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The percentage of mature height as a morphometric index of somatic growth: a formal scrutiny of conventional simple ratio scaling assumptions

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1 Abstract

2

3 **Purpose:** To assess conventional assumptions that underpin the percentage of mature height
4 index as the simple ratio of screening height (numerator) divided by actual or predicted adult
5 height (denominator). **Methods:** We examined cross-sectional data from 99 academy youth
6 soccer players (chronological age range, 11.5 to 17.7 yr) skeletally immature at the screening
7 time and with adult height measurements available at follow-up. **Results:** The y-intercept value
8 of -60 cm (95% confidence interval [CI], -115 to -6 cm) from linear regression between
9 screening height and adult height indicated the failure to meet zero y-intercept assumption. The
10 correlation coefficient between present height and adult height of 0.64 (95%CI, 0.50 to 0.74)
11 was not equal to the ratio of coefficient of variations between these variables ($CV_x/CV_y =$
12 0.46) suggesting Tanner's special circumstance was violated. The non-zero correlation
13 between the ratio and the denominator of 0.21 (95%CI, 0.01 to 0.39) indicated that the
14 percentage of mature height was biased low for players with generally shorter adult height, and
15 vice versa. **Conclusion:** For the first time, we have demonstrated that the percentage of mature
16 height is an inconsistent statistic for determining the extent of completed growth, leading to
17 potential biased inferences for research and applied purposes.

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20 **Keywords:** ratio, percentage of mature height, skeletal age, soccer, youth

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26 1. Introduction

27 Assessment of changes in growth and biological maturation is fundamental to support elite
28 youth athlete development. Growth is generally interpreted as any quantitative increase in size,
29 whereas maturation refers to a progressive process, where the onset of change, rate of change
30 and magnitude of change can differ between different people and different bodily systems
31 within the same person (1, 2). A number of indices are generally measured to monitor the
32 course of these processes. Such indices include the amount and patterning of pubic hair, the
33 size of penis and testes, skeletal age, dental age, age at maximum growth, and percentage of
34 mature height (3).

35
36 Of these indices, the determination of the percentage of mature height has received particular
37 attention as an integrated measure deemed useful for tracking the growth process of children
38 in general as well as athletic populations (4). Accordingly, exercise scientists have highlighted
39 the potential utility of the percentage of mature height for informing the performance
40 stratification of youth athletes rather than the use of chronological age categories according to
41 the bio-banding strategy (5). The percentage of mature height (%) is calculated as the simple
42 ratio of the height at the time of observation divided by the mature or adult height multiplied
43 by 100 (5). Bayley first coined this index after measurements were obtained from a group of
44 children examined as part of the adolescent growth study of the University of California at
45 Berkeley's Institute of Child Welfare (6). The formulation of this index as a percentage aimed
46 to express the relationship between skeletal and physical growth in terms of the individual's
47 own relative maturity while addressing the influence of body size differences between subjects
48 (6).

49

50 The percentage of mature height index has many advantages as a measure of maturity and
51 completed growth. Nevertheless, it naturally cannot be calculated until growth in height is
52 complete (3). To overcome such a practical caveat, researchers have generally calculated this
53 index, but using an available estimate of the predicted adult height (7, 8). This approach has
54 been adopted in several studies applied to sports, with predicted adult height derived using the
55 Khamis-Roche protocol (7). Using the predicted adult height in the calculations of this index
56 would be empirically supported only in the absence of error between the predicted and actual
57 adult height values, which is unlikely given the published evidence against this assumption (9-
58 14). Percentages or size-specific indices are popular among biomedical researchers, but there
59 is the potential for compounding errors originating from inconsistent simple ratio
60 normalization (15-18). Ratio indices are ubiquitous in all fields of research (19-25). For
61 example, oxygen uptake is typically divided by body mass in exercise physiology (26), left
62 ventricular ejection fraction is the ratio of stroke volume to end-diastolic volume in cardiology
63 (27), the percentage flow-mediated dilation index is used in cardiovascular physiology (28),
64 and there are finger, and other anthropometric, ratios commonly used in evolutionary biology
65 (29).

