Estimating somatic maturity in adolescent soccer players: Methodological comparisons

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Running Head: Estimating somatic maturity in soccer

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Abstract

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

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

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

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

Keywords: adolescence, growth, maturation, team-sports
Introduction
Systematic identification and development of attributes that equal success are a primary focus for practitioners. The holistic and systematic identification and development of the physiological, psychosocial and/or biomechanical attributes that contribute to success, are a primary focus for team sport practitioners (Bergeron et al., 2015). These attributes are often determined through observation and/or assessment of ‘elite’ adult athletes, but talent development studies highlight speed, endurance and decision making as prominent attributes (Murr et al., 2018; Roberts et al., 2019). Subsequently, youth athletes demonstrating these attributes are identified, recruited and promoted towards excellence. However, development trajectories are complicated when adolescents experience the non-linear, inter-individual variations in tempo and timing of development throughout maturation (Cumming et al., 2017).

Towlson et al. (2018) reported staggered asynchronous development trajectories of physical and performance characteristics that were exposed to dynamic temporal changes across peak height velocity (PHV). Maturation varies substantially within chronological age-groups, particularly around peak height velocity (PHV), with large variations in physical characteristics such as body mass (~50%), stature (~29cm), percentage of predicted adult height (PAH: 10-15%) and fat free mass (3-8.6kg) not uncommon (Figueiredo et al., 2010; Hannon et al., 2020), leading to uncertainty regarding athletic potential. This level of diversity in maturity, even within relatively homogenous groups, creates uncertainty surrounding relative talent and future potential in young athletes, therefore confounding talent development processes.

Professionalisation of the academy system (Premier League, 2011) now requires monitoring and evaluation of maturation to inform individual talent development decisions (Cumming et al., 2017). Skeletal age is a ‘clinical’ method of assessing maturity status, but is regarded as impractical within academy soccer (Fransen et al., 2018). As a result, surrogate ‘non-invasive’ somatic equations to estimate maturity status using anthropometric proportionality
differences alongside longitudinal growth data are now common (Fransen et al., 2018; Khamis & Roche, 1994; Malina & Koziel, 2014; Moore et al., 2015). These methods offer an indication of biological age either by predicting the age of PHV onset, whilst informing on the proximity distance of this in time (years) from PHV—in the form of a maturity offset (MO), or estimate current percentage of adult height (PAH%) (Khamis & Roche, 1994). If standardised and routinely assessed, these methods can estimate both the timing and tempo of maturation and have been used with adolescent team sports players previously (Johnson et al., 2020; C. Towlson et al., 2018; van der Sluis et al., 2015).

Each method has received critical review surrounding their ecological validity (see Mills et al., 2017 for a detailed appraisal). The original offset equation (Mirwald et al., 2002) was claimed to predict the timing of PHV to within 1-year 95% of the time which was applicable to individuals aged between 10 and 18 years. Malina and Koziel (2014) longitudinally applied this method to Polish boys in an attempt to re-validate the equation but identified a systematic discrepancy between predicted and observed PHV. The timing of PHV was underestimated at younger ages and overestimated in older age groups. This was also supported by Mills et al. (2017) who added that the equation overestimated the timing of PHV when assessed immediately preceding PHV. Malina and Koziel noted that the magnitude of error tended to be accentuated in early- and late-maturing males, both of which are of particular prevalence in youth sports programmes. Moore et al. (2015) then attempted to simplify and externally validate the equation to cater for this overfitting, but still reported an increase in prediction error the further removed from PHV the individual is. A further iteration of this equation has since been validated with academy soccer players (Fransen et al., 2018). Authors claim that it appears to better account for the systematic error by adopting a polynomial model and estimating a maturity ratio to better reflect the non-linear growth process. However, subsequent
critique by Nevill and Burton (2018) outlined potential flaws in the equation and the increased likelihood of spurious findings due to chronological age appearing on both sides of the maturity ratio, with similar concerns over accuracy also reported by Teunissen et al (2020).

