Published in final edited form as:

Ann Nutr Metab. 2014 ; 65(2-3): 167–174. doi:10.1159/000365894.

Comparative Study of Four Growth Models Applied to Weight and Height Growth Data in a Cohort of US Children from Birth to 9 Years

N. Regnault^{a,b}, M. W. Gillman^a, K. Kleinman^a, S. Rifas-Shiman^a, and J. Botton^{b,c}

^aObesity Prevention Program, Department of Population Medicine, Harvard Medical School/ Harvard Pilgrim Health Care Institute, Boston, Mass., USA

^bINSERM U1018, Center for Research in Epidemiology and Population Health, Team Epidemiology of Diabetes, Obesity and Renal Diseases: Lifelong Approach, Villejuif

^cFaculté de Pharmacie, Université Paris-Sud, Châtenay-Malabry, France

Abstract

Background/Aims—The objective of our study was to compare the fit of four growth models for weight and height in contemporary US children between birth and 9 years.

Methods—In Project Viva, we collected weight and height growth data between birth and 9 years. We compared the Jenss model, the adapted Jenss model that adds a quadratic term, and the Reed 1st and 2nd order models. We used the log likelihood ratio test to compare nested models and the Akaike (AIC)/Bayesian information criterion (BIC) to compare nonnested models.

Results—For weight and height, the adapted Jenss model had a better fit than the Jenss model (for weight: $p < 0.0001$), and the Reed 2nd order model had a better fit than the Reed 1st order model (for weight: $p < 0.0001$). Compared with the Reed 2nd order model, the adapted Jenss model had a better fit for both weight (adapted Jenss vs. Reed 2nd order, AIC: 66,974 vs. 82,791, BIC: 67,066 vs. 82,883) and height (adapted Jenss vs. Reed 2nd order, AIC: 87,108 vs. 87,612, BIC: 87,196 vs. 87,700).

Conclusions—In this pre-birth study of children aged 0–9 years, for both weight and height the adapted Jenss model presented the best fit of all four tested models.

Introduction

Since the initial findings by Barker and colleagues, the field of the developmental origins of health and disease is quickly expanding.^{1,2} Epidemiologists increasingly use a life course approach and there is a growing interest for early growth. Indeed, patterns of growth, in particular weight growth in infancy and early childhood, have been associated with diseases

Corresponding Author : Nolwenn Regnault, INSERM U1018, Center for Research in Epidemiology and Population Health Team Epidemiology of Diabetes, Obesity and Renal Diseases: Lifelong Approach, 16, avenue Paul-Vaillant-Couturier, FR-94807 Villejuif Cedex (France), nolwenn.regnault@inserm.fr.

Disclosure Statement

The authors declare that they have no conflicts of interest.

later in life, such as obesity, type 2 diabetes, hypertension or stroke.³ Many contemporary pre-birth or birth cohorts started to collect detailed growth data to study the determinants and consequences of these growth trajectories. This is often done in two steps. The first step consists of modeling the growth data and the second step aims at studying the associations of the parameters derived from the growth model (e.g. predicted weight, height or velocities) with determinants or outcomes of growth. Often, in the past, growth models were fitted for each child separately. Now, growth trajectories can be modeled using mixed (multilevel) models. The model comprises a fixed-effect part that represents the population growth curve and a random-effect part that allows for individual variation around the population curve. An advantage of these models is that they do not require that data be measured at the same time points for all individuals nor do they require that all individuals have complete data at all time. It is then possible to use different sources of data: research measures at a given age as well as clinical measures from routine well-child visits. The difficulty lies in the choice of the model. There are structural and nonstructural models. Nonstructural models do not postulate a particular form of the growth curve; this category includes fractional polynomials⁴ and splines.⁵ They usually fit very well the data but their parameters cannot be interpreted. Compared to nonstructural models, structural models imply a basic functional form and have usually fewer parameters that allow some biological interpretation.