66

67 Roche and colleagues (page 364) highlighted previously the simple ratio properties of the
68 percentage of mature/predicted adult height index as a method '*for measuring physical*
69 *maturity that is applicable to cross-sectional data*' (8). Researchers have typically computed
70 simple ratio statistics to obtain an index that allows inter-individual and inter-group
71 comparisons. This approach entails the division of the numerator variable (e.g., Y = present
72 height) by a denominator variable (e.g., X = mature height) to derive a standardised variable
73 deemed adequate to quantify, as well as, help interpret a given process in relative terms (21,
74 30, 31). The formulation of a simple ratio index can serve its purpose in an unbiased manner

75 only if fundamental assumptions are satisfied (21, 30, 31). First, the bivariate regression of the
76 numerator and denominator should yield a straight line that intersects with the origin (y -
77 intercept = 0) of both axes (31). Second, Tanner's special circumstance should hold, whereby
78 the ratio of the present height and adult height variable coefficient of variations (CV_x/CV_y)
79 should equal the correlation coefficient ($r[x,y]$) between the same two variables (32). Third,
80 the relationship between the ratio and its denominator should yield a zero correlation (30).

81

82 Using data available from a sample of elite youth Middle Eastern soccer players, we aimed to
83 scrutinise the above assumptions that underpin the percentage of mature height as a simple
84 ratio index for tracking completed growth in children and adolescents.

85

86 **2. Methods**

87 **2.1 Study participants and procedures**

88 The study sample included cross-sectional data for 99 academy youth soccer players
89 (chronological age range: 11.5 to 17.7 yr, standing height range: 137.5 to 187 cm, body mass
90 range: 28.9 to 78.7 kg) skeletally immature at the time of assessment (3, 33) and adult height
91 measurements available at follow-up (chronological age range, 19.4 to 27.2 yr). Adult standing
92 height was defined as the height for a participant older than 18 yr (34). Hand x-rays, standing
93 height, body mass and performance test measurements collected in student-athletes as part of
94 the annual screening were retrieved from the Academy medical records, anonymised, analysed
95 and used to determine skeletal age at the time of the first screening visit. Assessment of skeletal
96 age involved standard radiographs (Digital Diagnost, Philips, USA) of the radius, ulna, carpals,
97 metacarpals and phalanges (33). Modern technology now allows minimal exposure to radiation
98 of as little as 0.0001 millisievert (mSv), which is commensurate to less than natural background
99 radiation walking around a city centre, or any radiation associated with a 2-hr flight (33).

100 Roentgenograms were evaluated according to manual and automated procedures. The manual
101 assessment was conducted by the same rater (AJ), who had twenty years of experience, as per
102 the Tanner-Whitehouse radius-ulna-short (RUS) bones protocol. RUS scores were converted
103 to Tanner-Whitehouse II (TW-II) skeletal ages using relevant conversion tables (1). Automated
104 assessment of roentgenograms involved digital images processing using the computerized
105 BoneXpert[®] determination method (35) according to the manufacturer's recommendations
106 (version 3.1.4, Visiana, Holte, Denmark). A new standard version of the TW-II skeletal age
107 rating was implemented using the BoneXpert[®] method and calibrated on manual rating data
108 from the First Zürich Longitudinal Study (36). Data relevant to tracking skeletal maturation
109 and growth in this population (10) informed the determination of skeletal ages according to the
110 TW-II protocol (RUS score range: 283 to 999 au). Signed parental consent was obtained before
111 each academy season to use data for research purposes. This retrospective study was approved
112 by the Aspire Zone Foundation Institutional Review Board, Doha, State of Qatar (protocol
113 number: E202008009).

