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Prediction of adult height in girls: The Beunen-Malina-Freitas method

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Abstract

The purpose of this study was to validate and cross-validate the Beunen-Malina-Freitas method for non-invasive prediction of adult height in girls. A sample of 420 girls aged 10–15 years from the Madeira Growth Study were measured at yearly intervals and then 8 years later. Anthropometric dimensions (lengths, breadths, circumferences, and skinfolds) were measured; skeletal age was assessed using the Tanner-Whitehouse 3 method and menarcheal status (present or absent) was recorded. Adult height was measured and predicted using stepwise, forward, and maximum R^2 regression techniques. Multiple correlations, mean differences, standard errors of prediction, and error boundaries were calculated. A sample of the Leuven Longitudinal Twin Study was used to cross-validate the regressions. Age-specific coefficients of determination (R^2) between predicted and measured adult height varied between 0.57 and 0.96, while standard errors of prediction varied between 1.1 and 3.9 cm. The cross-validation confirmed the validity of the Beunen-Malina-Freitas method in girls aged 12–15 years, but at lower ages the cross-validation was less consistent. We conclude that the Beunen-Malina-Freitas method is valid for the prediction of adult height in girls aged 12–15 years. It is applicable to European populations or populations of European ancestry.

Keywords: *Biological maturation, non-invasive method, adolescence*

Introduction

An accurate estimation of biological maturity status is often central to studies of children and adolescents. It is not only of interest to paediatricians and paediatric endocrinologists but also to exercise and sports scientists who are concerned about adequate guidance for young athletes and other sports practitioners (Beunen, Rogol, & Malina, 2006; Malina, Bouchard, & Bar-Or, 2004; Roche, Wainer, & Thissen, 1975; Tanner et al., 1975, 1983b; Tanner, Healy, Goldstein, & Cameron, 2001; Tanner, Landt, Cameron, Carter, & Patel, 1983). Skeletal maturation is considered by most researchers to be the best single maturity indicator, since it spans childhood through adolescence; unfortunately, it is an invasive method that involves exposure to a limited dose of radiation. The method also requires expertise and adequate training in the assessment technique. In addition, a visit to a radiologist or hospital is usually required and extra costs are involved, including X-ray film and technicians to take the radiographs and assess skeletal maturity or skeletal age for each child. Although the radiation exposure is minimal with present apparatus, total radiation exposure in the child and in the environment has increased. These reasons, among others, underlie interest in the development of non-invasive techniques for estimating biological maturity status of children and adolescents.

Other methods for estimating biological maturation include sexual, morphological, and dental protocols (Beunen et al., 2006; Malina et al., 2004). Although widely used, clinical and self-assessment of sexual maturity provides only a crude ordinal scale. Dental maturity also requires radiation

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exposure, expertise in the assessment and adequate training, and is not highly correlated with other indicators of biological maturity (Beunen et al., 2006; Malina et al., 2004). The percentage of adult (mature) stature attained at a given age has been proposed as a valid indicator of morphological or somatic maturity because it reaches the same end-point in all individuals (100%) and increases monotonically with age (Roche, Tyleshevski, & Rogers, 1983; Wainer, Roche, & Bell, 1978). Several techniques that provide accurate prediction of adult stature are available, but the most accurate protocols require skeletal age in the regression equations (Bayley, 1962; Roche et al., 1975; Tanner et al., 1975, 1983a, 1983b, 2001). Non-invasive techniques have been developed that do not include skeletal age to predict adult stature (Beunen et al., 1997; Khamis & Roche, 1994; Roche et al., 1983; Sherar, Mirwald, Baxter-Jones, & Thomis, 2005; Wainer et al., 1978). Another technique, the maturity offset protocol, predicts time before or after peak height velocity from age, height, weight, sitting height, and estimated leg length (Mirwald, Baxter-Jones, Bailey, & Beunen, 2002). Age at peak height velocity can be estimated from the maturity offset. Among boys aged 13–16 years, accurate predictions of adult stature can be obtained with chronological age, current stature, sitting height, subscapular skinfold, and triceps skinfold as predictors (Beunen et al., 1997). This method, called the Beunen-Malina method, was cross-validated in an independent sample (Beunen et al., 2010) and shown to have adequate validity for use in European populations. Non-invasive methods to predict adult height in girls validated for European populations and using the Tanner-Whitehouse predictions (Tanner et al., 2001) as a reference have not been published.

The purpose of the present study was to validate and cross-validate a non-invasive method (Beunen-Malina-Freitas method) for prediction of adult height in girls of European origin.

