

Review

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

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## Abstract

Biological maturation can be defined as the timing and tempo of progress to achieving 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 was 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 have provided key stakeholders with a practical online tool for estimating player maturation status ([Supplementary Maturity Estimation Tools](#)). 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

## 1. Introduction

Within an academy soccer context, biological maturation can be defined as the status, timing, and tempo of progress to achieving a mature state.<sup>1</sup> The timing and tempo of growth are highly individual and asynchronous with decimal age across adolescence,<sup>2</sup> with academy soccer players undergoing an estimated phase of accelerated growth (approximately 7.5–9.7 cm/year) between 10.7 and 15.2 years of age.<sup>2,3</sup> This enhanced tempo in growth is commonly referred to as peak height velocity (PHV).<sup>4</sup> 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.<sup>5,6</sup> For example, advanced anthropometric dimensions (stature and weight) and performance characteristics (power, speed, strength, and endurance) often contribute to a maturity-selection bias, which is characterized by the overselection of early-maturing players retained by academy soccer-development programs.<sup>7,8</sup>

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 frameworks (English Premier League)<sup>9</sup> that account for the influence of biological maturity.<sup>10,11</sup> Despite such investment, there is limited empirical evidence to suggest that

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adolescent soccer players experience “windows of opportunity” for training adaptations around PHV.<sup>10,12</sup> The Youth Physical Development model<sup>13</sup> 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.<sup>14</sup> This response subsequently improves strength and sprinting performance during and after PHV<sup>15,16</sup> 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 long-term athlete development frameworks.<sup>12</sup>

Although attempts to establish the relationship of onset, tempo, and age of PHV cessation with decimal age and academy soccer-player development have been made,<sup>8,17</sup> a lack of clarity remains regarding the accuracy of the methods practitioners use to estimate maturity status and how they may influence prescribed training loads that optimize training adaptation and minimise injury risk. Therefore, this narrative review aims to (1) critically discuss many of the methods that are used to estimate maturation in the applied soccer setting and (2) 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 ([Supplementary Maturity Estimation Tools](#)), 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)<sup>18–20</sup> and surrogate measures (dental age and secondary sex characteristics).<sup>21–23</sup> Traditionally, in research settings, wrist X-rays (e.g., Greulich–Pyle Atlas)<sup>18</sup> and validated scales that describe a child’s sexual development (e.g., Tanner Scale)<sup>23</sup> 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.<sup>18</sup> However, the FELS method,<sup>19</sup> 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.<sup>19</sup> The FELS method then uses statistics based on odds ratios to

determine the most appropriate indicator of skeletal age for the child’s decimal age.<sup>19</sup> Although these methods<sup>18–20</sup> have been used to assess 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 they typically require a high level of expertise to administer.<sup>24</sup>

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.<sup>25</sup> 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.<sup>26</sup> 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 utilize noninvasive, field-based techniques that allow data collection to take place safely in the applied environment.<sup>27</sup>

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.<sup>9,28</sup> Although various maturity prediction equations exist, a recent survey found that the 2 most prominent methods used across soccer academies were the percentage of final estimated adult stature attainment (%EASA) and the maturity offset method.<sup>29</sup> These approaches are likely to be 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,<sup>9</sup> 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.

Considering the playing-position selection biases associated with transient enhancements in maturity-related anthropometric characteristics,<sup>17,30</sup> 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 ([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.<sup>31</sup> If the statures of the child’s biological parents are 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.<sup>32</sup> For boys, mid-parental height = (mother’s height + father’s height + 13)/2. For girls, mid-parental height = (mother’s height + father’s height – 13)/2. This is known as the Khamis–Roche method ([Table 1](#)),<sup>31</sup> 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.<sup>33</sup> 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.<sup>34</sup> have converted the percentage of adult stature to express maturation as a biological age (using UK 1990 growth reference data).<sup>35</sup>

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.<sup>36,37</sup> For example, if the required data are collected accurately (for specific protocol guidelines, see Stewart et al.<sup>38</sup>), the reported error is ~2.0 cm for those individuals within the 50th percentile.<sup>39</sup> 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 (11–15-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 categorized according to their maturation status (known as bio-banding)<sup>28,36,40</sup> 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 suggests inputting self-reported birth-parent stature (corrected for overestimation)<sup>41</sup> or using national mean stature values for males and females.<sup>31</sup> Both of these inferior approaches likely inflate the error to a level above those reported in previous studies,<sup>42</sup> although the relatively small coefficients associated with the mid-parent height within the equation minimize the magnitude of this. Therefore, although we recognized 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.<sup>24</sup> 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.<sup>43</sup> predictive equation initially was validated using 152 Canadian and Belgian children (79 boys and 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 for late-maturing children, reducing efficacy for those at the extremes of maturation (e.g., regression to the mean).<sup>44</sup> Further iterations of the equation by

Moore et al.<sup>45</sup> and later by Koziel and Malina<sup>46</sup> ([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.<sup>47</sup> validated a “maturity ratio” (for males only) using a reanalysis of the Mirwald et al.<sup>43</sup> dataset plus 1330 Belgian high-level youth soccer players ([Supplementary Maturity Estimation Tools](#)). This approach potentially overcomes some of the limitations of previous equations, but it 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 maturity from anthropometric variables in boys and is, perhaps, the most suitable method available for youth soccer players in general. However, this approach has since been criticized by Nevill and Burton,<sup>48</sup> who cited mathematical errors with regard to spuriously high  $R^2$  values, but their argument was subsequently rebutted by Fransen et al.<sup>49</sup> Therefore, further investigative work is needed in this area.