A PAH% developed by Khamis and Roche is also widely used within adolescent soccer (Salter et al., 2020). Utilising several of the same anthropometric variables and the addition of birth parent stature to ascertain mid-parent stature, the equation can predict the progress towards adult stature as a percentage. If measured accurately the equation is reported to predict the adult stature to within 2.2 and 5.3 cm for the 50th and 90th percentile respectively, although this error may increase to 5.5-7.2 cm when applied only to the age groups where it relates to the adolescent growth spurt (11-15 years) (Malina et al., 2019). Objectively measuring parent stature is logistically difficult and therefore equation often uses self-reported parent stature and should therefore be corrected for overestimation (Epstein et al., 1995). In some cases adolescent athletes are not in contact with one or both birth parents, or for whatever reason an accurate stature is not accessible. In such cases the equation suggests using mean national values for male and females, likely reducing the data fidelity via regression to the mean, particularly for those with birth parents with stature significantly different from the mean which may cause additional error.

PHV Peak-height velocity has been suggested to coincide with increased risk and incidence of non-contact and training related injury in team sports (Bult et al., 2018; Chris Towlson et al., 2020) which causes concern for practitioners. It is common within literature to dichotomise the maturation process into periods, often termed pre-, circa- or post-PHV to categorise individuals (Meyers et al., 2017; Radnor et al., 2020; Ryan et al., 2018; van der Sluis et al., 2015). In the applied setting, this categorisation may be utilised to implement maturity
specific interventions, produce reports or inform talent (de)selection decisions (Cumming et al., 2017). Categorisation of individuals to facilitate maturity specific interventions is common to produce reports or inform talent (de)selection decisions (Cumming et al., 2017). Several studies have used such classifications to assess the impact of maturation on performance, such as speed (Meyers et al., 2017), neuromuscular performance (De Ste Croix et al., 2019) and aerobic endurance (Buchheit & Mendez-Villanueva, 2014). Due to error, typical bandwidth thresholds of ±1-year, or ±0.5-years have been utilised to determine whether individuals are pre-, circa- or post-PHV. Similar conservative (85-96%) and less conservative thresholds (88-93%) exist for PAH%, based on longitudinal data (Cumming et al., 2017; Sanders et al., 2017).

Despite each method having this categorisation capacity, it is unclear as to the agreement between the various approaches, which potentially differs based on the nuances between estimation equations.

Validation of these methods have generally used large scale reference samples from mostly white-Caucasian, middle-class backgrounds, leading to questions surrounding the applicability of this to modern elite soccer environments. In addition, these methods are applied widely and almost interchangeably within adolescent soccer (Salter et al., 2020) and academic literature. This lack of commonality complicates comparisons and generates uncertainty within the field. Therefore, this study has two main aims; a) to observe the agreement of maturity status estimations between methods using the same anthropometric data and b) compare concordance between methods when looking to categorise players as circa-PHV using established thresholds. It is hoped that findings provide grounding for practitioners to select which method to accurately monitor growth and maturation and to encourage consistency within organisations when looking to track biological maturation. Methods are used interchangeably within adolescent soccer (Salter et al., 2020) and literature. This lack of consistency
complicates comparisons, generating uncertainty within the field. Therefore, this study has two main aims; a) to observe agreement between estimates of maturity status and b) compare concordance when looking to categorise players.

Methodology

Participants

113 Male adolescent academy soccer players ($n = 113$) (mean ± SD; age, 14.3 ± 1.1 years; stature 170.1 ±10.6 cm; body mass, 58.7 ± 10.5 kg) were recruited from two Elite Player Performance Plan academies. Players were predominantly from White British ethnicity, although some participants were from more diverse ethnic minorities (<10%). Data from 57 participants was collected from a single assessment during the 2017-18 season, with the remaining 55 participants providing three repeated measurements during the 2018-19 season, resulting in 222 total estimations. Participants were eligible to take part if they were registered with the academies and free from time-loss injury prior to the stratified random recruitment process to ensure a relatively homogenous sample. Ethical approval was granted by the University ethics committee (REC 17.71.5.2).

