiation of the athlete's growth spurt ('take-off') occurs at 9.5 years, while PHV is attained at approximately 11.5 years, respectively. Increasing measurement frequency to every 3-4 months around the PHV stage is recommended to help identify more subtle changes in growth. The amount of deviation above her expected pre-adolescent growth percentile curve, however, indicates that an earlier onset of heightened growth tempo was experienced. If she had experienced continued deviation below her expected pre-adolescent growth percentile curve followed by a delayed increase in growth tempo would have indicated later maturational timing. As seen in Figure 17, height measures returned downward toward the 75th percentile after 12 years of age indicating growth curves returned to pre-adolescent levels (percentiles) post-PHV. Post-PHV reflects cessation of peak maturational growth and marks the stage of more modest height accumulation up until full adult height attainment. Thus, the capability to identify when peak growth has subsided may also be helpful to coaches, sporting practitioners (e.g., strength and conditioning practitioners) and NSOs when it comes to understanding athlete performance progression and managing training loads. Specifically, performance progression may now be more modest given reduced growth and physical development changes occurring post-PHV, yet peak growth has now finished indicating a potential time point for training modification.

Figure 17: Female athlete growth curve plotted across Peak Height Velocity (PHV) stages between 9-14 years.



4.1.2 Maturation

Practical challenges associated with collecting repeated (longitudinal) athlete height measurements within sporting clubs and institutes/academies can mean that calculating growth tempo and tracking maturation is difficult. Four different mathematical formulas can be used to estimate the amount of time (in years) to/from PHV (i.e., YPHV) and categorise athlete maturity status (e.g., pre-PHV, mid-PHV, post-PHV) in boys and girls without needing to repeatedly measure height (Fransen et al., 2018; Mirwald et al., 2002; Moore et al., 2015). These equations are based on known patterns of proportional growth derived from Caucasian Canadian and Belgian youth populations. The most used method in youth sport is the Mirwald et al. (2002)

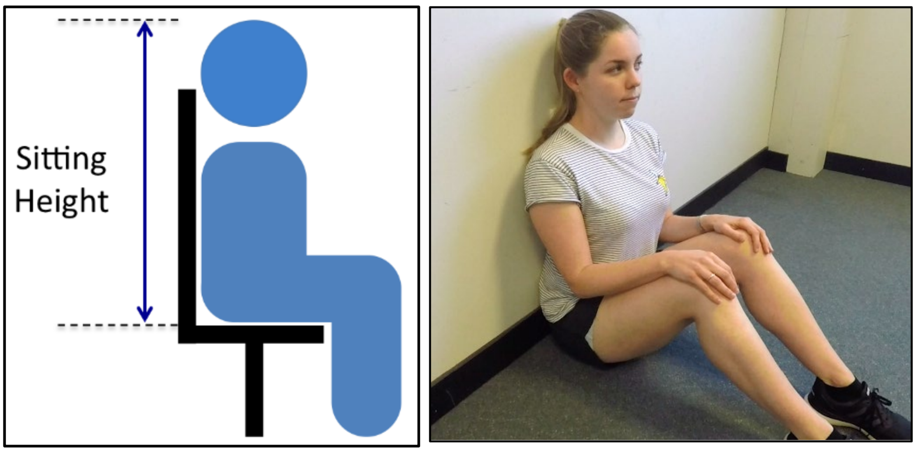
equation which estimates maturity status, expressed as YPHV. Meanwhile, the Fransen et al. (2018) method is a more recent equation based on Australian male youth soccer players which can also generate YPHV. This method has shown some improvement in estimation accuracy yet is presently restricted to males only. Depending on the formula, measurements required to calculate YPHV include height, sitting height, weight and decimal age as calculated using athletes' date of birth and date of measurement. Having already covered how to accurately measure height, correct sitting height, and body weight measurement instructions will now be described for the purpose of maturity status assessment.

Measuring Sitting Height

1. Seat athlete preferably on a measuring box or level platform (of known height) with their back up straight and against a wall as seen in Figure 18. Alternatively, measurements can also be taken with the athlete seated on the floor with the legs bent slightly and feet flat on the floor as shown in Figure 18.

Figure 18: Illustration of body positioning measuring sitting height from (i) box/bench measurement or (ii) floor.

(i) (ii)



2. Adjust the athlete's head to ensure the eyes and ears are level (i.e., in the Frankfort plane).
3. Instruct athlete to take and hold a deep breath while keeping the head level (in the Frankfort plane). At the same time, place the headboard (e.g., clipboard, ruler, or hard cover book) firmly down on the top of the head, crushing the hair as much as possible. Ensure the athlete does not contract the gluteal muscles nor push with the legs.
4. Mark the point on the wall at the end of the deep inward breath – measure and record the distance from the firm bench (box/stool) or floor up to the mark on the wall to the nearest 0.1 centimetres.
5. Ask the athlete to step off the box or floor and away from the wall
6. Repeat steps 1 to 4
7. If the 2 measurements differ by more than 0.4 cm, then repeat steps 1 to 4
8. If two measurements, record the average value. If three measurements record the median value.
    - Note, if using a box/bench and you have measured from the floor (and not the box/bench surface), you will need to subtract the box/bench height in order to accurately measure sitting height.
    - Leg Length can then be calculated as the athlete's standing Height (cm) minus their sitting height (cm). You will need the sitting height and leg length values for maturity status estimation equations.

Measuring Weight Using Scales

During infancy, medical practitioners periodically measure body weight to monitor developmental progress (trajectory) and other important biological milestones. Maturation onset marks another life milestone followed by a period of considerable anthropometric (e.g., height and weight) changes. In much the same way as during infancy, body height and weight can inform developmental progress and help identify important growth time points. Within the context of this resource, body weight is measured solely for the purpose of tracking maturation.