Collectively, findings here highlight that equation-based (specifically, Mirwald et al.<sup>43</sup>) 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.<sup>17</sup> Hence, we recommend that anthropometric measurements and subsequent estimations of maturation status should be performed a minimum of 3 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 considered accurate only with 2 or more years of data so as to prevent misinterpretations through seasonal variation.<sup>50</sup>

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 be appropriately considered by each multidisciplinary team before a method is adopted. At present, it appears that either the Fransen et al.<sup>47</sup> or the Moore et al.<sup>45</sup> equation is most suitable for estimating maturity offset and that the Khamis and Roche<sup>31</sup> equation is the preferred method for estimating %EASA, with cumulative height velocity curves also offering some merit.<sup>42</sup> Practitioners looking to select a method based on accuracy and precision are directed to the recent work of Parr et al.<sup>51</sup> This study compared the accuracy of maturity offset (using the Mirwald et al.<sup>43</sup> method) and %EASA of 28

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

Author (publication year)	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. (2018) <sup>47</sup>	$\begin{aligned} \text{Maturity ratio} = & -6.986547255416 \\ & + (0.115802846632 \times \text{CA}) \\ & + (0.001450825199 \times \text{CA}^2) \\ & + (0.004518400406 \times \text{BM}) \\ & - (0.000034086447 \times \text{BM}^2) \\ & - (0.151951447289 \times \text{S}) \\ & + (0.000932836659 \times \text{S}^2) \\ & - (0.000001656585 \times \text{S}^3) \\ & + (0.032198263733 \times \text{LL}) \\ & - (0.000269025264 \times \text{LL}^2) \\ & - (0.000760897942 \times (\text{S} \times \text{CA})) \end{aligned}$	Unavailable	Reanalysis of Mirwald et al. <sup>43</sup> 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 ( $n = 1581$ )	$\pm 1$ year (but reduced error for early and late maturers)	Sample of 1330 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 Builds on the previous maturity offset calculations by applying a polynomial model Has been accused of artificially inflating the explained variance (Nevill and Burton <sup>48</sup> )	Yes
Moore et al. (2015) <sup>45</sup>	$\begin{aligned} \text{Maturity offset} = & -8.128741 \\ & + (0.0070346 \times (\text{CA} \times \text{SH})) \\ \text{Maturity offset} = & -7999994 \\ & + (0.0036124 \times (\text{CA} \times \text{S})) \end{aligned}$	$\begin{aligned} \text{Maturity offset} = & -7.709133 \\ & + (0.0042232 \times (\text{CA} \times \text{S})) \end{aligned}$	Participants' data were 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) Equations later validated by Koziel and Malina <sup>46</sup> using data used from Wrocław Growth Study (1961–1972), $n = 193$ boys (8–18 years old) and $n = 198$ girls (8–16 years old) $n = 152$ Canadian children aged 8–16 years ( $n = 79$ boys and $n = 73$ girls) followed for 7 years (1991–1997)	$\pm 1$ year	Offers equation without utilizing sitting height due to previous growth studies not always including this data Suggested to be of less use to those individuals who are early or late maturing, offering less sensitivity and leading to mean regression Recently validated by Koziel and Malina <sup>46</sup> or average maturing boys close to onset of PHV	Yes
Mirwald et al. (2002) <sup>43</sup>	$\begin{aligned} \text{Maturity offset} = & -9.236 \\ & + (0.0002708 \times (\text{LL} \times \text{SH})) \\ & + (-0.001663 \times (\text{CA} \times \text{LL})) \\ & + (0.007216 \times (\text{CA} \times \text{SH})) \\ & + (0.02292 \times (\text{BM}/\text{S})) \end{aligned}$	$\begin{aligned} \text{Maturity offset} = & -9.376 \\ & + (0.0001882 \times (\text{LL} \times \text{SH})) \\ & + (-0.0022 \times (\text{CA} \times \text{LL})) \\ & + (0.005841 \times \text{CA} \times \text{SH}) \\ & - (0.002658 \times \text{CA} \times \text{BM}) \\ & + (0.07693 \times (\text{BM}/\text{S})) \end{aligned}$	$n = 152$ Canadian children aged 8–16 years ( $n = 79$ boys and $n = 73$ girls) followed for 7 years (1991–1997)	$\pm 1$ year	Accused of producing predicted PHV ages that are overestimated for early-maturing children and underestimated for late-maturing children, reducing efficacy for those at the extremes of maturation (e.g., regression to the mean) (Malina and Koziel <sup>44</sup> ; Koziel and Malina <sup>46</sup> ) Adjusted equations included within the Koziel and Malina <sup>46</sup> study, including the final element of the equation multiplied by 100 Boys maturity offset = $-9.236 + (0.0002708 \times (\text{LL} \times \text{SH})) + (-0.001663 \times (\text{CA} \times \text{LL})) + (0.007216 \times (\text{CA} \times \text{SH})) + (0.02292 \times (\text{BM}/\text{S} \times 100))$ Girls maturity offset = $-9.376 + (0.0001882 \times (\text{LL} \times \text{SH})) + (-0.0022 \times (\text{CA} \times \text{LL})) + (0.005841 \times (\text{CA} \times \text{SH})) - (0.002658 \times (\text{CA} \times \text{BM})) + (0.07693 \times (\text{BM}/\text{S} \times 100))$	No
Khamis and Roche (1994) <sup>31</sup>	$\begin{aligned} \text{Predicted adult stature} = & \beta_0 + \beta_1 \times \text{stature} \\ & + \beta_2 \times \text{weight} + \beta_3 \times \text{mid-parent height} \end{aligned}$ <p><math>\beta_1</math>, <math>\beta_2</math>, and <math>\beta_3</math> are the coefficients <math>\beta_0</math> see smoothed regression coefficients for boys and girls within Khamis and Roche<sup>31</sup></p>	$\begin{aligned} \text{Predicted adult stature} = & \beta_0 + \beta_1 \times \text{stature} \\ & + \beta_2 \times \text{weight} + \beta_3 \times \text{mid-parent height} \end{aligned}$ <p><math>\beta_1</math>, <math>\beta_2</math>, and <math>\beta_3</math> are the coefficients <math>\beta_0</math> see smoothed regression coefficients for boys and girls within Khamis and Roche<sup>31</sup></p>	$n = 223$ males and $n = 210$ females, with stature measured at 18 years old, participating within the FELS Longitudinal Study	Boys: 2.1–5.3 cm (50th percentile), 2.4–7.3 cm (90th percentile) Girls: 1.7–2.2 cm (50th percentile), 2.1–4.4 cm (90th percentile)	Validated against white, middle-class Americans only using hand-wrist X-rays	Yes