Procedures

Following International Society for the Advancement of Kinanthropometry (ISAK) recommendations (Stewart et al., 2011) anthropometric measurements were obtained from all participants wearing light sportswear to facilitate maturity estimations (Fransen et al., 2018; Khamis & Roche, 1994; Malina & Kozieł, 2014; Moore et al., 2015). A portable stadiometer (Seca® 217, Chino, USA) was used to measure standing stature when participants stood barefoot with feet together and their head in the Frankfort plane. The participants were required to take a deep breath and hold their head still whilst duplicate measures of standing stature
were recorded to an accuracy of 0.1cm and subsequently the mean was calculated with a third taken if necessary (>4mm difference) and the median recorded. Following similar procedures, participants seated stature was measured whilst sat on a standardised plinth (40cm high) with feet together and hands rested on thighs. Body-mass was recorded using portable weighing scales (Seca® robusta 813, Chino, USA) whilst participants were stood barefoot wearing normal training attire. Duplicate readings were taken and if measurements varied by 0.2kg a third measure was taken and the median recorded. All measurements were taken by the same researcher to minimise error, with typical error (coefficient of variation [CV]) for both stature (0.13% CV) and seated stature (0.21% CV) comparable with reported norms (Massard et al., 2019). Mid-parental height was calculated using self-reported values corrected for overestimation (Epstein et al., 1995; Malina et al., 2019).

Maturity Equations

Estimations of MO and PAH% were calculated using anthropometric measures (standing stature, seated stature & body-mass) and decimal age (years). Typical error (coefficient of variation; CV%) for both stature and seated stature was 0.2% and therefore comfortably within accepted levels. The Fransen et al. (2018) method initially calculates a ratio which was subsequently converted to MO for comparison. The Khamis-Roche (PAH%) equation required the addition of birth parent height which was self-reported and corrected for overestimation (Cumming et al., 2017). Exact equations are available in the supplementary material to this commentary study.

Statistical Analysis

Raw data are presented in Table 1. Agreement between measures was assessed using Pearson product correlation coefficient (r) and Bland-Altman plots with 95% limits of agreement, with 90%
confidence limits (Hopkins et al., 2009) using Jeffreys Amazing Statistics Program (JASP) Prism 9 software (v0.11.19.1.0, University of Amsterdam, Netherlands GraphPad Software LLC). The Mirwald equation (Malina & Koziel, 2014) was used as a surrogate criterion reference as this is most widely reported in literature. Due to measuring different constructs, both MO (APHV+MO) and PAH% (using growth reference charts, Wright, 2002) were both subsequently converted to represent an estimation of biological age to facilitate analysis. Concordance agreement analysis was conducted using Cohen’s Kappa (κ) coefficients derived from contingency tables. Two evidence informed thresholds to categorise circa-PHV for MO and PAH% were applied, a) conservative ±1-year and 85-96%; and b) less conservative ±0.5-years or 88-93% (Cumming et al., 2017; Sanders et al., 2017). The magnitude of correlation, agreement and associated qualitative inference were rated using standardised thresholds (Hopkins et al., 2009).

Results

Descriptive analysis indicates minimal variation between all MO methods, particularly between those that predict MO, with the closest agreement between the Moore and Fransen methods (±0.05 years). (Table 1) - method revealed larger ranges than MIRWALDAPHV and MOOREAPHV. The mean PAH% (93.6%) denotes a chronological age of ~14.1 years (Malina et al., 2019), signifying close alignment to the actual sample mean age (14.3 years). Additionally, growth rates at this stage of development (3% per year) (Wright, 2002) would suggest that PAH% predicted a APHV comparable to MO estimations. There were very large to almost perfect agreements between methods when predicting maturity status Bland-Altman analysis indicates that MO methods typically agree within <0.3 years 95% of the time, but Khamis-Roche PAH% offers broader limits of agreement (-1.65-0.87 years) -(Table 2) Figure ***Insert Table 1 around here***
Bias indicates that Khamis-Roche estimates biological age to be ~0.6 years higher than MO methods (Table 2).

Concordance between methods is presented in Table 3. When conservative (±1 year) there was substantial agreement (64-67%) between MO methods with moderate agreement (44-50%) between MO and PAH% methods. There was an unsurprising decline to moderate agreement (58-60%) between MO methods and fair-moderate between MO and PAH% (31-43%) when utilising the less conservative threshold.