114

115 **2.2 Statistical analysis**

116 Demographic and anthropometric characteristics of participants at the first screening and
117 follow-up visits are presented as mean \pm standard deviation (SD), alongside the respective
118 percentage coefficient of variation (%CV) and range for continuous variables. Ordinary least-
119 squares (Type I) regression procedures were used to explore the presence of zero y-intercept
120 for the bivariate relationship between height at the time of observation and adult height.
121 Pearson's product moment correlation coefficients (r) were derived to describe relationships
122 between the numerator and the ratio index with the denominator variables. Coefficients were
123 interpreted according to the following scale: $r < 0.1$, trivial; 0.1 to 0.3, small; 0.3 to 0.5,
124 moderate; 0.5 to 0.7, large; 0.7 to 0.9, very large; 0.9 to 1.0 almost perfect. The correlation

125 coefficient ($r[x,y]$) for adult height and screening height was compared with the ratio of the
126 coefficients of variation (%CV) for the same two variables (CVx/CVy) to assess Tanner's
127 special circumstance. Regression parameters were reported as point estimates with 95%
128 confidence intervals (CI). Statistical analyses were conducted using R (version 3.6.3, R
129 Foundation for Statistical Computing).

130

131 *Table 1 about here*132 *Figure 1 about here*

133

134 **3. Results**

135 Summary statistics for demographic and anthropometric data at the first screening and follow-
136 up are presented in Table 1, with Figure 1 showing the distribution of values for height at the
137 time of observation by chronological age. Figure 2 shows 95% prediction limits for the
138 relationship between adult height and TW-II predicted adult height by manual and automated
139 assessment methods. The average width of this 95% prediction interval was 2.84 and 2.30 on
140 either side, respectively (Figure 2).

141

142 *Figure 2 about here*

143

144 The negative y-intercept value of -60 cm (95% CI, -115 to -6 cm) observed in the bivariate
145 relationship between screening height and adult height indicated that the assumption of the per-
146 ratio standards model of a zero y-intercept was violated (Figure 3). The correlation coefficient
147 between present height and adult height of 0.64 (95% CI, 0.50 to 0.74) was not equal to the
148 ratio of coefficient of variations between these variables ($CVx/CVy = 0.46$), suggesting
149 Tanner's special circumstance was not satisfied. The correlation coefficient between the

150 percentage of mature height index and the denominator of the index was 0.21 (95% CI, 0.01 to
151 0.39). This non-zero correlation coefficient indicates that this ratio was not normalizing
152 measured height for final height in a consistent manner across the measurement range.
153 Percentage of mature height was biased low for players with generally shorter adult height, and
154 *vice versa*. Likewise, conventional assumptions for simple ratio formulation were not upheld
155 with the TW-II predicted adult height specified as an alternative denominator of the percentage
156 of mature height index (Figure 4). The bivariate relationship between screening height and
157 TW-II predicted adult height revealed a y-intercept value of -99 cm (95% CI, -148 to -51 cm)
158 and -93 cm (95% CI, -146 to -40 cm) as per manual and automated methods, respectively.
159 The substantial difference between CV_x/CV_y and the observed correlation coefficient between
160 these variables based on manual (0.46 ≠ 0.74) and automated (0.44 ≠ 0.70) skeletal age
161 assessments indicated further the inappropriateness of the percentage of mature height for
162 tracking somatic growth in this particular dataset. Likewise, the non-zero correlations between
163 the percentage of predicted mature height index and the denominator based on manual 0.30
164 (95% CI, 0.11 to 0.47) and automated 0.28 (95% CI, 0.09 to 0.46) assessments suggested that
165 this simple ratio failed to meet underlying assumptions for appropriate normalization
166 irrespective of the skeletal age determination method.

167

168 *Figure 3 about here*169 *Figure 4 about here*

170

171 **4. Discussion**

172 For the first time, we report the failure of the percentage of mature height index to meet
173 underlying assumptions relevant to consistent ratio scaling. The lack of a directly proportional
174 association between the numerator and denominator variables (Tanner's special circumstance)

175 suggests the use of this index hinders the understanding of the true extent of completed growth
176 in male children and adolescents. In practical terms, the percentage of mature height will be
177 underestimated for people who are relatively tall as adults, and *vice versa*. This inconsistent
178 normalization for adult height could lead to inaccurate assessments of individuals and
179 erroneous conclusions in research when the percentage of mature height index is used.