Methods

Sample

The sample was made up of girls from the Madeira Growth Study (Freitas et al., 2004), a mixed-longitudinal study with five birth cohorts (8, 10, 12, 14, and 16 years) observed at yearly intervals (1996, 1997, and 1998) and four overlapping ages (10, 12, 14, and 16). The girls were re-measured after an interval of 8 years. Data from cohorts at 10, 12, 14, and 16 years were used for the present analysis. Initial and final observations in the youngest cohort were made, on average, at, 10.0 and at 17.1 years. More than 90% of girls in the Madeira Growth Study reached skeletal maturity by the Tanner-Whitehouse 2 (TW2) method (Freitas et al., 2004). With the Tanner-Whitehouse 3 (TW3) revision, girls aged 15 years with a TW3 score of 1000 (mature skeletal maturity) grew on average 1.0 cm, and in girls from 9 years and older, the difference between TW2 (RUS-age, radius, ulna, and short bones) and TW3 (RUS-age) is approximately 1 year (Tanner et al., 2001). It is thus very unlikely that the girls in the youngest cohort did not yet reach adult or mature stature. This was confirmed by the mean and standard deviation of the measured adult height of this cohort (160.7 cm and $s = 5.8$ cm) being well within the means (159.7–161.3 cm) and standard deviations (5.3–5.8 cm) for measured heights of the other cohorts. The total sample consisted of 420 girls: 50 at 10 years, 78 at 11 years, 60 at 12 years, 84 at 13 years, 62 at 14 years, and 86 at 15 years. The population-based sample was stratified according to the number of districts in Madeira, educational level of the parents, and school facilities. The study received approval from the Medical Ethics Committee of the University of Madeira.

For cross-validation, we used a sample from the Leuven Longitudinal Twin Study (Beunen et al., 2000; Maes et al., 1996). The Leuven Longitudinal Twin Study is a pure longitudinal study of 110 twin pairs (both mono- and dizygotic of both sexes). Measurements included skeletal and sexual maturity, anthropometric dimensions, physical fitness test battery, physical activity, and health history and health behaviour. Furthermore, parents and siblings, if available, were studied on one occasion. The twins were initially observed at 10 years of age and were seen at half-yearly intervals through 16 years and again at 18 years. In total, 110 twin pairs were followed. One girl from each twin pair was used in the cross-validation analysis (n varies between 43 and 59). The project received approval from the Medical Ethics Committee of the Faculty of Physical Education and Physiotherapy of KU Leuven.

Measurements

Chronological age groups were defined as whole years, i.e. 10+ years varied between 10.00 and 10.99 years.

Anthropometric dimensions were made using the procedures described by Claessens and colleagues (Claessens, Vanden Eynde, Renson, & Van Gerven, 1990). The Appendix provides a description of measurement protocols for dimensions that were finally included in the regression equation to predict adult height. This is relevant since the error of prediction will most likely increase if measurement protocols deviate from those used to derive the equations. The following measurements were eventually selected: height, sitting height, forearm circumference, body mass, biacromial diameter, and bicristal diameter.

Subischial leg length (hereafter leg length) was derived from height minus sitting height. Stature was measured with a Harpenden stadiometer, and sitting height with a Harpenden stadiometer mounted on a standardized table. Biacromial and bicristal diameters were measured with a spreading calliper and forearm circumference was measured with a steel tape. All measurements were taken to the nearest millimetre. Before the respective studies began, anthropometrists were trained and both intra- and inter-observer reliability were verified. In-field reliability was also verified during the course of the respective studies. All reliabilities were well within the ranges of previously reported reliability coefficients and measurement errors (Beunen et al., 2000; Claessens et al., 1990, Freitas et al., 2004).

Leg length was calculated as the difference between height and sitting height. The ratio of sitting height divided by height (sitting height ratio) and body mass index (BMI, $kg \cdot m^{-2}$) were also used as potential predictors. Menarcheal status (1 = present, 0 = absent) was also included among potential predictors. The TW3 prediction of adult height requires skeletal age to be known (Tanner et al., 2001). The same trained observers assessed the skeletal age of all participants in the Madeira Growth Study using the radius-ulna and short bones protocol (RUS-score) (Freitas et al., 2004).