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

adolescent players over a 5-year period, which enabled them to assess objectively 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 approach ( $\pm 1$ -year generic age).<sup>51</sup> In addition, presentation of individual data illustrates that in many cases the %EASA method was accurate to within 2%, which is in line with error values reported by the validating authors, Khamis and Roche.<sup>31</sup> Therefore, this single study, using 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 various ethnic groups<sup>24</sup> to better represent academy soccer populations. It is also worth highlighting that the 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 acknowledge that many elite soccer academies routinely collect anthropometric measures and assess subsequent maturity data,<sup>29</sup> 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 monitor a young player's growth routinely 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, classify players suitably 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.<sup>52,53</sup> Previous research has highlighted that academy soccer players elicit superior physical capacities compared to their sub-elite counterparts.<sup>2</sup> Training to improve these physical qualities in youth soccer players is a longitudinal process that involves the systematic manipulation of training load incorporating the differing aspects of the demands of match play.<sup>54</sup> Therefore, the consideration of maturation within the long-term athlete development model for youth soccer is of utmost importance for soccer practitioners.<sup>11</sup>

Previous research in the field of the physical development of youth athletes has suggested that potential windows of opportunity may exist during the various stages of maturity (pre-, circa-, and post-PHV).<sup>10</sup> However, this phrase has also been critiqued because it suggests, without evidential support,

that adaptation is limited outside of these windows of opportunity.<sup>13</sup> Thus, the authors suggest that the phrase “periods of accelerated gains” may be more appropriate for practitioners when explaining developmental opportunities for youth athletes.<sup>13</sup> Within youth soccer, there appears to be some aspect of these periods of accelerated gains across different physical-development qualities. Philippaerts et al.<sup>2</sup> assessed the longitudinal changes in youth soccer players in relation to PHV and revealed that balance, explosive strength, speed, and agility demonstrated peak development circa-PHV, whereas flexibility exhibited the greatest development during the post-PHV stage.<sup>2</sup> 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.<sup>55</sup> In terms of aerobic development, Doncaster et al.<sup>56</sup> 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 peak oxygen uptake were higher in circa-PHV players, values were similar between groups when expressed relative to body mass and fat-free mass. Malina et al.<sup>57</sup> found that training experience (determined by years of training) was more closely associated with aerobic performance rather with maturity *per se*. A recent meta-analysis conducted in male youth athletes revealed that speed training demonstrated greater adaptive responses in circa-PHV and post-PHV groups compared to pre-PHV groups.<sup>15</sup> 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.<sup>58,59</sup> Therefore, previous literature would suggest that these periods of accelerated gains may exist within youth soccer, and practitioners can potentially up- or downregulate athlete development programs accordingly.

