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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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Abstract

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

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

1. Introduction

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

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

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

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Roche and colleagues (page 364) highlighted previously the simple ratio properties of the percentage of mature/predicted adult height index as a method '*for measuring physical maturity that is applicable to cross-sectional data'* (8). Researchers have typically computed simple ratio statistics to obtain an index that allows inter-individual and inter-group comparisons. This approach entails the division of the numerator variable (e.g., Y = present height) by a denominator variable (e.g., X = mature height) to derive a standardised variable deemed adequate to quantify, as well as, help interpret a given process in relative terms (21, 30, 31). The formulation of a simple ratio index can serve its purpose in an unbiased manner only if fundamental assumptions are satisfied (21, 30, 31). First, the bivariate regression of the numerator and denominator should yield a straight line that intersects with the origin (y-intercept = 0) of both axes (31). Second, Tanner's special circumstance should hold, whereby the ratio of the present height and adult height variable coefficient of variations (CVx/CVy) should equal the correlation coefficient (r[x,y]) between the same two variables (32). Third, the relationship between the ratio and its denominator should yield a zero correlation (30).

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

2. Methods

2.1 Study participants and procedures

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

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

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2.2 Statistical analysis

Demographic and anthropometric characteristics of participants at the first screening and follow-up visits are presented as mean ± standard deviation (SD), alongside the respective percentage coefficient of variation (%CV) and range for continuous variables. Ordinary least-squares (Type I) regression procedures were used to explore the presence of zero y-intercept for the bivariate relationship between height at the time of observation and adult height. Pearson's product moment correlation coefficients (r) were derived to describe relationships between the numerator and the ratio index with the denominator variables. Coefficients were interpreted according to the following scale: $r < 0.1$, trivial; 0.1 to 0.3, small; 0.3 to 0.5, moderate; 0.5 to 0.7, large; 0.7 to 0.9, very large; 0.9 to 1.0 almost perfect. The correlation coefficient (*r*[x,y]) for adult height and screening height was compared with the ratio of the coefficients of variation (%CV) for the same two variables (CVx/CVy) to assess Tanner's special circumstance. Regression parameters were reported as point estimates with 95% confidence intervals (CI). Statistical analyses were conducted using R (version 3.6.3, R Foundation for Statistical Computing).

Table 1 about here

Figure 1 about here

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3. Results

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

Figure 2 about here

The negative y-intercept value of –60 cm (95% CI, –115 to –6 cm) observed in the bivariate relationship between screening height and adult height indicated that the assumption of the per-ratio standards model of a zero y-intercept was violated (Figure 3). The correlation coefficient between present height and adult height of 0.64 (95% CI, 0.50 to 0.74) was not equal to the ratio of coefficient of variations between these variables (CVx/CVy = 0.46), suggesting Tanner's special circumstance was not satisfied. The correlation coefficient between the percentage of mature height index and the denominator of the index was 0.21 (95% CI, 0.01 to 0.39). This non-zero correlation coefficient indicates that this ratio was not normalizing measured height for final height in a consistent manner across the measurement range. Percentage of mature height was biased low for players with generally shorter adult height, and *vice versa*. Likewise, conventional assumptions for simple ratio formulation were not upheld with the TW-II predicted adult height specified as an alternative denominator of the percentage of mature height index (Figure 4). The bivariate relationship between screening height and TW-II predicted adult height revealed a y-intercept value of –99 cm (95% CI, –148 to –51 cm) and –93 cm (95% CI, –146 to –40 cm) as per manual and automated methods, respectively. The substantial difference between CVx/CVy and the observed correlation coefficient between these variables based on manual (0.46 ≠ 0.74) and automated (0.44 ≠ 0.70) skeletal age assessments indicated further the inappropriateness of the percentage of mature height for tracking somatic growth in this particular dataset. Likewise, the non-zero correlations between the percentage of predicted mature height index and the denominator based on manual 0.30 (95% CI, 0.11 to 0.47) and automated 0.28 (95% CI, 0.09 to 0.46) assessments suggested that this simple ratio failed to meet underlying assumptions for appropriate normalization irrespective of the skeletal age determination method.