Statistical analyses

Six whole-year chronological age groups (10, 11, 12, 13, 14, and 15 years) were considered. Age-specific regression equations were calculated using several multiple regression techniques: stepwise, forward, and maximal R^2 methods (i.e. regressions with combinations of 2, 3 or more predictors) for 2 to 9 predictors with up to the 10 best (R^2) regressions for each of the number of predictors. Somatic dimensions were introduced as continuous variables and menarche as a dummy variable. Selection of the predictors in the stepwise and forward procedures was made by using an alpha of 0.15 for inclusion and exclusion and by selecting, as much as possible, the same somatic dimensions at each age level. An alpha of 0.15 was chosen to ensure the inclusion of all dimensions associated with adult height.

Unfortunately, it was not possible to use the same somatic dimensions as predictors at each age level even though we attempted regression models with similar explained variances using the maximal R^2 method with up to 10 regression models for each age level and the different numbers of predictors (2 to 9). For girls aged 10–12 years, two regression equations resulted, for convenience identified as the Beunen-Malina-Freitas 1 method (with 3 or 4 predictors at 10–12 years) and the Beunen-Malina-Freitas 2 method (with 4 or 5 predictors at 10–12 years). For all regressions, R^2, average standard error of prediction, median standard error of prediction, and their boundaries (percentiles 25 and 75%, 5 and 95%; or P25–75, P5–95 error bounds) were calculated. Collinearity was verified with tolerance and variance inflation.

Age-specific mean differences between predicted adult heights using different methods (Beunen-Malina-Freitas, Tanner) were tested with a repeated-measures analysis of variance (ANOVA) and paired *t*-test.

For cross-validation, the selected age-specific regression equations were used to predict adult height of girls aged 10–15 years of the Leuven Longitudinal Twin Study. Following Tanner et al. (1975), height measured at 18 years was considered to be adult or mature height. All calculations were done in SAS using the procedures: MEANS, FREQ, UNIVARIATE, REG and CORR (SAS Institute Inc., 2004).

Results

The age-specific regression equations, intercept, regression coefficients for the selected measurements, R^2, and standard error of prediction are given in Table I. No evidence for collinearity was detected in the Beunen-Malina-Freitas 1 regression equations presented in Table I. R^2 increases from 0.55 at 11 years to 0.96 at 15 years. Standard errors of prediction decrease from 3.8–3.9 cm at the youngest ages to 1.1 cm at 15 years. Lengths (height, leg length, sitting height/height ratio), forearm circumference, and menarcheal status are the significant predictors. At 10 and 11 years, height is not a significant predictor of adult height when leg length and the sitting height ratio are entered in the regressions. Forearm circumference, a good indicator of limb muscle development, is a significant predictor in girls aged 10–13 years. Menarcheal status is a significant predictor from 12 years onwards when a significant percentage (27.4%) of the girls had attained menarche.

Somewhat better predictions are obtained in girls aged 10–12 years when additional somatic dimensions are included in the regressions (Beunen-Malina-Freitas 2 method, Table I). Biacromial and bicristal diameters enter the regressions as significant predictors. The R^2-values increase from 0.55–0.60 to 0.60–0.68, and standard errors of prediction decrease slightly from 3.5–3.9 to 3.1–3.7 cm. Unfortunately, when both height and leg length are used as predictors at 10 years, there is a problem with collinearity and the Beunen-Malina-Freitas 1 equation with 3 predictors is to be preferred. No collinearity was detected in the regressions for girls at ages 11 and 12 years.

Means and standard deviations for predicted adult height using the regression equations given in Table I were compared with the measured adult height and predicted adult height using the TW3 prediction equations (Tanner et al., 2001). As expected, mean Beunen-Malina-Freitas-predicted heights are identical with measured adult height and the TW3 predictions deviate slightly from measured adult height. Mean differences were non-significant in girls aged 10–12 years, but became significant thereafter. However, mean differences at 13 and 14 years were small (0.4 and 0.7 cm respectively). The TW3 prediction of adult height provided virtually unbiased estimates of adult height. Standard deviations of the Beunen-Malina-Freitas predictions are systematically lower than the standard deviations of measured adult height and TW3-predicted height (Table II). When 3 or 4 predictors are used, the accuracy of the Beunen-Malina-Freitas method is somewhat lower than the TW3 predictions. For the TW3 method, R^2 varies between 0.66 at 11 years and 0.90 at 13 years. The accuracy of the Beunen-Malina-Freitas 2 method using 4 or 5 predictors is higher than that of the Beunen-Malina-Freitas 1 method using 3 or 4 predictors. Only 4–6% less variance of measured adult height is explained with the Beunen-Malina-Freitas 2 method compared with the TW3 method.