Youth soccer match play is a key part of a player's physical development across all stages of 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.<sup>60</sup> Buchheit et al.<sup>61</sup> 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.<sup>62</sup> 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 does not appear to affect the tactical performance of players<sup>63</sup> or the rate of neuromuscular recovery post-match.<sup>64</sup> 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 responses to a given stimulus are associated with appropriate workloads.<sup>65</sup> It is clear that systematic training with adequate loads within a soccer academy setting will enhance the physical capacities of players over time.<sup>66</sup> The amount of training load that players are exposed to systematically increases as players progress across the various chronological age-group categories.<sup>54</sup> 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 categorized 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 programs, therefore making accurately assessing training load “chaotic”.<sup>67</sup> For example, U15 players may train 3–4 times per week with their respective academies, but then may also represent their school teams or 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 Elite Player Performance Plan’s introduction in 2011, coaching-based contact time has increased ~2.2 folds when compared to the UK’s previous soccer academy system.<sup>9</sup> 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 among players. Injury risk is elevated in adolescent athletes when compared to both their adult and younger counterparts,<sup>6</sup> which can be attributed primarily 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).<sup>68,69</sup> 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 days and 25.7 days lost from training and match-play activity, respectively).<sup>70,71</sup> The most common injuries occur to the lower limbs (78%), with soft-tissue haematoma, muscle tears or strains, and ligament sprains being the most common across age groups.<sup>68</sup> Although injuries are multifactorial in nature, non-contact injuries are largely considered preventable but contribute from 46%–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.<sup>69–71</sup>

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.<sup>72</sup> However, around 17% of injuries were deemed to be of “gradual onset” because players could not confirm when their symptoms began.<sup>69</sup> 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 Schlatter disease). Therefore, these knee injuries may be due to overuse because knees have been identified as the most common site of overuse symptoms (61%) and tendinopathy (32%).<sup>70</sup> Additionally, because of the injury definition employed (time-loss), it is anticipated that overuse injuries are probably underestimated in these studies and are, therefore, significantly more common than reported.<sup>73,74</sup>

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.<sup>6</sup> found that later-maturing players were at an increased risk of injury. Rommers et al.<sup>75</sup> 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.<sup>76</sup> have also suggested that younger-maturing players are at increased risk. More recent work by Bult et al.<sup>77</sup> has suggested that the 6-month period after PHV is associated with increased injury risk, whereas the work of Johnson et al.<sup>78</sup> suggests that there is no influence of maturity timing on increased risk but agrees that PHV does increase risk. Direct comparisons are complex, due primarily to the variation in methods used for estimating maturity. For example, Johnson et al.<sup>78</sup> used the %EASA method, whereas both van der Sluis et al.<sup>6</sup> and Bult et al.<sup>77</sup> 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”.<sup>6,79</sup> During this sensitive period, boys can grow between 7 cm and 12 cm per year,<sup>43</sup> 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.<sup>80,81</sup> Adolescent players who have grown >0.6 cm in the previous month have been linked to a 1.63-fold increase in their risk of injury.<sup>72</sup> 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.<sup>82</sup>

The imbalance between strength and flexibility and associated transient abnormal movement mechanics observed during “adolescent awkwardness”<sup>6</sup> 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.<sup>83–85</sup> 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.<sup>54</sup> 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 pathways<sup>86</sup> may be a contributing factor to 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.<sup>6,87–89</sup> In addition, the period of PHV reduces muscular co-contraction, which causes temporary stimulation of Golgi-tendon organ activity that helps to stabilize and protect joint integrity. This aligns with the period of “adolescent awkwardness” and suggests that this may be a crucial period for “desensitising” Golgi-tendon organs to facilitate more effective movement.<sup>55</sup> Therefore, during this period repetitive mechanical loads that require rapid deceleration and change of direction should be reduced in favour of more technically driven movement drills. These drills should also include greater diversity in movement patterns to encourage movement competency and reduce mechanical strain.

Recent work by Fitzpatrick et al.<sup>90</sup> has found that metrics derived from micro-electromechanical 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.<sup>79</sup> 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 in athletic populations, the available evidence for non-athletic populations is not supportive.<sup>91</sup> 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 organized sports vs. free play time was >2:1, were at a greater risk of serious overuse injury.<sup>92</sup> This suggests, therefore, 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.<sup>91</sup> 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.<sup>77,87</sup> As recently advocated by McKay et al.,<sup>93</sup> 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 develop their knowledge of injury-risk profiles surrounding maturation so as 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.

