Assessment of height growth in Indian children using growth centiles and growth curves

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ABSTRACT

Background: Growth centiles and growth curves are two ways to present child anthropometry; however, they differ in the type of data used, the method of analysis, the biological parameters fitted and the form of interpretation.
Objectives: To fit and compare height growth centiles and curves in Indian children.
Methods and Subjects: 1468 children (796 boys) from Pune India aged 6-18 years with longitudinal data on age and height (n=7781) were analysed using GAMLSS (Generalized Additive Models for Location Scale and Shape) for growth centiles, and SITAR (SuperImposition by Rotation and Translation) for growth curves.
Results: SITAR explained 98.7% and 98.8% of the height variance in boys and girls, with mean age at peak height velocity 13.1 and 11.0 years, and mean peak velocity 9.0 and 8.0 cm/year, respectively. GAMLSS (Box-Cox Cole Green model) also captured the pubertal growth spurt but the centiles were shallower than the SITAR mean curve. Boys showed a mid-growth spurt at age 8 years.

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Conclusion: GAMLSS displays the distribution of height in the population by age and sex, while SITAR effectively and parsimoniously summarises the pattern of height growth in individual children. The two approaches provide distinct, useful information about child growth.

KEYWORDS

Height, growth curves, centiles, GAMLSS, SITAR, India.

1. Introduction

Growth centiles and growth curves represent two distinct ways to assess child growth. Height *centiles* (or per-centiles (Galton 1885)) describe the distribution of height in a population with respect to age; they are typically described through evenly spaced centiles on a *growth chart*, where each centile is labelled according to the percentage of the population below it (Bowditch 1891; World Health Organization 2006). In contrast height growth *curves* show serial changes in height with age in individuals, providing information on their height velocity as well as their height attained (Tanner 1962; Komlos et al. 1992).

The two methods have evolved separately and they have different aims. Primarily they differ in the type of data used for their construction. Growth centiles are based on cross-sectional data, where the measurements—usually one per subject—are treated as independent, covering the age range under study (Cole 2012). Growth curves, on the other hand, are developed from longitudinal data, utilising repeated measurements for each child (Johnson 2015; Crozier et al. 2019).

The construction of growth centiles requires modelling the frequency distribution of the measurement at each age and smoothing the centiles across age. The World Health Organization (Borghi et al. 2006) recommends using Generalized Additive Models for Location Scale and Shape (GAMLSS) (Rigby and Stasinopoulos 2005a) to construct the centiles, which models moments of the distribution as smooth curves in age.

Growth curve modelling involves summarising the shape of individual curves as a mean curve. Early methods—known as *parametric* or structural models—used parametric functions applied to data for individuals to describe the curve shape (Jenss and Bayley 1937; Preece and Baines 1978; Karlberg 1989). Later, *semi-parametric* or non-structural models were developed using fractional polynomials or cubic splines to estimate the curve shape, optimising the number of parameters based on the data—this provides extra flexibility but can lack biological interpretability (Hauspie et al. 2004; Chirwa et al. 2014).

In the 1980s hierarchical mixed-effects models including fixed effects and random effects became available, capturing both individual variation and the population trend in a unified framework (Goldstein 1986). The growth curve model SuperImposition by Translation And Rotation (SITAR) (Cole et al. 2010) is a semi-parametric hierarchical model with three subject-specific random effects that together explain up to 99% of the variance in longitudinal height growth.

Even though growth centiles and growth curves are different, the GAMLSS and SITAR models to fit them have some similarities; both are semi-parametric, using cubic splines to estimate curve shape, and both—in their most common form—involve three underlying summary statistics (three moments for GAMLSS and three random effects for SITAR). It is useful to fit the two models to the same data, both to compare the shapes of the resulting centiles and curves, and to emphasise their different purpose. A few previous studies have applied the two methods to the same data (Blackwell et al. 2017; Spencer et al. 2018), but none have directly compared them.

Height centiles for Indian children have been available and regularly updated since 1992 (Agarwal et al. 1992; Khadilkar et al. 2007; Indian Academy Of Pediatrics Growth Charts Committee et al. 2015; Khadikar et al. 2020). However there have been only small studies of Indian height growth curves (Hauspie et al. 1980; Satyanarayana et al. 1989; de Onis et al. 2001; Mirzaei and Sengupta 2012).

The motivation behind this study is threefold: i) to construct growth centiles and growth curves using the GAMLSS and SITAR models, respectively, using a large, recent longitudinal height dataset of Indian children aged between 6 and 18 years; ii) to compare the shapes of the resulting curves, highlighting particularly the pubertal growth spurt, summarised as the mean peak height velocity (PV) and the mean age at peak height velocity (APV), and iii) to compare the centiles with others published for Indian children.

2. Methods

2.1. Data sets

The data came from the Pune School Children Growth study (PSCG), consisting of age and height measurements of 1472 affluent urban children (798 boys and 674 girls) aged 3 to 18 years living in Pune, Western India (Khadilkar et al. 2019). The data were collected annually between 2007 and 2013, with a median of 6 (range 1 to 6) measurements per subject. Height was measured using a portable stadiometer (Leicester Height Meter; Child Growth Foundation, London, UK) calibrated with a standard height rod. Further details of the PSCG data collection can be found in Khadilkar et al. (2019). Written informed consent was obtained from the parents of the subjects, and verbal assent was obtained from subjects aged over 7 years. The data collection was approved by the Ethics Committee of the Jehangir Clinical Development Centre Pune (dated 26th June 2007). Permission for secondary data analysis was obtained from the Ethics Committee of the Indian Institute of Science Education and Research Pune (IECHR/Admin/2021/001).

2.2. Models

2.2.1. Cross-sectional GAMLSS model for growth centiles

Growth centiles are traditionally created using cross-sectional data, independent observations, y_i, for $i \in \{ 1, 2, \ldots, N\}$. The state of the art method to construct growth centiles is Generalized Additive Models for Location, Scale and Shape (GAMLSS) (Rigby and Stasinopoulos 2005a). The data are assumed to come from a distribution $f_Y(y)$ whose first four moments are the mean (μ), standard deviation or coefficient of variation (σ), skewness (ν) and kurtosis (τ). Classical linear regression assumes a normal distribution for $f_Y(y)$, with μ linearly related to the explanatory variable (here age), constant σ, zero ν and τ fixed at 3. GAMLSS by contrast allows $f_Y(y)$ to be selected from a wide range of available distributions, and the moments can be specified as functions of age or more generally.

