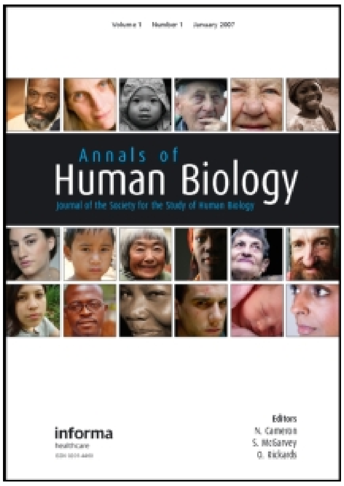

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Analysis of the adolescent growth spurt using smoothing spline functions

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Summary. Height growth velocity curves between 4·5 and 17·75 years were estimated, using smoothing spline functions, for 112 boys and 110 girls from the Zurich Longitudinal Study (1955–1976). Parameters characterizing the growth process, such as peak height velocity and age at peak height velocity, were calculated directly from the estimated curves.

The variability of parameters describing the adolescent growth spurt is large, both between and within sexes. Peak height, defined as increase of height velocity during the growth spurt, and age at peak height velocity both characterize the sex difference in growth in a highly significant manner. Peak height of at least 4 cm/year is found in 70% of the boys, but in only 11% of the girls. The age at peak height velocity averages 12·2 years in girls and 13·9 years in boys and has a wide range of 5·7 years and 3·8 years respectively.

The sex difference in adult height of 12·6 cm is composed of the following 4 factors: +1·6 cm caused by more prepubertal growth in boys, +6·4 cm by the boys' delay in spurt, +6·0 cm by the more extensive spurt in boys and −1·4 cm by more post-spurt growth in girls.

Correlations between parameters indicate that the adult height depends neither on the duration of growth, nor on the duration and height of the peak. Minimal pre-spurt height velocity and peak height velocity, but not peak height, are age- and height-dependent.

Partial correlations given adult height reveal two compensating mechanisms between growth in the prepubertal and in the pubertal period. Small prepubertal height and low height velocity with respect to adult height are followed by a late adolescent spurt and vice versa. Small height at the onset of the spurt with respect to adult height is followed by a longer lasting, but not higher spurt and vice versa.

1. Introduction

The analysis of longitudinal growth data usually consists of two steps: first, parameters have to be defined which summarize the important properties of the growth process; second, a method has to be found which assigns to each individual series of measurements the corresponding set of parameter values. The distribution of these parameters over the sample can then be analysed by classical statistical procedures.

Hitherto, the commonly used method to perform the first step was to choose a parametric family of curves and to ascertain the parameter values for each individual by the method of least squares. However, prepubertal growth is completely different from pubertal growth, and the pubertal component shows features with a high variability over the population. This makes it difficult to find a parametric family of curves which meets the following two requirements: (*a*) it should fit all individual series of measurements without systematic errors; (*b*) its parameters should summarize those properties of the curve in which one is interested.

In view of requirement (*a*), most authors (Deming, 1957; Marubini, Resele and Barghini, 1971: Marubini, Tanner and Whitehouse, 1972; Tanner, Whitehouse, Marubini and Resele, 1976) restrict themselves to a description of the growth spurt. Bock, Wainer, Petersen, Thissen, Murray and Roche (1973) use the superposition of two logistic functions to describe both the prepubertal and the pubertal period. However, their family of curves does not meet requirement (*a*). An average squared residual of $2{\cdot}0\ \mathrm{cm}^2$ in boys and $0{\cdot}3\ \mathrm{cm}^2$ in girls indicates a clear lack of fit. As far as requirement (*b*) is concerned, the parameters of the logistic function accounting for prepubertal growth vary greatly between sexes. This indicates that they do not summarize the properties of growth in early childhood very well. Prepubertal growth is known to be almost the same for both sexes.

In our study, the methodological approach is different. We estimate the individual curves of growth velocity non-parametrically, using smoothing spline functions. Parameters such as peak height velocity and age at peak height velocity are then calculated directly from the estimated individual curves. With the help of these parameters, the variability over the population and sex differences in the growth spurt are described. In a further analysis of prepubertal and pubertal growth, the parameters are presented as linear functions of four independent factors and the relationships between the parameters are evaluated.

