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Maturity-associated considerations for training load, injury risk, and physical performance within youth soccer: One size does not fit all

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Running title: Maturity youth soccer

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Received 12 June 2020; revised 24 July 2020; accepted 7 August 2020

Graphical abstract

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Highlights

- Estimates of player maturity status should be taken every 3–4 months during an annual season, with a focus on players approaching and during peak height velocity (PHV).
- Key stakeholders should be educated about maturation and PHV, particularly in relation to the potential use of bio-banding strategies.

- volume of weekly physical activity each child is engaged in.

- The prediction error embroiled within each maturity estimation equation should be considered, along with the implications of additional errors imposed by spurious anthropometric measurements (i.e., self-reported birth parent stature).

- Key stakeholders should be aware of the increased risk of injuries owing to inappropriate training loads across PHV.

Abstract

Biological maturation can be defined as the timing and tempo of progress to achieve a mature state. The estimation of age of peak height velocity (PHV) or percentage of final estimated adult stature attainment (%EASA) is typically used to inform the training process in young athletes. In youth soccer, maturity-related changes in anthropometric and physical fitness characteristics are diverse among individuals, particularly around PHV. During this time, players are also at an increased risk of sustaining an overuse or growth-related injury. As a result, the implementation of training interventions can be challenging. The purpose of this review is to (1) highlight and discuss many of the methods that can be used to estimate maturation in the applied setting and (2) discuss the implications of manipulating training load around PHV on physical development and injury risk. We also have provided key stakeholders with a practical online tool for estimating player maturation status (see online supplementary maturity estimation tool(s)). Whilst estimating maturity using predictive equations is useful in guiding the training process, practitioners should be aware of its limitations. To increase the accuracy and usefulness of data, it is also vital that sports scientists implement reliable testing protocols at predetermined time-points.

Keywords: Growth; Injury; Maturation; Soccer; Training

Within an academy soccer context, biological maturation can be defined as the status, timing and tempo of progress to achieving a mature state.¹ The timing and tempo of growth is highly individual and asynchronous with decimal age across adolescence,² with academy soccer players undergoing an estimated phase of accelerated growth (approximately 7.5–9.7 cm/year) between 10.7 to 15.2 years of age.^{2,3} This enhanced tempo in growth is commonly referred to as peak height velocity (PHV).⁴ Timing of PHV onset is of relevance to academy soccer practitioners given that temporary, maturity-related enhancements in anthropometric and physical fitness characteristics have been shown to be significant for injury risk and confound the selection processes employed by soccer academies.^{5,6} For example, advanced anthropometric dimensions (stature and weight) and performance characteristics (power, speed, strength, and endurance) often contribute toward a maturity selection bias, which is characterised by the over selection of early-maturing players retained by academy soccer development programmes.^{7,8}

Several professional soccer clubs and league governing bodies (e.g., English Premier League) have invested in the development of research-informed, long-term athlete development (LTAD) frameworks (English Premier League)⁹ that account for the influence of biological maturity.^{10,11} Despite such investment, there is limited empirical evidence to suggest that adolescent soccer players experience ‘windows of opportunity’ for training adaptations around PHV.^{10,12} The Youth Physical Development (YPD) model¹³ strongly states that such enhanced training phases are absent and that most components of fitness are trainable across the development continuum. However, evidence exists to suggest that specific training among male youth athletes during ages associated with PHV (during or post) may elicit an enhanced training response due to enhanced concentrations of anabolic hormones.¹⁴ This response subsequently improves strength and sprinting performance during and after PHV^{15,16} and offers plausible justification for maturity-related manipulations of training volume. That said, a recent review exploring the existence of sensitive training periods across adolescence provides compelling counter-evidence that questions the validity and existence of sensitive periods within LTAD frameworks.¹²

with decimal age and academy soccer player development have been made,^{8,17} a lack of clarity remains regarding the accuracy of the method(s) practitioners use to estimate maturity status and how this may influence prescribed training loads that optimize training adaptation and minimise injury risk. Therefore, this narrative review aims to (1) to critically discuss many of the methods that are used to estimate maturation in the applied soccer setting and (2) and discuss the implications of manipulating training load around periods associated to PHV on physical development and player injury risk. In addition, we have also provided key stakeholders with a practical online tool for estimating player maturation status (see online supplementary maturity estimation tool(s)), culminating in a review that provides stakeholders with informed recommendations and practical online tools for more effectively managing this period of development.

2. Methods for estimating maturity status

The biological maturity status of children can be estimated using a number of different direct measures (i.e., skeletal age)^{18–20} and surrogate measures (dental age and secondary sex characteristics).^{21–23} Traditionally, in research settings, wrist x-rays (e.g., Greulich-Pyle Atlas)¹⁸ and validated scales that describe the child's sexual development (e.g., Tanner Scale)²³ have been implemented to estimate biological maturity.