In this study, we focused on structural models of weight and height growth.⁶ Several models have been developed to model infant weight and height growth (Count and Kouchi models, and infancy component of the Karlberg model),^{7,8,9,10} childhood growth (Jenss and Reed 1st and 2nd order models),^{11,12} pubertal growth or total growth.¹³ However, their respective ability to fit actual data has seldom been compared. Comparing five weight growth models among 95 Congolese boys and girls between birth and 13 months, Simondon et al.¹⁴ suggested that the Reed 1st order model should be preferred over the Count model, the Kouchi model, the infancy part of the Karlberg model and the Reed 2nd order model. In 1982, Berkey¹⁵ showed that in US children the Jenss model seemed to perform well for both length and weight between birth and 6 years of age compared to the Count model, which is a simpler form of the Reed 1st order model. In a more recent report, in South Africa, Chirwa et al.¹⁶ showed that the Reed 1st order model fitted consistently well from infancy into childhood, whereas the Jenss model did not fit well to height growth measurements in the early years. Yet, to our knowledge, no recent comparison of these models has been made in US children.

The objective of our study was to compare the fit of four growth models (the Jenss model, an adapted version of the Jenss model, and Reed 1st and 2nd order models) for weight and height growth data in contemporary US children between birth and 9 years of age using mixed models.

Methods

Study Population and Data Collection

Project Viva is an ongoing prospective pre-birth cohort study that recruited pregnant women at their initial prenatal visit at Harvard Vanguard Medical Associates, a large multispecialty group practice in eastern Massachusetts, between April 1999 and July 2002. Details of

recruitment and retention procedures are available elsewhere.¹⁷ All mothers gave informed consent, and institutional review boards of participating institutions approved the study. All procedures were in accordance with the ethical standards established by the Declaration of Helsinki.¹⁸

Anthropometric measures were obtained from three sources: hospital records, research examinations and clinical data. Birth weight was abstracted from the maternity hospital records at the time of birth. In Project Viva, research examinations were organized in infancy (mean age 6.5 months, range 5.2–9.9), in early childhood (mean age 39.4 months, range 33.6–131.1) and mid-childhood (mean age 95.5 months, range 78.8–131.1). Project staff members weighed infants in infancy and early childhood with a Seca 881 digital scale (Seca, Hanover, Md., USA) and in mid-childhood with a Tanita TBF-300A (Tanita, Arlington Heights, Ill., USA). Trained research assistants measured infant length at birth and 6 months of age and infant height in early childhood with a Shorr measuring board and in mid-childhood using a calibrated stadiometer (Shorr Productions, Olney, Md., USA). Research assistants performing the measurements followed standardized techniques¹⁹ and participated in biannual in-service training to ensure measurement validity (Irwin J. Shorr, MPH, MPS, Shorr Productions). Inter- and intrarater measurement errors were well within published reference ranges for all of the measurements (example for length: rater 1, 0.22 cm; rater 2, 0.35 cm; rater 3, 0.19 cm; rater 4, 0.25 cm, and between raters, 0.29 cm).²⁰ Experienced field supervisors provided ongoing quality control by observing and correcting the measurement technique every 3 months. Pediatric practices recorded length/height and weight data at each well-child visit during infancy and childhood. We used macros developed by the World Health Organization and the Centers for Disease Control and Prevention to identify potential outliers.²¹

Sample Selection

Since Botton et al.²² suggested that neonatal weight loss might create difficulties in fitting our monotone models, we excluded birth weight from the dataset. We included all the children with at least 2 measures between birth and 109 months, just before the onset of puberty in girls.⁶ We modeled weight and height separately, and our final sample included 1,723 children with at least 2 measures of weight and 1,749 with at least 2 measures of height.

Growth Models

To model weight and height between birth and 8 years, we compared four growth models: the Jenss model proposed by Jenss and Bailey in 1937 (also called Jenss-Bailey),²³ an adapted version of the Jenss model, and two models developed by Berkey and Reed in the 1980s (the Reed 1st order and Reed 2nd order, also called the Berkey-Reed models).

All the comparisons have been performed using mixed models. For the sake of simplicity, we present only the fixed-effect models below, except for the adapted Jenss model, for which we provide the mixed model.