Figure 3 about here

Figure 4 about here

4. Discussion

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

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

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

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

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relate to the between-subject variability in growth and the degree of error in the adult height predictions as surrogate estimates of actual adult height. To illustrate this point, we shall consider the case of a youth academy player from our dataset with a chronological age of 13.2 yr, a present height of 143.9 cm, a TW-II skeletal age of 12.6 yr, and a TW-II predicted adult height of 167.5 cm based on automated ratings. Findings from a recent comparison study involving Middle Eastern youth soccer players (10) revealed an error (SD) in the TW-II predicted adult height of ± 2.6 cm (95%CI, 2.4 to 2.8 cm). Accordingly, the calculated percentage of TW-II predicted adult height of [(143.9 ÷ 167.6) × 100)] = 85.9% would suggest that this person is just passing through the pubertal period. However, using the estimated error statistic from the reference population, we can calculate the respective 95% prediction interval (47). Despite the general shortcomings of continuous measurements into categorical variables for grouping of youth athletes (48), the lower and upper limits of this interval range from 83.3% to 88.6% and indicate a substantial degree of uncertainty in drawing any definitive conclusion relevant to the categorisation of this person, given the thresholds suggested in this field (38). Importantly, the degree of uncertainty in the point prediction for adult height is anticipated to be worse in protocols that exclude estimates of skeletal age, with a particular reference to the Khamis-Roche method (7). Taken together, using the percentage of mature/predicted adult height to inform applied strategies (e.g., bio-banding) for player development is also limited by other practical and empirical factors beyond inconsistent simple ratio scaling (Figure 3-4).

Practical alternatives to the use of the percentage of mature height index are available, with serial anthropometric data necessary for appropriately tracking growth and maturation in elite youth athletes (49). A simple difference between present height and predicted adult height can be derived if the objective is to understand the extent of residual height growth at the time of observation yet require accounting for the error in the prediction. This simpler approach seems

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

5. Conclusion

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

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Disclosure statement

The authors declare no conflicts of interest.

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Figure captions

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

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.

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.

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.

Table captions

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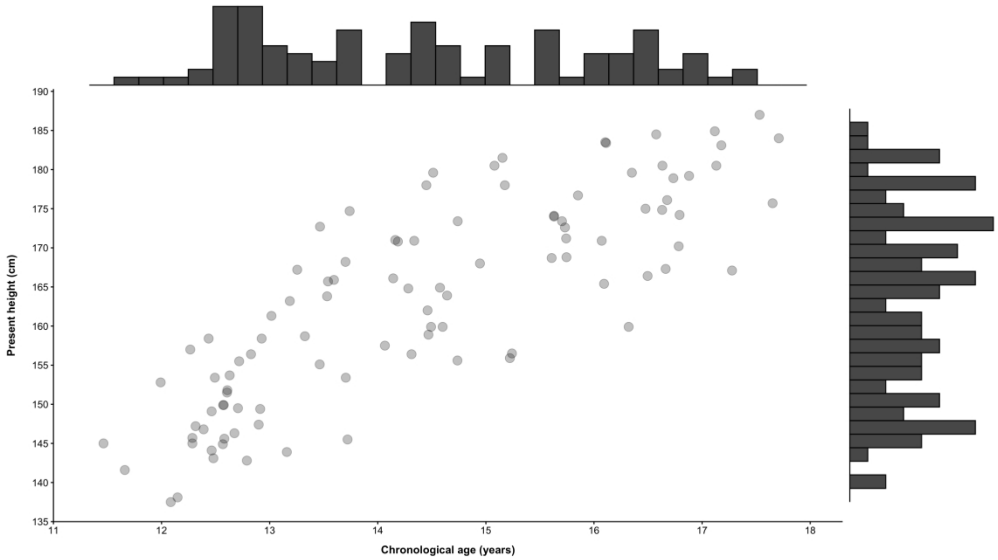

Figure 1. Scatterplot showing distribution for present height at the screening visit by chronological age (range: 11.5 to 17.7 yr).

10668x6096mm (10 x 10 DPI)

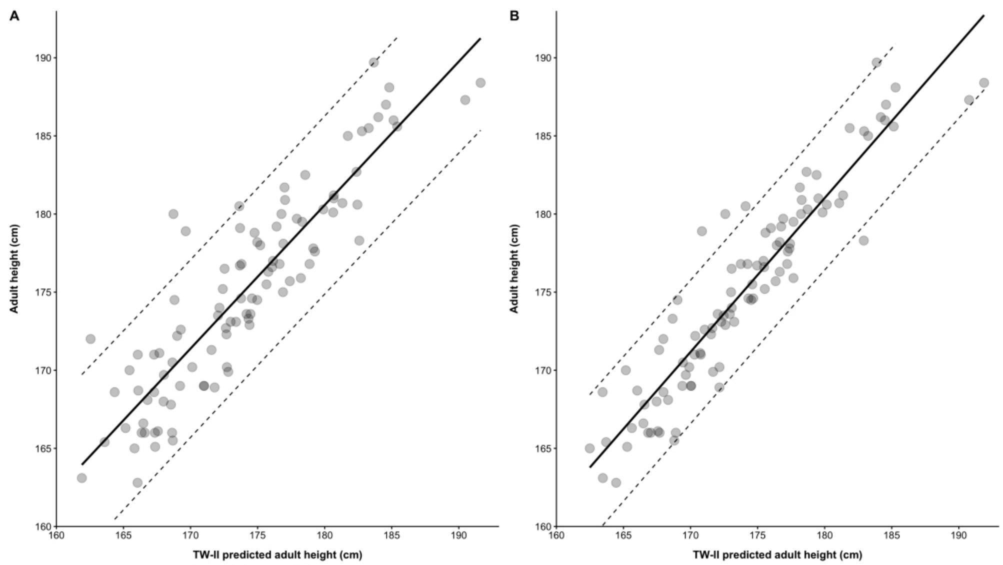

Figure 2. Scatterplots showing the linear bivariate relationship between adult height and TW-II predicted adult height by manual (A) and automated (B) assessment methods, with 95% prediction limits.