For wrist x-rays, the Greulich-Pyle method requires that a trained physician compare a radiograph image of a child's left hand-wrist bone morphology against a standardized image of a known skeletal maturity at a specified decimal age, using the median age of the visible bones to determine the child's overall skeletal age.¹⁸ However, the Fels method,¹⁹ which also uses radiographs of the left hand-wrist, offers a more comprehensive analysis of bone morphology because it considers the size and shape of individual carpals, accompanied by the corresponding epiphyses and diaphyses of long bones (radius and ulna) and short bones (metacarpals and phalanges of the first, third, and fifth digits), in relation to a described criterion.¹⁹ The Fels method then uses statistics based on odds-ratios to determine the most appropriate

maturity status in children, they present clear disadvantages in that they expose the participants to a significant amount of radiation; are invasive, costly, and time intensive; and typically require a high level of expertise to administer.²⁴

In contrast to assessing skeletal age, assessing sexual maturity requires the participant (child) to self-report his or her own sexual maturity, or it requires a clinician to evaluate the child's secondary sex characteristics to indirectly estimate pubertal status compared to a reference population.²⁵ Although it is possible to use self-report measures carried out by children to assess sexual maturity, these measures have an inferior degree of reliability.²⁶ Assessing sexual maturity through secondary sex characteristics, such as stage of pubic hair development, is considered equally problematic by practitioners, considering the invasive nature of the measures, the need for trained physicians and the added risk of safeguarding the child. Thus, to assess physical development, it has become increasingly common for researchers and practitioners to utilise non-invasive, field-based techniques that allow data collection to safely take place in the applied environment.²⁷

The use of somatic equations derived from anthropometric measurements to estimate maturation status, to estimate time from PHV and to predict adult stature is now commonplace in academy soccer, with benchmarking protocols also available from some national governing bodies.^{9,28} Although various maturity prediction equations exist, a recent survey found that the 2 most prominent methods used across soccer academies were the estimated percentage of adult stature attainment (%EASA) and the maturity offset method.²⁹ These approaches are likely the most frequently used because they are actively facilitated by national soccer governing bodies such as the English Premier Leagues and the Elite Player Performance Plan (EPPP),⁹ with calculations and sophisticated visual displays integrated within the online player management applications. In the absence of clear and uniform guidance, it is therefore each soccer academy's prerogative to choose its own preferred approach for classifying its players.

anthropometric characteristics,^{17,30} the opportunity for soccer practitioners to estimate the final adult stature and current %EASA of youth soccer players is appealing. As per the maturity estimate spreadsheet (see the online supplementary maturity estimation tools), this approach requires precise measurement of decimal age, standing stature (cm), and body mass (kg) of the individual, ideally combined with the accurate stature of both birth parents.³¹ If the stature of the child's biological parents is available, then the mid-parent stature can be calculated in conjunction with the current stature and body mass of the youth soccer player and used to estimate mature stature.³² For boys, mid-parental height = (mother's height + fathers height + 13) / 2. For girls, mid-parental height = (mother's height + fathers height - 13) / 2. This is known as the Khamis-Roche method (Table 1),³¹ an equation that incorporates smoothed values of the intercept and regression coefficients using data from the "Fels longitudinal study". The method can be applied to healthy Caucasian children aged between 4.0 and 17.5.³³ These data can also be compared against age- and sex-specific standards in order to determine the degree to which a child is advanced or delayed in maturation and is often reported as a Z-score. Additionally, Gillison et al.³⁴ have converted the percentage of adult stature to express maturation as a biological age (using UK 1990 growth reference data).³⁵

Whilst such data may provide high value to the youth soccer practitioner, it is important to acknowledge the associated error. The median error for the Khamis-Roche method across the 4.0–17.5-year age span approximates just over 2 cm in boys and just under 2 cm in girls.^{36,37} For example, if the required data is collected accurately (for specific protocol guidelines, see Stewart et al.),³⁸ the reported error is ~2.0 cm for those individuals within the 50th percentile.³⁹ However, this error can increase to ~0.3 cm at the 90th percentile when considering the age-groups of interest in relation to maturation tempo (11- to 15-year-olds), with the median error reported as 2.4–2.8 cm to 5.5–7.3 cm for the 50th and 90th percentiles respectively (approximately 1%–3%). Therefore, it is possible that individuals may be incorrectly categorised according to their maturation status (known as bio-banding)^{28,36,40} as a result of systematic error rather than biological maturity. These errors are slightly elevated when we consider the logistical, social, and practical constraints, meaning that birth-parent height is either often self-reported or unavailable. Therefore, validation guidance

stature values for males and females.³¹ Both of these inferior approaches likely inflate the error to a level above those reported in previous studies,⁴² although the relatively small coefficients associated with the mid-parent height within the equation minimize the magnitude of this. Therefore, although we recognised that the Khamis-Roche method may possess superior maturity estimation precision, the fidelity of the composite anthropometric data is of utmost importance if practitioners are to use this approach to classify their players and inform their physical development decisions.