The Jenss model is a 4-parameter model. It is a negatively accelerated exponential which approaches a linear asymptote. The model is as follows:

$$\hat{y}_{ij} = a_i + b_i \cdot t_{ij} - e^{c_i + d_i \cdot t_{ij}}$$

and expressed as the j th growth measure of the i th subject with y being the weight or height and t age. This model is adequate to fit childhood growth since early growth is very rapid (the exponential part) but becomes linear sometimes during the preschool years.

The adapted Jenss model was developed and described by Botton et al.²⁴ to estimate child growth from 0 to 12 years of age instead of 0–8 years, as in the initial Jenss model). The model is as follows:

$$\hat{y}_{ij} = a_i + b_i \cdot t_{ij} - e^{c_i + d_i \cdot t_{ij}} + e_i \cdot t_{ij}^2.$$

It differs from the original Jenss model by the addition of a quadratic term $e_i t_{ij}^2$. This term models the increase in growth velocity at the onset of puberty. This model has been found to fit well for weight and height growth in a French population of children between birth and 12 years.²⁴ The equation below shows the complete model used in the comparisons. It includes both fixed and random effects.

$$y_{ij} = A + a_i + (B + b_i) \cdot t_{ij} - e^{C + c_i + (D + d_i) \cdot t_{ij}} + (E + e_i) \cdot t_{ij}^2 + \varepsilon_{ij}.$$

With $\varepsilon_{ij} \sim N$ and $a_i, b_i, c_i, d_i, e_i \sim$ multivariate normal distribution.

The Reed models¹¹ have been developed by adding one or more deceleration terms to a more simple model (the Count model).¹⁰ This allows greater flexibility of the model that fits a wider variety of growth patterns in early childhood.²³ Compared to the Jenss model and the adapted Jenss model that are nonlinear in parameters, the Reed models are linear. The 1st order Reed model is a 4-parameter model expressed as the j th growth measure of the i th subject with y being the weight or height and t age:

$$\hat{y}_{ij} = a_i + b_i \cdot t_{ij} + c_i \cdot \ln(t_{ij}) + \frac{d_i}{t_{ij}}.$$

The 2nd order Reed model is defined as follows:

$$\hat{y}_{ij} = a_i + b_i \cdot t_{ij} + c_i \cdot \ln(t_{ij}) + \frac{d_i}{t_{ij}} + \frac{e_i}{t_{ij}^2}.$$

The 1st order version was shown to perform well on height between 3 months and 6 years: only a few children needed the 2nd order version.²³

Weight and Height Growth Velocity

In addition to weight and height at different ages, we also computed weight and height growth velocities for all children, using the estimated parameters from the first derivative of the growth models, given here for the adapted Jenss model.

$$\frac{dy}{dt} = e^{(B+b_i)} + e^{(C+c_i-D+d_i)} \cdot e^{(-e^{-(D+d_i)} \cdot t)} + 2 \cdot e^{(E+c_i)} \cdot t.$$

Assessment of Goodness of Fit

We performed nonlinear regression and nonlinear mixed regression to compare the models. Nested models were compared using the log likelihood ratio test (Jenss vs. adapted Jenss models and Reed 1st vs. 2nd order models). Nonnested models were compared using the Akaike (AIC)/Bayesian information criterion (BIC). Lower AIC and BIC indicate a better fit. Fitting of both linear and nonlinear models was achieved in the R package NLME, which gives least-square estimates of the parameters using an iterative Gauss-Newton algorithm. Our nonlinear models did not converge in PROC NLMIXED in SAS 9.2, even after using the values of the parameters produced by R as the initial values. In R 2.15.3 using NLME, we were able to fit all the models with a diagonal variance-covariance matrix for the random effects, but not an unstructured matrix. All comparisons were done using a diagonal variance-covariance matrix for the random effects in the mixed models. To fit the final models, we subsequently used the SAEMIX package developed by Comets, Lavenu and Lavielle. This package uses an algorithm that maximizes the exact likelihood without approximation of the likelihood. It is very helpful for fitting complex nonlinear mixed models. We successfully fitted the final models for weight and height/length with an unstructured matrix in R with the SAEMIX package.