1. Weight is measured with minimal clothing and shoes removed (see Figure 19)
2. Two measurements are recorded to the nearest 0.1 kilograms (kg)
3. If the two measurements differ by more than 0.4 kg then a third measure is required (i.e., repeat steps 1 to 4)
4. If two measurements, record the average value. If three measurements, record the median (middle) value.

Figure 19: Illustration of foot positioning during body weight measurements.

It is important that measurements are taken accurately to reduce error associated maturity status estimates generated. Once completed, measurements can be inserted into the equations to generate YPHV estimates. To align with the content presented in this resource and encourage maturation tracking as part of standard athlete development practices, a freely downloadable calculation spreadsheet has been developed and can be accessed here. Maturity status (YPHV) estimation is most accurate around the actual (observed) PHV event. Therefore, it is suggested that YPHV equations are utilised most between ages 12-16 years in boys and 10-14 years in girls. Like with any estimation method, YPHV calculations do have some margins of error associated. In 'On-time' maturing boys, YPHV estimates may be off by approximately 0.57 years (or 6-8 months) and 0.12 years (or 1-2 months) in girls. For example, an 'On-time' maturing 10-year-old female with an actual PHV of 12 years has an estimated YPHV of -2 years with a range between -2.12 and -1.88 years. In 'Early' and 'Later' maturing boys and girls, error ranges may increase up to 12 months (Moore et al., 2015). Estimate methods have been successfully applied in youth athletes of non-Caucasian backgrounds (e.g., Brazilian, Italian); however, the equations themselves were developed using Caucasian youths, and so, users need to be aware when assessing.

In addition to estimating PHV, the percentage of predicted adult height (%PAH) method can be used to assess maturity status. The %PAH method describes the amount of growth completed at the time of observation in relation to the total predicted mature adult stature (i.e., 100%). For example, a higher percentage assumes closer proximity to the fully mature adult stature (i.e., 100%). When assessed among youth athletes of the same chronological age, athletes who are closer to their predicted adult height (i.e., a higher %PAH) are more progressed in maturation compared to those further away from their predicted adult height. The Khamis-Roche (K-R) formula can be used to predict adult height (Khamis & Roche, 1994). Similar to PHV assessment, the K-R method requires chronological age, height, and weight for calculation. In addition to PHV methods, height measures from both biological parents are required. Variations in adult height predictions during peak growth periods (i.e., 14-15.5 years in boys and 11.5-12.5 years in girls are within 3.1 cm and 2.3 cm respectively (Khamis

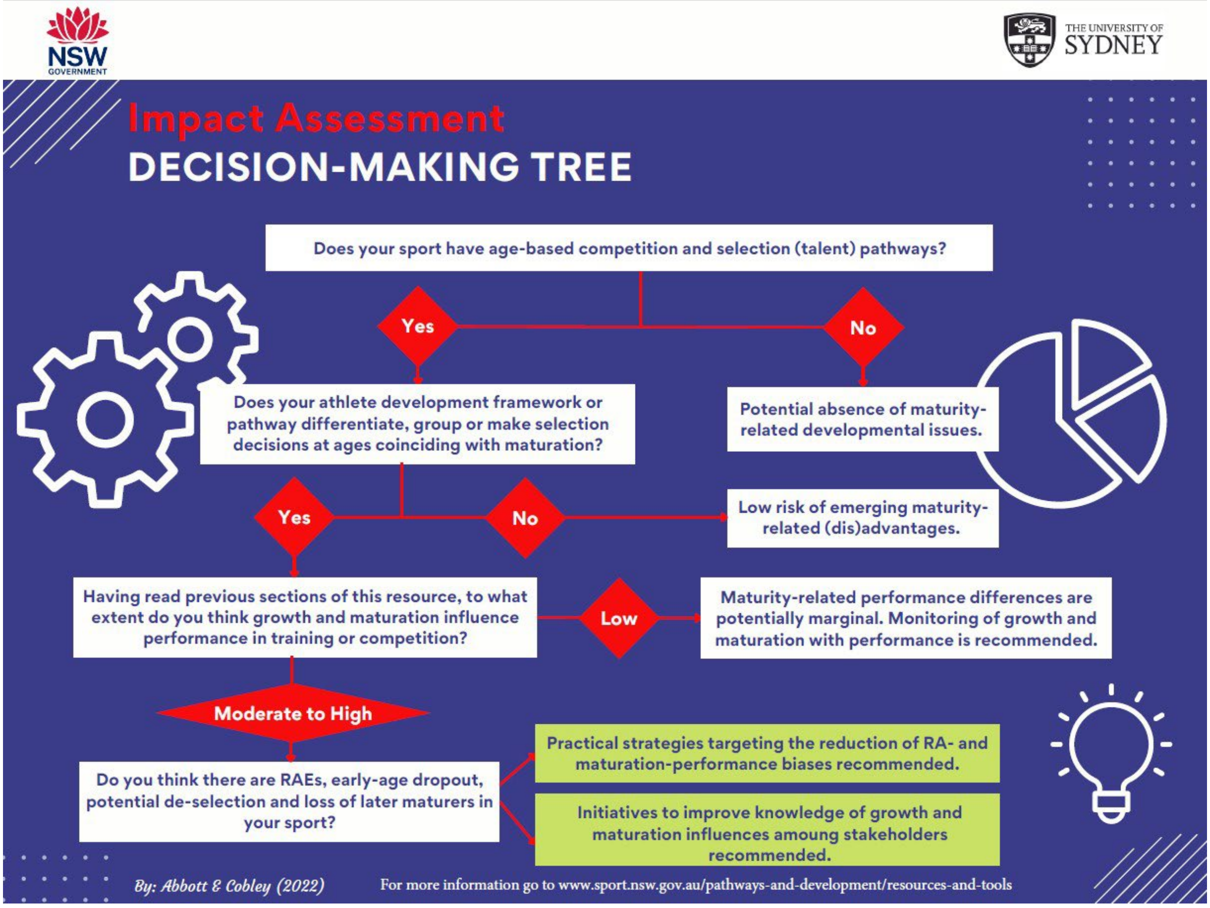
& Roche, 1994). It should be noted that the %PAH method is not designed to assess the number of years to/from PHV and may not sufficiently capture other maturational events that may follow full adult height attainment (e.g., peak weight and strength gains).