The normal distribution (called NO in GAMLSS) estimates μ and σ as curves in age, and ignores skewness and kurtosis. But for other distributions ν and/or τ can be explicitly estimated from the data. For centile estimation GAMLSS has three distributions, which all raise y to Box-Cox power ν. To model skewness, there is the Box-Cox Cole and Green distribution (BCCG), while if both skewness and kurtosis are present, it has the Box-Cox power exponential (BCPE) and Box-Cox t (BCT) distributions (Cole and Green 1992; Rigby and Stasinopoulos 2004, 2006). Note that the BCCG distribution is equivalent to the LMS method (Cole and Green 1992), where ν is called λ and transformed y is standard normally distributed. With BCPE, transformed y assumes a standard power exponential distribution, and with BCT it follows a Student's t distribution. GAMLSS fits the three distributions with identity links for μ and ν, and a log link for σ. The distributions can also be fitted with a log link for μ, denoted by GAMLSS as BCCGo, BCPEo, and BCTo, respectively. The spline curves in age for each moment were fitted using penalised B-splines or P-splines (Eilers and Marx 1996), with the default degrees of freedom (*df*) estimated by cross-validation.

Pseudo-velocity curves were constructed for the GAMLSS models by differentiating the median (μ) curves, and APV and PV were identified as the age and value of peak "velocity"; note that this does not represent true velocity as the data are cross-sectional, but for simplicity it is referred to here as velocity.

Despite being longitudinal, the PSCG data were treated as cross-sectional for the GAMLSS analysis. With balanced data such as the PSCG this works fine, as the centiles are unbiased. However they are less precise than for cross-sectional data, being based on fewer subjects.

2.2.2. Longitudinal SITAR model for growth curves

The SuperImposition by Translation And Rotation (SITAR) model (Cole et al. 2010) describes the height $y_{i,j}$ of individual i (where $i \in \{ 1, 2, \ldots, n\}$) at time t_j as,

$$y_{i,j} = a_0 + \alpha_i + H\big(\frac{g(t_j) - b_0 - \beta_i}{\exp(-c_0 - \gamma_i)}\big) + \epsilon_i, \qquad (1)$$

where a_0, b_0, and c_0 are fixed effects, α_i, β_i and γ_i are subject-specific random effects named size, timing and intensity, respectively, $g(t)$ denotes a link function for age such as the log or power transformation, $H(t)$ is the population average height curve fitted using a natural cubic B-spline and ϵ is the independent and identically distributed (i.i.d.) random error term. The random effects are assumed to be normally distributed with SD estimated from the sample. The B-spline curve $H(t)$ has a number of knots which can be tuned by optimising their number and position on the age scale—this defines the degrees of freedom (*df*) of the curve.

The three subject-specific random effects can be interpreted biologically as follows: size α_i represents the subject's offset compared to mean height, that is, by how much they are taller or shorter than average, adjusted for age. Timing of the pubertal growth spurt β_i measures by how much the subject's age at peak height velocity (APV) occurs earlier or later than the population–average APV (the velocity curve is estimated as the first derivative of $H(t)$). Intensity of the growth spurt γ_i indicates by how much the subject's peak height velocity (PV) is higher or lower than the average PV, measured as a proportion.

2.3. Data analysis

Boys and girls were analysed separately using the packages *gamlss* (version 5.3.4) (Rigby and Stasinopoulos 2005b) and *sitar* (version 1.2.0) (Cole 2021) available in the statistical language R (version 4.0.5) (R Core Team 2021). Growth velocity in early life is much higher and more variable than later in childhood, and to avoid this dominating the analysis the data were restricted to the age range 6 to 18 years.

The data were initially cleaned by removing obvious errors using conditional plots of height on age (3 points in boys and 3 in girls). All subjects with at least one measurement were included in the analysis. A preliminary SITAR model was fitted, and points with standardised residuals beyond ±4 SD were considered as outliers and excluded from the analysis (10 in boys and 4 in girls). The final analysis included 796 boys with 4242 measurements and 672 girls with 3539 measurements (0.3% and 0.2% excluded respectively).

Multiple plausible GAMLSS models of height on age were fitted: comparing the

NO, BCCGo, BCPEo and BCTo distributions; and trying square root and log transformations for height and age. Similarly, different SITAR models were fitted varying the *df* of the spline curve from 4 to 9; omitting the fixed effects b_0 and/or c_0, and with log transformations for height and age. The optimal model was selected by minimising the Bayesian Information Criterion (BIC) (Schwarz 1978).

Standard errors (SE) for mean APV and mean PV based on GAMLSS and SITAR were obtained with the bootstrap (500 samples). Diagnostic plots for the optimal models are given in supplementary figures S1 and S2.

3. Results

3.1. Height centiles in Indian children using GAMLSS

Height centiles for the PSCG data set are constructed using GAMLSS with the BCCGo distribution. However the distribution for girls is not skew at any age, so the Box-Cox power ν is constrained to 1, equivalent to a normal distribution. The fitted centiles are shown by sex in Figure 1: the nine curves are spaced two-thirds of a z-score apart, extending from the 0.4^{th} to the 99.6^{th} centile (Cole 1994). The individual heights are

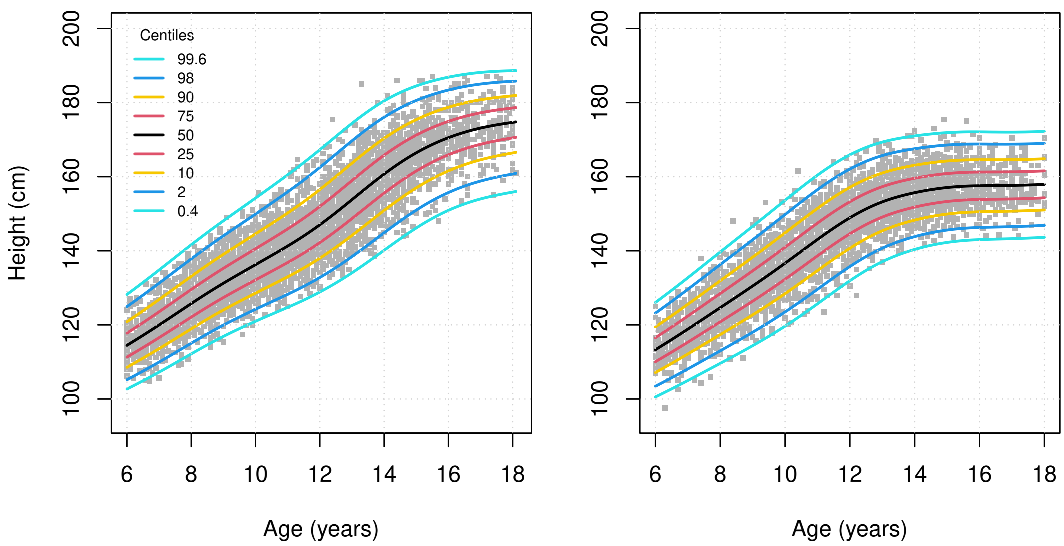

Figure 1. GAMLSS-fitted height centile curves based on the BCCGo distribution in boys (left) and the normal distribution in girls (right). The nine centiles are equally spaced on the z-score scale. Individual heights are shown in grey ($n = 4242$ for boys and $n = 3539$ for girls).

