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Salter, Jamie, Cumming, Sean, Hughes, Jonathan and De Ste Croix, Mark (2021) Estimating somatic maturity in adolescent soccer players: Methodological comparisons. International Journal of Sport Science and Coaching. (In Press)

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1 **Estimating somatic maturity in adolescent soccer players: Methodological comparisons**

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8

9 **Running Head:** *Estimating somatic maturity in soccer*

10

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20

21 Abstract Word Count: 182

22 Main Text Word Count: 2855

23 Tables: 3

24 Figures: 1

25

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28

29 **Abstract**

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

34

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

39

40 *Results:* Analysis indicates tight (\pm 0.3 year) agreement between maturity offset methods (MO),
41 but broader agreement between MO and predicted adult height methods (-1.5 to 1 year).
42 However, Kappa Cohen k suggests moderate to substantial (44-67%) and fair to moderate (31-
43 60%) concordance between methods when using the conservative and less conservative circa-
44 PHV thresholds respectively.

45

46 *Conclusion:* Despite MO equation iterations claiming to reduce systematic error, they provide
47 very similar estimations. Additionally, practitioners should not use maturity offset and
48 predicted adult height methods interchangeably and are encouraged to apply either method
49 consistently when looking to estimate maturity status or biologically calssify players.

50

51 *Keywords:* adolescence, growth, maturation, team-sports

52

53

54 **Introduction**

55 The holistic and systematic identification and development of the physiological, psychosocial
56 and/or biomechanical attributes that contribute to success, are a primary focus for team sport
57 practitioners (Bergeron et al., 2015). These attributes are often determined through observation
58 and/or assessment of ‘*elite*’ adult athletes, but talent development studies highlight speed,
59 endurance and decision making as prominent attributes (Murr et al., 2018; Roberts et al., 2019).
60 Subsequently, youth athletes demonstrating these attributes are identified, recruited and
61 promoted towards excellence. However, development trajectories are complicated when
62 adolescents experience the non-linear, inter-individual variations in tempo and timing of
63 development throughout maturation (Cumming et al., 2017). Towlson et al. (2018) reported
64 staggered asynchronous development trajectories of physical and performance characteristics
65 that were exposed to dynamic temporal changes across peak height velocity (PHV). Maturation
66 varies substantially within chronological age-groups, particularly around PHV, with large
67 variations in physical characteristics such as body mass (~50%), stature (~29cm), percentage
68 of predicted adult height (PAH: 10-15%) and fat free mass (3-8.6kg) not uncommon
69 (Figueiredo et al., 2010; Hannon et al., 2020). This level of diversity in maturity, even within
70 relatively homogenous groups, creates uncertainty surrounding relative talent and future
71 potential in young athletes, therefore confounding talent development processes.

72

73 Professionalisation of the academy system (Premier League, 2011) now requires monitoring
74 and evaluation of maturation to inform individual talent development decisions (Cumming et
75 al., 2017). Skeletal age is a ‘clinical’ method of assessing maturity status, but is regarded as
76 impractical within academy soccer (Fransen et al., 2018). As a result, surrogate ‘non-invasive’
77 somatic equations to estimate maturity status using anthropometric proportionality differences
78 alongside longitudinal growth data are now common (Fransen et al., 2018; Khamis & Roche,
79 1994; Malina & Koziel, 2014; Moore et al., 2015). These methods offer an indication of

80 biological age either by predicting the age of PHV onset, whilst informing on the proximity of
81 this in time (years) in the form of a maturity offset (MO), or estimate current percentage of
82 adult height (PAH%) (Khamis & Roche, 1994). If standardised and routinely assessed, these
83 methods can estimate both the timing and tempo of maturation and have been used with
84 adolescent team sports players previously (Johnson et al., 2020; C. Towlson et al., 2018; van
85 der Sluis et al., 2015).