5. Where do Sporting Organisations and Practitioners go from here?

5.1 Assessing the Problem

Before considering and implementing strategies to account for growth maturation, it is necessary to first determine whether growth and maturation are in fact impacting athlete inclusion, opportunity, and development. Sporting organisations and policymakers can assess whether junior and youth participation and athlete development pathways in a given youth sport context are being impacted by growth and maturation. Figure 20 provides an example decision-making tree (flowchart) of how an initial impact assessment might look:

Figure 20: Decision-making tree for sporting organisation assessment of Relative Age (RA) and maturity status impact in youth sport.



5.2. What are some potential strategies you can consider?

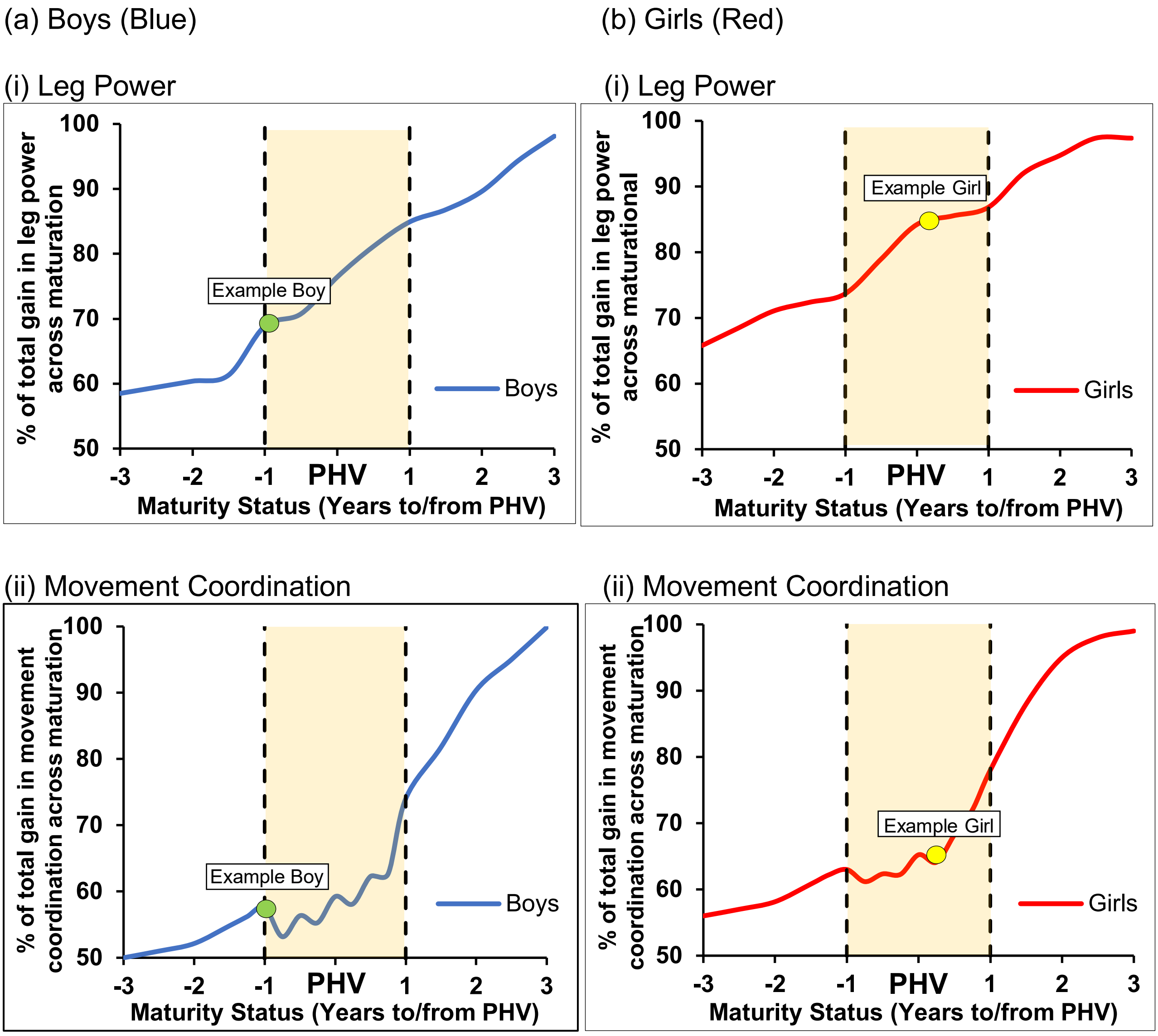
The following section now summarises several strategies that can be considered and implemented to address the issue of growth and maturation across multiple youth sport contexts. The strategies outlined aim to reduce inadvertent maturity-related biases (e.g., RAEs) and negative outcomes (e.g., athlete dropout). The effectiveness and practicality of the strategy applied will depend on the youth sporting context (e.g., individual- or team-based), system-level (e.g., participation and competitive pathways), and stakeholder-tier (e.g., organisational to individual coach/practitioner). Therefore, this section will also highlight the relevant youth sporting stakeholders and levels best suited for each proposed strategy. The strategies provided are grounded in research and have already been applied in various youth sports contexts worldwide. The provided overview does not include an exhaustive list of strategies, nor does one single strategy provide an all-encompassing solution. Instead, each strategy is intended as an initial step toward counteracting identified growth and maturation influences on athlete development, and it is up to the relevant stakeholders to consider how to best implement and adapt based on the context of their respective sport.