Anthropometric measurements can also be used to estimate “maturity offset”. In this case, seated and standing stature (cm), combined with body mass (kg) and leg length (cm), are incorporated into a sex-specific calculation that estimates the amount of time, in years, where the individual is in relation to PHV, which allows categorization of the individual as pre-, circa-, or post-PHV.²⁴ Within the literature, maturity offset can be estimated using a number of equations, each with its own limitations (Table 1). For example, the Mirward et al.⁴³ predictive equation initially was validated using 152 Canadian and Belgian children (79 boys, 73 girls) followed across 7 years from 1991 to 1997. Although commonly applied within the literature, this equation has been shown to produce predicted PHV ages that are overestimated for early-maturing children and underestimated late-maturing children, reducing efficacy for those at the extremes of maturation (e.g., regression to the mean).⁴⁴ Further iterations of the equation by Moore et al.⁴⁵ and later by Koziel and Malina⁴⁶ (see online supplementary maturity estimation tools) used a large cohort of Polish children (193 boys aged 8–18 years and 198 girls aged 8–16 years) to mitigate this, but a systematic discrepancy between predicted and observed PHV for early and late developers persists (Table 1).

Recently Fransen et al.⁴⁷ validated a “maturity ratio” (for males only) using a reanalysis of the Mirwald et al.⁴³ dataset plus 1330 Belgian high-level youth soccer players (see online supplementary maturity estimation tools). This approach potentially overcomes some of the limitations of previous equations, but this has yet to be corroborated by third-party research (Table 1). The authors modelled a non-linear polynomial relationship between anthropometric variables and a maturity ratio, as opposed to a maturity offset. The authors argue that this equation should become standard practice for the estimation of

soccer players in general. However, this approach has since been criticised by Nevill and Burton,⁴⁸ who cited mathematical errors with regards to spuriously high R^2 values, but their argument was subsequently rebutted by Fransen et al.⁴⁹. Therefore, further investigative work is needed in this area.

Collectively, findings here highlight that equation-based (specifically, Mirwald et al.)⁴³ predictions of maturity offset, whilst valid when implemented closer to PHV, have limitations in early- and late-maturing individuals and when implemented prior to the age of 11. Nonetheless, the aforementioned disadvantages of administering radiographic assessments of skeletal maturity mean that the most practical option in youth soccer environments is to use non-invasive estimates of skeletal maturity via anthropometric measurement.¹⁷ Hence, we recommend that anthropometric measurements and subsequent estimations of maturation status should be performed a minimum of three times annually to coincide with typical extended breaks within academy programmes (e.g., September, January, and April), accompanied by the further recommendation that practitioners may wish to consider more regular testing intervals (monthly) during time periods associated the adolescent growth spurt in order to capture the onset and cessation of PHV, whilst understanding that such processes are only considered accurate with 2 or more years of data to prevent misinterpretations through seasonal variation.⁵⁰

Whilst a range of methods to predict maturity status exist, it is recommended that both the theoretical and logistical (e.g., accurate attainment of mid-parental height) limitations are appropriately considered by each multidisciplinary team before a method is adopted. At present, it appears that either the Fransen et al.⁴⁷ or Moore et al.⁴⁵ equations are most suitable for estimating maturity offset and that the Khamis and Roche³¹ equation is the preferred method for estimating %EASA, with cumulative height velocity curves also offering some merit.⁴² Practitioners looking to select a method based on accuracy and precision are directed towards the recent work of Parr et al.⁵¹ This study compared the accuracy of maturity offset (using the Mirwald et al.⁴³ method) and %EASA of 28 adolescent players over a 5-year period, which enabled them to objectively assess the timing of PHV. Their findings indicate that 96% of the sample experienced PHV during the specified window (85%–96% EASA) in comparison to only 61% using the maturity offset

the %EASA method was accurate to within 2%, which is in line with error values reported by the validating authors, Khamis and Roche.³¹ Therefore, this single study utilising a relatively small sample may indicate that the %EASA approach is superior, although it does require the most information to compute. However, it is worth noting that no single somatic method is regarded as the “gold standard”, and all methods require further validation using athletic populations and different ethnic groups²⁴ to better represent academy soccer populations. It is also worth highlighting that measurement of growth and maturation in children is a complex and non-linear problem, in which no single study has a definitive scientific design that would enable sport scientists to apply better systems to manage maturation effects in youth soccer.

Although we acknowledged that many elite soccer academies routinely collect anthropometric measures and assess subsequent maturity data,²⁹ we also acknowledge that such practices may still be emerging within the lower tiers of the soccer pyramid and within other codes of football. Therefore, from a practical standpoint, it is important that whilst the tools used to estimate growth are somewhat limited, sport science practitioners should continue to routinely monitor a young player’s growth in a consistent manner. A systematic, reliable anthropometric measurement system will allow practitioners to provide growth curves (cm/month), identify the onset and cessation of PHV and therefore suitably classify players and prescribe training loads according to maturation status. The use of such information in conjunction with other data from the multidisciplinary team will likely aid the development and preparation of young soccer players for the demands of the sport.