86

87 Each method has received critical review surrounding their ecological validity (see Mills et al.,
88 2017 for a detailed appraisal). The original offset equation (Mirwald et al., 2002) was claimed
89 to predict the timing of PHV to within 1-year 95% of the time which was applicable to
90 individuals aged between 10 and 18 years. Malina and Koziel (2014) longitudinally applied
91 this method to Polish boys in an attempt to re-validate the equation but identified a systematic
92 discrepancy between predicted and observed PHV. The timing of PHV was underestimated at
93 younger ages and overestimated in older age groups. This was also supported by Mills et al.
94 (2017) who added that the equation overestimated the timing of PHV when assessed
95 immediately preceding PHV. Malina and Koziel noted that the magnitude of error tended to be
96 accentuated in early- and late-maturing males, both of which are of particular prevalence in
97 youth sports programmes. Moore et al. (2015) then attempted to simplify and externally
98 validate the equation to cater for this overfitting, but still reported an increase in prediction
99 error the further removed from PHV the individual is. A further iteration of this equation has
100 since been validated with academy soccer players (Fransen et al., 2018). Authors claim that it
101 appears to better account for the systematic error by adopting a polynomial model and
102 estimating a maturity ratio to better reflect the non-linear growth process. However, subsequent
103 critique by Nevill and Burton (2018) outlined potential flaws in the equation and the increased

104 likelihood of spurious findings due to chronological age appearing on both sides of the maturity
105 ratio, with similar concerns over accuracy also reported by Teunissen et al (2020).

106

107 A PAH% developed by Khamis and Roche is also widely used within adolescent soccer (Salter
108 et al., 2020). Utilising several of the same anthropometric variables and the addition of birth
109 parent stature to ascertain mid-parent stature, the equation can predict the progress towards
110 adult stature as a percentage. If measured accurately the equation is reported to predict the adult
111 stature to within 2.2 and 5.3 cm for the 50th and 90th percentile respectively, although this error
112 may increase to 2.8-7.2 cm when applied only to the age groups where it relates to the
113 adolescent growth spurt (11-15 years) (Malina et al., 2019). Objectively measuring parent
114 stature is logistically difficult and therefore equation often uses self-reported parent stature and
115 should therefore be corrected for overestimation (Epstein et al., 1995). In some cases
116 adolescent athletes are not in contact with one or both birth parents, or for whatever reason an
117 accurate stature is not accessible. In such cases the equation suggests using mean national
118 values for male and females, likely reducing the data fidelity via regression to the mean,
119 particularly for those with birth parents with stature significantly different from the mean which
120 may cause additional error.

121

122 Peak-height velocity has been suggested to coincide with increased risk and incidence of non-
123 contact and training related injury in team sports (Bult et al., 2018; Monasterio et al., 2020;
124 Chris Towlson et al., 2020) which is concerning for practitioners. It is common within literature
125 to di-, or tri-chotomise the maturation process into periods, often termed pre-, circa- or post-
126 PHV to categorise individuals (Meyers et al., 2017; Radnor et al., 2020; Ryan et al., 2018; van
127 der Sluis et al., 2015). In the applied setting, this categorisation may be utilised to implement
128 maturity specific interventions, produce reports or inform talent (de)selection decisions

129 (Cumming et al., 2017). Several studies have used such classifications to assess the impact of
130 maturation on performance, such as speed (Meyers et al., 2017), neuromuscular performance
131 (De Ste Croix et al., 2019) and aerobic endurance (Buchheit & Mendez-Villanueva, 2014). Due
132 to error, typical bandwidth thresholds of ± 1 -year, or ± 0.5 -years have been utilised to
133 determine whether individuals are pre-, circa- or post-PHV. Similar conservative (85-96%) and
134 less conservative thresholds (88-93%) exist for PAH%, based on longitudinal data (Cumming
135 et al., 2017; Sanders et al., 2017). Despite each method having this categorisation capacity, it
136 is unclear as to the agreement between the various approaches, which potentially differs based
137 on the nuances between estimation equations.

138

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

150

151 **Methodology**

152 *Participants*

153 Male adolescent academy soccer players ($N = 113$) (mean \pm SD; age, 14.3 ± 1.1 years; stature
154 170.1 ± 10.6 cm; body mass, 58.7 ± 10.5 kg) were recruited from two Elite Player Performance
155 Plan academies. Players were predominantly from White British ethnicity, although some
156 participants were from more diverse ethnic minorities (<10%). Data from 57 participants was
157 collected from a single assessment during the 2017-18 season, with the remaining 55
158 participants providing three repeated measurements during the 2018-19 season, resulting in
159 222 total estimations. Participants were eligible to take part if they were registered with the
160 academies and free from time-loss injury prior to the stratified random recruitment process to
161 ensure a relatively homogenous sample. Ethical approval was granted by the University ethics
162 committee (REC 17.71.5.2).