The median differences (and P25–P75 and P5–P95 error bounds) between measured adult height and Beunen-Malina-Freitas- and TW3-predicted adult heights are given in Table III. Median differences are equal or less than 0.5 cm with two exceptions, and the P25–P75 and P5–P95 error bounds are similar for the Beunen-Malina-Freitas and TW3 methods. Differences between the P5 and the P95 error bounds vary between 11.5 and 13.7 cm at 10–11 years, 9.3 and 12.6 cm at 12 years, and 5.3 and 7.8 cm at 13–15 years. At 10–12 years, the differences are always higher with the Beunen-Malina-Freitas 1 method using 3 or 4 predictors

Table I. Regression coefficients for the prediction of adult height in girls: Beunen-Malina-Freitas methods 1 and 2 (BMF1, BMF2).

Age (years)	*Interc* *a*	*HT* *b*	*LL* *c*	*SH/HT* *d*	*FARM* *e*	*MEN* *f*	*BM*	*BIAC*	*BICR*	R^2	*SEP*
BMF1											
10	−9.84	–	1.46	183.92	−1.14	–	–	–	–	0.57	3.8
11	18.88	–	1.33	132.72	−0.97	–	–	–	–	0.55	3.9
12	120.46	0.62	–	−72.18	−0.75	−3.34	–	–	–	0.60	3.5
13	72.85	0.88	–	−71.72	−0.50	−2.61	–	–	–	0.83	2.4
14	16.52	0.94	–	–	–	−5.05	–	–	–	0.83	2.1
15	8.94	0.99	–	–	–	−5.79	–	–	–	0.96	1.1
BMF2											
11	17.44	–	1.57	165.52	−1.44	–	0.19	−0.97	–	0.60	3.7
12	142.71	0.50	–	–	−2.93	− 4.73	0.67	−0.72	–	0.68	3.1

Abbreviations: HT = height, LL = leg length, SH/HT = sitting height/height ratio, BM = body mass, BIAC = biacromial diameter, BICR = bicristal diameter, FARM = forearm circumference, MEN = menarche (yes/no), SEP = standard error of prediction.
Note: All measurements are in centimetres, except body mass in kilograms, and post-menarche = 1.
– indicates that the variable is not in the regression at this age.
a, *b*, *c*, *d*, *e*, *f* used in final regressions provided in the Discussion to refer to the age-specific regression coefficients.

Table II. Means (and standard deviations) for measured adult height of girls in each age cohort and predicted adult height by different methods at the specified ages.

Age (years)	Measured adult height (cm)	TW3 (cm)	Predicted BMF1 (cm)	BMF2 (cm)
10 ($n = 50$)	160.7 (5.8)	160.0 (6.1)	160.7 (4.4)	160.7 (4.7)
11 ($n = 78$)	161.3 (5.8)	160.6 (5.7)	161.3 (4.3)	161.3 (4.5)
12 ($n = 60$)	160.2 (5.5)	160.1 (5.8)	160.2 (4.2)	160.2 (4.5)
13 ($n = 84$)	160.5 (5.7)	160.1 (5.5)*	160.5 (5.2)	–
14 ($n = 62$)	159.7 (5.3)	160.3 (5.2)*	159.7 (4.9)	–
15 ($n = 86$)	160.3 (5.6)	–	160.3 (5.5)	–

Note: BMF1 = Beunen-Malina-Freitas method with 2–5 predictors. BMF2 = Beunen-Malina-Freitas 2 method with 4–5 predictors.
– indicates that a prediction is not available at these ages.
*Significantly ($P < 0.05$) different from BMF1 and measured adult height.

compared with the Beunen-Malina-Freitas 2 method using 4 to 5 predictors.

Beunen-Malina-Freitas regression equations (Table I) were cross-validated using data for Belgian girls from the Leuven Longitudinal Twin Study. From 12 years onwards, R^2 and the standard deviation of the difference scores (predicted adult height minus measured adult height) of the cross-validation sample (Table IV) correspond quite closely to the standard errors of prediction from the validation sample (Beunen-Malina-Freitas 1; Table I). However, at 12 years, there is a systematic bias (–3.7 cm for Beunen-Malina-Freitas 1) in the estimated adult height. For Beunen-Malina-Freitas 2, R^2 and the standard deviation of the difference scores of the cross-validation sample differ considerably from the R^2 and standard errors of prediction of the validation sample. Among girls aged 10–11 years, the cross-validation study yields lower R^2-values and higher standard deviation of difference scores compared with the validation statistics in addition to a systematic bias. Measured adult height and predicted adult height using the TW3 (Tanner et al., 2001), Beunen-Malina-Freitas 1, and Beunen-Malina-Freitas 2 equations are reported in Table V. Mean differences between predicted Beunen-Malina-Freitas 1 and 2 and measured adult height are apparent in girls 10–14 years, while with the TW3 prediction significant differences are apparent only at 10 years.