10668x6096mm (10 x 10 DPI)

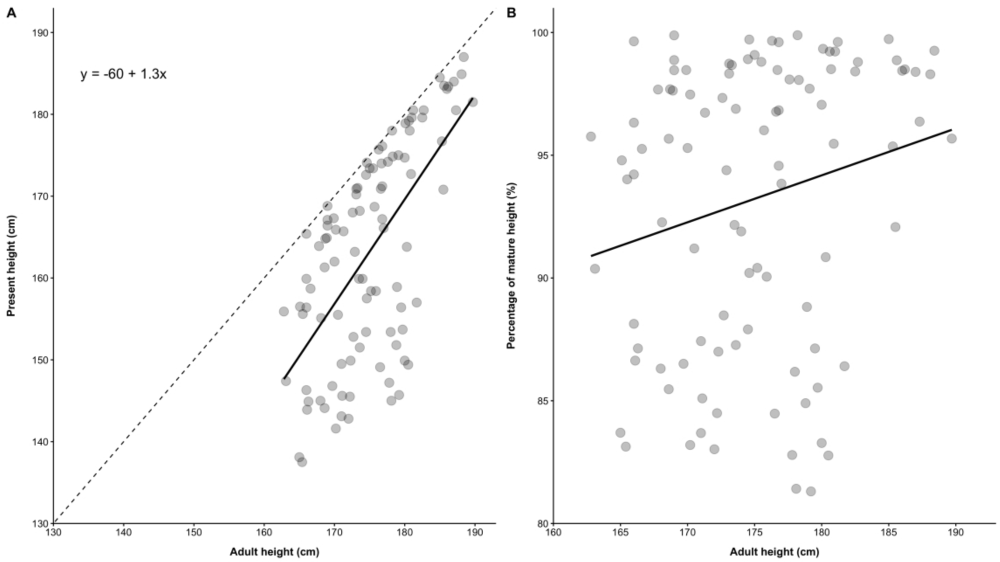

Figure 3. Scatterplots showing the linear bivariate relationship between present height at the screening and adult height (A), and the linear relationship between the percentage of mature height and adult height (B) at the follow-up visits.

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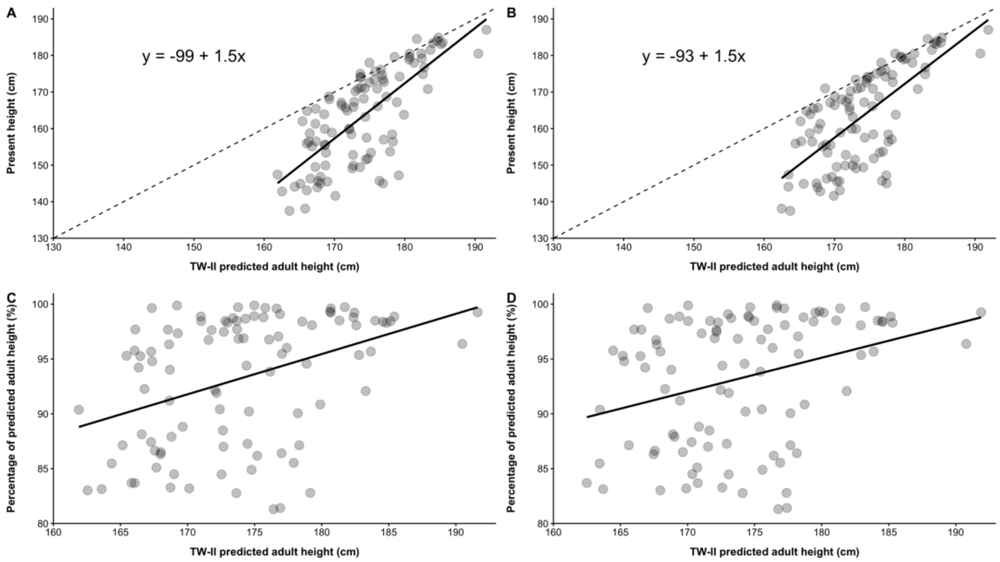

Figure 4. Scatterplots showing the linear bivariate relationship between present height at the screening visit and TW-II predicted adult height (A,B), and the linear relationship between the percentage of predicted adult height and TW-II predicted adult height (C,D) by manual and automated assessment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

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