163

164 *Procedures*

165 Following International Society for the Advancement of Kinanthropometry (ISAK)
166 recommendations (Stewart et al., 2011) anthropometric measurements were obtained from all
167 participants wearing light sportswear to facilitate maturity estimations (Fransen et al., 2018;
168 Khamis & Roche, 1994; Malina & Kozieł, 2014; Moore et al., 2015). A portable stadiometer
169 (Seca[®] 217, Chino, USA) was used to measure standing stature when participants stood
170 barefoot with feet together and their head in the Frankfort plane. The participants were required
171 to take a deep breath and hold their head still whilst duplicate measures of standing stature
172 were recorded to an accuracy of 0.1cm and subsequently the mean was calculated with a third
173 taken if necessary (>4mm difference) and the median recorded. Following similar procedures,
174 participants seated stature was measured whilst sat on a standardised plinth (40cm high) with
175 feet together and hands rested on thighs. Body-mass was recorded using portable weighing
176 scales (Seca[®] robusta 813, Chino, USA) whilst participants were stood barefoot wearing
177 normal training attire. Duplicate readings were taken and if measurements varied by 0.2kg a

178 third measure was taken and the median recorded. All measurements were taken by the same
179 researcher to minimise error, with typical error (coefficient of variation [CV]) for both stature
180 (0.13% CV) and seated stature (0.21% CV) comparable with reported norms (Massard et al.,
181 2019). Mid-parental height was calculated using self-reported values corrected for
182 overestimation (Epstein et al., 1995; Malina et al., 2019).

183

184 *Maturity Equations*

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

193

194 *Statistical Analysis*

195 Raw data are presented in Table 1. Agreement between measures was assessed using Bland-
196 Altman plots with 95% limits of agreement, using Prism 9 software (9.1.0, GraphPad Software
197 LLC). The Mirwald equation (Malina & Kozielec, 2014) was used as a surrogate reference as
198 this is most widely reported in literature. Due to measuring different constructs, both MO
199 (APHV+MO) and PAH% (using growth reference charts (Wright, 2002)) were both
200 subsequently converted to represent an estimation of biological age to facilitate analysis.
201 Concordance analysis was conducted using Cohen's Kappa (k) coefficients derived from
202 contingency tables. Two evidence informed thresholds to categorise circa-PHV for MO and

203 PAH% were applied, a) conservative ± 1 -year and 85-96%; and b) less conservative ± 0.5 -years
204 or 88-93% (Cumming et al., 2017; Sanders et al., 2017).

205 ***Insert Table 1 around here***

206

207 **Results**

208 Descriptive analysis indicates minimal variation between all methods, particularly
209 between those that predict MO, with the closest agreement between the Moore and Fransen
210 methods (± 0.05 years). (Table 1). Bland-Altman analysis indicates that MO methods typically
211 agree within < 0.3 years 95% of the time, but Khamis-Roche PAH% offers broader limits of
212 agreement (-1.65 - 0.87 years) (Figure 1). Bias indicates that Khamis-Roche estimates
213 biological age to be ~ 0.6 years higher than MO methods (Table 2).

214

215 ***Insert Figure 1 around here***

216 ***Insert Table 2 around here***

217

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

223 ***Insert Table 3 around here***

224

225 **Discussion**

226 This study observed agreement between methods of estimating maturity status, aiming to
227 inform practitioners of differences and interchangeability feasibility between them. All

228 methods of MO produce a similar estimate of biological age (14.3-14.7 years). Findings
229 suggest there are tight limits of agreement between MO methods (± 0.3 years) despite
230 methodological nuances. However, biological age estimations derived from Khamis-Roche
231 calculations offer a much broader agreement window (approx. -1.5 to 1 year) with the MO
232 methods. Unsurprisingly, there is greater concordance when using conservative thresholds (44-
233 67%) than when using less conservative bandwidth thresholds (31-60%).

234

235 The tight agreement thresholds of biological age between MO is initially unsurprising based
236 on them being inherent iterations of the original regression equation. Moore et al. (2015) aimed
237 to reduce prediction error by removing seated stature from the equation. The almost perfect
238 agreement observed here (particularly between Moore-Fransen) is interesting based on
239 reported error associated with seated stature, which is historically greater than other
240 components of the equation (Mills et al., 2017). However, typical error for both seated and
241 standing stature in the current study was low (0.2%), which is comparable with reported error
242 (Massard et al., 2019). This suggests that the inclusion/exclusion of seated stature has little
243 impact on the outcome of the equation if measurement error is adequately controlled. This may
244 alleviate some of the concerns raised by Massard et al (2019) who indicated that failure to pay
245 close attention to sitting height protocol may influence the outcomes for PHV estimation. This
246 suggests that practioners have flexibility to utilise MO methods with or without sitting height,
247 based on logistical constraints within their setting. However, considering the tight agreement
248 between the methods, the Fransen calculation was validated in adolescent soccer, and therefore
249 likely reflects the true population (i.e., ethnicity, maturation tempo) compared with other
250 methods validated in predominantly white-caucasian school children. Additionally, this
251 method offers a maturity ratio preceding MO, which is suggested to help model fit (Fransen et

252 al., 2018). Therefore, for practitioners working in youth team-sports, the Fransen MO method
253 may offer the most value, whilst maintaining agreement with other approaches.