Overall, players suffer more injuries across PHV, and these injuries are more severe than they are 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.<sup>55,79</sup> 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 recognized 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.<sup>94</sup> Therefore, for the welfare of each child and to ensure that appropriate training (and rest) loads are prescribed, it is necessary for key stakeholders (children, parents/guardians, school, and academies) 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 PHV. Last, practitioners should also consider the prediction error embroiled within each maturity-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 the 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 categorization 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, 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, JJM, 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 and also led 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.

#### Supplementary materials

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#### References

1. Malina RM, Eisenmann JC, Cumming SP, Ribeiro B, Aroso J. Maturity-associated variation in the growth and functional capacities of youth football (soccer) players 13–15 years. *Eur J Appl Physiol* 2004;**91**:555–62.
2. Philippaerts RM, Vaeyens R, Janssens M, et al. The relationship between peak height velocity and physical performance in youth soccer players. *J Sports Sci* 2006;**24**:221–30.
3. Towlson C, Cogley S, Parkin G, Lovell R. When does the influence of maturation on anthropometric and physical fitness characteristics increase and subside. *Scand J Med Sci Sports* 2018;**28**:1946–55.
4. Malina RM, Coelho ESMJ, Figueiredo AJ, Carling C, Beunen GP. Interrelationships among invasive and non-invasive indicators of biological maturation in adolescent male soccer players. *J Sports Sci* 2012;**30**:1705–17.
5. Figueiredo AJ, Gonçalves CE, Coelho E, Silva MJ, Malina RM. Characteristics of youth soccer players who drop out, persist or move up. *J Sports Sci* 2009;**27**:883–91.
6. van der Sluis A, Elferink-Gemser MT, Coelho-e-Silva MJ, Nijboer JA, Brink MS, Visscher C. Sport injuries aligned to peak height velocity in talented pubertal soccer players. *Int J Sports Med* 2014;**35**:351–5.
7. Carling C, Le Gall F, Malina RM. Body size, skeletal maturity, and functional characteristics of elite academy soccer players on entry between 1992 and 2003. *J Sports Sci* 2012;**30**:1683–93.
8. Vaeyens R, Malina RM, Janssens M, et al. A multidisciplinary selection model for youth soccer: The Ghent Youth Soccer Project. *Br J Sports Med* 2006;**40**:928–34.
9. Premier League. *The elite player performance plan (EPPP)*. Available at: <https://www.goalreports.com/EPLPlan.pdf>. [accessed 06.04.2020].
10. Balyi I, Hamilton A. Long-term athlete development: Trainability in childhood and adolescence. *Olympic Coach* 2004;**16**:4–9.
11. Ford P, De Ste Croix M, Lloyd R, et al. The long-term athlete development model: Physiological evidence and application. *J Sports Sci* 2011;**29**:389–402.
12. Van Hooren B, De Ste Croix M. Sensitive periods to train general motor abilities in children and adolescents: Do they exist? A critical appraisal. *Strength Cond J* 2020;**42**:7–14.
13. Lloyd RS, Oliver JL. The youth physical development model: A new approach to long-term athletic development. *Strength Cond J* 2012;**34**:61–72.
14. Rogol AD, Roemmich JN, Clark PA. Growth at puberty. *J Adolesc Health* 2002;**31**:192–200.
15. Moran J, Sandercock G, Rumpf MC, Parry DA. Variation in responses to sprint training in male youth athletes: A meta-analysis. *Int J Sports Med* 2017;**38**:1–11.
16. Moran J, Sandercock GR, Ramírez-Campillo R, Meylan C, Collison J, Parry DA. A meta-analysis of maturation-related variation in adolescent boy athletes' adaptations to short-term resistance training. *J Sports Sci* 2017;**35**:1041–51.
17. Towlson C, Cogley S, Midgley AW, Garrett A, Parkin G, Lovell R. Relative age, maturation and physical biases on position allocation in elite-youth soccer. *Int J Sports Med* 2017;**38**:201–9.