Table III. Median differences, and 25th (P25) and 75th (P75) percentile and 5th (P5) and 95th (P95) percentile error bounds for predicted adult stature by three different methods (Tanner, BMF1, BMF2).

Age (years)	Prediction method	Median diff. (cm)	P25, P75 (cm)	P5, P95 (cm)
10	BMF1	–0.9	–2.2, 2.0	–5.5, 8.2
	BMF2	–0.5	–2.3, 1.8	–5.1, 6.8
	Tanner	–0.2	–2.8, 2.6	–7.3, 4.2
11	BMF1	–0.4	–2.4, 2.7	–6.6, 6.2
	BMF2	–0.5	–2.7, 2.5	–5.4, 6.8
	Tanner	–0.9	–2.8, 1.6	–7.1, 5.4
12	BMF1	0.2	–2.6, 1.9	–5.4, 7.2
	BMF2	–0.5	–2.3, 2.4	–4.7, 4.9
	Tanner	–0.1	–1.7, 2.1	–5.3, 4.0
13	BMF1	–0.3	–1.5, 1.1	–3.4, 5.8
	Tanner	–0.3	–1.5, 0.7	–3.7, 2.4
14	BMF1	0.2	–1.0, 1.4	–2.6, 2.7
	Tanner	0.3	–0.2, 1.3	–2.1, 3.4
15	BMF1	–0.2	–0.6, 0.5	–1.7, 2.5

Note: BMF1 = Beunen-Malina-Freitas method with 2–5 predictors. BMF2 = Beunen-Malina-Freitas 2 method with 4–5 predictors.

Following Nevill and Atkinson (1997), mean differences and standard deviation of these difference scores or ratios and limits of agreement are reported. At 10 years, the limits of agreement for the Beunen-Malina-Freitas 1 method indicate that for a predicted adult height of 160.0 cm, the 95% limits of agreement are $160 \times 1.05 = 168$ cm and $160/1.05 = 152.38$ cm. At 14 years, these limits are $160.0 \times 1.02 = 163.2$ cm and $160.0/1.02 = 156.86$ cm respectively.

Discussion

The Beunen-Malina-Freitas equations provide an accurate estimation of adult or mature height without the use of skeletal maturity. The accuracy of prediction and error bounds compare favourably with the accuracy and error bounds of Tanner-Whitehouse 3 predictions using skeletal maturity (RUS-scores) as one of the predictors. For girls aged 10–12 years, two Beunen-Malina-Freitas regression equations are proposed: Beunen-Malina-Freitas 1 with 3 or 4 predictors and Beunen-Malina-Freitas 2 with 4 or 5 predictors. The equations with fewer predictors are less accurate and show slightly larger errors and error bounds. When 3 or 4 predictors are used, height, leg length, sitting height/height ratio, forearm circumference, and menarcheal status are the predictors. With the Beunen-Malina-Freitas 1 equations, 3 predictors are used at 10 and 11 years, 4 are used at 12 and 13 years, and 2 are used at 14 and 15 years. However, for all age groups, only three anthropometric dimensions (height, sitting height, and forearm circumference) and menarcheal status are needed. Leg length and the ratio sitting height/height are derived variables.

Table IV. Cross-validation of the Beunen-Malina-Freitas (BMF1 and BMF2) method, coefficients of determination (R^2), and mean differences (*s*) between predicted and measured adult height.

	10 years	11 years	12 years	13 years	14 years	15 years
BMF1						
R^2	0.47	0.44	0.71	0.82	0.88	0.95
Mean diff.	–3.0 (4.3)	–2.9 (4.6)	–3.7 (3.7)	–1.4 (2.4)	–0.6 (1.7)	0.3 (0.9)
BMF2						
R^2	0.37	0.41	0.49			
Mean diff.	–6.1 (4.7)	–3.2 (4.8)	–3.9 (4.7)			

Note: BMF1 = Beunen-Malina-Freitas method with 2–5 predictors. BMF2 = Beunen-Malina-Freitas 2 method with 4–5 predictors.

Table V. Means (and standard deviations) for measured adult height of girls in each age cohort and predicted adult height and mean difference (*s*) or limits of agreement by different methods at the specified ages: cross-validation with sample of Leuven Longitudinal Twin Study.