5.2.1 Account for Growth and Maturation in Performance Assessment

Most suitable for: Pathway managers, practitioners, and coaches

Practitioners can integrate growth and maturation assessments conducted and provided by parents as part of standard athlete monitoring practices. Practitioners are considered as those individuals interacting and working with youth athletes at the individual level on a regular basis (e.g., club coaches, strength & conditioning practitioners). The strategies provided attempt to inform training practices (e.g., programming and strategies), athlete progression and competition performance. At the same time, this should serve as a starting point for when working with individual athletes and teams and is by no means a stand-alone strategy. Practitioners could combine with other suggested strategies (e.g., CAPs, bio-banding) but will need to consider how to best implement and adapt based on their respective sports context. Using the maturation assessment guide (in Section 4), coaches, with parent help, can now track, their athlete's growth and maturation alongside performance progression across a range of relevant performance indices (e.g., cardiorespiratory endurance and strength). By reviewing growth and maturity status assessments periodically, coaches now have a practical strategy whereby individual athlete maturity status can be plotted onto the graphs (figures) provided in Section 3 and tracked over time. To help show how this can be done, Figure 21 re-illustrates the expected developmental patterns for muscular power and movement coordination taken from Figures 10 and 15 in Sections 3.3 and 3.6, respectively. This time, the maturity status of a male (Boy 1) and a female athlete (Girl 1) have been superimposed onto each respective figure. Athlete 1 has a maturity status of -1 years to PHV indicating he is about to enter a period of heightened growth. During this developmental stage, practitioners and coaches can anticipate improvements in muscular leg power, however, coaches should also be aware of potential disruption to movement coordination capability and mechanical efficiency. As a result, coaches may need to consider suitable activities and tasks for Boy 1 over the coming 12-18 months (e.g., fundamental movement skills). On the other hand, the female athlete – Girl 1 – is within her peak growth period (i.e., maturity status of +0.25 YPHV). Practitioners and coaches can utilise this information to identify that she may have already experienced large biological gains in muscular leg power and future improvements could be more modest. Interestingly however, practitioners will see that temporary disruptions to movement coordination associated with increased growth tempo (around PHV) have now likely passed which may inform future training interventions aimed at supplementing/counteracting potentially diminished biological gains in leg power (e.g., weight and power training). Tracking athlete maturation with physical performance progression provides a practical strategy aimed at informing more individualised athlete development practices that consider both early and late maturing athletes. It also ensures more equitable athlete comparison (i.e., inclusive of late maturers).

Figure 21: Tracking Maturity Status (Years to/from Peak Height Velocity) with (i) Leg Power and (ii) Movement Coordination in youth athletic (a) boys and (b) girls.



In addition to tracking individual maturity status alongside physical performance characteristics, it is also important to account for maturity status differences if coaches are comparing youth athletes within and across age groups. It can be difficult for coaches and practitioners to understand whether performance differences are a result of genuine physical and technical skill proficiency or simply reflective of growth and maturation. Although not recommended, if coaches and practitioners are going to compare youth athletes, then athlete assessment results should at least show, and be accompanied by, maturity status indices. Coaches and practitioners should take note and consider potential growth and maturational differences similar to how they may consider chronological (relative) age differences. Examples of how such practices may be implemented during athlete evaluation procedures may include, for instance, including a separate column titled 'Maturity Status' next to each athlete's physical performance test score. If coaches and practitioners are ranking athletes, another strategy is to supplement raw results with additional athlete rankings accounting for maturity status. Figure 22 illustrates one example for how accounting for maturity status when ranking and comparing multiple athletes can be applied to inform athlete evaluation. Figure 22 shows physical performance assessment scores from a maximum push-up, vertical jump, 60-m sprint, and multi-stage fitness test (MSFT) battery for two athletes (A and B) within the same age group. Athlete A is more mature (+1.0 YPHV), and Athlete B is less mature (-1.0 YPHV). On the left and in yellow, each athlete's assessment ranking score (z-scores) is illustrated according to the total athlete cohort test scores within their age group. Figure 22 shows Athlete A achieved consistently higher rankings across all tests relative to Athlete B suggesting superior physical performance. However, when ranked according to maturity status (on the right; in green), performance differences are reduced, and in most cases reversed. Athlete B now demonstrates improved physical performance relative to Athlete A when maturity status is considered.

Figure 22: Physical performance assessment results for two age-group athletes according to age (yellow) and maturity status (green).

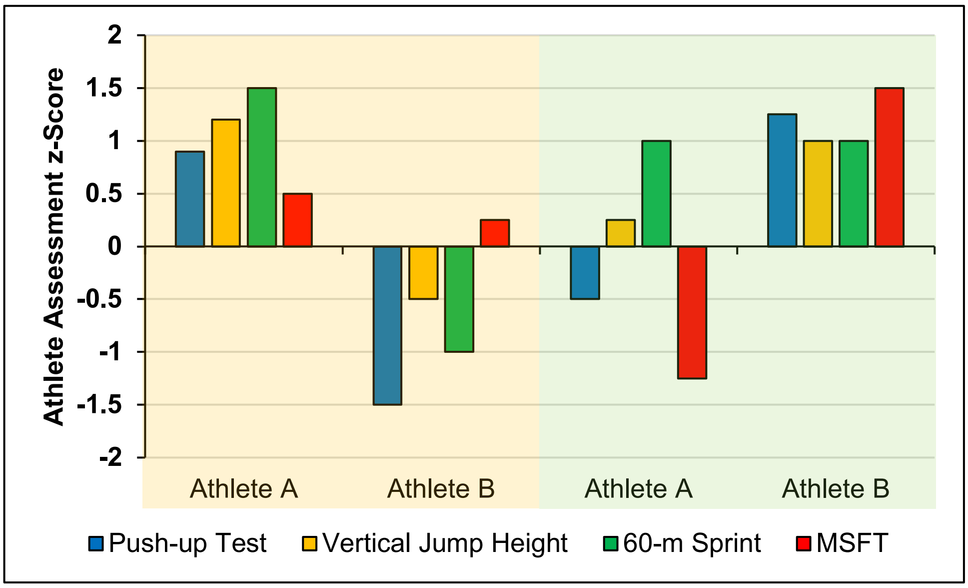


Figure Note: Athlete Assessment z-Scores reflect modified values calculated in order to compare results across physical tests (e.g., cm with metres per second). Z-scores are calculated as the athlete's individual test score minus the respective age group's average test score divided by the group standard deviation; MSFT indicates Multi-Stage Fitness Test.