3. Influence of maturity status on physical performance

The intermittent nature of soccer places high demands across a number of physiological systems, including aerobic and anaerobic energy pathways, strength, speed and flexibility.^{52,53} Previous research has highlighted that academy soccer players elicit superior physical capacities compared with their sub-elite counterparts.² Training to improve these physical qualities in youth soccer players is a longitudinal process that involves the systematic manipulation of training load incorporating the different aspects for the

soccer is of utmost importance for soccer practitioners.¹¹

Previous research in the physical development of youth athletes has suggested that potential “windows of opportunity” may exist during the different stages of maturity (pre-, circa-, and post-PHV).¹⁰ However, this phrase has also been critiqued because it suggests, without evidential support, that adaptation is limited outside of these windows of opportunity.¹³ Thus, the authors suggest that the phrase “periods of accelerated gains” may be more appropriate for practitioners when explaining developmental opportunities for youth athletes.¹³ Within youth soccer, there appears to be some aspect of these periods of accelerated gains across different physical development qualities. Philippaerts et al.² assessed the longitudinal changes in youth soccer players in relation to PHV and found revealed that balance, explosive strength, speed, and agility demonstrated peak development circa-PHV, whereas flexibility exhibited the greatest development during the post-PHV stage.² Additionally, growth-related musculoskeletal adaptations (e.g., tendon and fascicle length, pennation angles, and motor unit recruitment patterns) settle post-PHV and better represent adult characteristics, predisposing athletes to both an increased magnitude and rate of force development potential.⁵⁵ In terms of aerobic development, Doncaster et al.⁵⁶ found that pre-PHV soccer players showed superior aerobic running economy compared to circa-PHV players. The study also revealed that whilst absolute measures of VO_{2peak} were higher in circa-PHV players, values were similar between groups when expressed relative to body mass and fat-free mass. Malina et al.⁵⁷ found that training experience (determined by years of training) was more associated with aerobic performance rather with maturity *per se*. A recent meta-analysis conducted on male youth athletes revealed that speed training demonstrated greater adaptive responses in circa-PHV and post-PHV groups compared to pre-PHV.¹⁵ However, soccer-related research has revealed that improvements in speed and strength can still be attained at pre-PHV with 6–8 weeks of relatively low-volume resistance-type training.^{58,59} Therefore, previous literature would suggest that these periods of accelerated gains may exist within youth soccer, and practitioners can potentially up- or down-regulate athlete development programmes accordingly.

development from pre-adolescence to adolescence. When considering chronological age alone, it appears that players generally cover more distance, both at low and high speeds, as they move up through academy age groups.⁶⁰ Buchheit et al.⁶¹ also found a similar trend when considering physical match output dependent upon PHV status. The authors revealed that significantly greater higher speed distances were covered by the more mature players, although no differences in overall total distance were observed. Francini et al.⁶² confirmed these findings, revealing that moderate associations existed between predicted age at PHV and high-speed distances covered during competitive match-play. Despite these differences in physical output, maturation status doesn't appear to affect the tactical performance of players⁶³ or the rate of neuromuscular recovery post-match.⁶⁴ Therefore, it would appear that age at PHV may influence the physical output produced by youth soccer players. Further research is required to determine the impact of these differences on longitudinal recovery between matches, particularly during intensified periods (e.g., youth tournaments).

Understanding how youth soccer players respond to a given training stimulus over time is of utmost importance for soccer practitioners. Previous research has highlighted a dose-response effect within academy soccer players, in which the players' internal response to a given stimulus is associated with appropriate workloads.⁶⁵ It is clear that systematic training with adequate loads within a soccer academy setting will enhance the physical capacities of players over time.⁶⁶ The amount of training load that players are exposed to systematically increases as players progress across the different chronological age-group categories.⁵⁴ However, to our knowledge, no study has investigated the relationship between the dose-response effect of training load over a longitudinal period when accounting for different maturation status around PHV, nor have studies been conducted on the potential impact of changes in training load onset by playing players "up" (typically early maturers) and "down" (typically late maturers) chronologically categorised age groups. This is likely attributable to the complexities surrounding players training with multiple teams at various training locations simultaneously whilst also participating in school-based and extracurricular physical activities, which are often not accounted for within player development programmes, therefore making accurately assessing training load "chaotic".⁶⁷ For example, U15 players may

their respective counties in training camps. Thus, further work is required in order to fully understand the link between periods of accelerated gains and appropriate dose-response loads across maturation within youth soccer players.