Age (years)	Measured adult height (cm)	TW3 (cm)	Mean diff. (*s*) (cm)	Predicted BMF1 (cm)	Ratio (limit)[a]	BMF2 (cm)	Ratio (limit)[a]
10 ($n = 56$)	164.16 (5.9)	162.60 (5.4)*	–1.6 (2.8)	161.19 (3.6)*	0.98 (×/÷ 1.05)	158.07* (3.9)	0.96 (×/÷ 1.06)
11 ($n = 59$)	164.63 (6.2)	163.38 (5.6)	–1.2 (3.3)	161.75 (4.1)*	0.98 (×/÷ 1.06)	161.40* (4.5)	0.98 (×/÷ 1.06)
12 ($n = 48$)	164.64 (6.3)	163.91 (6.1)	–0.7 (3.1)	160.98 (4.5)*	0.98 (×/÷ 1.04)	160.78* (4.8)	0.98 (×/÷ 1.06)
13 ($n = 46$)	164.70 (6.4)	165.09 (6.7)	0.3 (1.9)	163.33 (5.7)*	–1.4 (2.4)[b]	–	
14 ($n = 45$)	165.21 (6.6)	165.67 (6.8)	0.4 (0.8)	164.64 (5.7)*	1.0 (×/÷ 1.02)	–	
15 ($n = 43$)	165.31 (6.8)	–		165.65 (6.6)	0.3 (0.9)[b]	–	

Note: BMF1 = Beunen-Malina-Freitas method with 2–5 predictors. BMF2 = Beunen-Malina-Freitas 2 method with 4–5 predictors.– indicates that a prediction is not available at these ages.*Significantly ($P < 0.05$) different from measured adult height. [a]Following Nevill and Atkinson (1997) ratios and limits of agreement are provided when mean difference scores are not normally distributed or correlate with mean scores. [b]Mean difference score and standard deviation.

For girls aged 10–12 years, the accuracy of the Beunen-Malina-Freitas method is somewhat better when 4 or 5 predictors are used than when 3 or 4 predictors are used; the standard errors of prediction are also somewhat lower. For the latter regression equations, six anthropometric dimensions (height, sitting height, forearm circumference, body mass, biacromial and bicristal diameters) and menarcheal status are required. Other predictors are derived from the six dimensions. At 14 and 15 years, only height and menarcheal status are needed. As noted in the Methods, measurement protocols for each dimension (Appendix) should be followed carefully to achieve similar prediction accuracy and prediction error. It should be noted that the average adult height of Madeira's women (160–161 cm) is less than the adult height of the cross-validation sample taken from the Leuven Longitudinal Twin Study. Moreover, the average adult height of the Belgian twins did not deviate significantly from Belgian reference data (Beunen et al., 2000).

The cross-validation relative to girls from the Leuven Longitudinal Twin Study indicated good agreement at ages 12 (Beunen-Malina-Freitas 1 method) through 15 years. For girls aged 10–11 years, there was a systematic bias; R^2-valuess were lower and standard deviations of the difference scores were higher indicating a lack of generalizability at these ages. This bias likely reflected sample differences related to accelerated growth in height and specifically leg length during the early phase of the adolescent growth spurt in most girls (Beunen et al., 2000). The net results were more variability in height, sitting height, leg length, and sitting height ratio due to the maturity spread, i.e. inter-individual differences in maturity timing. In addition, at these younger ages, age at menarche cannot be used as a predictor since most girls had not yet attained this maturity landmark, which occurs, on average, after peak height velocity in the majority of girls (Malina et al., 2004). Although it is possible that the validation and cross-validation samples differed in maturity status, the median difference in skeletal maturity between samples was small (Freitas et al., 2004). Given the collinearity observed in the predictors of the Beunen-Malina-Freitas 2 equation at 10 years and the cross-validation results for the Beunen-Malina-Freitas 2 equation in girls aged 10–12 years, use of the Beunen-Malina-Freitas 2 equation is not recommended until further validation. As such, the following Beunen-Malina-Freitas 1 age-specific equations are recommended:

- *10 and 11 years*: adult height = $a + c$ (leg length) + d (sitting height/height) + e (forearm circumference) (measurements in cm, a, b, c, d as in Table I).
- *12 and 13 years*: adult height = $a + b$ (height) + d (sitting height/height) + e (forearm circumference) + f (menarche) (measurements in cm, menarche 0 absent, 1 present, a, b, d, e, f as in Table I).
- *13 and 14 years*: adult height = $a + b$ (height) + f (menarche) (height in cm, menarche 0 absent, 1 present, a, b, f as in Table I).