5.2.2 Delayed Ages for Competition and Selection Opportunities

Most suitable for: Sporting organisations, competition coordinators, and coaches

In sports contexts where peak performance occurs at later chronological ages (e.g., 18+ years of age), performance at youth-level competition could be de-emphasised as a way of shifting focus away from physical capabilities influenced by maturation. A consequence of implementing adult-based training and competition models targeting performance at early ages increases the likelihood of identifying and (de-)selecting youth athletes based on growth and maturation rather than genuine (technical) skill. Delay strategies involve moving more intensified sporting opportunities (e.g., training specialisation, competition, and selection) to later chronological ages, specifically post-maturation. By temporarily removing early age-based competition and athlete evaluation during periods of growth and maturation, RAEs can be reduced, and later maturing athletes may be retained. Recently, delay strategies have been implemented in Australian swimming at the national age-group competition level, whereby boys do not commence competition until ages 14 years and girls 13 years. While successfully implemented, the long-term benefits are yet to be fully evaluated.

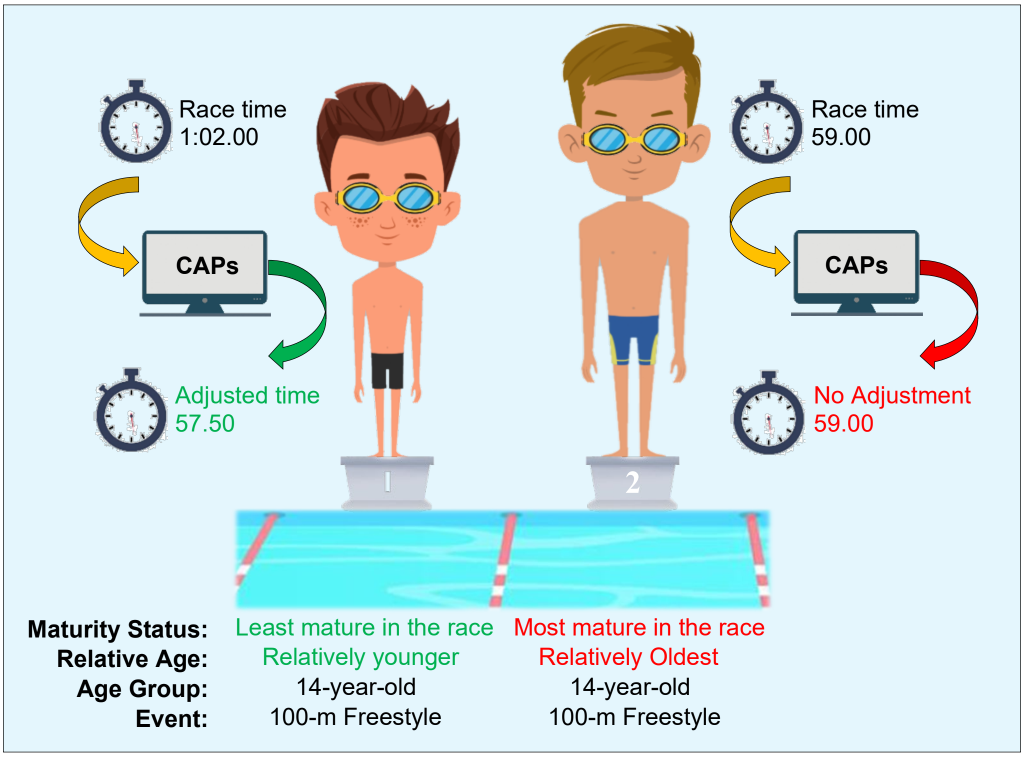
5.2.3 Corrective Adjustment Procedures

Most suitable for: Sports Organisations, Managers, District/Regional Coaches, and Selectors (all levels).

In many youth sports contexts, measurable markers (indices) are used to determine (or rate) individual performance (Moesch et al., 2011). Such measures may include centimetres, seconds, kilograms, or metres per second and are used across training and competition environments in various sports such as swimming, athletics, football, and rowing. In addition to physical components contributing toward performance, these sports also depend on technical and tactical skill and, in the case of team-based sports, external influences (e.g., opposing team interactions). Given growth and maturation influence physical performance and may obscure genuine technical skill and ability, it would be useful if the impact of growth and maturation could be separated from developing youth athletes to allow for fairer performance evaluation. Somewhat similar to how a handicap in golf reflects a player's performance capability based on their previous scores, Corrective Performance Adjustments, also known as Corrective Adjustment Procedures (CAPs) can adjust (or scale) an athlete's performance according to their developmental (relative age, maturity status) stage (Romann & Cobley, 2015). The method uses previously captured maturity, relative age, and performance data from large groups of youth athletes (~500+) to mathematically re-calculate a current youth athletes' performance (e.g., time, distance) based on their individual maturity status or relative age (e.g., 100-m

Freestyle in Swimming, Long Jump Distance in Track & Field Athletics). As illustrated in Figure 23, a youth athlete who is relatively younger or later maturing within their age group would receive a greater performance adjustment (correction) compared to a relatively older or earlier maturing athlete within the same age group. Corrective adjustments allow for fairer athlete evaluation practices and can be used for more equitable athlete comparison, and/or individual progression tracking (Cobley et al., 2019). When interpreting corrective adjustments, any performance differences between two different athletes, or the same athlete over two different occasions (e.g., different competitions), are now more reflective of genuine technical and tactical skill levels given physical growth and maturation have been removed. For example, performance between one early and one late maturing athlete following CAPs may differ less than differences observed between their actual performance times because maturational influences have now been removed. Such differences are likely explained by technical and tactical skill differences, and other external (e.g., environmental) or psychosocial factors (e.g., team sports). Likewise, two correctively adjusted performances from the same athlete but completed 4-months apart may show a more conservative rate of improvement given growth and maturation undergone over the previous 4-months may have been the dominant drivers behind performance progression during this time.