4. Maturity, training load, and injury risk

Since the EPPP's introduction in 2011, coaching-based contact time has increased ~2.2 fold when compared to the UK's previous soccer academy system.⁹ This has been accompanied by a linear increase in training volumes for youths aged 12–16 years, coinciding with a high degree of variability in growth rates between players. Injury risk is elevated in adolescent athletes when compared to both their adult and younger counterparts,⁶ which can be primarily attributed to high training loads overlapping with rapid annual changes in growth. Recent studies indicate that injury incidence in adolescence increases with age and demonstrates seasonal variation, peaking during September and January (following periods of relative inactivity).^{68,69} On average, each player suffers 1.32–1.43 injuries and loses around 21.9 days per season due to injury, with this peaking in the U14 and U15 age groups (26.2 and 25.7 days lost from training and match-play activity, respectively).^{70,71} The most common injuries occur to the lower limbs (78%), with soft tissue haematoma, muscle tears or strains and ligament sprains being the most frequent across age groups.⁶⁸ Although injuries are multifactorial in nature, non-contact injuries are largely considered preventable but contribute from 46% to 72% of the incidence of injuries to the lower limbs. Severe injuries (>4 weeks of time loss) accounted for 21%–26% of total injuries and were more frequent among the U15–U18 age groups (>0.35 severe injuries per player), with moderate injuries accounting for 30%–43% of injuries.^{69–71}

Injury rate was considerably higher during matches (18.2–24.1 injuries per 1000 h) than during training (1.5–3.3 injuries per 1000 h), with the majority of injuries being traumatic in nature.⁷² However, around 17% of injuries were deemed as “gradual onset” because players could not confirm when their symptoms began.⁶⁹ This injury type was more prominent in U12–U14 players (which aligns with the onset of the adolescent growth spurt in earlier developers) and was often associated with the knee (e.g., Osgood

Sch as the most frequent site of overuse symptoms (61%) and tendinopathy (32%).⁷⁰ Additionally, because of the injury definition employed (time-loss), it is anticipated that overuse injuries are likely underestimated in these studies and are therefore significantly more common than reported.^{73,74}

The influence of maturity timing, status and tempo on injury risk is currently unclear, and much debate exists, making direct inferences complex. For example, Van der Sluis et al.⁶ found that later-maturing players were at an increased risk of injury. Rommers et al.⁷⁵ also inferred an association between transient, maturity, and growth-related changes in anthropometric characteristics of adolescent soccer players when they found an association between these changes and an increased risk of sustaining a non-contact injury. Le Gall et al.⁷⁶ has also suggested that younger-maturing players are at an increased risk. More recent work by Bult et al.⁷⁷ has suggested that the 6-month period after PHV is associated with increased injury risk, whereas the work of Johnson et al.⁷⁸ suggests that there is no influence of maturity timing on increased risk but agrees that PHV does increase risk. Direct comparisons are complex, primarily due to the variation in methods used for estimating maturity. For example, Johnson et al.⁷⁸ used the %EASA method, whereas both Van der Sluis et al.⁶ and Bult et al.⁷⁷ employed a maturity offset approach. Collectively, however, this research does suggest that although the exact mechanisms at play are unclear, there is an association between maturation and injury, and practitioners should be mindful of this when prescribing training loads.

The adolescent growth spurt aligns with changes in joint stiffness, bone density, and imbalances between strength and flexibility, which contributes to “skeletal fragility”.^{6,79} During this sensitive period, boys can grow between 7 and 12 cm per year,⁴³ which may partially explain the phenomenon “adolescent awkwardness”, whereby the trunk and lower limb length have increased but soft tissues have yet to adapt to the size and weight of the frame, causing abnormal movement mechanics that negatively impact performance.^{80,81} Adolescent players who grow >0.6 cm in the previous month have been linked to a 1.63-fold increase in their risk of injury.⁷² This rapid change in musculoskeletal structure and apparent lag time to adequate relative strength is individually variable based on maturity tempo, which likely corresponds to a variation in readiness to perform and, by inference, to vulnerability to injuries.⁸²

mechanics observed during “adolescent awkwardness”⁶ may partly explain maturity-injury associations. Previous studies have well described the associated temporary impairment in movement kinematics and associated increased demands placed on the lower limbs during biological maturation.⁸³⁻⁸⁵ The well-reported adolescent growth changes in turn result in increased demands being placed on muscular, tendinous, and ligamentous structures at a period in adolescents’ athletic development when they are exposed to repeated high competition and training loads. Male academy soccer players are required to assign the majority of their time to competitions or on-field conditioning, with proportionally less time allocated to strength training.⁵⁴ Thus, players may be physically underprepared to meet the demands of these high training loads. Contemporary training practices are also characterized by the use of small-sided games in an attempt to increase ball contact time, thus improving skill proficiency but also increasing physical conditioning in a time-efficient manner. However, it could be suggested that training focusing on small-sided games will increase the frequency of utility movements performed, thus increasing the exposure to mechanically demanding actions such as, but not limited to, jumps, changes of direction, sprinting, accelerations, and decelerations. This repeated mechanical demand placed on highly variable and often underprepared skeletal structures and associated load-response pathways⁸⁶ may be a contributing factor into the increased injury incidence observed at this period. Load accumulation, *per se*, may not have a direct causal relationship on injury incidence, but evidence has exposed clear associations when this frequent and potentially excessive load is “superimposed” on individuals during growth and maturation.^{6,87-89} In addition, the period of PHV reduces muscular co-contraction, which causes temporary stimulation of golgi-tendon organ (GTO) activity that helps stabilise and protect joint integrity. This aligns with the period of “adolescent awkwardness” and suggests that this may be a crucial period for “desensitising” GTOs to facilitate more effective movement.⁵⁵ Therefore, during this period repetitive mechanical loads that require rapid deceleration and change of direction should be reduced in favour of more technical-driven movement drills. These drills should also include greater diversity in movement patterns to encourage movement competency and reduce mechanical strain.