Discussion

This study observed agreement between methods of estimating maturity status, aiming to inform practitioners of differences and interchangeability feasibility between methods. All methods of MO produce an identical-similar estimate of APHV-biological age (13.3±14.3-14.7 years) with mean PAH (93.6%) eluding to a slightly older mean age (~14.1 years) (Malina et al., 2019). Findings suggest there are tight limits of very large to near perfect agreement between estimates MO methods (± 0.3 years) despite methodological nuances. However, biological age estimations derived from Khamis-Roche calculations offer a much broader agreement window (approx. -1.5 to 1 year) with the MO methods. Unsurprisingly, there is greater concordance when using conservative thresholds (44-67%) than when using less conservative bandwidth thresholds (31-60%).
The near perfect agreement thresholds of biological age between MO estimations is initially unsurprising based on them being inherent iterations of the original regression equation. Moore et al. (2015) aimed to reduce prediction error by removing seated stature from the equation. The almost perfect agreement observed here (particularly between Moore-Fransen) is interesting based on reported error associated with seated stature, which is historically greater than other components of the equation (Mills et al., 2017). However, typical error for both seated and standing stature in the current study was a comparatively low (0.2%), which is comparable with reported error (Massard et al., 2019) may explain the agreement observed here. This suggests that the inclusion/exclusion of seated stature has little impact on the outcome of the equation if measurement error is adequately controlled. This may alleviate some of the concerns raised by Massard et al (2019) who indicated that failure to pay close attention to sitting height protocol may influence the outcomes for PHV estimation. This suggests that practitioners have flexibility to utilise methods with or without sitting height, based on logistical constraints within their setting. However, considering the tight agreement between the methods, based on this, claims that these equations may only be reliably applicable for average maturing boys close to APHV may be upheld (Fransen et al., 2018; Kozieł & Malina, 2018). Despite near perfect correlations (r = 0.97), the increased range observed with the Fransen method (Table 1), may indicate that this iteration of the MO equation reduces overfitting to some extent (2020) (2018). This is the Fransen version calculation was validated in adolescent soccer, is and therefore likely more reflective of the true population (i.e., ethnicity, maturation tempo) compared with and as such likely a better option for practitioners other methods validated in predominantly white-caucasian school children. Specifically Additionally, this is method facilitated by the calculation offers a maturity ratio preceding MO, thus enhancing model fit which is suggested to help model fit (Fransen et al., 2018). Consequently, this approach is likely best if looking to utilise MO to estimate maturity.
Therefore, for practitioners working in youth team-sports, the Fransen method may offer the most value, whilst maintaining agreement with other approaches.

The PAH\% equation displayed very large agreement with MO equations—presented much broader agreement with MO estimations (Table 2). Very large associations are novel based on both methods measuring slightly different constructs. This may be explained by them initially calculating two separate constructs (PAH\% and MO) but both can be converted to biological age using known growth trends, as in this study. The PAH\% mean (93.6\%) biological age of 14.7 years affiliates with the period shortly following expected PHV (~90\%) in young soccer players (Sanders et al., 2017) and Bland-Altman analysis suggest the PAH\% offers a ~0.6 year bias compared to MO methods. This bias is more substantial than any of the MO compared with one another, therefore suggesting that practitioners should use either an MO method, or PAH\%, but not both interchangeably. Parr et al. (2020) conducted longitudinal analysis to observe timing of PHV, and illustrated that PAH\% was accurate 96\% of the time, with MO correct 61\% of the time. However, it should be noted that Parr et al. (2020) utilised the original not modified Mirwald et al. (2002) equation as employed here. Previous work has highlighted that PHV typically occurs between the 13 and 13.5 years of age (Malina et al., 2019). Therefore, the data from this study would suggest that PAH\% is a good useful indicator of maturity status in youth soccer team-sport players. However, however, the logistical constraints mean that it is unrealistic to routinely measure adult stature need to be considered (i.e., measurement of parent heights). Failure to do so, or to appropriately correct the equation (Malina et al., 2019), will ultimately undermine its accuracy and inflate error beyond that reported, reducing fidelity of predictions and thus leave MO approaches as better alternatives.
Despite high associations, discrepancy exists when categorising players as circa-PHV using both MO thresholds. The 64-67% concordance leaves a disagreement (i.e. players categorised differently) of approximately 30-35% and up to 50% when using conservative or stringent thresholds respectively. This disagreement further increases when comparing MO to PAH% to 31-50% respectively. Therefore, a third to two-thirds of the data would potentially disagree and lead to categorisation error, potentially influencing on the practices these individuals are exposed to. For example, a player may be categorised as circa-PHV using one method, but pre-PHV in another, potentially exposing them to different training stimulus or reducing/increasing their perceived level of risk incorrectly. This disagreement further increases when comparing MO to PAH% to 31-50% respectively.