also shown as grey points. Each median curve corresponds to the age trend for μ, while

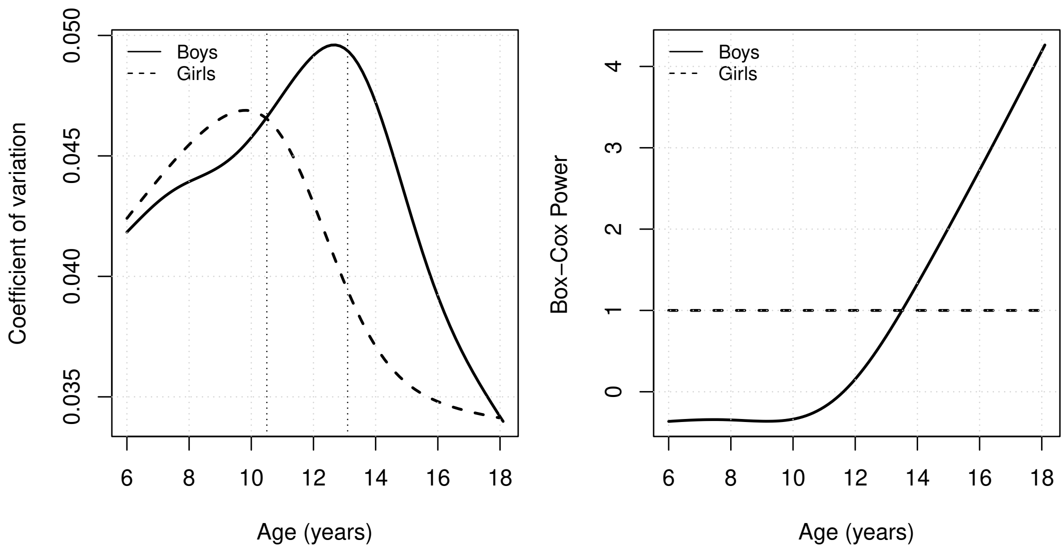

Figure 2. Fitted age trends for the BCCGo coefficient of variation (σ) and skewness (ν) for boys (solid lines) and girls (dashed lines). The vertical dotted lines indicate APV by sex based on the median (μ) curve.

the age trends for σ and ν are shown in Figure 2.

The σ curves peak at around 13 years in boys and 10 years in girls, similar to APV as based on the μ curve. In boys the ν curve rises steeply through puberty, indicating increasing left skewness.

3.2. Height growth curves in Indian children using SITAR

Individual height growth curves in the PSCG data set are best described by SITAR models of height on log age, with 6 *df* in boys and fixed effects for size, timing, and intensity; and 5 *df* in girls with fixed effects for size and intensity - the models explain 98.7% of the variance in boys and 98.8% in girls. Figure 3 shows the individual height curves in grey. Each grey curve, when adjusted by the individual's fitted random effects, provides an estimate of the mean curve, and the adjusted curves appear colour-coded in Figure 3 with the mean curve in white. Four unadjusted curves are shown in colour to highlight the PSCG study design, where individuals had no more than six annual measurements, yet SITAR was able to estimate the entire mean curve from 6 to 18 years. The fitted mean curves by sex are shown in Figure 4 along with the mean height velocity curves, calculated as the first derivative of the mean curve.

In boys, mean APV (95% CI) is 13.1 (13.0, 13.3) years, and mean PV is 9.0 (8.7,

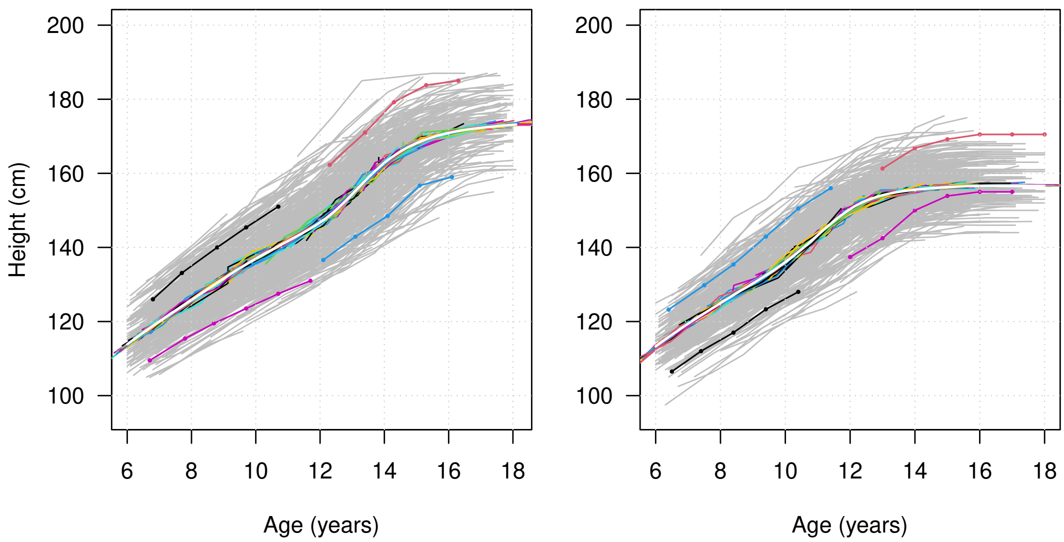

Figure 3. Individual height growth curves for 796 boys (left) and 672 girls (right) from the PSCG data set. Unadjusted curves are in grey, and curves adjusted using subject-specific SITAR random effects are in colour. The fitted mean curve is superimposed on the coloured curves and partially obscures them. Four unadjusted curves in colour show the PSCG study design.