Figure 23: Conceptual illustration of Relative Age and Maturation-based Corrective Adjustment Procedures (CAPs) application in youth sport.



Recently, CAPs have been tested in track & field, swimming and soccer (Abbott et al., 2020a; Abbott et al., 2020b; Brustio et al., 2022; Cobley et al., 2019; Romann & Cobley, 2015). In Australian youth competitive swimming, for example, post-race CAPs as part of Swimming Australia's athlete development initiative - Project H2grOw - have been implemented to inform domestic (state-based) team selection and coaching decision-making (e.g., training approaches). Such procedures have proven effective in removing RAEs and maturity-selection biases in these youth sports contexts. When implemented, a major practical advantage of CAPs is it allows existing training and competition structures to remain (e.g., annual age-grouping), whilst providing an effective solution. That said, the benefits of the application in other youth sporting contexts have not yet been fully evaluated. Nonetheless, CAPs could be particularly useful for improving the competition experiences of relatively younger and later maturing athletes who are physically disadvantaged in age-based competition across youth multiple sporting contexts.

5.2.4 Weight, Birthday and Maturity Matching

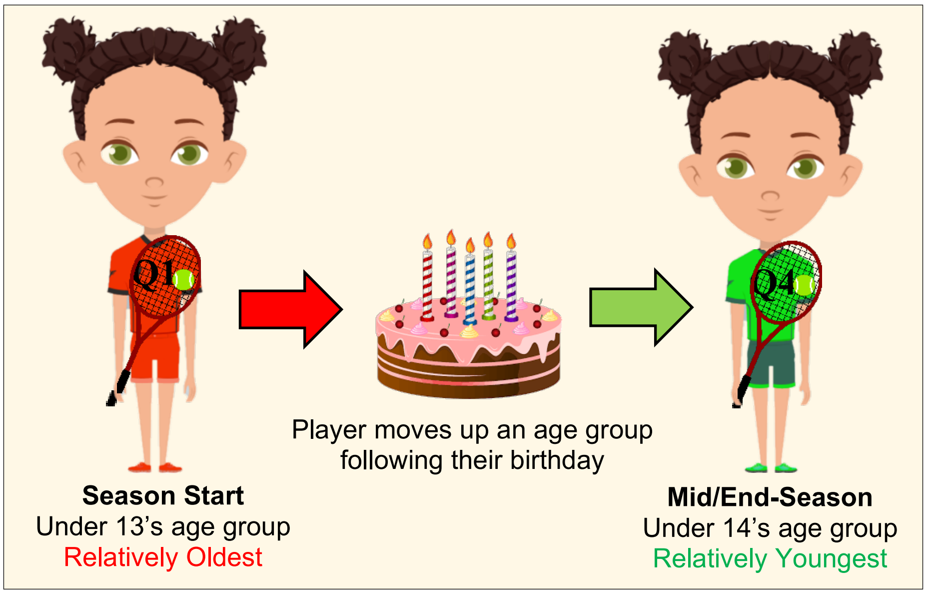
Most suitable for: Sporting organisations, competition coordinators, and coaches

Grouping youth athletes according to developmental characteristics such as weight, relative age and maturity adjunct to annual age grouping practices is an alternative strategy that could also be beneficial.

Weight categories. Body mass-based classifications are used to ensure fair play in youth combat and contact sports such as boxing, judo, taekwondo, wrestling, and rugby where greater body size typically provides competitive advantages (Giudicelli et al., 2020; Lentin et al., 2021). Many sporting organisations have already implemented such practices to improve athlete safety, particularly at time points when body size can vary considerably with annual age groups. For example, Australian Rugby League has trialled weight-based competition formats alongside traditional age-based open-weight competition to encourage safe participation at the junior level. Such strategies mean that players of different chronological ages may play together depending on the weight category (e.g., Under 13’s and 14’s playing in the Under 48-kg category).