180

181 The statistical inconsistency of the percentage of mature height has far-reaching implications
182 with the potential for biasing clinical and practical insights into the human growth process.
183 Notably, the percentage of mature height has become the criterion measure to inform the
184 grouping of youth athletes into maturity categories also defined, more recently, as “*bio-*
185 *banding*”. This approach is designed to reduce maturity-related mismatches in anthropometric
186 and performance characteristics during training and competition (37). Specifically, researchers
187 have suggested that youth athletes should be differentiated using percentages of predicted adult
188 heights of less than 85% described as prepubertal, from 85% to 90% labelled as early pubertal,
189 from 90% to 95% termed as mid-pubertal, and above > 95% described as late pubertal (38).
190 Researchers have recently explored the potential of bio-banded tournaments to facilitate
191 optimal soccer academy player development (39-41). Nevertheless, the percentage of mature
192 height may have inaccurate validity as an index of completed growth since we have shown that
193 estimates of relative height at the observation are generally biased low for shorter adult height,
194 and *vice versa*. In practice, failure to control for between-subject differences in body size at
195 adult stages can bias the percentage of mature height ratio and, ultimately, lead to
196 misrepresentation of a subject’s completed growth profile. Because we found that the
197 fundamental assumptions of ratios were violated (21, 30-32), the notion of accurate “*maturity*
198 *matching*” informed by percentage of mature height measures for categorising a continuous,
199 non-linear process as human growth is, therefore, empirically unsupported.

200 We also contend that, although the percentage of mature height index is relatively simple to
201 calculate, its determination has some limitations from conceptual and practical standpoints.
202 First, an accurate calculation of the percentage of mature height ratio rests on assumptions
203 inconsistent with the allometric nature of changes in body size from childhood to adulthood.
204 Historically, researchers in biometry explored individual growth trajectories using higher-order
205 polynomials and smoothing splines that, by definition, represent flexible mathematical
206 interpolations better suited than constrained linear methods for modelling non-linear effects in
207 anthropometric measurements (42). Second, researchers in this field illustrated different
208 methods for calculating the percentage of mature height, but there is still an absence of expert
209 consensus on protocol selection. Bayley was the first to publish tables for predicting adult
210 height from present height and skeletal age, originally according to the Todd atlas and then this
211 was subsequently revised according to Greulich-Pyle standards (6, 43, 44). Roche and
212 colleagues provided alternative versions based on protocols with or without inclusion of
213 skeletal age. Specifically, the theoretical basis for this method relates to deriving the percentage
214 mature height *at* a particular Greulich-Pyle skeletal age (45). Nevertheless, Tanner and
215 colleagues highlighted that three separate versions of these tables are available and their
216 application depends on prior knowledge of relative skeletal maturity, which represents an
217 additional practical disadvantage for accurate determination of completed growth (13). These
218 sources, however, may remain of limited utility when applied to populations other than those
219 from which the standards were derived since, for example, estimates of skeletal age are prone
220 to bias if determined on the basis of Greulich-Pyle standards in Middle Eastern subjects (10,
221 46). Third, pre-defined thresholds have been suggested to differentiate a subject's growth
222 progression according the percentage of mature height index (38). Although such an approach
223 is practical in applied contexts, the generalisation of established threshold values is prone to
224 bias. The caveats underlying the use of fixed thresholds to define growth/maturity categories