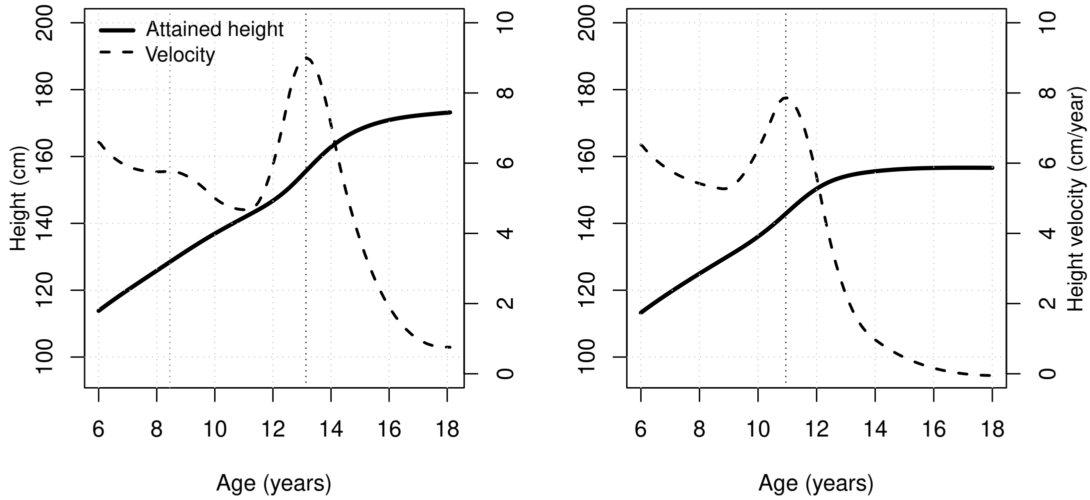

Figure 4. SITAR-fitted mean height growth curves (solid) and height velocity curves (dashed) by sex (boys left, girls right) in the PSCG data set. The vertical dotted lines indicate the ages at peak height velocity (at 13.1 years in boys and 11.0 years in girls) and the boys' mid-growth spurt (at 8.6 years).

9.3) cm/year. A small peak similar to a mid-growth spurt (Tanner and Cameron 1980) is seen at 8.6 years with mean PV 5.7 cm/year. In girls, mean APV occurs at 11.0 (10.8, 11.2) years with mean PV 8.0 (7.8, 8.2) cm/year. Summary statistics of the SITAR models are shown by sex in Table 1. Quantile-quantile (Q-Q) plots of the three random effects show that size is normally distributed; however, timing and intensity deviate from normality in the lower tail (Figure S2). The correlations between random effects are shown in Table 2. A scatter plot matrix showing these correlations appears in Figure S3.

Table 1. Standard deviations of SITAR random effects and the residual standard deviation by sex.

	Boys ($n = 796$)	Girls ($n = 672$)
Size (cm)	6.85	6.14
Timing (fractional)	0.084	0.085
Intensity (fractional)	0.15	0.14
Residual (cm)	0.76	0.67

Table 2. Correlations between SITAR random effects by sex. See Figure S3 for the scatter plot matrix.

	Boys ($n = 796$)		Girls ($n = 672$)	
	Size	Timing	Size	Timing
Timing	0.31		0.34	
Intensity	0.48	0.45	0.44	0.31

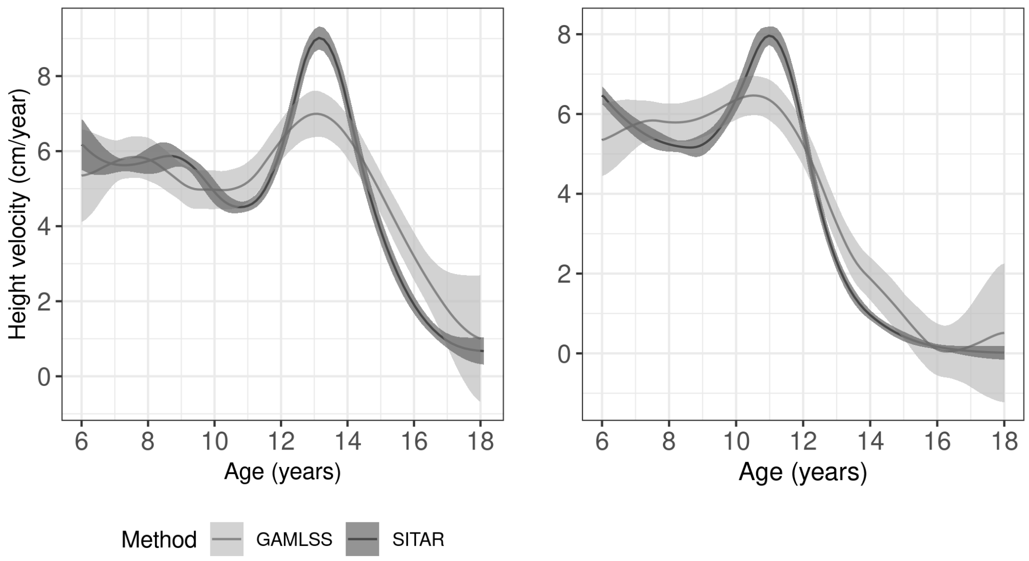

Figure 5. Mean height velocity curves and 95% bootstrap confidence interval bands as estimated by SITAR (dark gray) and GAMLSS (light gray) by sex (boys left, girls right).

Figure 5 shows mean height velocity curves for GAMLSS (dashed lines) and SITAR (solid lines) by sex, estimated as derivatives of the mean and median curves, respectively, with 95% confidence bands. There is a small peak in boys around 8 years in both curves. APV and PV for the curves are shown in Table 3; the APVs are similar, but the PVs are appreciably smaller for GAMLSS, and the confidence intervals do not overlap, due to GAMLSS being based on cross-sectionally analysed data.

Figure 6 compares height centiles recommended for Indian children by the Indian Academy of Pediatrics (IAP) (Indian Academy Of Pediatrics Growth Charts Committee et al. 2015) with the GAMLSS-estimated PSCG centiles. The IAP centiles were

Table 3. APV and PV as estimated from the SITAR and GAMLSS velocity curves by sex.

	Boys		Girls	
	SITAR	GAMLSS	SITAR	GAMLSS
APV (95% CI) years	13.1 (13.0, 13.3)	13.1 (12.4, 13.6)	11.0 (10.8, 11.2)	10.3 (8.3, 11.2)
PV (95% CI) cm/year	9.0 (8.7, 9.3)	7.1 (6.5, 7.7)	8.0 (7.8, 8.2)	6.6 (6.2, 7.0)

constructed using the LMS method on a much larger cross-sectional data set. The 3^{rd}, 50^{th} and 97^{th} IAP centiles are drawn as dashed red curves superimposed on the 3^{rd}, 50^{th} and 97^{th} PSCG centiles shown in black. The IAP and PSCG medians match fairly well, but the outer centiles less so.