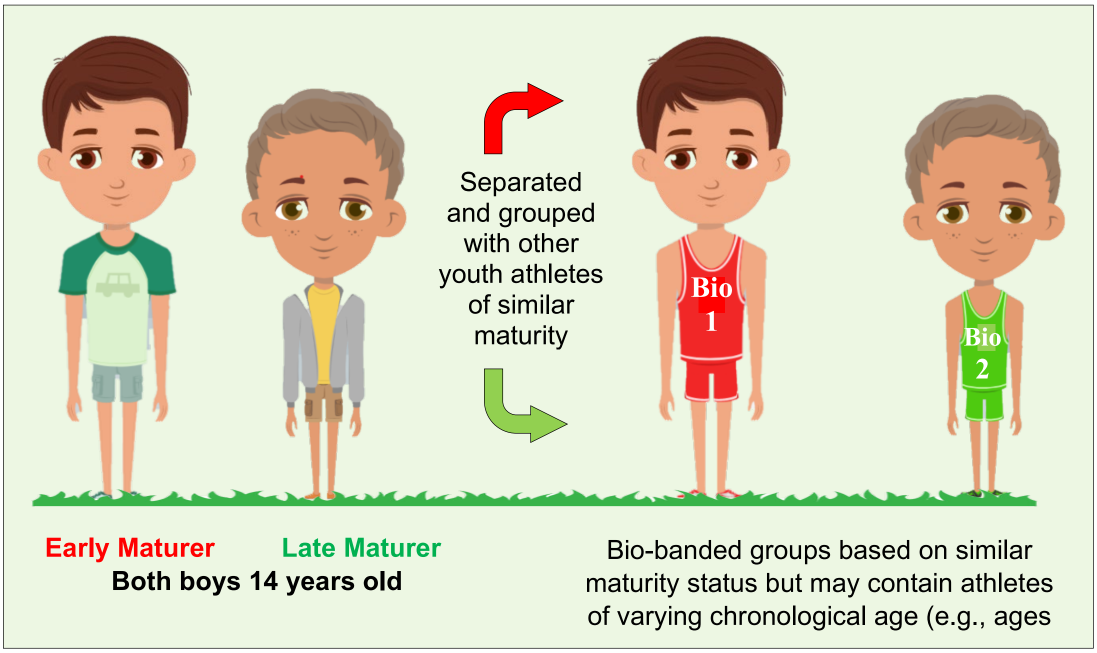
Birthday-banding. Body mass does not increase steadily across maturation. Therefore, body mass may vary between athletes depending on maturity status (Martinho et al., 2021), whilst also being influenced by other genetically determined (e.g., ethnicity) and lifestyle (e.g., nutrition) factors (Duckham et al., 2021; Stang & Story, 2005). With these factors considered, research suggests that weight-based classification strategies do not seem consistently remove relative age and maturational differences in youth sporting contexts, indicating alternative strategies may prove more effective (Delorme et al., 2009). In youth sports using fixed age-group approaches (e.g., Birthday as of the 1st of January), birthday-banding refers to the practice of moving athletes up to the next age group during the participation (playing) or competitive season on their birthday. The aim of birthday-banding is to create more equal developmental opportunities by providing athletes with the playing/completive experience of being both relatively younger and older within their respective age groups across the season. As shown in Figure 24, for example, a U13 athlete would move up to the U14 age group on their birthday and remain in that age group until their following birthday (potentially the following season). As a result, the athlete has gained training and competitive experience as both the relatively oldest (in the U13s) and then relatively oldest (U14s). Such, ‘ageing up’ practices have been implemented in England's youth competitive squash and tested to show the strategy was effective for removing RAEs (Kelly et al., 2020).

Figure 24: Conceptual illustration of Birthday-banding to reduce Relative Age Effects (RAEs) in youth sport.



Maturity-matching ('Bio-banding'). Given growth variation can exceed one-year (12-month) annual age groups, an alternative strategy of biological maturity banding could also prove beneficial. Bio-banding is the practice of (re-)organising youth athletes into groups based on their maturity status as illustrated in Figure 25 (Cumming et al., 2018a; Romann, Lüdin, & Born, 2020). Typically implemented at time points when growth and maturation differences within age groups are largest (e.g., 11-15 years), youth athletes are generally bio-banded based on maturity timing (i.e., 'Early', 'On-time', 'Late') or maturity status (pre-PHV, mid-PHV, post-PHV) categories as assessed using estimated PHV (Mirwald et al., 2002) or %PAH (Malina et al., 2019). Bio-banding has been successfully trialled in team sports (e.g., soccer and basketball, whereby early maturers are potentially challenged more in terms of sport-specific skills while later maturers are provided more opportunities to demonstrate physical and technical attributes compared to the age-group competition (Arede et al., 2021; Cumming et al., 2018a; Romann et al., 2020).

Figure 25: Conceptual illustration of Bio-banding to reduce maturity differences in youth sport.



6. Recommendations for what you should do

6.1 Sporting Organisations and Schools

- Acknowledge growth and maturation may influence youth sports performance when considering policy, strategy, and education of stakeholders.
- Emphasise learning and fundamental skill development at all levels and stages.
- Integrate how growth and maturation assessment information can be utilised for athlete development into coach education and accreditation courses.
- Consider growth and maturation status tracking information as standard when drafting talent (e.g., development) athlete evaluation (e.g., monitoring).
- Differentiate which factors (e.g., psychological, anthropometric, physiological) are contributing to performance during athlete ‘snapshot’ evaluation and ensure it is not growth and maturation.
- Apply strategies to reduce the impact of growth and maturation on performance, long-term participation, and selection in youth sports (e.g., CAPs, athlete matching, delay strategies).
- Keep technically skilled later maturers in the system and help facilitate their development.

6.2 Youth Pathway Managers and Administrators

- Encourage parents and coaches track athlete growth and maturation over time (longitudinal) and utilise such information as part of youth talent identification and development programs to inform athlete evaluation and improve decision-making related to selection and training intervention.
- Integrate how growth and maturation assessment information can be utilised for athlete development into coach education and accreditation courses.

- Considering maturity status and technical skill level will provide a more informed 'picture' of a youth athlete's longer-term performance potential and developmental trajectory. Keep in mind, that maturity status may influence technical skill depending on how technical skill is assessed.
- Differentiate which factors (e.g., psychological, anthropometric, physiological) are contributing to performance during athlete 'snapshot' evaluation and ensure it is not growth and maturation.
- Apply strategies to reduce the impact of growth and maturation on performance, long-term participation, and selection in youth sports (e.g., CAPs, athlete matching, delay strategies).
- Keep technically skilled later maturers in the system and help facilitate their development.

6.3 Coaches and Other Supporting Practitioners

- Collaborate with parents to track growth and maturation every 3-4 months, particularly between ages 12-16+ years in boys and 10-14+ in girls.
- Obtain growth and maturity status information from parents and utilise such information alongside physical performance characteristics as standard practice.
- Understand how maturity status influence various sport-specific physical performance indices to inform youth athlete development decision-making (e.g., evaluation, selection, and training).
- Only evaluate individual performance relative to others when maturation status and relative age are accounted for in the evaluation process.