254

255 The PAH% equation presented much broader agreement with MO estimations (Table 2). This
256 may be explained by them initially calculating two separate constructs (PAH% and MO) but
257 both can be converted to biological age using known growth trends, as employed in this study.

258 The PAH% mean biological age of 14.7 years and Bland-Altman analysis suggest the PAH%
259 offers a ~0.6 year bias compared to MO methods. This bias is more substantial than any of the

260 MO compared with one another, therefore suggesting that practitioners should use either a MO
261 method, or PAH%, but not both interchangeably. Parr et al. (2020) conducted longitudinal

262 analysis to observe timing of PHV, and illustrated that PAH% was accurate 96% of the time,
263 with MO correct 61% of the time. This, combined with other studies (Malina & Kozieł, 2014;

264 Teunissen et al., 2020) highlight potential limitations with MO methods having a tendency to
265 regress towards the mean which may limit their efficacy when differentiating between stages

266 of maturation. Data from the current study would suggest that PAH% is a useful indicator of
267 maturity status in youth team-sport players, however, it does provide maturity estimations that

268 differ from MO methods. Based on the aforementioned limitations of MO methods, and in
269 conjunction with previous findings, PAH% may offer increased accuracy (Parr et al., 2020;

270 Teunissen et al., 2020), but is not reliably comparable to MO methods. Therefore, practitioners
271 should employ either a MO or PAH% method of maturity estimation consistently across the

272 various facets of application (e.g., time to PHV and/or bio-banding). Failure to obtain accurate
273 parental heights, or appropriately correcting the equation (Malina et al., 2019), will ultimately

274 undermine its accuracy and inflate error beyond that reported, reducing fidelity of predictions
275 and thus leave MO approaches more efficacious.

276

277 Despite the agreement discussed, discrepancy exists when categorising players as circa-PHV
278 using both MO thresholds. The 64-67% concordance leaves a disagreement (i.e. players
279 categorised differently) of approximately 30-35% and up to 50% when using conservative or
280 stringent thresholds respectively. This disagreement further increases when comparing MO to
281 PAH% to 31-50% respectively. Therefore, a third to two-thirds of the data would potentially
282 disagree and lead to categorisation error, potentially influencing on the practices these
283 individuals are exposed to. For example, a player may be categorised as circa-PHV using one
284 method, but pre-PHV in another, potentially exposing them to different training stimulus or
285 reducing/increasing their perceived level of risk incorrectly. This has implications for
286 practitioners who may use both MO and PAH% methods synonymously for different purposes
287 (i.e. time to PHV and bio-banding), and are therefore encouraged to identify the most feasible
288 and logical method within their context and apply this consistently.

289

290 The absence of a criterion value to compare maturity estimations limits confidence in the
291 conclusions from this study, and prevents formal conclusions about which method may be
292 superior, if any. Previous work has attempted to address this (Mills et al., 2017; Parr et al.,
293 2020) but further studies are required to corroborate these findings. However, this multicentre
294 dataset offers insight into the interchangeability (or lack of) of the common approaches, and
295 highlights how the same anthropometrical data may be interpreted differently based on the
296 approach used. Further work surrounding somatic maturity estimation accuracy is required,
297 and where possible should include longitudinal data obtained from multi-ethnic groups.

298

299 Findings indicate tight agreement between MO equations, but broader agreement thresholds
300 for MO and PAH% methods. Additionally, concordance between methods to categorise players
301 is moderate at best and may be misleading if multiple methods are employed. Therefore, we

302 conclude that although MO methods are interchangeable with each other, they are not
303 interchangeable with PAH% which may provide different biological categorisation of players.
304 Academies are consequently encouraged to implement an informed approach to apply either
305 MO or PAH% consistently for both research and applied purposes, based on the resources and
306 constraints of their environment. Previously cited limitations (Malina & Kozieł, 2014) of MO
307 methods and the observed bias here would suggest that a PAH% approach may offer increased
308 accuracy when looking to monitor maturity status and timing (Parr et al., 2020; Teunissen et
309 al., 2020). It is further recommended that practitioners monitor both height and weight velocity
310 and plot their respective growth curves over time. With consideration of these findings
311 practitioners can have greater confidence in maturity estimations, leading to appropriate
312 maturity-specific development and evaluation of talent.