Results

Sample

Among the 1,723 children with at least 2 measures of weight, 48.5% were girls. Mean maternal age at the beginning of pregnancy was 32.0 ± 5.2 years, 67.2% were white, 16.2% were African-American and 67.3% were at least college graduates. There were 1,749 children with at least 2 measures of height. The mean numbers of measures were 19.3 for weight and 12.3 for height, with more frequent measures in the first 18 months, reflecting clinical practice (Table 1).

Table 2 shows that for weight and height, the adapted Jenss model had a better fit than the original Jenss model (for weight: likelihood ratio = 17,597, $p < 0.0001$) and the Reed 2nd order model had a better fit than the Reed 1st order model (for weight: likelihood ratio = 3,340, $p < 0.0001$). We then compared the better Reed model with the better Jenss model. Compared with the Reed 2nd order model, the adapted Jenss model had a better fit, as shown by lower AIC and BIC for both weight (adapted Jenss vs. Reed 2nd order, AIC: 66,974 vs. 82,791, BIC: 67,066 vs. 82,883) and height (adapted Jenss vs. Reed 2nd order, AIC: 87,108 vs. 87,612, BIC: 87,196 vs. 87,700), although the difference between the two

models was smaller for height. Figure 1 shows the standardized residuals of the four candidate models for weight plotted against age. As indicated by the comparison of AIC and BIC, the adapted Jenss model was the best fitting model: the boxes appear nicely centered on the $Y = 0$ and, compared to the other models, with less variability across different ages although some heteroscedasticity remains. Residuals from other models reveal ages where the models fail to fit the mean of the data and greater heteroscedasticity. Figure 2 presents similar graphics for height. The negative residuals in the adapted Jenss model for the first 18 months suggested a slight overestimation of the predicted values compared to the observed measures but a good fit at subsequent ages. Table 3 presents the parameters estimated by SAEMIX in the final models (adapted Jenss with an unstructured variance-covariance matrix of the random effects). Briefly, B represents the asymptotic slope (growth rate after 2 years); E represents the increase in growth velocity at the onset of puberty, and the decreasing exponential function contributes to model the decelerating rate of growth in infancy. In another parameterization of the Jenss model presented by Botton et al.,²² A can also be interpreted and is the predicted value at time $t = 0$, e.g. length or extrapolated weight at birth. Table 4 presents the predicted weight, height and velocities at different ages calculated using the parameters.

Discussion

In this study of over 1,700 children from the United States followed from birth to age 9 years, we found that a nonlinear model with 5 parameters (adapted Jenss model) provided better numerical and visual fit to observed longitudinal weight and length/height data than did three other commonly used models. While convergence was sometimes an issue in the past, this model can now be easily fitted using the new SAEMIX package in R and applied to similar longitudinal data from other cohorts.

In addition to showing that the adapted Jenss model is superior in our study population, we provide the parameter estimates from our final models, which other researchers could use as starting values in other samples. NLME and SAEMIX both require that starting values be specified. Good starting values are crucial to reduce convergence issues in modeling nonlinear equations, especially when the number of model parameters increases. We also present the steps to compare different models. Even though human growth presents some constant features, there are variations across populations. Thus, it is important to compare different models to select the model that fits best to the data and to pay attention to the diagnostics of the selected model.

Although the overall fit of the final models was good, we identified a slight overestimation of height in the first 18 months. Clinical measurement of length in the first 2 years of life typically overestimates research measures. Indeed, starting at around 24 months, clinical practices begin to measure standing height instead of length; standing height is, on average, 0.75 cm less than recumbent length for the same person at the same time.²⁵ We performed sensitivity analyses by including a correction factor developed in a setting similar to the clinical centers included in the study. Predictions in the first 18 months were improved using the correction factor, but the fit was not as good as the model without correction for older ages.

We included all children with at least 2 measures in the modeling phase. Mixed models can accommodate subjects with few measures. The growth trajectory of the children with few measures is then very similar to the population mean growth curve. However, trajectories of children with very few measurements may not be informative. Subsequent analyses of the weight or height predicted from these models should be done on a subset of children with at least a certain number of measures followed by sensitivity analyses that include the remaining children. Another issue, however, is that the children with fewer measurements may also differ from the others in terms of other characteristics. We excluded birth weight from the dataset, it is then possible in the second step to correlate early growth with measured birth weight.