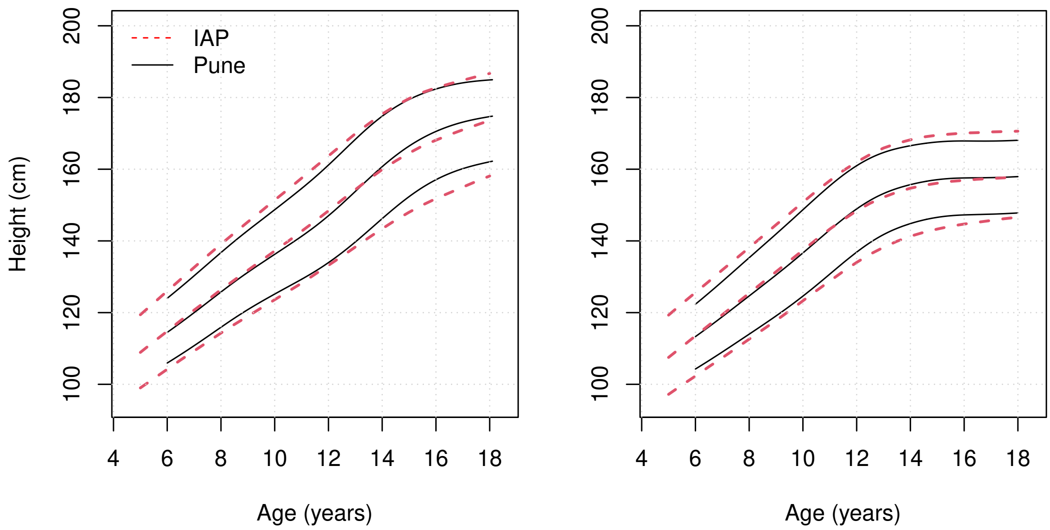

Figure 6. Comparing height centiles based on the PSCG data set and those recommended for the Indian population by the IAP (Indian Academy Of Pediatrics Growth Charts Committee et al. 2015). The black curves show the PSCG 3^{rd}, 50^{th}, and 97^{th} centiles, while the red dashed lines are the IAP 3^{rd}, 50^{th}, and 97^{th} centiles in each sex (boys left, girls right).

4. Discussion

Growth centiles and growth curves provide two distinct perspectives on individual and population growth. In this study, we analysed height growth in the PSCG data set to contrast the two tools in an Indian context. We constructed growth centiles with GAMLSS and growth curves with SITAR based on Indian children aged 6 to 18 years. The distribution of height in the population is well captured by the GAMLSS BCCGo centiles (Figure 1), which show the coefficient of variation peaking at around 13 years in boys and 10 years in girls (Figure 2). There is increasing left skewness in the boys' data (but not the girls') after 10 years, suggesting that a minority of boys fall behind progressively in height during puberty, extending the lower tail of the distribution. SITAR models the pubertal growth spurt effectively and explains 98.7% of the observed variance in boys and 98.8% in girls, shrinking the height SD from 7 cm to 0.7 cm. Boys also show a small mid-growth spurt, peaking at 8.6 years.

SITAR works well with the PSCG study design in that even though individuals are followed for no more than six years, the mean growth curve is estimated over the twelve-year period from 6 to 18 years—-SITAR is able to combine the individual growth curves to obtain the bigger picture.

The two methods, GAMLSS and SITAR, when applied to the same data, provide distinct information that is relevant in different contexts. Centile charts are useful in *clinical medicine* as they illustrate the child's recent growth as compared to their contemporaries, and this helps the clinician to make decisions about their management. The chart can also be used to see how fast the child has been growing and predict how fast they will grow in the future, depending on their treatment.

SITAR in contrast is of little value in clinical medicine—it works with the child's entire growth curve, and so it cannot provide "real time" growth information relevant for management. Instead it is valuable in two other contexts: *experimental medicine* and *life course epidemiology*. The SITAR mean growth curve is useful in experimental studies such as randomised clinical trials investigating the effect of a growth promoting agent such as oxandrolone in Turner Syndrome or calcium supplementation in rural Gambian children (Gault et al. 2011; Prentice et al. 2012). The SITAR model can test whether the intervention affects the size and/or timing and/or intensity of the mean curve. Separately, the SITAR subject random effects summarise individual pubertal growth patterns which can be related to individual-level stressors and adverse outcomes later in the life course (Johnson et al. 2014; Pizzi et al. 2014; Filteau et al. 2019). For example Kuh et al. (2016) have shown that early puberty is associated with better bone health in later life.

The height velocity curves estimated by GAMLSS and SITAR provide insights into the timing and intensity of the growth spurt. The APVs are comparable, but the PVs are appreciably smaller with GAMLSS. Mean APV was 13.1/10.3 years for boys/girls with GAMLSS and 13.1/11.0 years with SITAR, respectively 2.7 and 2.1 years apart (Figure 4). However mean PV was only 7.1/6.6 cm/year by sex with GAMLSS, some 20% smaller compared to 9.0/8.0 cm/year with SITAR. Similar results were observed by Blackwell et al. (2017), who applied the two methods to the same mixed longitudinal data set. Merrell (1931) and Cole et al. (2008) have explained this discrepancy algebraically: when individuals vary in their APV (i.e. the SD of the timing random effect is greater than zero), the mean PV based on cross-sectional data is attenuated compared to that based on longitudinal data. Note too that the velocity confidence bands for SITAR in Figure 4 are narrower than for GAMLSS, showing that the variance explained by SITAR is higher than for GAMLSS due to its longitudinal analysis.

Another estimate of PV came from the Indian height velocity charts of Khadilkar et al. (2019) based on annual height measurements: they reported median APV (PV) in boys and girls as 13.5 years (6.8 cm/year) and 10.5 years (PV 6.6 cm/year). The APVs are slightly later than for PSCG GAMLSS, while the PVs are similar. The Khadilkar et al. (2019) charts were constructed based on individual height velocity, i.e. year-wise differences in height used to construct the median height velocity centile, whereas GAMLSS here uses the median height centile. In practice the two should be similar, since the mean height increment is equal to the difference in the mean heights.

Reference height centile charts for Indian children have been developed by the IAP (Indian Academy Of Pediatrics Growth Charts Committee et al. 2015). They are useful for documenting the high prevalence of stunting in India (Hemalatha et al. 2020; Kumar et al. 2021). We compared the IAP charts, which are recommended for clinical use, with the GAMLSS-modelled PSCG centiles. The median curves are in good agreement throughout the age range in girls and until puberty in boys. However, the 3^{rd} and 97^{th} centiles match less well, especially the 3^{rd} centile, which is the formal cut-off to define stunting in India. The percentages of PSCG children below the IAP 3^{rd} centile are 1.5% of boys and 1.4% of girls, about half the expected rate. This discrepancy is due mainly to the smaller *df* used for the IAP μ curve, leading to the IAP centiles being stiffer and hence more linear, particularly during puberty. In addition the IAP charts were based on a nationally representative sample (unlike the

PSCG children living in Pune) and hence were more heterogeneous, and this could explain the IAP outer centiles being more widely spaced.

A small growth spurt before puberty, called the mid-growth spurt, was previously reported in boys between 5.9 and 8.5 years (El Lozy 1978; Tanner 1962; Tanner and Cameron 1980; Molinari et al. 1980; Gasser et al. 1985; Remer and Manz 2001; Virani 2005). In particular Virani (2005) reported a mid-growth spurt in Indian boys at 6.2 years. There was also a mid-growth spurt at 9 years in a subgroup of boys with late puberty in the Harpenden Growth Study (Cole 2020). We observe a small peak in height velocity around 8 years in both the GAMLSS and SITAR models. Note that the SITAR confidence band in Figure 5 is wider at 8 years, which may indicate variation in the timing of the mid-growth spurt.