In addition to height and menarcheal status (presence or absence), other predictors are lengths (leg length, sitting height/height ratio), diameters (biacromial and bicristal), and forearm circumference. It is surprising that height is not always selected as a predictor and is replaced by leg length and the sitting height ratio at some ages. This most likely reflects the timing of the adolescent growth spurt in lower (leg length) and upper (sitting height or trunk length) segments of stature. The other predictors are indicators of skeletal breadths (biacromial and bicristal diameter) and limb muscle (forearm circumference), which also tend to attain maximum growth after peak height velocity (Beunen & Malina, 1988; Malina et al., 2004; Tanner, Whitehouse, Marubini, & Resele, 1976). The addition of chronological age did not improve the predictions. More predictors were needed at younger ages for two reasons: menarcheal status could not be used as a predictor and, due to the time spread of the adolescent growth spurt, tracking in height and its segments is lower resulting in lower associations with adult height. An attempt was made to have the same predictors at all ages as in our previous study of boys (Beunen et al., 1997). Although up to 10 regression equations (maximum R^2 regression method) were calculated for each combination of 2–9 predictors, it was not possible to realize this objective without losing 10% or more of the explained variance with a concomitant increase in prediction error.

The Beunen-Malina-Freitas equations for girls are slightly more accurate (R varies between 0.70 and 0.87 in boys and between 0.74 and 0.98 in girls) and have lower prediction errors (standard error of prediction varies between 3.0 and 3.7 in boys and between 1.1 and 3.9 in girls) than Beunen-Malina predictions of adult height in boys. The accuracy of the Beunen-Malina-Freitas method compares favourably with the Tanner-Whitehouse 3 method (Tables II and III) using skeletal maturity scores as one of the predictors. Note that the TW3 method for prediction of adult height has fairly high accuracy and virtually no systematic bias (only 0.4–0.7 cm at 13 and 14 years). In addition, the TW3 prediction in the cross-validation sample was also largely unbiased, except at 10 years, and R^2 vary between 0.71 at 11 years and 0.94 at 14 years. Finally, the prediction error of the Beunen-Malina-Freitas 1 compared favourably with those of Sherar et al, (2005), who use predicted maturity offset and sex-specific areas under the cumulative height velocity curves for early, average, and late maturing individuals. Sherar et al. (2005) also used a sample of the Leuven Longitudinal Twin Study to cross-validate their method, the 95% confidence intervals for predicted adult height being $\pm$6.81 cm. With the Beunen-Malina-Freitas 1 method, the age-specific confidence intervals were $\pm$8.5 cm at 10 years, $\pm$9.1 cm at 11 years, $\pm$7.2 cm at 12 years, $\pm$5.4 cm at 13 years, $\pm$4.6 cm at 14 years, and $\pm$3.0 cm at 15 years.

If adult height can be predicted with a reasonable level of accuracy from anthropometric dimensions and menarcheal status at a single observation, the percentage of adult height attained at a given age can be derived and used as an estimate of biological maturity status in children and adolescents. The rational for this approach is as follows: Two girls of the same age can have the same height, but one is closer to mature height than the other. The individual who is closer to mature height is advanced in maturity status compared with the individual who is more removed from mature height (Malina et al., 2004). The percentage of mature height attained at a given age is positively related to skeletal maturity during childhood (Beunen et al., 2006; Malina et al., 2004; Tanner et al., 1983a) and to sexual, skeletal, and somatic maturity during adolescence (Bayer & Bayley, 1959; Bayley & Pinneau, 1952; Beunen & Malina, 2008; Bielicki, Konariek, & Malina, 1984; Nicolson & Hanley, 1953; Wainer et al., 1978).

The use of percentage of predicted adult (mature) height has been applied in a variety of settings. It was used as a maturity indicator in studies of the contribution of maturity status to activity levels in children aged 5–9 years (Eaton & Yu, 1989) and adolescent boys and girls (Cumming, Standage, Gillison, & Malina, 2008). The protocol has also been used in studies of growth status of youth American football players (Malina, Cumming, Morano, Barron, & Miller, 2005) and of perceptions of physical and social competence in male and female youth soccer players (Cumming, Standage, & Malina, 2004). Percentage of predicted adult height has also been validated against skeletal age (Fels Method) in youth American football players (Malina, Dompier, Powell, Barron, & Moore, 2007). Together, these observations provide evidence that percentage of predicted adult height attained at a given age provides a valid indicator of biological maturity status.