18. Greulich WW, Pyle SI. *Radiographic atlas of skeletal development of the hand and wrist*. Redwood City, CA: Stanford University Press; 1959.
19. Chumlea WC, Roche AF, Thissen D. The FELS method of assessing the skeletal maturity of the hand-wrist. *Am J Hum Biol* 1989;1:175–83.
20. Tanner JM, Whitehouse R, Cameron N, Marshall W, Healy M, Goldstein H. *Assessment of skeletal maturity and prediction of adult height (TW2 method)*. London: Academic Press; 2001.
21. Rai V, Saha S, Yadav G, Tripathi AM, Grover K. Dental and skeletal maturity: A biological indicator of chronologic age. *J Clin Diagn Res* 2014;8:ZC60–4.
22. Anderson DL, Thompson GW, Popovich F. Interrelationships of dental maturity, skeletal maturity, height and weight from age 4 to 14 years. *Growth* 1975;39:453–62.
23. Tanner JM. *Growth at adolescence*. Oxford: Blackwell; 1962.
24. Marshall WA, Tanner JM. Variations in the pattern of pubertal changes in boys. *Arch Dis Child* 1970;45:13–23.
25. Malina RM, Cumming SP, Morano PJ, Barron M, Miller SJ. Maturity status of youth football players: A noninvasive estimate. *Med Sci Sports Exerc* 2005;37:1044–52.
26. Matsudo SMM, Matsudo VKR. Self-assessment and physician assessment of sexual maturation in Brazilian boys and girls: Concordance and reproducibility. *Am J Hum Biol* 1994;6:451–5.
27. Meylan C, Cronin J, Oliver J, Hughes J, Hughes M. Talent identification in soccer: The role of maturity status on physical, physiological and technical characteristics. *Int J Sports Sci Coach* 2010;5:571–92.
28. Cumming SP, Brown DJ, Mitchell S, et al. Premier League academy soccer players' experiences of competing in a tournament bio-banded for biological maturation. *J Sports Sci* 2018;36:757–65.
29. Salter J, De Ste Croix MBA, Hughes JD, Weston M, Towlson C. Monitoring practices of training load and biological maturity in UK soccer academies. *Int J Sports Physiol Perform* 2021;16:395–406.
30. Deprez D, Franssen J, Boone J, Lenoir M, Philippaerts R, Vaeyens R. Characteristics of high-level youth soccer players: Variation by playing position. *J Sports Sci* 2015;33:243–54.
31. Khamis HJ, Roche AF. Predicting adult stature without using skeletal age: The Khamis-Roche method. *Pediatrics* 1994;94:504–7.
32. Tanner JM, Goldstein H, Whitehouse RH. Standards for children's height at ages 2–9 years allowing for heights of parents. *Arch Dis Child* 1970;45:755–62.
33. Siervogel RM, Roche AF, Guo SM, Mukherjee D, Chumlea WC. Patterns of change in weight/stature<sup>2</sup> from 2 to 18 years: Findings from long-term serial data for children in the Fels longitudinal growth study. *Int J Obes* 1991;15:479–85.
34. Gillison F, Cumming S, Standage M, Barnaby C, Katzmarzyk P. Assessing the impact of adjusting for maturity in weight status classification in a cross-sectional sample of UK children. *BMJ Open* 2017;7:e015769. doi:10.1136/bmjopen-2016-015769.
35. Freeman JV, Cole TJ, Chinn S, Jones PR, White EM, Preece MA. Cross sectional stature and weight reference curves for the UK, 1990. *Arch Dis Child* 1995;73:17–24.
36. Cumming SP, Lloyd RS, Oliver JL, Eisenmann JC, Malina RM. Bio-banding in sport: Applications to competition, talent identification, and strength and conditioning of youth athletes. *Strength Cond J* 2017;39:34–47.
37. Cumming SP, Searle C, Hemsley JK, et al. Biological maturation, relative age and self-regulation in male professional academy soccer players: A test of the underdog hypothesis. *Psychol Sport Exerc* 2018;39:147–53.
38. Stewart A, Marfell-Jones M, Olds T, De Ridder H. *International standards for anthropometric assessment (ISAK)*. Wellington, New Zealand: International Society for the Advancement of Kinanthropometry; 2011.
39. Malina RM, Cumming SP, Rogol AD, et al. Bio-banding in youth sports: Background, concept, and application. *Sports Med* 2019;49:1671–85.
40. Romann M, Lüdin D, Born DP. Bio-banding in junior soccer players: A pilot study. *BMC Research Notes* 2020;13:240. doi:10.1186/s13104-020-05083-5.