225 relate to the between-subject variability in growth and the degree of error in the adult height
226 predictions as surrogate estimates of actual adult height. To illustrate this point, we shall
227 consider the case of a youth academy player from our dataset with a chronological age of 13.2
228 yr, a present height of 143.9 cm, a TW-II skeletal age of 12.6 yr, and a TW-II predicted adult
229 height of 167.5 cm based on automated ratings. Findings from a recent comparison study
230 involving Middle Eastern youth soccer players (10) revealed an error (SD) in the TW-II
231 predicted adult height of ± 2.6 cm (95%CI, 2.4 to 2.8 cm). Accordingly, the calculated
232 percentage of TW-II predicted adult height of $[(143.9 \div 167.6) \times 100] = 85.9\%$ would suggest
233 that this person is just passing through the pubertal period. However, using the estimated error
234 statistic from the reference population, we can calculate the respective 95% prediction interval
235 (47). [Despite the general shortcomings of continuous measurements into categorical variables](#)
236 [for grouping of youth athletes](#) (48), the lower and upper limits of this interval range from 83.3%
237 to 88.6% and indicate a substantial degree of uncertainty in drawing any definitive conclusion
238 relevant to the categorisation of this person, [given](#) the thresholds suggested in this field (38).
239 Importantly, the degree of uncertainty in the point prediction for adult height is anticipated to
240 be worse in protocols that exclude estimates of skeletal age, with a particular reference to the
241 Khamis-Roche method (7). Taken together, using the percentage of mature/predicted adult
242 height to inform applied strategies (e.g., bio-banding) for player development is also limited
243 by other practical and empirical factors beyond inconsistent [simple](#) ratio scaling (Figure [3-4](#)).
244
245 Practical alternatives to the use [of the](#) percentage of mature height index are available, with
246 serial anthropometric data necessary for appropriately tracking growth and maturation in elite
247 youth athletes (49). A simple difference between present height and predicted adult height can
248 be derived if the objective is to understand the extent of residual height growth at the time of
249 observation yet require accounting for the error in the prediction. This simpler approach seems

250 preferable to the scrutiny of a simple ratio statistic failing to serve its purpose in an unbiased
251 manner for tracking growth progression in children and adolescents. Classical growth charts
252 from the reference population can also be helpful, with centile status providing information
253 inherent to the relative standing for a given measurement on a height-on-chronological age
254 standard (50). Monitoring yearly height velocities is another potential solution valuable to
255 address the practical demands of a sporting academy setting (49).

256

257 **5. Conclusion**

258 The findings of our study indicate that, in Middle Eastern youth soccer players, problems
259 associated with the simple ratio scaling approach appear to limit the validity of the percentage
260 of mature height as a measure of completed growth. If the lack of a true directly proportional
261 relationship between height at time of observation with mature height and predicted adult
262 height is confirmed in other data sets, then formulation of the percentage of mature height may
263 merely result in confounding, rather than assisting, the understanding of completed growth in
264 children and adolescents.

265

266 **Disclosure statement**

267 The authors declare no conflicts of interest.

268

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396 **Figure captions**

397

398 **Figure 1.** Scatterplot showing distribution for present height at the screening visit by
399 chronological age (range: 11.5 to 17.7 yr).

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401 Figure 2. Scatterplots showing the linear bivariate relationship between adult height and TW-
402 II predicted adult height by manual (A) and automated (B) assessment methods, with 95%
403 prediction limits.

404

405 **Figure 3.** Scatterplots showing the linear bivariate relationship between present height at the
406 screening and adult height (A), and the linear relationship between the percentage of mature
407 height and adult height (B) at the follow-up visits.

408

409 **Figure 4.** Scatterplots showing the linear bivariate relationship between present height at the
410 screening visit and TW-II predicted adult height (A,B), and the linear relationship between the
411 percentage of predicted adult height and TW-II predicted adult height (C,D) by manual and
412 automated assessment methods, respectively.

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414 **Table captions**

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416 **Table 1.** Summary statistics for demographic and anthropometric data at the first screening
417 and follow-up

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Table 1. Summary statistics for demographic and anthropometric data at the first screening and follow-up

Variable	minimum	maximum	μ	σ	CV (%)
Chronological age (yr)	11.5	17.7	14.4	1.7	11.84
Height (cm)	137.5	187.0	163.3	13.0	7.95
TW-II skeletal age (yr) ^a	9.4	18.1	15.0	2.2	14.92
TW-II skeletal age (yr) ^b	9.4	18.1	15.1	2.3	15.05
TW-II predicted adult height (cm) ^a	161.9	191.6	174.0	6.3	3.64
TW-II predicted adult height (cm) ^b	162.5	191.9	173.9	6.1	3.53
Adult chronological age (yr)	19.4	27.2	22.7	2.2	9.63
Adult height (cm)	162.8	189.7	175.0	6.5	3.69

^a, manual method; ^b, automated method; μ , mean; σ , standard deviation; CV, coefficient of variation.