systems and measured using the tri-axial accelerometer are sensitive to residual fatigue responses during a standardised run (a 3-min run performed at 12 km/h) performed sometime during the day following a game. Specifically, the authors found that load-based metrics were sensitive to acute changes in movement efficiency. Therefore, such metrics could also be made for youth athletes, whereby the longitudinal assessment of standardised tasks can be used to assess changes in movement smoothness and efficiency during different phases of maturation, thus limiting non-contact and growth-related injury risk. The intensive training programmes that highly trained youth athletes participate in at the academy level, combined with the tissues' decreased load-capacity capabilities, could, in turn, create a susceptible athlete.⁷⁹ Thus, variability in relation to the design and structure of strength and conditioning practices may be key for reducing injury risk and best preparing players for the demands of competition.

Interestingly, although the relationship between maturation, growth, and musculoskeletal conditions is well supported by research on athletic populations, the available evidence for non-athletic populations is not supportive.⁹¹ For example, it has previously been suggested that youths who completed more hours of sport per week than their age in years, or whose ratio of organised sports versus free play time was $> 2:1$, were at a greater risk of serious overuse injury.⁹² This therefore suggests that although exercise *per se* may be considered as “medicine”, too much sport-specific conditioning at key periods of the maturation continuum is potentially detrimental in relation to both acute and recurrent injury risk and can potentially lead to future health implications.⁹¹ In addition to increased training loads, youth athletes are also susceptible to high match congestion, which has also been shown to result in an increased injury incidence in this group of athletes.^{77,87} As recently advocated by McKay et al.,⁹³ sports participation should be encouraged and maintained across adolescence and beyond. However, practitioners and researchers should consider their responsibilities as applied scientists and athletic coaches and better develop their knowledge of injury risk profiles surrounding maturation to better structure practices that will reduce injuries. This assumes that athletes with fewer injuries are likely to increase their training and match-play exposures, leading to enhanced player safety, learning, and development.

post PHV. Post PHV, injuries appear to be less traumatic and severe and, instead, are more often overuse injuries. Traumatic injuries can be related to factors such as, but not limited to, impaired joint stiffness, tendon maturity, impaired movement efficiency and decreased bone density.^{55,79} Overuse injuries, on the other hand, may be attributable to the disproportionate development of skeletal maturity in relation to muscular development. Practitioners therefore need to be aware of these maturation-dependent differences in injury risk, thus allowing for specific interventions to be implemented, with special consideration given to the highly demanding mechanical load of training practices and intensified periods of match-play often experienced during tournament-format soccer.

5. Practical applications

Our review article provides a critical overview of the current literature in relation to maturity-associated considerations for youth soccer match-play and training. We provide an online maturity estimation tool and practical considerations around the timing of PHV within youth soccer in relation to physical development, injury risk and phases of growth. It is recommended that practitioners measure estimates of player maturity status every 3–4 months during an annual season, with particular focus on players approaching PHV and during PHV. Practitioners should ensure that they use high-quality, standardized equipment for their measurements, with consistent protocols and procedures (e.g., same time of day, same person taking the measurements, *etc.*). There is also a need for sports scientists to educate key stakeholders, such as coaches and parents, about maturation and PHV, particularly in relation to the potential use of bio-banding within their player development strategies. Furthermore, it is recognised that academy practitioners are challenged by the added complexities associated with prescribing suitable long-term athlete development plans to children, who are also rightly engaged with school-based and extracurricular activities.⁹⁴ Therefore, for the welfare of each child and to ensure that appropriate training (and rest) loads are prescribed, it is necessary for key stakeholders (child, parent/guardians, school, and academy) to establish clear lines of communication to identify the volume of weekly physical activity each child is engaged in, along with subjective anecdotal and visual indicators and scientific recognition of critical time-points associated with

estimation equation, accompanied by the implications of additional errors imposed by spurious anthropometric measurements (i.e., self-reported birth-parent stature). Therefore, as part of best-practice guidelines, we recommend that practitioners responsible for taking anthropometric measures engage in ensuring reliability of measurements, and use subsequent statistical metrics (e.g., typical error, coefficient of variation, and smallest meaningful change) to enhance the contextualisation of player growth and maturation. Such oversight may lead to the incorrect categorisation of players for bio-banded match-play and training sessions and subsequently undermine maturity-related talent identification and injury prevention strategies.