2. Subjects and methods

Subjects

In 1955 a prospective longitudinal study of growth and development of 412 healthy Swiss children was initiated at the Kinderspital Zurich and is still in progress. The work is being done in coordination with four other longitudinal growth studies in Europe (Brussels, London, Paris and Stockholm), and the Centre International de l'Enfance (CIE) in Paris. In the present work, data of 112 boys and 110 girls are included. In none of these children were more than three measurements or two consecutive measurements missing between 4 and 18 years. No child was suffering from a disease which might have hampered growth. Six boys and two girls of very tall stature were treated with high doses of sex hormones in order to reduce predicted adult height and were therefore excluded from the study.

Measurements

Height was measured according to the direction of the CIE (Falkner, 1960), using gentle upward pressure under the mastoid process. After the age of 8 years all measurements were done by the same trained anthropometrist (Miss M. Willisegger). Before the age of 9 years in girls and 10 years in boys the children were measured yearly at birthday ± 14 days. Afterwards they were measured 6-monthly within the same limits until the annual increment in height was less than 0·5 cm/year. Thereafter, the measurements were done again annually and were discontinued when the increment had become less than 0·5 cm in 2 years.

Editing

Gross errors were looked for by searching for negative increments in height and by visual inspection of the raw and smoothed velocity curves on the computer display. The few which could not be corrected with the help of the original sheets were treated as missing data. Missing observations were completed using an iterative procedure which assured that the filled-in pseudo-observations had zero residuals when the series of height measurements was smoothed. Results of cross-validation (Wahba and Wold, 1975) and visual comparison of measured velocities with simulated velocities, where the variance of the "random" errors was known, suggest that the "random" fluctuations in height measurements have a standard deviation of about 4 mm.

All computations were performed on the CDC 6400/6500 of the Computer Centre of the Swiss Federal Institute of Technology (ETH), Zurich. For the graphical output a Textronix 4014 display and a Benson plotter were used.

Methods

(*a*) *Smoothing spline functions.* For detailed description of the statistical methods and the algorithms used, see Stuetzle (1977). Since the methods are quite important with respect to the present findings, a qualitative explanation follows.

In any statistical analysis of longitudinal data, one tries to determine those traits in the individual curves which are consistent over the population, and to disregard the superposed fluctuations which stem from the histories of single individuals and are not related to the growth process per se. This leads to the following decomposition:

$$f_j(t_i) = f_j^*(t_i) + e_j(t_i),$$

where f_j = series of measurements at times t_i, f_j^* = unknown growth pattern of individual j, and e_j = random term, including measurement error.

We would like to estimate f_j^* as accurately as possible. There exist two different approaches, the regression and the smoothing method, both with specific advantages and disadvantages.

The regression method postulates one functional form for the growth process over a certain epoch for all individuals; e.g. the logistic function (Marubini *et al.*, 1971)

$$f^*(t) = a/\{1 + \exp[-b(t-c)]\}$$

or the Gompertz function (Deming, 1957), both of which are used for fitting height measurements:

$$f^*(t) = a \exp\{-\exp[-b(t-c)]\}$$

For each individual, parameters a, b, and c are estimated by least squares. The above functions are no more than a clever guess, and a serious bias may result due to the differences between the estimated curve and the real growth process. A residual analysis on individuals, e.g. by a run test, is not likely to reveal a distinct bias over the population; this is due to the low discrimination power for small sample size. The introduction of regression functions with more parameters may lower the bias, but at the price of higher variability of the estimated parameters.

The smoothing approach does not assume a unique form of the growth process for all individuals, and we need not postulate a functional form. A graphical procedure, as used in Tanner *et al.* (1966), may be biased and is only reproducible in skilled hands.