41. Epstein LH, Valoski AM, Kalarchian MA, McCurley J. Do children lose and maintain weight easier than adults: A comparison of child and parent weight changes from six months to ten years. *Obes Res* 1995;3:411–7.
42. Sherar LB, Mirwald RL, Baxter-Jones AD, Thomis M. Prediction of adult height using maturity-based cumulative height velocity curves. *J Pediatr* 2005;147:508–14.
43. Mirwald RL, Baxter-Jones AD, Bailey DA, Beunen GP. An assessment of maturity from anthropometric measurements. *Med Sci Sports Exerc* 2002;34:689–94.
44. Malina RM, Kozielec SM. Validation of maturity offset in a longitudinal sample of Polish girls. *J Sports Sci* 2014;32:1374–82.
45. Moore SA, McKay HA, Macdonald H, et al. Enhancing a somatic maturity prediction model. *Med Sci Sports Exerc* 2015;47:1755–64.
46. Kozielec SM, Malina RM. Modified maturity offset prediction equations: Validation in independent longitudinal samples of boys and girls. *Sports Med* 2018;48:221–36.
47. Franssen J, Bush S, Woodcock S, et al. Improving the prediction of maturity from anthropometric variables using a maturity ratio. *Pediatr Exerc Sci* 2018;30:296–307.
48. Nevill A, Burton RF. Commentary on the article “Improving the prediction of maturity from anthropometric variables using a maturity ratio”. *Pediatr Exerc Sci* 2018;30:308–10.
49. Franssen J, Baxter-Jones A, Woodcock S. Responding to the commentary on the article “Improving the prediction of maturity from anthropometric variables using a maturity ratio”. *Pediatr Exerc Sci* 2018;30:311–3.
50. Mills K, Baker D, Pacey V, Wollin M, Drew MK. What is the most accurate and reliable methodological approach for predicting peak height velocity in adolescents? A systematic review. *J Sci Med Sport* 2017;20:572–7.
51. Parr J, Winwood K, Hodson-Tole E, et al. Predicting the timing of the peak of the pubertal growth spurt in elite youth soccer players: Evaluation of methods. *Annals Hum Biol* 2020;47:400–8.
52. Bangsbo J. The physiology of soccer: With special reference to intense intermittent exercise. *Acta Physiol Scand Suppl* 1994;619:1–155.
53. Bangsbo J. Performance in sports—with specific emphasis on the effect of intensified training. *Scand J Med Sci Sports* 2015;25(Suppl. 4):S88–99.
54. Wrigley R, Drust B, Stratton G, Scott M, Gregson W. Quantification of the typical weekly in-season training load in elite junior soccer players. *J Sports Sci* 2012;30:1573–80.
55. Radnor JM, Oliver JL, Waugh CM, Myer GD, Moore IS, Lloyd RS. The influence of growth and maturation on stretch-shortening cycle function in youth. *Sports Med* 2018;48:57–71.
56. Doncaster G, Iga J, Unnithan V. Assessing differences in cardiorespiratory fitness with respect to maturity status in highly trained youth soccer players. *Pediatr Exerc Sci* 2018;30:216–28.
57. Malina RM, Bouchard C, Bar-Or O. *Growth, maturation, and physical activity*. Champaign, IL: Human Kinetics; 2004.
58. Chaabene H, Negra Y. The effect of plyometric training volume on athletic performance in prepubertal male soccer players. *Int J Sports Physiol Perform* 2017;12:1205–11.
59. Rodríguez-Rosell D, Franco-Márquez F, Pareja-Blanco F, et al. Effects of 6 weeks resistance training combined with plyometric and speed exercises on physical performance of pre-peak-height-velocity soccer players. *Int J Sports Physiol Perform* 2016;11:240–6.
60. Harley JA, Barnes CA, Portas M, et al. Motion analysis of match-play in elite U12 to U16 age-group soccer players. *J Sports Sci* 2010;28:1391–7.
61. Buchheit M, Mendez-Villanueva A. Effects of age, maturity and body dimensions on match running performance in highly trained under-15 soccer players. *J Sports Sci* 2014;32:1271–8.
62. Francini L, Rampinini E, Bosio A, Connolly D, Carlomagno D, Castagna C. Association between match activity, endurance levels and maturity in youth football players. *Int J Sports Med* 2019;40:576–84.
63. Borges PH, Cumming S, Ronque ERV, et al. Relationship between tactical performance, somatic maturity and functional capabilities in young soccer players. *J Hum Kinet* 2018;64:160–9.