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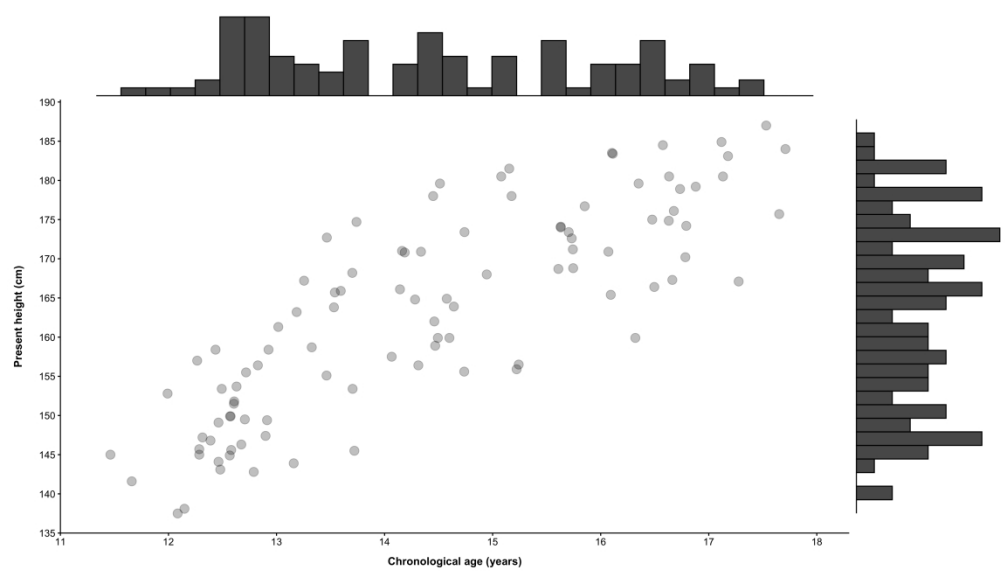


Figure 1. Scatterplot showing distribution for present height at the screening visit by chronological age (range: 11.5 to 17.7 yr).

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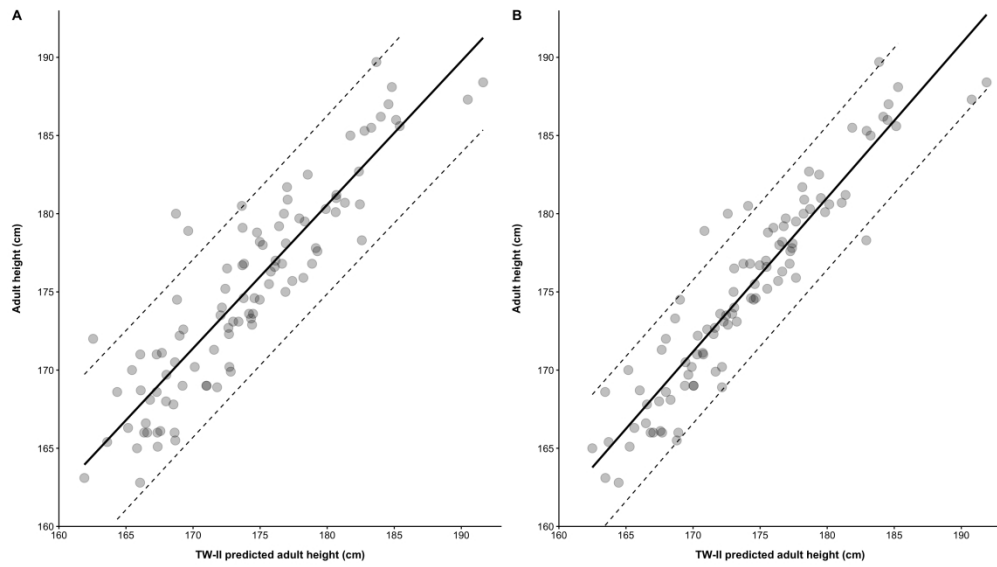


Figure 2. Scatterplots showing the linear bivariate relationship between adult height and TW-II predicted adult height by manual (A) and automated (B) assessment methods, with 95% prediction limits.