We estimate f_j^* by cubic smoothing spline functions (Reinsch, 1967). Such a function (s) allows for an arbitrary squared deviation C from the measured values:

$$\sum_i [s(t_i)-f(t_i)]^2 \leqslant C$$

and in addition has to be made as smooth as possible:

$$\int s''(t)^2\, \mathrm{d}t = \min!$$

Mathematics can prove that s consists piecewise of cubic polynomials, and that the pieces are pasted together very smoothly (with continuous first and second order derivatives). Two extreme cases illustrate how the choice of the smoothing constant C influences the shape of the estimated curve:

(1) $C=0$: s passes through the measurements $(t_i, f(t_i))$

(2) $C=\infty$: s becomes the least squares straight line

The crucial point of any smoothing method lies in the choice of the smoothing constant C. Too large a C may introduce an intolerable bias, and with C too low, we are faced with a large variability. The optimal C makes a compromise between bias and variability. The bias problem here is more transparent than in regression since the smoothing procedure tends to flatten the peaks and fill-up the troughs.

Instead of using common trial-and-error approach, the constant C has been determined by cross-validation (Wahba and Wold, 1975) for each individual. This "one-hold-out" technique has been successful, judged both by eye for the real data and by statistical criteria in simulation. The smoothing approach is excellent, as long

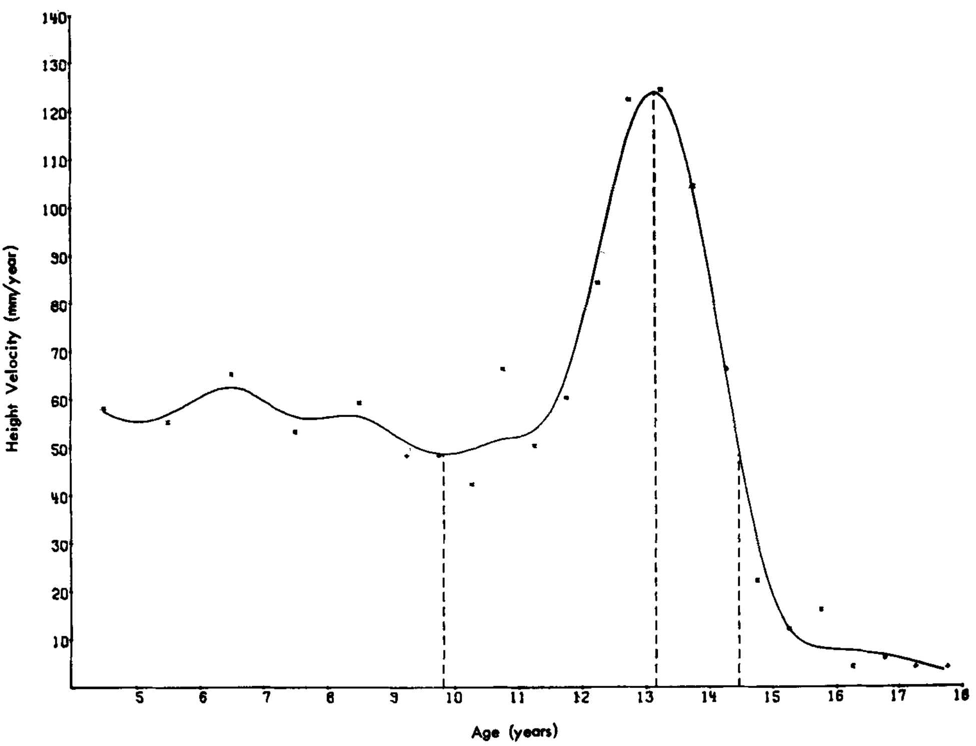

Figure 1. Raw height velocities (divided differences of measured heights) and estimated height velocity curve of a boy who had one of the most prominent growth spurts.

as we remain with descriptive processes; for real modelling, parametric methods become necessary and fruitful, as will be demonstrated in a forthcoming paper (Stuetzle, Gasser, Largo, Prader and Huber, in the press).