64. De Ste Croix M, Lehnert M, Maixnerova E, et al. Does maturation influence neuromuscular performance and muscle damage after competitive match-play in youth male soccer players? *Eur J Sport Sci* 2019;**19**:1130–9.
65. Fitzpatrick JF, Hicks KM, Hayes PR. Dose–response relationship between training load and changes in aerobic fitness in professional youth soccer players. *Int J Sports Physiol Perform* 2018;**13**:1–6.
66. Wrigley RD, Drust B, Stratton G, Atkinson G, Gregson W. Long-term soccer-specific training enhances the rate of physical development of academy soccer players independent of maturation status. *Int J Sports Med* 2014;**35**:1090–4.
67. Phibbs PJ, Jones B, Roe G, et al. Organized chaos in late specialization team sports: Weekly training loads of elite adolescent rugby union players. *J Strength Cond Res* 2018;**32**:1316–23.
68. Read PJ, Oliver JL, De Ste Croix MB, Myer GD, Lloyd RS. The scientific foundations and associated injury risks of early soccer specialisation. *J Sports Sci* 2016;**34**:2295–302.
69. Renshaw A, Goodwin PC. Injury incidence in a Premier League youth soccer academy using the consensus statement: A prospective cohort study. *BMJ Open Sport Exerc Med* 2016;**2**:e000132. doi:10.1136/bmjsem-2016-000132.
70. Read PJ, Oliver JL, De Ste Croix MBA, Myer GD, Lloyd RS. An audit of injuries in six English professional soccer academies. *J Sports Sci* 2018;**36**:1542–8.
71. Tears C, Chesterton P, Wijnbergen M. The elite player performance plan: The impact of a new national youth development strategy on injury characteristics in a premier league football academy. *J Sports Sci* 2018;**36**:2181–8.
72. Kemper GL, van der Sluis A, Brink MS, Visscher C, Frencken WG, Elferink-Gemser MT. Anthropometric injury risk factors in elite-standard youth soccer. *Int J Sports Med* 2015;**36**:1112–7.
73. Bacon CS, Mauger AR. Prediction of overuse injuries in professional U18–U21 footballers using metrics of training distance and intensity. *J Strength Cond Res* 2017;**31**:3067–76.
74. Clarsen B, Myklebust G, Bahr R. Development and validation of a new method for the registration of overuse injuries in sports injury epidemiology: The Oslo Sports Trauma Research Centre (OSTRC) overuse injury questionnaire. *Br J Sports Med* 2013;**47**:495–502.
75. Rommers N, Rössler R, Goossens L, et al. Risk of acute and overuse injuries in youth elite soccer players: Body size and growth matter. *J Sci Med Sport* 2020;**23**:246–51.
76. Le Gall F, Carling C, Reilly T, Vandewalle H, Church J, Rochcongar P. Incidence of injuries in elite French youth soccer players: A 10-season study. *Am J Sports Med* 2006;**34**:928–38.
77. Bult HJ, Barendrecht M, Tak IJR. Injury risk and injury burden are related to age group and peak height velocity among talented male youth soccer players. *Orthop J Sports Med* 2018;**6**:2325967118811042. doi:10.1177/2325967118811042.
78. Johnson DM, Williams S, Bradley B, Sayer S, Murray Fisher J, Cumming S. Growing pains: Maturity associated variation in injury risk in academy football. *Eur J Sport Sci* 2019;**20**:544–52.
79. Ford KR, Myer GD, Hewett TE. Longitudinal effects of maturation on lower extremity joint stiffness in adolescent athletes. *Am J Sports Med* 2010;**38**:1829–37.
80. Davies PL, Rose JD. Motor skills of typically developing adolescents: Awkwardness or improvement? *Phys Occup Ther Pediatr* 2000;**20**:19–42.
81. Sheehan DP, Lienhard K. Gross motor competence and peak height velocity in 10- to 14-year-old Canadian youth: A longitudinal study. *Meas Phys Educ Exerc Sci* 2019;**23**:89–98.
82. Dudink A. Birth date and sporting success. *Nature* 1994;**368**:592. doi:10.1038/368592a0.
83. Hewett TE, Myer GD, Kiefer AW, Ford KR. Longitudinal increases in knee abduction moments in females during adolescent growth. *Med Sci Sports Exerc* 2015;**47**:2579–85.
84. Portas MD, Parkin G, Roberts J, Batterham AM. Maturation effect on Functional Movement Screen™ score in adolescent soccer players. *J Sci Med Sport* 2016;**19**:854–8.
85. Read PJ, Oliver JL, De Ste Croix MBA, Myer GD, Lloyd RS. Landing kinematics in elite male youth soccer players of different chronologic ages and stages of maturation. *J Athl Train* 2018;**53**:372–8.
86. Verheul J, Nedergaard NJ, Vanrenterghem J, Robinson MA. Measuring biomechanical loads in team sports: From lab to field. *Sci Med Football* 2020;**4**:246–52.
87. Hawkins D, Metheny J. Overuse injuries in youth sports: Biomechanical considerations. *Med Sci Sports Exerc* 2001;**33**:1701–7.
88. Maternea O, Farooq A, Johnson A. *Relationship between injuries and somatic maturation in highly trained youth soccer players*. Proceedings of the World Congress on Science and Soccer. Abingdon: Routledge; 2015.
89. Pfirrmann D, Herbst M, Ingelfinger P, Simon P, Tug S. Analysis of injury incidences in male professional adult and elite youth soccer players: A systematic review. *J Athl Train* 2016;**51**:410–24.
90. Fitzpatrick JF, Hicks KM, Russell M, Hayes PR. The reliability of potential fatigue-monitoring measures in elite youth soccer players. *J Strength Cond Res* 2019 doi:10.1519/JSC.0000000000003317. [Epub ahead of print].
91. Swain M, Kamper SJ, Maher CG, Broderick C, McKay D, Henschke N. Relationship between growth, maturation and musculoskeletal conditions in adolescents: A systematic review. *Br J Sports Med* 2018;**52**:1246–52.
92. Jayanthi NA, LaBella CR, Fischer D, Pasulka J, Dugas LR. Sports-specialized intensive training and the risk of injury in young athletes: A clinical case-control study. *Am J Sports Med* 2015;**43**:794–801.
93. McKay CD, Cumming SP, Blake T. Youth sport: Friend or foe. *Best Pract Res Clin Rheumatol* 2019;**33**:141–57.
94. Scantlebury S, Till K, Sawczuk T, Dalton-Barron N, Phibbs P, Jones B. The frequency and intensity of representative and nonrepresentative late adolescent team-sport athletes' training schedules. *J Strength Cond Res* 2020 doi:10.1519/JSC.0000000000003449. [Epub ahead of print].