In summary, the protocol used in the present study is non-invasive and does not require radiation as in skeletal and dental maturity or invasion of privacy as in assessments of secondary sex characteristics. Adult (mature) height was predicted from height, leg length, sitting height ratio, forearm circumference, and menarcheal status. Only three measurements are needed: height, sitting height, and forearm circumference, in addition to menarcheal status. These dimensions can be measured accurately with experience. The Beunen-Malina-Freitas method is thus a non-invasive and valid addition to techniques for the estimation of biological maturity status in girls aged 12–15 years, but the method lacks generalizability in girls of 10–11 years. Given the cross-validation results, we advise using the Beunen-Malina-Freitas 1 equations presented in Table I with younger girls. The method also has the advantage of being expressed on a continuous scale in contrast to ordinal scales for secondary sex characteristics. However, we propose using this method when, for some reason, it is not possible to predict adult height using skeletal maturity as one of the predictors, since these methods are more accurate and have lower prediction error. Further validation of the Beunen-Malina-Freitas 1 and 2 methods is needed, especially in samples of elite athletes and in small children at the extremes of normal variation in body dimensions.

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Appendix: Description of measurements (after Claessens et al., 1990)

The girls are preferably measured wearing bathing suits. All one-sided measurements are taken on the left side of the body.

Height. Height is measured with the Harpenden portable stadiometer (Holtain Ltd., Crosswell, Crymych, Dyfed, UK). The participant is instructed to stand upright against the stadiometer so that the heels, buttocks, and scapulae are in contact with the backboard and the feet are together. The head should be positioned in the Frankfurt plane, and the headboard of the instrument should be moved down to make contact, with a small pressure, to compress the hair onto the vertex of the skull. With the participant in the correct position, she is instructed to stand as erect as possible. The measurement is made to the last complete unit (1 mm). Height is expressed in centimetres.

Sitting height. Sitting height is measured with the Harpenden sitting height table (manufactured by Holtain Ltd., Crosswell, Crymych, Dyfed, UK). The participant is positioned so that the head is in the Frankfurt plane, the shoulders relaxed, the back straight, the upper surface of the thighs horizontal, and the feet supported so that the knees form a right angle. The distance from the seat to the head's highest point (vertex) is measured and after the headboard is lowered, again with a small pressure to compress the hair, the participant is instructed to sit as straight as possible. The measurement is made to the last complete unit (1 mm). Sitting height is expressed in centimetres.

Subischial leg length. Subischial leg length is the difference between height and sitting height. Leg length is expressed in centimetres.

Sitting height/height ratio. The sitting height/height ratio is the sitting height divided by height, with both measurements expressed in centimetres.

Body mass. Body mass is measured with a beam balance accurate to 0.1 kg. The participant stands straight and is instructed to stand still. Body mass is expressed in kilograms.

Biacromial diameter. Biacromial diameter is the distance between the tips of the acromial processes. It is measured from the rear of the participant with the Harpenden anthropometer (curved branches). The position of the lateral tips of the acromial processes is slightly different in each girl; it is therefore necessary for the observer to carefully mark the exact position before applying the instrument. When the participant stands with relaxed shoulders, the observer places the anthropometer blades to the lateral tips of the acromial processes. The blades must be pressed firmly against these protuberances so that the layer of soft tissues that cover them is minimized. The measurement is made to the last complete unit (1 mm). Biacromial diameter is expressed in centimetres.

Bicristal diameter. Bicristal diameter is the distance between the most lateral points of the iliac crest, and is measured with the Harpenden anthropometer (straight blades). The participant stands with her front to the observer, in a relaxed position, with the hands away from her sides to ensure a clear view of the iliac crests. The antrhopometer is held horizontally and the blades are applied to the most lateral points of the iliac crests. To obtain the "bony" measurement, the blades must be pressed firmly against the crests so that the layer of tissues that covers them is minimized. The measurement is made to the last complete unit (1 mm). Bicristal diameter is expressed in centimetres.

Forearm circumference. Maximum forearm circumference is measured at a point immediately distal to the elbow joint. The participant stands relaxed, facing the observer, with her left arm slightly upward and her hand in a supination position. The steel tape (Regulator tape manufactured by Stanley) is passed around the arm at the maximum horizontal or at the greatest bulge of the muscles. The tape is tightened so that it touches the skin all around the circumference. The measurement is made to the last complete unit (1 mm). Forearm circumference is expressed in centimetres.

Menarcheal status. Menarche is by definition the first menstruation (not necessarily regular menstruations). A female test instructor inquires, in private, about the menarche status using wording that is familiar and appropriate for the age of the girl. The observer first inquires about the familiarity of the girl with the event and subsequently she asks whether or not the girl has already her first menstruation. Premenarche is scored as 0 and post-menarche as 1.