Hitherto, growth curves have been analysed using series of measurements of height attained. In this study, the smoothing spline functions are applied to series of values of height velocity. Velocity curves may present more difficulties with regard to estimation and interpretation than distance curves because of large stochastic variations (which are inversely related to the time intervals between the measurements). But these difficulties are more than outweighed by the detailed picture of the dynamics of the growth process which velocity curves offer. Unequal variance and the correlation structure, introduced by forming velocities, can both be accounted for in spline computations. In the case of growth velocity curves we expect the largest bias at the age of peak height velocity (APHV) (Figures 1, 2). The population average of the bias at this point can be estimated by the following procedure:

(*a*) For each individual the residuals (differences between measurements and estimated curve) are determined.

(*b*) The individual curves and the residuals are shifted on the time scale until all the APHV coincide.

(*c*) The residuals are smoothed by a moving average.

The maximal mean residual in our sample was about 5 mm/yr.

The same idea of alignment is used by Tanner *et al.* (1966) to construct their individual type standards.

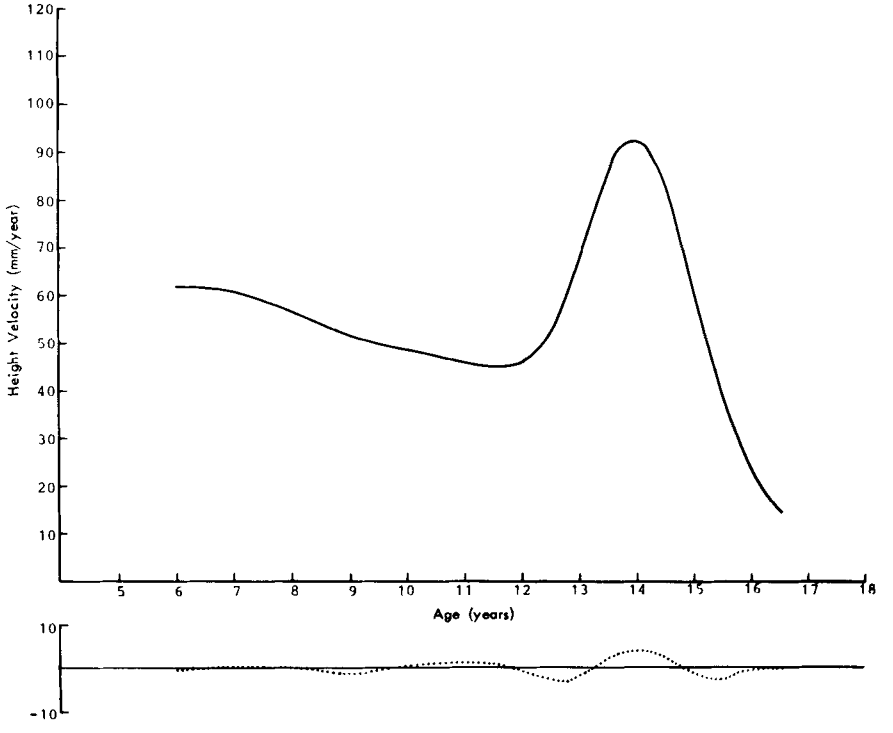

Figure 2. 50th percentile of height velocity in boys (peak height centred). At the bottom mean smoothed bias curve (see methods, section (*c*)).

(b) Definition of the parameters (Figure 3 and Table 1)

Prepubertal height velocity (PV) is defined as the mean annual increment between age 4 and 6½ years. This age period was chosen because during this period there were no major changes in height velocity, especially those due to the onset of pubertal growth. Minimal pre-spurt height velocity (MHV) signifies the onset of the growth spurt; age at minimal pre-spurt height velocity (AMHV) denotes the age at which the spurt begins. Peak height velocity (PHV) is defined as the maximum height velocity during the growth spurt and age at peak height velocity (APHV) as the age at which PHV occurs. Peak height (PH), or increase in height velocity during the growth spurt, is defined as the difference between peak height velocity (PHV) and minimal pre-spurt height velocity (MHV). Minimal pre-spurt height velocity return (MHVR) and age at minimal pre-spurt height velocity return (AMHVR) are height velocity and age when after the spurt, MHV is again attained. AMHVR defines—somewhat arbitrarily—the end of the spurt and is a measure for the duration of growth. Peak basis (PB) is defined as AMHVR − AMHV and is a measure for the duration of the spurt. Peak area (PAR) is defined as PH × PB and is a measure for the intensity of the spurt.