When cleaning clinical data that contain measurement errors, it is sometimes difficult to distinguish an outlier from a temporary physiological phenomenon leading to an apparent discontinuity in the growth curve (e.g. a plateau or a mid-childhood growth spurt) or even from a pathological phenomenon (e.g. diseases in infancy, or depression or dieting in later childhood can lead to weight loss in a short period). Our parametric models require monotone growth and are not intended to accommodate a decrease in weight. This might be an issue especially after puberty.

Our data extend the previous sparse literature that compared different growth models in childhood. The choice of the model depends on the observations (range, frequency and regularity of the observations), the period of growth investigated (infancy, childhood and adolescence) and the type of measure (weight, but also sitting height/body composition). Berkey¹⁵ showed that in US children the Jenss model seemed to perform well for both length and weight, better than the Count model, a simple form of the Reed 1st order model. Yet, the adapted Jenss model was not part of the comparison of Berkey.¹⁵ In a study of children in India, Johnson et al.²⁶ found that the Reed 1st order model fitted better to infant weight and height growth compared to the Count model. Pizzi et al.¹³ compared the Jenss model, the Reed 1st order and the SITAR method in three cohorts and showed that the Reed 1st order model had the best fit. In South-Africa, Chirwa et al.¹⁶ showed that the Reed 1st order model fitted consistently well from infancy into childhood, whereas the Jenss and adapted Jenss models did not fit well to growth measurement in the early years. However, they concede in their discussion that this could be due to the limited number of measurement occasions that leads to a failure by the model to capture the asymptotic curve in infancy. It is also possible that growth in an African transitioning population and in US children might not be identical.¹⁶

The modeling technique used in this study is not the only growth modeling technique available. Other techniques can also be used; many of them are presented in this issue. The fixed and random coefficients obtained from our two-step approach using a mixed model can be used to compute weight, height and weight/height growth velocities at any age between birth and 9 years. It is also possible to calculate body mass index from the predicted weight and height.

In conclusion, in this pre-birth study of children aged 0 to 9 years, the adapted Jenss model presented the best fit of all four models tested for weight and height. This model can be used

to model weight and height/length growth in infancy and childhood and to ultimately study the determinants and outcomes of growth trajectories.