- Encourage a wide range of technical skill development and activity (sport) sampling pre-and during PHV. Specialisation and increased training loads may be implemented with caution post-PHV.
- Consider more physiologically intense training loads and competition demands may need to be reduced during PHV and replaced with technical skill, re-learning, and injury prevention emphasis.
- In relation to strength-based (and emphasised) conditioning, coach and practitioners should generally prescribe ‘lighter’ body mass loads and focus on functional movement skill development, while higher loads can be introduced post-PHV (e.g., >1 YPHV).
- Monitor training load, competition exposure, injury, fatigue, and psycho-social wellbeing around peak growth periods (i.e., PHV).
- Ensure adequate energy intake and sleep quality protecting against fatigue and athlete burnout.

6.4 Parents and Athletes

- Understand substantial differences in growth and maturation occur between children, particularly at 11-14 years in girls and 12-16 years in boys. These differences substantially affect youth sport performance.
- Track growth and maturation every 3-4 months, particularly between ages 12-16+ years in boys and 10-14+ in girls.
- Improve knowledge related to how growth and maturation trajectories lead to different age time points of youth sport performance acceleration and deceleration.
- Do not compare youth athlete performances (11-14 years – girls; 12-16 years - boys) without consideration of growth and maturation differences.

- De-emphasise physical-based athletic performance success. Training and competition exposure should also be carefully monitored.
- Parents of ‘late maturers’ (relative to ‘early maturers’) should understand earlier training intensification and specialisation are not beneficial (unless in specific sports), due to temporary developmental differences and may be detrimental to long-term sporting involvement.
- Parents of ‘late maturers’ should focus on fun as well as technical and tactic skill development until growth and maturity status differences between youth athletes dissipate.
- Parents of ‘early maturers’ (relative to ‘late maturers’) should understand their child may be afforded physical performance advantages and are more likely to be perceived as talented in many sports. However, such advantages are likely to reduce as ‘later maturers’ catch up, going through their growth and maturation.

Appendices – Resource Infographics

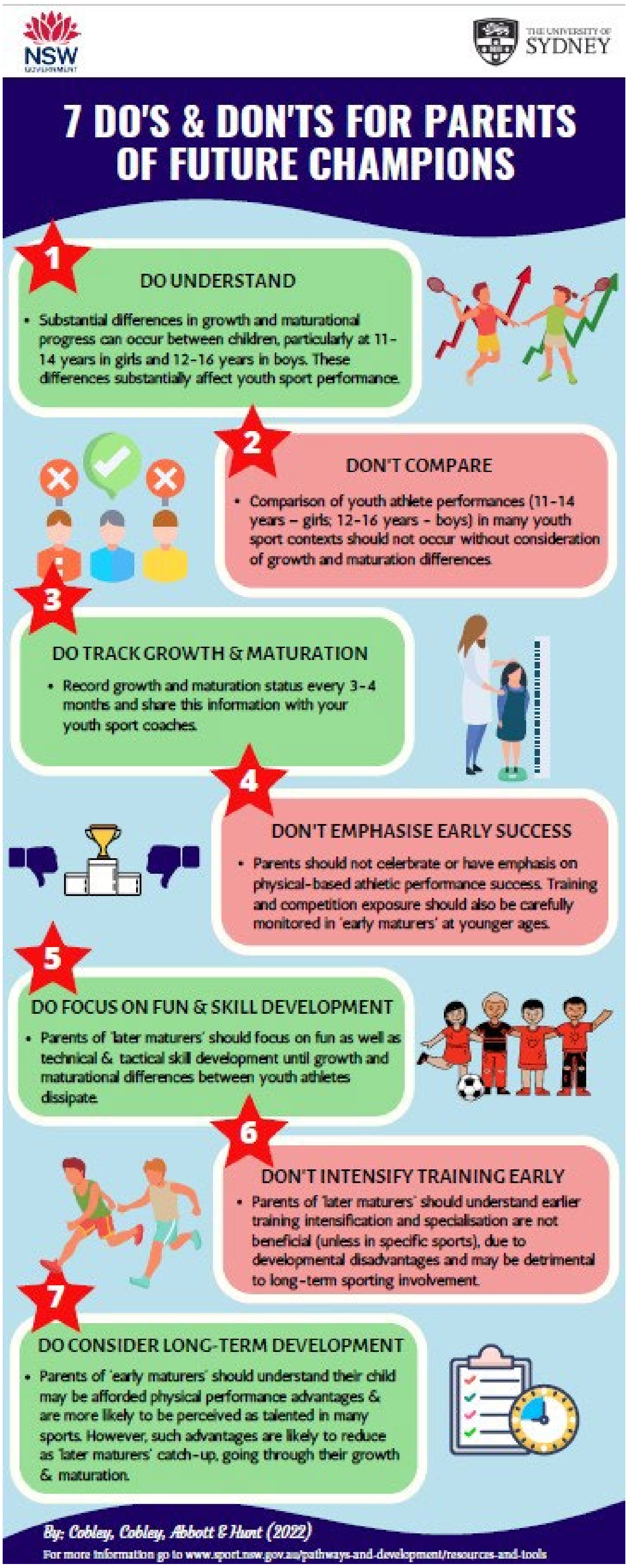
Please note all of these can be found at https://www.sport.nsw.gov.au/pathways-and-development/resources-and-tools)

Appendix 1: Infographic for Sporting Organisations and Schools

Appendix 2: Infographic for Youth Pathway Managers and Administrators

Appendix 3: Infographic for Coaches and Practitioners

Appendix 4: Infographic for Parents and Athletes



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To reference this resource, please reference using the details below. The below examples are set out in APA format.

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To reference a particular sub-section of page of the resource, please reference using the following guidelines with page number(s) specified:

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