H4 is height at age 4. HMHV, HPHV and HMHVR are defined as height at the onset, at the peak and at the end of the growth spurt. HA (adult height) is defined in 57 boys and 78 girls as the height measured after a 2-year period with an increment in height of less than 0·5 cm. In the other 55 boys and 32 girls who have not yet reached that stage at 20 years of age HA represents height at the age of 20 years.

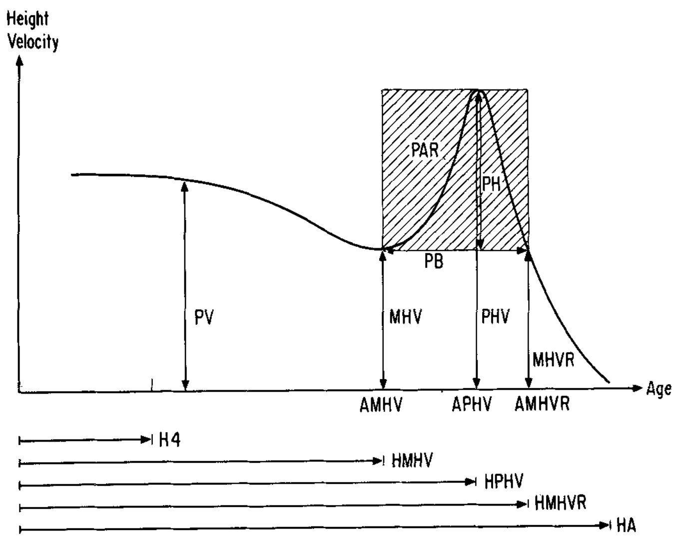

Figure 3. Definition of the parameters.

Results

General description of the adolescent spurt (Table 1 and Figure 4)

From 4 to 9½ years there is only a slight difference in height velocity between boys and girls. The adolescent spurt starts in girls at a mean age of 9·6 years, ranging from 6·6 to 12·9 years (AMHV). In boys the spurt begins 1·4 years later than in girls, at a mean age of 11·0 years, with the earliest onset at 7·8 years and the latest at 13·5 years. As the peak curve has an asymmetrical shape, the peak height velocity (PHV) is attained only at the beginning of the third part of the peak, that is, at 12·2 years in

Parameters		Sex	Mean	SD	Range
AMHV	Age at minimal prespurt height velocity (yr)	m	11·0	1·2	7·8– 13·5
		f	9·6	1·1	6·6– 12·9
APHV	Age at peak height velocity (yr)	m	13·9	0·8	12·0– 15·8
		f	12·2	1·0	9·3– 15·0
AMHVR	Age at minimal prespurt height velocity return (yr)	m	15·5	0·9	13·5– 17·4
		f	13·5	1·1	10·0– 16·2
H4	Height at age 4 (cm)	m	104·3	3·7	96·3–114·0
		f	103·1	3·7	93·4–111·9
HMHV	Height at minimal prespurt height velocity (cm)	m	143·8	7·7	122·7–164·9
		f	135·8	7·3	112·2–151·0
HPHV	Height at peak height velocity (cm)	m	161·9	6·2	149·3–177·5
		f	150·5	5·7	135·9–161·8
HMHVR	Height at minimal prespurt height velocity return (cm)	m	173·0	5·9	161·4–187·6
		f	159·0	5·6	144·9–170·7
HA	Adult height (cm)	m	177·4	6·2	165·8–193·5
		f	164·8	5·7	149·8–176·6
PV	Prepubertal height velocity at age 4–6½ (cm/year)	m	6·3	0·6	4·9– 8·1
		f	6·3	0·6	4·8– 8·1
MHV	Minimal prespurt height velocity (cm/yr)	m	4·2	0·6	2·9– 6·0
		f	4·8	0·7	3·0– 7·0
PHV	Peak height velocity (cm/yr)	m	9·0	1·1	6·7– 12·4
		f	7·1	1·0	5·0– 10·1
PH	Peak height (cm/yr)	m	4·8	1·3	1·9– 7·7
		f	2·4	1·0	0·7– 5·6
PB	Peak basis (yr)	m	4·5	0·9	2·6– 8·2
		f	3·9	0·8	1·3– 6·5
PAR	Peak area = PH × PB (cm)	m	21·7	6·8	8·2– 53·2
		f	9·4	4·5	0·1– 25·2

Table 1. Means, SD and range of the parameters.