References

1. Barker DJ, Osmond C, Golding J, Kuh D, Wadsworth ME. Growth in utero, blood pressure in childhood and adult life, and mortality from cardiovascular disease. *BMJ*. 1989; 298:564–567. [PubMed: 2495113]
2. Barker DJP. The developmental origins of adult disease. *J Am Coll Nutr*. 2004; 23:588S–595S. [PubMed: 15640511]
3. Eriksson JG. Early growth and coronary heart disease and type 2 diabetes: findings from the Helsinki Birth Cohort Study (HBCS). *Am J Clin Nutr*. 2011; 94(6 suppl):1799S–1802S. [PubMed: 21613556]
4. Wen X, Kleinman K, Gillman MW, Rifas-Shiman SL, Taveras EM. Childhood body mass index trajectories: modeling, characterizing, pairwise correlations and socio-demographic predictors of trajectory characteristics. *BMC Med Res Methodol*. 2012; 12:38. [PubMed: 22458308]
5. Tilling K, Davies NM, Nicoli E, Ben-Shlomo Y, Kramer MS, Patel R, Oken E, Martin RM. Associations of growth trajectories in infancy and early childhood with later childhood outcomes. *Am J Clin Nutr*. 2011; 94(6 suppl):1808S–1813S. [PubMed: 21633072]
6. Hauspie, RC.; Cameron, N.; Molinari, L. *Methods in Human Growth Research*. 1. Cambridge: Cambridge University Press; 2004.
7. Karlberg J, Engstrom I, Karlberg P, Fryer JG. Analysis of linear growth using a mathematical model. I. From birth to three years. *Acta Paediatr Scand*. 1987; 76:478–488. [PubMed: 3604665]
8. Kouchi M, Mukherjee D, Roche AF. Curve fitting for growth in weight during infancy with relationship to adult status, and familial associations of the estimated parameters. *Hum Biol*. 1985; 57:245–265. [PubMed: 3997129]
9. Kouchi M, Roche AF, Mukherjee D. Growth in recumbent length during infancy with relationships to adult status and familial associations of the estimated parameters of fitted curves. *Hum Biol*. 1985; 57:449–472. [PubMed: 4077044]
10. Count E. Growth pattern of the human physique. *Hum Biol*. 1943; 15:1–32.
11. Berkey CS, Reed RB. A model for describing normal and abnormal growth in early childhood. *Hum Biol*. 1973; 59:973–987. [PubMed: 3443447]
12. Jenss R, Bayley N. A mathematical method for studying the growth of a child. *Hum Biol*. 1937; 9:556–563.
13. Pizzi C, Cole T, Corvalan C, Dos Santos Silva I, Richiardi L, De Stavola BL. On modelling.
14. Simondon KB, Simondon F, Delpeuch F, Cornu A. Comparative study of five growth models applied to weight data from Congolese infants between birth and 13 months of age. *Am J Hum Biol*. 1992; 4:327–335.
15. Berkey CS. Comparison of two longitudinal growth models for preschool children. *Biometrics*. 1982; 38:221–234. [PubMed: 7082759]
16. Chirwa ED, Griffiths PL, Maleta K, Norris SA, Cameron N. Multi-level modelling of longitudinal child growth data from the Birth- To-Twenty Cohort: a comparison of growth models. *Ann Hum Biol*. 2014; 41:166–177.
17. Oken E, Baccarelli AA, Gold DR, et al. Cohort Profile: Project Viva. *Int J Epidemiol*. 2014
18. World Medical Association. Declaration of Helsinki. Recommendations guiding physicians in biomedical research involving human subjects. *JAMA*. 1997; 277:925–926. [PubMed: 9062334]
19. Shorr, I. *How to Weigh and Measure Children: Assessing the Nutritional Status of Young Children in Household Surveys*. New York: United Nations; 1986.
20. Mueller, W.; Martorell, R. Reliability and accuracy of measurement. In: Lohman, T.; Roche, A., editors. *Anthropometric Standardization Reference Manual*. Champaign: Human Kinetics; 1988.
21. Growth Chart Training. A SAS Program for the CDC Growth Charts. Atlanta: Centers for Disease Control and Prevention; 2014. <http://www.cdc.gov/nccdphp/dnpao/growthcharts/resources/sas.htm>

22. Botton J, Scherdel P, Regnault N, Heude B, Charles M-A. EDEN Mother-Child Cohort Study Group. Postnatal weight and height growth modelling and prediction of body mass index over time: a general method for the study of growth determinants. *Ann Nutr Metab.* 2014; 65:156–166. [PubMed: 25413654]
23. Hauspie, R.; Molinari, L. Parametric models for postnatal growth. In: Hauspie, R.; Cameron, N.; Molinari, L., editors. *Methods in Human Growth Research*. Cambridge: Cambridge University Press; 2004. p. 205-233.
24. Botton J, Heude B, Maccario J, Ducimetiere P, Charles M-A. FLVS Study Group. Postnatal weight and height growth velocities at different ages between birth and 5 y and body composition in adolescent boys and girls. *Am J Clin Nutr.* 2008; 87:1760–1768. [PubMed: 18541566]
25. Rifas-Shiman SL, Rich-Edwards JW, Scanlon KS, Kleinman KP, Gillman MW. Misdiagnosis of overweight and underweight children younger than 2 years of age due to length measurement bias. *Med Gen Med.* 2005; 7:56.
26. Johnson W, Vazir S, Fernandez-Rao S, Kankipati VR, Balakrishna N, Griffiths PL. Using the WHO 2006 child growth standard to assess the growth and nutritional status of rural south Indian infants. *Ann Hum Biol.* 2012; 39:91–101. [PubMed: 22324834]

Figure 1. Residuals of the four candidate models for weight growth plotted against age (birth to 109 months): data from 1,723 boys and girls from Project Viva