Coaches should also be aware of the increased risk of injuries owing to training load if it is not managed appropriately. Intervention methods suitable for managing this process include not scheduling consecutive training days (e.g., on, off, on/on, on and off), regular monitoring of player readiness and allowing more time for players to recover between training sessions and matches. Coaches should also appropriately modify the sessions of players deemed at higher risk, for example, by strategically using these players as “floaters” during possession drills or small-sided game drills and focusing part of training sessions on mobility and movement competency.

Authors' contributions

CT, JM, RMP, KE, JS, and LDH were responsible for concept, design and written content of this narrative review; JDA provided insight for the practical relevance of the discussed content, culminating with JDA leading the practical applications section. All authors have read and approved the final version of the manuscript, and agree with the order of the presentation of the authors.

Competing interests

The authors declare that they have no competing interests.

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Table 1 Summary of equations for estimating maturity and maturation status in youth soccer players.

Author(s)	Equation for boys	Equation for girls	Population used to formulate/validate equation	Suggested limit thresholds	Considerations	Available for use via supplementary spreadsheets
Fransen et al. ⁴⁷	$\begin{aligned} & \text{Maturity ratio} = -6.986547255416 \\ & + (0.115802846632 \times CA) \\ & + (0.001450825199 \times CA^2) \\ & + (0.004518400406 \times BM) \\ & - (0.000034086447 \times BM^2) \\ & - (0.151951447289 \times S) \\ & + (0.000932836659 \times S^2) \\ & - (0.000001656585 \times S^3) \\ & + (0.032198263733 \times LL) \\ & - (0.000269025264 \times LL^2) \\ & - (0.000760897942 \end{aligned}$	Unavailable	Reanalysis of Mirwald et al. ⁴³ dataset ($n = 251$) plus ($n = 1330$) high-level male youth soccer players (8.0–17.0 years old) from Belgian soccer academies and from various ethnic backgrounds, with the majority of players of Caucasian descent ($n = 1581$).	± 1 year (but reduced error for early and late maturers).	<p>Sample of 1130 high-level youth soccer players (8.0–17.0 years old) of various ethnic backgrounds recruited from Belgian soccer academies offers validation within a sport-specific population.</p> <p>Builds on the previous maturity offset calculations by applying a polynomial model.</p> <p>Has been accused of artificially inflating the explained variance, see Nevill and Burton.⁴⁸</p>	Yes

Moore et al. ⁴⁵	<p>Maturity Offset = $-8.128741 + (0.0070346 \times (CA \times SH))$</p> <p>Maturity Offset = $-7.999994 + (0.0036124 \times (CA \times S))$</p>	<p>Maturity Offset = $-7.709133 + (0.0042232 \times (CA \times S))$</p>	<p>Participants' data was used from the Paediatric Bone Mineral Accrual Study (PBMAS) (1991–1997) ($n = 79$ boys and $n = 72$ girls; 10.3–15.6 years old), the Healthy Bones Study III (1999–2012) ($n = 42$ boys and $n = 39$ girls; 10.5–15.9 years old) and the Harpenden Growth Study (1948–1971) ($n = 38$ boys and $n = 32$ girls; 9.8–16.2 years old).</p> <p>Equations later validated by Koziel and Malina⁴⁶ using data used from Wrocław Growth Study (1961–1972), $n = 193$ boys (aged 8–18 years) and $n = 198$ girls (aged 8–16 years).</p>	±1 year	<p>Offers equation without utilising sitting height due to previous growth studies not always including this data.</p> <p>Suggested to be of less use to those individuals who are early or late maturing, offering less sensitivity and leading to mean regression.</p> <p>Recently validated by Koziel and Malina⁴⁶ or average maturing boys close to onset of PHV.</p>	Yes
Mirwald et al. ⁴³	<p>Maturity Offset = $-9.236 + (0.0002708 \times (LL \times SH))$</p> <p>+ $(-0.001663 \times (CA \times LL))$</p> <p>+ $(0.007216 \times (CA \times SH))$</p> <p>+ $(0.02292 \times (BM/S))$</p>	<p>Maturity Offset = $-9.376 + (0.0001882 \times (LL \times SH))$</p> <p>+ $(-0.0022 \times (CA \times LL))$</p> <p>+ $(0.005841 \times CA \times SH)$</p> <p>– $(0.002658 \times CA \times BM)$</p> <p>+ $(0.07693 \times (BM/S))$</p>	<p>$n = 152$ Canadian children aged 8–16 years ($n = 79$ boys; $n = 73$ girls) followed for 7 years (1991–1997).</p>	±1 year	<p>Accused of producing predicted PHV ages that are overestimated for early-maturing children and underestimated late-maturing children, reducing efficacy for those at the extremes of maturation (e.g., regression to the mean) (Malina and Koziel.⁴⁴ Koziel and</p>	No