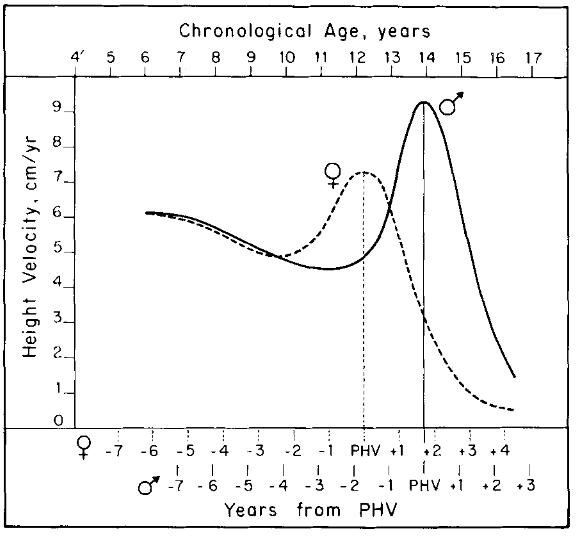

Figure 4. 50th percentile of height velocity in boys and girls (peak height centred).

girls and at 13·9 years in boys (APHV). Peak height (PH), or increase in height velocity during the growth spurt, in boys is 4·8 cm/year, which is twice as high as in girls. Peak height velocity (PHV), the sum of the minimal pre-spurt height velocity (MHV) and the peak height (PH), averages 9·0 cm/year in boys and 7·1 cm/year in girls. The end of the adolescent spurt (AMHVR), defined as the age when the minimal prepubertal velocity (MHVR) is again attained, is reached 3·8 years after the onset of the spurt in girls and 4·5 years thereafter in boys.

The adult height (HA) is 177·4 cm in boys and 164·8 cm in girls. Adult height is mildly underestimated for two reasons. Firstly, according to our definition of adult height (see methods), growth ceased only in two thirds of the girls and in half of the boys at 20 years of age. Secondly, the exclusion from the study of six boys and two girls of very tall stature decreases the mean adult height by about 8 mm in boys and 2 mm in girls.

Variations in the adolescent spurt (Table 1 and Figure 5)

The age at peak height velocity (APHV) averages 12·2 years in girls and 13·9 years in boys and has a wide range of 5·7 years or 3·8 years respectively. The peak basis (PB), which is a measure of the duration of the growth spurt, may be as short as 1·3 years in girls or 2·6 years in boys and may reach 6·5 years or 8·2 years respectively. In 2% of the boys and 33% of the girls, the peak height (PH) is less than 2 cm/year (Figure 5). A peak height of at least 4 cm/year, or in terms of peak height velocity (PHV), a doubling of the minimal pre-spurt velocity (MHV), is found in 70% of the boys and only 11% of the girls. A peak height higher than 6 cm/year is observed in 17% of the boys and in none of the girls.