Figure 2. Residuals of the four candidate models for length growth plotted against age (birth to 109 months): data from 1,749 boys and girls from Project Viva

Table 1

Number of measures per child and per age period. Data from boys and girls from Project Viva (n = 1,723 for weight and n = 1,749 for length/height)

Age Group	Mean number of measures (SD)	
	weight	length/height
0 – 1.5 years	10.3 (5.6)	7.2 (2.6)
1.5 – 3 years	2.9 (3.3)	1.4 (1.0)
3 – 4.5 years	2.6 (2.7)	1.8 (1.2)
4.5 – 6.5 years	1.8 (2.9)	0.8 (1.1)
6.5 – 9.3 years	1.8 (2.5)	1.1 (1.1)
TOTAL PER CHILD	19.3 (13.4)	12.3 (5.2)

Table 2

Comparison of the goodness of fit of the four models (Jenss, adapted Jenss, and Reed 1st and 2nd order models). Data from boys and girls from Project Viva (n = 1,723 for weight and n = 1,749 for length/height)

Model	Fixed and random effects					
	Residual SD	AIC	BIC	log likelihood	likelihood ratio	p value
<i>Weight</i>						
Jenss	0.71	84,567	84,643	-42,274		-
Adapted Jenss	0.50	66,974	67,066	-33,476	17,597	<0.0001
Reed 1 st order	0.72	86,127	86,202	-43,054	-	-
Reed 2 nd order	0.68	82,791	82,883	-41,384	3,340	<0.0001
<i>Length/height</i>						
Jenss	1.45	87,917	87,989			-
Adapted Jenss	1.42	87,108	87,196			<0.0001
Reed 1 st order	1.47	87,644	87,716			-
Reed 2 nd order	1.47	87,612	87,700			<0.0001

Table 3

Parameters estimated in the final models (adapted Jenss model with an unstructured variance-covariance matrix of the random effects). Data from boys and girls from Project Viva (n = 1,723 for weight and n = 1,749 for length/height)

Parameter	Weight		Length/Height	
	Mean	SD	Mean	SD
A	1.17	0.01	3.93	0.001
B	2.17	0.02	0.38	0.008
C	1.78	0.01	3.05	0.007
D	1.76	0.01	1.80	0.010
E	-7.69	0.04	0.00	0.00004
$v_{ij} = A + a_i + (B + b_i) \cdot t_{ij} - e^{C + c_i + (D + d_i) \cdot t_{ij}} + (E + e_i) \cdot t_{ij}^2 + \epsilon_{ij}$				

Table 4

Mean weight, height and growth velocities (SD) at different ages. Data from boys and girls from Project Viva (n=1723 for weight and n=1749 for length/height): adapted Jenss model

	Weight		Length/height	
	attained, kg	velocity, kg/month	attained, cm	Velocity, cm/month
Birth		-	50.81 (2.16)	-
1 month	4.35 (0.48)	1.01 (0.21)	54.73 (2.18)	3.68 (0.32)
3 months	6.07 (0.69)	0.73(0.11)	61.20 (2.25)	2.81 (0.20)
6 months	7.86 (0.87)	0.49 (0.08)	68.26 (2.32)	1.97 (0.15)
1 year	10.05 (1.07)	0.28 (0.06)	77.20 (2.44)	1.15 (0.11)
2 years	12.68 (1.43)	0.19 (0.05)	87.67 (2.83)	0.72 (0.07)
3 years	14.91 (1.90)	0.19 (0.06)	95.67 (3.27)	0.63 (0.06)
4 years	17.24 (2.53)	0.20 (0.07)	103.02 (3.74)	0.59 (0.05)
5 years	19.76 (3.37)	0.22 (0.09)	109.98 (4.19)	0.57 (0.04)
6 years	22.47 (4.43)	0.24 (0.11)	116.60 (4.60)	0.54 (0.04)
7 years	25.40 (5.73)	0.25 (0.13)	122.90 (4.95)	0.51 (0.03)
8 years	28.54 (7.27)	0.27 (0.15)	128.87 (5.23)	0.48 (0.03)
9 years	31.90 (9.05)	0.29 (0.17)	134.51 (5.46)	0.46 (0.03)