10668x6096mm (10 x 10 DPI)

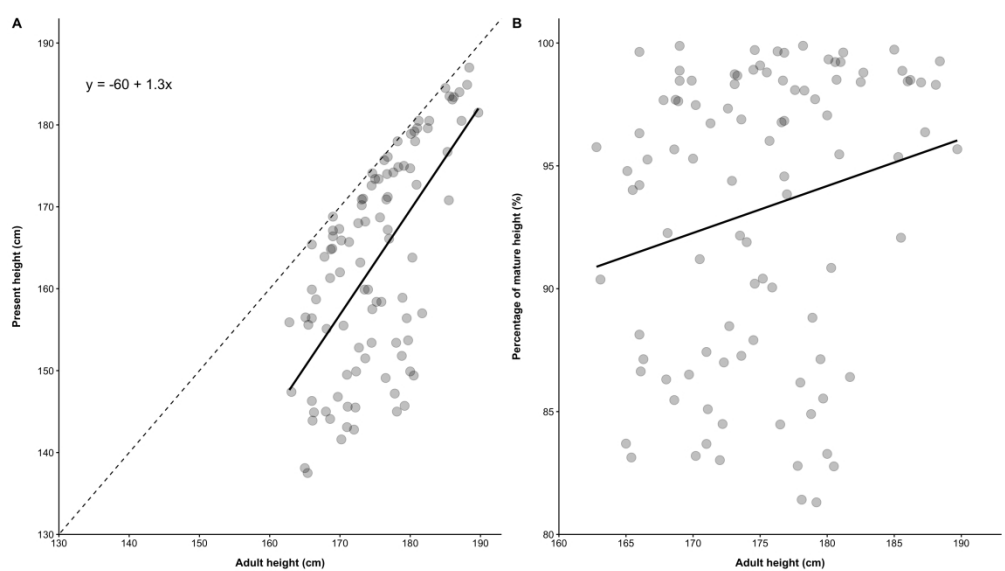


Figure 3. Scatterplots showing the linear bivariate relationship between present height at the screening and adult height (A), and the linear relationship between the percentage of mature height and adult height (B) at the follow-up visits.

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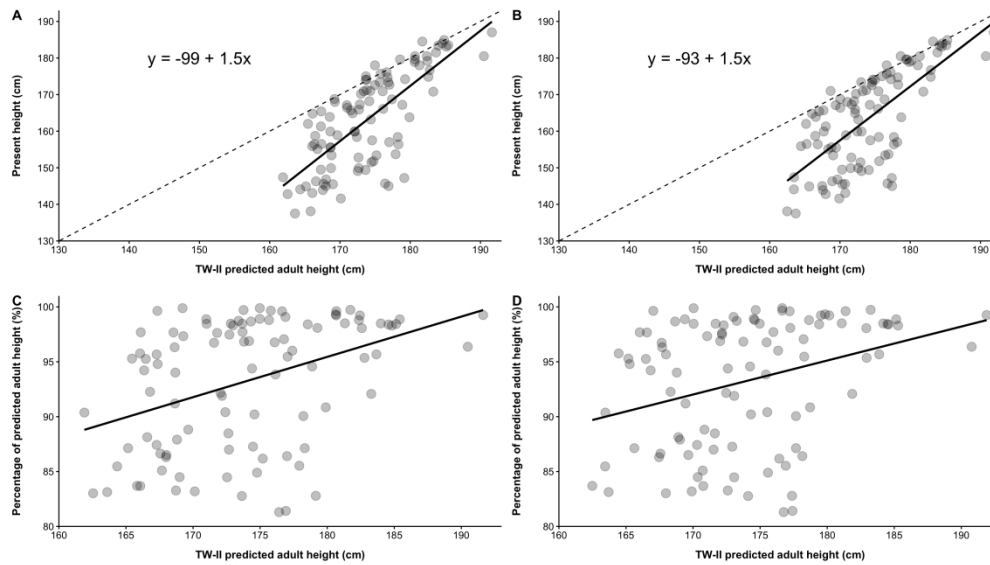


Figure 4. Scatterplots showing the linear bivariate relationship between present height at the screening visit and TW-II predicted adult height (A,B), and the linear relationship between the percentage of predicted adult height and TW-II predicted adult height (C,D) by manual and automated assessment methods, respectively.

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