Adolescent spurt and sex differences in adult height (Table 2)

At age 4 the boys are 1·2 cm taller than the girls. The difference between the height of the girls at the onset of their spurt (AMHV) and the height of the boys at the corresponding age, namely 1·4 years before the onset of the boys' spurt (height at (AMHV minus 1·4 years)) is 1·6 cm. The sex difference in height at the age of minimal prespurt height velocity (AMHV) is 8·0 cm; at the age of peak height velocity (APHV)

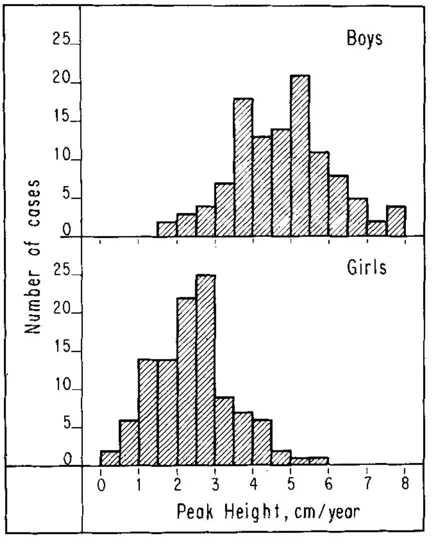

Figure 5. Histograms of peak height in boys and girls.

		Height (cm)	% of HA	Sex difference (cm)
H4	f	103·1	62·6	
	m	104·3	58·8	1·2
HMHV	f	135·8	82·4	
H (AMHV − 1·4 yr)	m	137·4	77·5	1·6
HMHV	m	143·8	81·1	8·0
HPHV	f	150·5	91·3	
	m	161·9	91·3	11·4
HMHVR	f	159·0	96·5	
	m	173·0	97·5	14·0
HA	f	164·8	100·0	
	m	177·4	100·0	12·6

Table 2. Sex difference.

it is 11·4 cm; at the end of the adolescent spurt, defined as the age when minimal pre-spurt height velocity is again attained (AMHVR), it is 14·0 cm. After the adolescent spurt, the sex difference drops to 12·6 cm at the age when growth has ceased. Thus the sex difference of 12·6 cm in adult height is composed of the following four components: +1·6 cm caused by the more extensive growth in boys during the prepubertal period, +6·4 cm by the boys' delay in spurt, +6·0 cm by the greater male spurt and −1·4 cm by the more extensive growth of the girls in the post-spurt period.

To further clarify the sex difference in height growth it is interesting to look at the percentages of adult height attained at different ages. At the girls' onset of the adolescent spurt (AMHV), 82·4% of the adult height is attained by girls; in boys, only 77·5% of the adult height is attained. Because of the delay in spurt, the boys have a lower percentage of adult height than girls at the same chronological prepubertal ages. So, at the age of 4, girls have attained 62·6% and boys 58·8% of the adult height. At the onset of the spurt (AMHV) in both sexes the percentage of adult height attained is 82·4% for girls and 81·1% for boys. At the end of the spurt, the boys have reached 97·7% and the girls 96·5%. This confirms that the adolescent spurt in boys contributes more to the adult height than it does in girls, whereas in the post-spurt period the contribution to adult height in girls is larger than in boys. The latter finding may be in part due to the fact that two thirds of the girls, but only half of the boys have attained adult height according to our definition.

Using only peak height (PH) and age at peak height velocity (APHV) in discriminant analysis, 90% of the individuals could be classified correctly by sex. If all derived parameters were used, this was possible in 97% of the children.

Relationships between the different parameters (*Figure 6*, *Table 3 and 4*)

A factor analysis yielded 4 independent factors (only the results for boys are given, the pattern in girls is the same). These factors reflect the parameters in linear combinations and explain about 90% of the variance in the 14-dimensional factor space. After appropriate rotation (Quartimax) the factors may be interpreted as follows: factor 1 is height (essentially identical with adult height); factor 2 is duration of growth (essentially identical with AMHVR); factor 3 is peak height (PH), and factor 4 is peak basis (PB). Figure 6 and Table 3 illustrate that adult height (HA ~ f1) is uncorrelated with the timing (AMHV, APHV, AMHVR ~ f2), the height (PH ~ f3),