313

314 **Disclaimer**

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

316

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

Measure	Mirwald	Moore	Fransen	Khamis-Roche
Mean ± SD	14.4 ± 1.9	14.3 ± 1.9	14.3 ± 1.2	14.7 ± 1.1
Minimum	11.6	12.1	12.1	11.5
Maximum	16.7	16.6	16.6	18
Range	5.1	4.5	4.5	6.4
SEM	0.08	0.08	0.08	0.08
Variance	1.4	1.4	1.4	1.35

SD, Standard Deviation; SEM, Standard Error of Measurement

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Table 2. Bland-Altman bias (SD) and 95% limits of agreement between biological age estimations

Measure	Mirwald	Moore	Fransen
Moore	0.17 -0.31 – 0.37	***	***
Fransen	0.16 -0.30 – 0.36	0.03 -0.05 – 0.05	***
Khamis-Roche	0.68 -1.65 – 1.04	0.61 -1.53 – 0.87	0.61 -1.53 – 0.87

*** N/A

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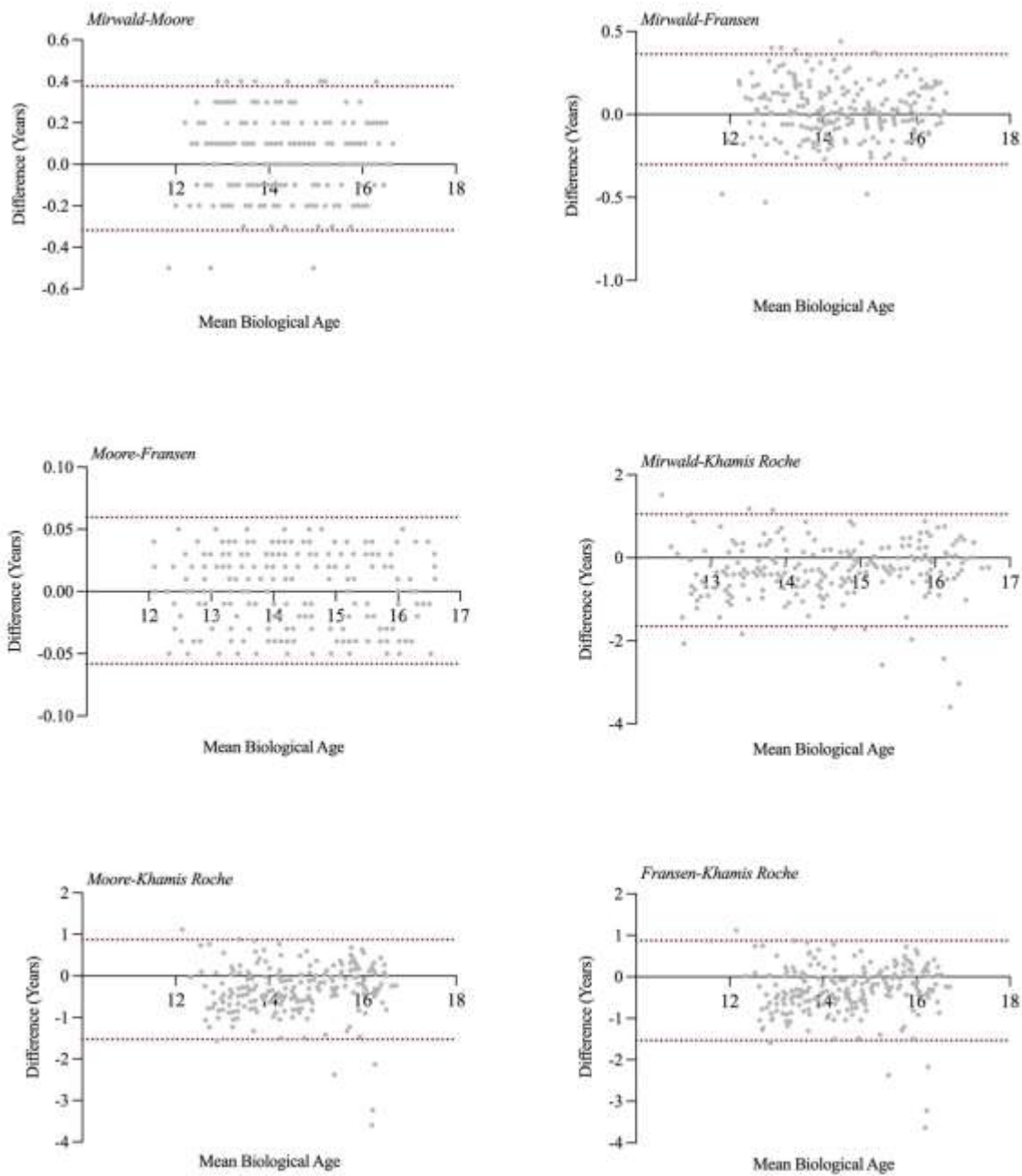
Table 3. Concordance (Kappa Cohen k coefficient) between maturity status estimation thresholds for circa-PHV