					<p>Adjusted equations included within the Koziel and Malina⁴⁶ study including the final element of the equation multiplied by 100.</p> <p>Boys Maturity Offset = $-9.236 + (0.0002708 \times (LL \times SH))$</p> <p>+ $(-0.001663 \times (CA \times LL))$</p> <p>+ $(0.007216 \times (CA \times SH))$</p> <p>+ $(0.02292 \times (BM/S \times 100))$</p> <p>Girls Maturity Offset = $-9.376 + (0.0001882 \times (LL \times SH))$</p> <p>+ $(-0.0022 \times (CA \times LL))$</p> <p>+ $(0.005841 \times (CA \times SH))$</p> <p>- $(0.002658 \times (CA \times BM))$</p> <p>+ $(0.07693 \times (BM/S \times 100))$</p>	
Khamis and Roche ³¹	<p>Predicted adult stature =</p> $\beta_0 + \beta_1 \text{ stature} + \beta_2 \text{ weight} + \beta_3 \text{ mid-parent height}$ <p>Where β_1, β_2 and β_3 are the coefficients by which stature,</p>	$n = 223$ male and $n = 210$ females, with stature measured at 18 years old, participating within the Fels Longitudinal	<p>Boys: 2.1–5.3 cm (50th percentile) 2.4–7.3 cm (90th percentile)</p> <p>Girls: 1.7–2.2cm (50th percentile) 2.1–4.4cm (90th percentile).</p>	Validated against white, middle-class Americans only using hand-wrist X-rays.	Yes	

parent height should be multiplied respectively.						
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β_0 See smoothed regression coefficients for boys and girls within Khamis and Roche.³¹

Abbreviations: BM = body mass (kg); CA = calendar age; LL = leg length (m); PHV = peak height velocity; S = standing height (m) and/or stature (m)

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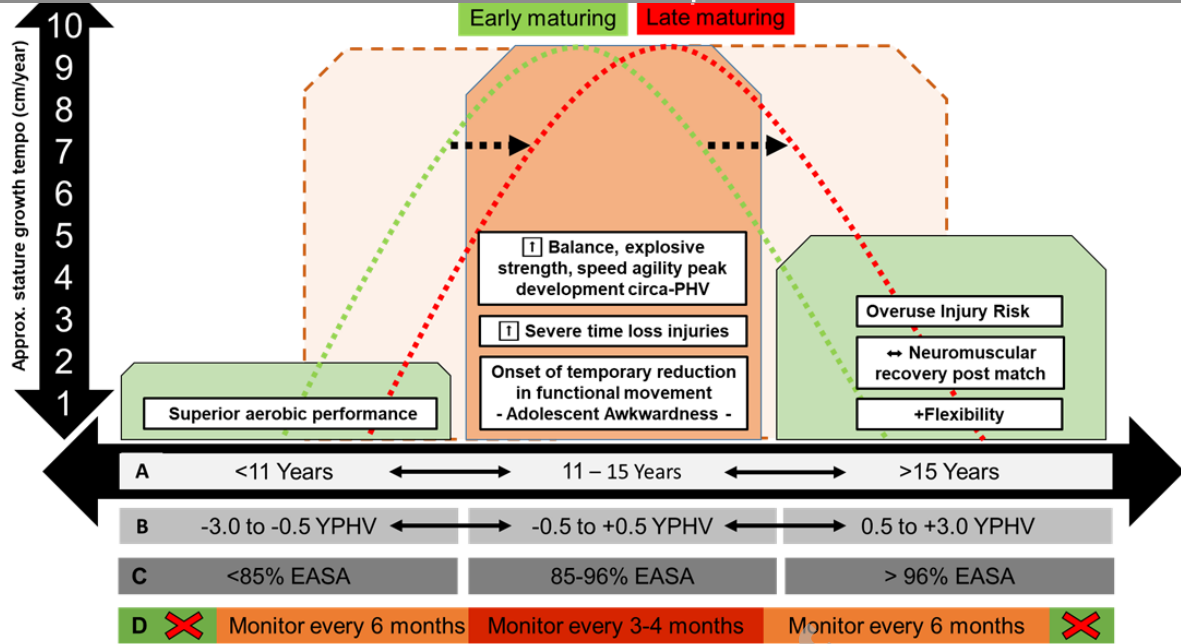


Figure 1. A summary schematic to show the timing of the adolescent growth spurt according to age (A), maturity offset (B) (years to peak height velocity [YPHV]) and percent of estimated adult stature attainment (C) (EASA). Accompanied by recommended annual maturity monitoring frequencies (D) and approximate annual stature growth tempo. Curves for 'late' and 'early' maturing players are a visual aid only, to illustrate the potential differences in onset and cessation of key landmarks.

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