Parr et al. (2020) conducted longitudinal analysis to observe timing of PHV, and illustrated that PAH% was accurate 96% of the time, with MO correct 61% of the time. This has implications for practitioners who may use both MO and PAH% methods synonymously for different purposes (i.e. time to PHV and bio-banding), and are therefore encouraged to identify the most feasible and logical method within their context and apply this consistently. This would suggest that the fair-moderate agreement observed here is in agreement and likely a product of the systematic error in MO estimation methods. (2002)

The absence of a criterion value to compare maturity estimations reduces limits confidence in the conclusions from this study, and prevents conclusions about which method may be superior, if any. Previous work has attempted to address this (Mills et al., 2017; Parr et al., 2020) but further studies are required to corroborate these findings. However, this multicentre dataset offers insight into the interchangeability (or lack of) of the common approaches, and supports claims from a recent study (Parr et al., 2020) whilst using a larger sample—and highlights how the same anthropometric data may be interpreted differently based on the
Further work surrounding somatic maturity estimation accuracy is required, and where possible should include longitudinal data obtained from multi-ethnic groups.

Findings indicate very high to near perfect tight agreement between MO equations, but broader agreement thresholds for MO and PAH% methods. Additionally, but concordance between these methods to categorise players is moderate at best and may be misleading if multiple methods are employed. Therefore, we conclude that these methods are not interchangeable and may provide different biological categorisation of players. Findings from this study combined with Parr et al (2020) indicate that PAH% likely offers increased accuracy above MO equations. Academies are therefore encouraged to implement this an informed approach to offer consistency for both research and applied purposes, based on the resources and constraints of their environment. It is also recommended that practitioners monitor both height and weight velocity and plot their respective growth curves over time. With consideration of these findings practitioners can have greater confidence in maturity estimations, leading to appropriate maturity-specific development and evaluation of talent.

Disclaimer

The authors note no conflict of interest involved with this study.
References

Bergeron, M. F., Mountjoy, M., Armstrong, N., Chia, M., Côté, J., Emery, C. A., Faigenbaum, A.,
Hall, G., Kriemler, S., Léglise, M., Malina, R. M., Pensgaard, A. M., Sanchez, A., Soligard,
International Olympic Committee consensus statement on youth athletic development. British

Buchheit, M., & Menez-Villanueva, A. (2014). Effects of age, maturity and body dimensions on
match running performance in highly trained under-15 soccer players. Journal of Sports
Sciences, 32(13), 1271–1278. https://doi.org/10.1080/02640414.2014.884721

Group and Peak Height Velocity Among Talented Male Youth Soccer Players. Orthopaedic
Journal of Sports Medicine, 6(12), 2325967118811042.
https://doi.org/10.1177/2325967118811042

Sport: Applications to Competition, Talent Identification, and Strength and Conditioning of
https://doi.org/10.1519/SSC.000000000000281

De Ste Croix, M., Lehnert, M., Maixnerova, E., Zaatar, A., Svoboda, Z., Botek, M., Varekova, R., &
Stastny, P. (2019). Does maturation influence neuromuscular performance and muscle
damage after competitive match-play in youth male soccer players? European Journal of
Sport Science, 19(8), 1130–1139. https://doi.org/10.1080/17461391.2019.1575913

Maintain Weight Easier Than Adults: A Comparison of Child and Parent Weight Changes
From Six Months to Ten Years. Obesity Research, 3(5), 411–417.
https://doi.org/10.1002/j.1550-8528.1995.tb00170.x


https://doi.org/10.1038/s41598-017-16996-w


https://doi.org/10.1111/sms.13198


https://doi.org/10.1016/j.jshs.2020.09.003


Table 1. Descriptive comparisons between methods to estimate biological age (years)