In boys, the GAMLSS median curve and the SITAR mean curve have not yet plateaued by the age of 18 years. Further, their height velocity is appreciably greater than zero at 18 years (Figure 5). Conversely for girls at 18 years, the height curves are flat and the mean velocity is zero. This indicates that unlike girls, boys continue growing after 18 years, and ideally the reference sample should extend into the third decade of life to document this growth period properly.

A strength of our study is that we provide a comparative analysis of two widely used methods of growth curve and growth centile analysis. We show that the height velocity curves estimated from the two methods are appreciably different. Further, while the GAMLSS model has been used to develop growth centiles in the Indian population, SITAR has not been previously applied. However there are also some limitations. Our analysis is restricted to a population in Western India, and GAMLSS is applied to longitudinal rather than cross-sectional data, which limits the number of subjects included in the analysis. The centiles created from longitudinal data should be unbiased as the measurements were made annually within a fixed protocol (Wade and Kurmanavicius 2009), but less precise.

In conclusion, we have shown different aspects of growth centile and growth curve analysis that are used widely to analyse growth from birth to maturity. The GAMLSS model captures the distribution of height by age which can be displayed as a growth chart, whereas the SITAR model estimates the shape of the mean height growth curve, which also applies to individuals . The pubertal peak in height velocity is shallower in GAMLSS centiles compared to SITAR curves. We believe that the two analyses add usefully to knowledge about growth in contemporary Indian children.

Software

The growth centiles and curves developed here are made available as a web application accessible at https://digimed.acads.iiserpune.ac.in/growth-charts.

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Disclosure statement

The authors declare no conflict of interest.

Data availability statement

Data sharing is not applicable to this article as no new data were created or analyzed in this study.

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References

Agarwal DK, Agarwal KN, Upadhyay SK, Mittal R, Prakash R, Rai S. 1992. Physical and sexual growth pattern of affluent Indian children from 5 to 18 years of age. Indian Pediatrics. 29(10):1203–1282. Available from: https://pubmed.ncbi.nlm.nih.gov/1286886.

Blackwell AD, Urlacher SS, Beheim B, von Rueden C, Jaeggi A, Stieglitz J, Trumble BC, Gurven M, Kaplan H. 2017. Growth references for Tsimane forager-horticulturalists of the Bolivian Amazon. American journal of physical anthropology. 162(3):441.

Borghi E, de Onis M, Garza C, Van den Broeck J, Frongillo EA, Grummer-Strawn L, Van Buuren S, Pan H, Molinari L, Martorell R, et al. 2006. Construction of the World Health Organization child growth standards: selection of methods for attained growth curves. Statistics in medicine. 25(2):247–265.

Bowditch H. 1891. The growth of children studied by Galton's percentile grades In 22nd annual report of the State Board of Health of Massachusetts (pp. 479–525). Boston, MA: Wright and Potter.

Chirwa ED, Griffiths PL, Maleta K, et al. 2014. Multi-level modelling of longitudinal child growth data from the Birth-to-Twenty Cohort: a comparison of growth models. Annals of Human Biology. 41(2):168.

Cole T. 1994. Do growth chart centiles need a face lift? Bmj. 308(6929):641–642.

Cole TJ. 2012. The development of growth references and growth charts. Ann Hum Biol. 39(5):382.

Cole TJ. 2020. Tanner's tempo of growth in adolescence: recent SITAR insights with the Harpenden Growth Study and ALSPAC. Ann Hum Biol. 47(2):181–198.

Cole TJ. 2021. sitar: Super imposition by translation and rotation growth curve analysis. R package version 1.2.0.9000; Available from: https://github.com/statist7/sitar.

Cole TJ, Cortina-Borja M, Sandhu J, Kelly FP, Pan H. 2008. Nonlinear growth generates age changes in the moments of the frequency distribution: the example of height in puberty. Biostatistics. 9(1):159–171.

Cole TJ, Donaldson MDC, Ben-Shlomo Y. 2010. SITAR—a useful instrument for growth curve analysis. Int J Epidemiol. 39(6):1558.

Cole TJ, Green PJ. 1992. Smoothing reference centile curves: The lms method and penalized likelihood. Stat Med. 11(10):1305–1319.

Crozier SR, Johnson W, Cole TJ, Macdonald-Wallis C, Muniz-Terrera G, Inskip HM, Tilling K. 2019. A discussion of statistical methods to characterise early growth and its impact on bone mineral content later in childhood. Annals of Human Biology. 46(1):17.

de Onis M, Dasgupta P, Saha S, Sengupta D, Blössner M. 2001. The National Center for Health Statistics reference and the growth of Indian adolescent boys. American Journal of Clinical Nutrition. 74(2):248–253.

Eilers PHC, Marx BD. 1996. Flexible Smoothing with B-splines and Penalties. Statistical Science. 11(2):89–102. Available from: https://www.jstor.org/stable/2246049.

El Lozy M. 1978. A critical analysis of the double and triple logistic growth curves. Ann Hum Biol. 5(4):389–394.

Filteau S, Kumar GT, Cole TJ, et al. 2019. Steady Growth in Early Infancy Is Associated with Greater Anthropometry in Indian Children Born Low Birth Weight at Term. Journal of Nutrition. 149(9):1633–1641.

Galton F. 1885. Anthropometric per-centiles. Nature. 31(793):223–225.

Gasser T, Müller H, Köhler W, et al. 1985. An analysis of the mid-growth and adolescent spurts of height based on acceleration. Ann Hum Biol. 12(2):129–148.

Gault EJ, Perry RJ, Cole TJ, et al. 2011. Effect of oxandrolone and timing of pubertal induction on final height in Turner's syndrome: randomised, double blind, placebo controlled trial. BMJ. 342.

Goldstein H. 1986. Efficient statistical modelling of longitudinal data. Annals of Human Biology. 13(2):129–141.

Hauspie RC, Cameron N, Molinari L. 2004. Methods in human growth research. vol. 39. Cambridge University Press.

Hauspie RC, Das SR, Preece MA, Tanner JM. 1980. A longitudinal study of the growth in height of boys and girls of West Bengal (India) aged six months to 20 years. Annals of Human Biology. 7(5):429–440.

Hemalatha R, Pandey A, Kinyoki D, et al. 2020. Mapping of variations in child stunting, wasting and underweight within the states of India: the Global Burden of Disease Study 2000–2017. eClinicalMedicine. 22.