circa-PHV Threshold	Measure	Mirwald	Moore	Fransen
± 1 year 85-96% PAH	Moore	0.67	***	***
	Fransen	0.66	0.64	***
	Khamis-Roche	0.49	0.50	0.44
± 0.5 year 88-93% PAH	Moore	0.60	***	***
	Fransen	0.59	0.58	***
	Khamis-Roche	0.31	0.43	0.39

*** N/A

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453 Figure 1. Bland-Altman plots (with 95% limits of agreement) for estimated biological age for the different

454 maturity estimation methods

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456 **Supplementary Material - Equations**457 *Equation 1: (Malina & Kozieł, 2014) (MIRWALD_{MO})*

$$\begin{aligned}
458 \quad & \text{Maturity Offset} = -9.236 + (0.0002708 * (\text{Leg Length} * \text{Sitting Height})) \\
459 \quad & \quad \quad \quad + (-0.001663 * (\text{Age} * \text{Leg length})) \\
460 \quad & \quad \quad \quad + (0.007216 * (\text{Age} * \text{Sitting Height})) \\
461 \quad & \quad \quad \quad +(0.02292 * (\text{Body Mass by stature ratio} * 100))
\end{aligned}$$

462

463 *Equation 2: (Moore et al., 2015) (MOORE_{MO})*

$$464 \quad \text{Maturity offset} = - 7.999994 + (0.0036124 * (\text{age} * \text{standing stature}))$$

465

466 *Equation 3: (Fransen et al., 2018) (FRANSEN_{Ratio})*

$$\begin{aligned}
467 \quad & \text{Maturity ratio} = 6.986547255416 \\
468 \quad & \quad \quad \quad + (0.115802846632 * \text{Chronological age}) \\
469 \quad & \quad \quad \quad + (0.001450825199 * \text{Chronological age (2)}) \\
470 \quad & \quad \quad \quad + (0.004518400406 * \text{Body mass}) \\
471 \quad & \quad \quad \quad - (0.000034086447 * \text{Body mass (2)}) \\
472 \quad & \quad \quad \quad - (0.151951447289 * \text{Stature}) \\
473 \quad & \quad \quad \quad + (0.000932836659 * \text{Stature (2)}) \\
474 \quad & \quad \quad \quad - (0.000001656585 * \text{Stature (3)}) \\
475 \quad & \quad \quad \quad + (0.032198263733 * \text{Leg length}) \\
476 \quad & \quad \quad \quad - (0.000269025264 * \text{Leg length (2)}) \\
477 \quad & \quad \quad \quad - (0.000760897942 * [\text{Stature} * \text{Chronological age}])
\end{aligned}$$

478

479 *Equation 4: (Fransen et al., 2018) (FRANSEN_{MO})*

$$480 \quad - \text{Maturity Offset} = \text{Age} / \text{Maturity ratio}$$

481

482 *Equation 5: (Khamis & Roche, 1994) (PAH)*483 Predicated Adult Height = β_0 + stature* β_1 + body mass*(β_2) + corrected mid-parent stature484 β_3

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486 Note: β_0 , β_1 , β_2 , and β_3 are the gender specific intercept and coefficients by which age, stature (in), body mass

487 (lbs) and mid-parent stature (in) respectively should be multiplied from the coefficients table available in

488 Khamis & Roche (1994). Correction factor for self-reported height in males is (Parental Height [cm]*0.955) +

489 2.316

490