<table>
<thead>
<tr>
<th>Measure</th>
<th>Mirwald</th>
<th>Moore</th>
<th>Fransen</th>
<th>Khamis-Roche</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean ± SD</td>
<td>14.4 ± 1.9</td>
<td>14.3 ± 1.9</td>
<td>14.3 ± 1.2</td>
<td>14.7 ±1.1</td>
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<tr>
<td>Minimum</td>
<td>11.6</td>
<td>12.1</td>
<td>12.1</td>
<td>11.5</td>
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<tr>
<td>Maximum</td>
<td>16.7</td>
<td>16.6</td>
<td>16.6</td>
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<tr>
<td>Range</td>
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<td>4.5</td>
<td>6.4</td>
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<tr>
<td>SEM</td>
<td>0.08</td>
<td>0.08</td>
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</tr>
<tr>
<td>Variance</td>
<td>1.4</td>
<td>1.4</td>
<td>1.4</td>
<td>1.35</td>
</tr>
</tbody>
</table>

SD, Standard Deviation; SEM, Standard Error of Measurement
Table 2. Bland-Altman bias (SD) and 95% limits of agreement between biological age estimations

<table>
<thead>
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<th>Measure</th>
<th>Mirwald</th>
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<th>Fransen</th>
</tr>
</thead>
<tbody>
<tr>
<td>Moore</td>
<td>0.17</td>
<td>***</td>
<td>***</td>
</tr>
<tr>
<td></td>
<td></td>
<td>-0.31 – 0.37</td>
<td></td>
</tr>
<tr>
<td>Fransen</td>
<td>0.16</td>
<td>0.03</td>
<td>***</td>
</tr>
<tr>
<td></td>
<td></td>
<td>-0.30 – 0.36</td>
<td>-0.05 – 0.05</td>
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<tr>
<td>Khamis-Roche</td>
<td>0.68</td>
<td>0.61</td>
<td>0.61</td>
</tr>
<tr>
<td></td>
<td>-1.65 – 1.04</td>
<td>-1.53 – 0.87</td>
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*** N/A
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<th>circa-PHV Threshold</th>
<th>Measure</th>
<th>Mirwald</th>
<th>Moore</th>
<th>Fransen</th>
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<tr>
<td>± 1 year 85-90% PAH</td>
<td>Moore</td>
<td>0.67</td>
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<td>***</td>
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<tr>
<td></td>
<td>Fransen</td>
<td>0.66</td>
<td>0.64</td>
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<tr>
<td></td>
<td>Khamis-Roche</td>
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<td>0.50</td>
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<td>± 0.5 year 88-93% PAH</td>
<td>Moore</td>
<td>0.60</td>
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<tr>
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<td>Fransen</td>
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<td>0.58</td>
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<td>Khamis-Roche</td>
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<td>0.43</td>
<td>0.39</td>
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*** N/A
Figure 1. Bland-Altman plots (with 95% limits of agreement) for estimated biological age for the different maturity estimation methods.
Supplementary Material - Equations

Equation 1: (Malina & Kozieł, 2014) (MIRWALDMO)

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

Equation 2: (Moore et al., 2015) (MOOOREMO)

\[
\text{Maturity offset} = -7.9999994 + (0.0036124 \times (\text{age} \times \text{standing stature}))
\]

Equation 3: (Fransen et al., 2018) (FRANSENRatio)

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

Equation 4: (Fransen et al., 2018) (FRANSENMO)

\[
\text{Maturity Offset} = \text{Age} / \text{Maturity ratio}
\]
Equation 5: (Khamis & Roche, 1994) (PAH)

Predicated Adult Height = \( \beta_0 + \text{stature} \times \beta_1 + \text{body mass} \times (\beta_2) + \text{corrected mid-parent stature} \times \beta_3 \)

Note: \( \beta_0, \beta_1, \beta_2, \) and \( \beta_3 \) are the gender specific intercept and coefficients by which age, stature (in), body mass (lbs) and mid-parent stature (in) respectively should be multiplied from the coefficients table available in Khamis & Roche (1994). Correction factor for self-reported height in males is (Parental Height [cm]*0.955) + 2.316