Indian Academy Of Pediatrics Growth Charts Committee, Khadilkar V, Yadav S, Agrawal KK, Tamboli S, Banerjee M, Cherian A, Goyal JP, Khadilkar A, Kumaravel V, et al. 2015. Revised IAP growth charts for height, weight and body mass index for 5- to 18-year-old Indian children. Indian Pediatrics. 52(1):47–55.

Jenss RM, Bayley N. 1937. A mathematical method for studying the growth of a child. Human Biology. 9(4):556.

Johnson L, van Jaarsveld CHM, Llewellyn CH, et al. 2014. Associations between infant feeding and the size, tempo and velocity of infant weight gain: SITAR analysis of the Gemini twin birth cohort. International Journal of Obesity. 38:980–987.

Johnson W. 2015. Analytical strategies in human growth research. American Journal of Human Biology. 27(1):69–83.

Karlberg J. 1989. A biologically-oriented mathematical model (ICP) for human growth. Acta Paediatr Scand Suppl. 350(70-94.):;.

Khadikar V, Khadilkar AV, Lohiya NN, Karguppikar MB. 2020. Extended growth charts for Indian children. Journal of Pediatric Endocrinology & Metabolism : JPEM. 34(3):357–362.

Khadilkar V, Khadilkar A, Arya A, Ekbote V, Kajale N, Parthasarathy L, Patwardhan V, Phanse S, Chiplonkar S. 2019. Height Velocity Percentiles in Indian Children Aged 5-17 Years. Indian Pediatr. 56(1):23–28. Available from: https://pubmed.ncbi.nlm.nih.gov/30806356.

Khadilkar VV, Khadilkar AV, Choudhury P, Agarwal KN, Ugra D, Shah NK. 2007. IAP growth monitoring guidelines for children from birth to 18 years. Indian Pediatrics. 44(3):187–197. Available from: https://pubmed.ncbi.nlm.nih.gov/17413194.

Komlos J, Tanner JM, Davies PSW, Cole T. 1992. The growth of boys in the Stuttgart Carlschule, 1771–93. Annals of Human Biology. 19(2):139–152.

Kuh D, Muthuri SG, Moore A, Cole TJ, Adams JE, Cooper C, Hardy R, Ward KA. 2016. Pubertal timing and bone phenotype in early old age: findings from a british birth cohort study. International journal of epidemiology. 45(4):1113–1124.

Kumar P, Chauhan S, Patel R, Srivastava S, Bansod DW. 2021. Prevalence and factors associated with triple burden of malnutrition among mother-child pairs in India: a study based on National Family Health Survey 2015–16. BMC Public Health. 21(1):1–12.

Merrell M. 1931. The relationship of individual growth to average growth. Human Biology. 3(1):37.

Mirzaei S, Sengupta D. 2012. Human growth curve estimation through a combination of longitudinal and cross-sectional data. World Academy of Science, Engineering and Technology, International Journal of Mathematical, Computational, Physical, Electrical and Computer Engineering. 6:760–765.

Molinari L, Largo RH, Prader A. 1980. Analysis of the growth spurt at age seven (mid-growth spurt). Helv Paediatr Acta. 35(4):325–334. Available from: https://pubmed.ncbi.nlm.nih.gov/7451236.

Pizzi C, Cole TJ, Richiardi L, et al. 2014. Prenatal Influences on Size, Velocity and Tempo of Infant Growth: Findings from Three Contemporary Cohorts. PLOS ONE. 9(2):e90291.

Preece MA, Baines MJ. 1978. A new family of mathematical models describing the human growth curve. Ann Hum Biol. 5(1):1–24.

Prentice A, Dibba B, Sawo Y, et al. 2012. The effect of prepubertal calcium carbonate supplementation on the age of peak height velocity in Gambian adolescents. American Journal of Clinical Nutrition. 96(5):1042–1050.

R Core Team. 2021. R: A language and environment for statistical computing. Vienna, Austria: R Foundation for Statistical Computing. Available from: https://www.R-project.org.

Remer T, Manz F. 2001. The Midgrowth Spurt in Healthy Children Is Not Caused by Adrenarche. J Clin Endocrinol Metab. 86(9):4183–4186.

Rigby RA, Stasinopoulos DM. 2004. Smooth centile curves for skew and kurtotic data modelled using the Box-Cox power exponential distribution. Stat Med. 23(19):3053–3076.

Rigby RA, Stasinopoulos DM. 2005a. Generalized additive models for location, scale and shape. Journal of the Royal Statistical Society: Series C (Applied Statistics). 54(3):507–554.

Rigby RA, Stasinopoulos DM. 2005b. Generalized additive models for location, scale and shape,(with discussion). Applied Statistics. 54:507–554.

Rigby RA, Stasinopoulos DM. 2006. Using the Box-Cox t distribution in GAMLSS to model skewness and kurtosis. Statistical Modelling. 6(3):209–229.

Satyanarayana K, Radhaiah G, Mohan KR, Thimmayamma BVS, Rao N, Rao BS, Akella S. 1989. The adolescent growth spurt of height among rural Indian boys in relation to childhood nutritional background: An 18 year longitudinal study. Annals of Human Biology. 16(4):289–300.

Schwarz G. 1978. Estimating the Dimension of a Model. Ann Stat. 6(2):461–464.

Spencer PR, Sanders KA, Judge DS. 2018. Growth curves and the international standard: How children's growth reflects challenging conditions in rural Timor-Leste. American Journal of Physical Anthropology. 165(2):286–298.

Tanner JM. 1962. Growth at adolescence. 2nd Edition, Blackwell Scientific Publications, Oxford.

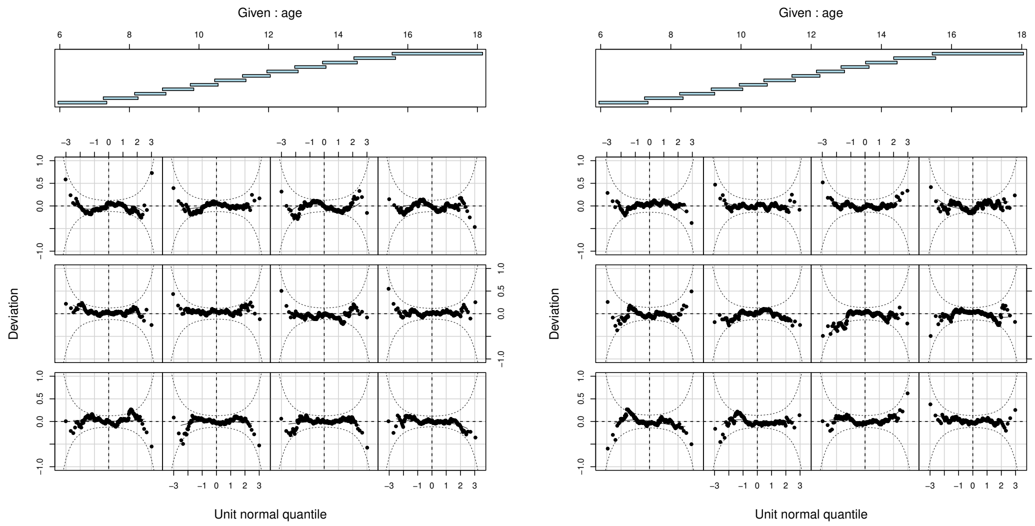
Tanner JM, Cameron N. 1980. Investigation of the mid-growth spurt in height, weight and limb circumferences in single-year velocity data from the London 1966–67 growth survey. Ann Hum Biol. 7(6):565–577.

Virani N. 2005. Growth patterns and secular trends over four decades in the dynamics of height growth of Indian boys and girls in Sri Aurobindo Ashram: A cohort study. Ann Hum Biol. 32(3):259–282.

Wade A, Kurmanavicius J. 2009. Creating unbiased cross-sectional covariate-related reference ranges from serial correlated measurements. Biostatistics. 10(1):147–154.

World Health Organization. 2006. WHO child growth standards: length/height-for-age, weight-for-age, weight-for-length, weight-for-height and body mass index-for-age: methods and development. World Health Organization:1–312. Available from: https://www.who.int/publications/i/item/924154693X.

Supplementary Information



(a) Boys (b) Girls

Figure S1. Detrended Q-Q plots (worm plots) of GAMLSS residuals in twelve age groups from 6 to 18 years by sex.

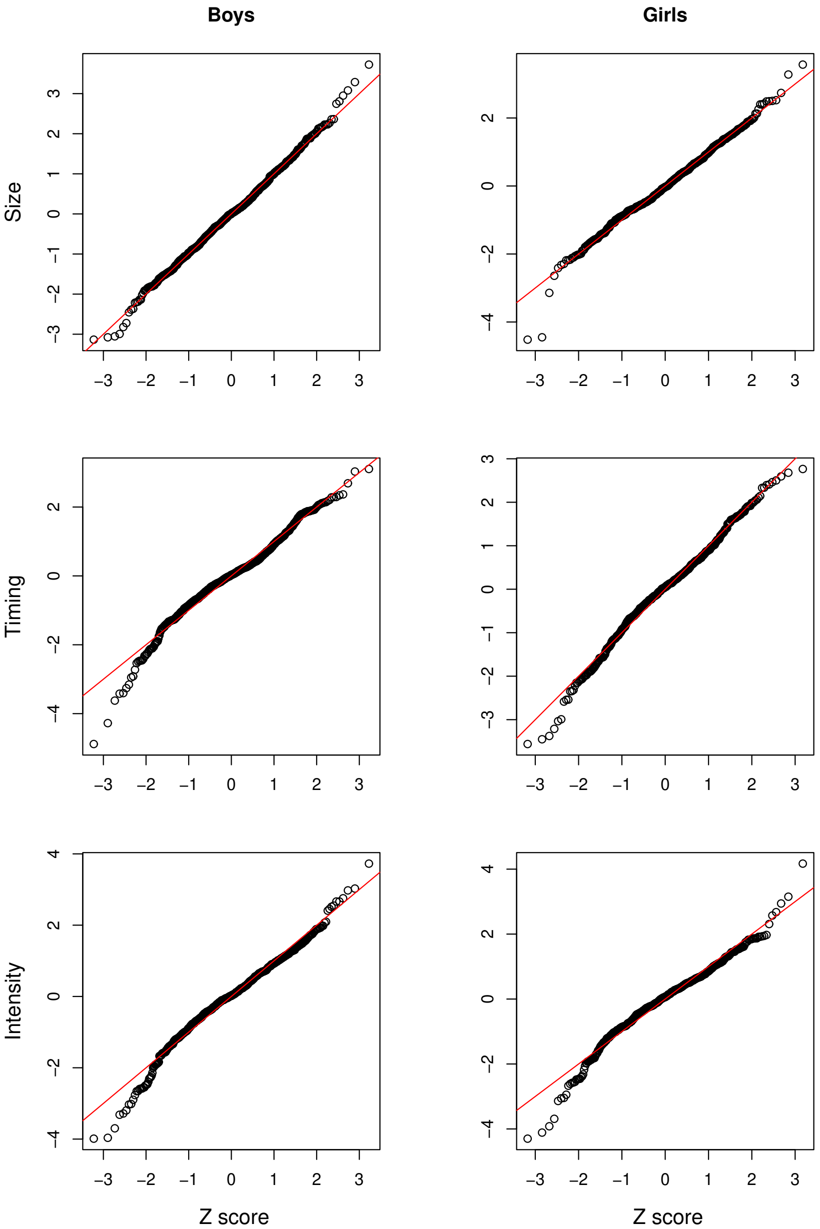
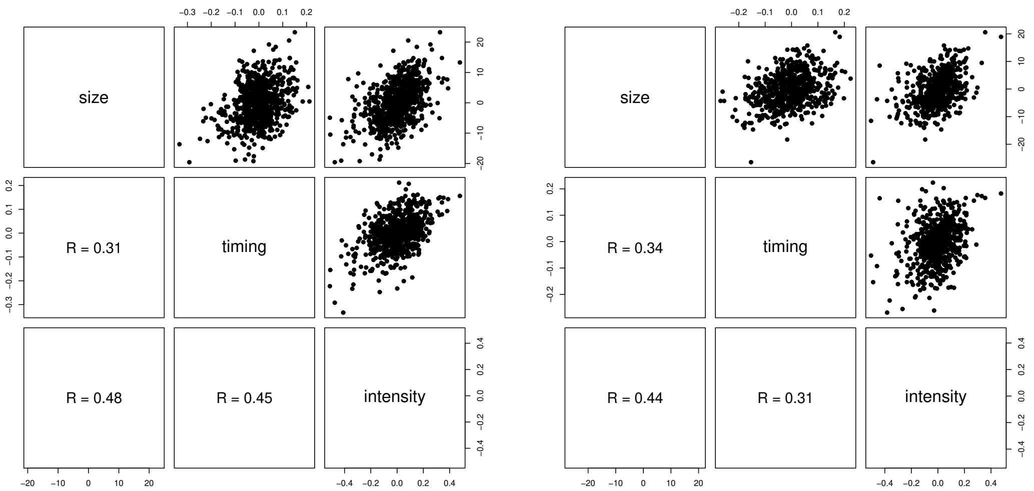


Figure S2. Q-Q plots of standardised SITAR random effects size, timing, and intensity by sex. A reference line (red) with unit slope and intercept 0 is given for comparison.



(a) Boys (b) Girls

Figure S3. Scatter plot matrices showing the correlations between SITAR random effects size, timing and intensity by sex.