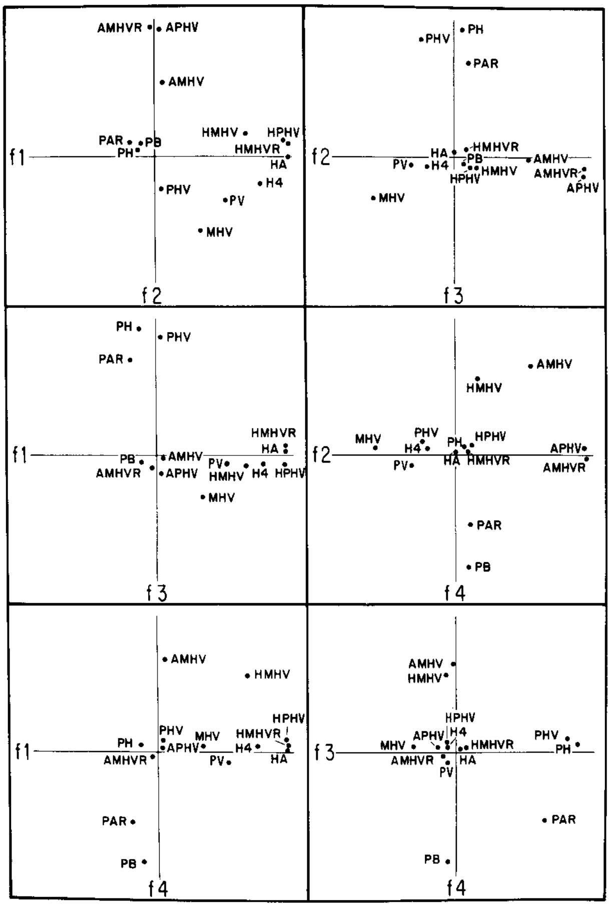

Figure 6. Factor analysis in boys. The four factors represent adult height, duration of growth, peak height and peak basis.

the duration (PB ~ f4) and the intensity (PAR) of the spurt. Minimal pre-spurt height velocity (MHV) and peak height velocity (PHV) are both negatively correlated with age; in remarkable contrast, peak height (PH) is independent of height and age.

A negative partial correlation given adult height was found between the age of minimal prepubertal height velocity (AMHV) and the height at age 4 (H4), and between the prepubertal height velocity (PV) and the age at the onset of the spurt (AMHV) (Table 4). The same applies to the age at peak height velocity (APHV) and the age at the end of the spurt. (AMHVR). Further there is a negative partial correlation given adult height between the height at the onset of the spurt (HMHV) and the peak basis (PB), a measure for the duration of the spurt, but there is no significant correlation between HMHV and peak height (PH).

Discussion

In this study, the onset of the adolescent growth spurt, defined as the age of minimal pre-spurt height velocity (AMHV), is 11·0 years in boys and 9·6 years in girls. Thus the onset of the pubertal growth spurt is slightly earlier than the appearance of the first sex characteristics and the clinically discernible growth spurt.

In our children, the spurt starts about 1·0 year earlier in boys and 0·7 year earlier

	BOYS													
	AMHV	APHV	AMHVR	H4	HMHV	HPHV	HMHVR	HA	PV	MHV	PHV	PH	PB	PAR
AMHV		0·65***	0·62***	−0·08	0·64***	0·20*	0·15	0·09	−0·26**	−0·34***	−0·11	0·06	−0·67***	−0·40***
APHV	0·80***		0·96***	−0·20*	0·24*	0·22*	0·13	0·04	−0·32***	−0·48***	−0·36***	0·09	0·09	−0·04
AMHVR	0·73***	0·97***		−0·27**	0·14	0·11	0·08	−0·01	−0·37***	−0·59***	−0·37***	−0·04	0·17	0·06
H4	−0·03	−0·25**	−0·30***		0·63***	0·78***	0·77***	0·78***	0·47***	0·37***	−0·01	−0·19	−0·15	−0·25
HMHV	0·67***	0·28**	0·16	0·63***		0·81***	0·76***	0·74***	0·36***	0·17	−0·04	−0·12	−0·66***	−0·54***
HPHV	0·48***	0·33***	0·25**	0·66***	0·87***		0·96***	0·95***	0·52***	0·35***	−0·04	−0·20*	−0·15	−0·28**
HMHVR	0·42***	0·33***	0·31***	0·59***	0·75***	0·95***		0·98***	0·51***	0·32***	0·09	−0·07	−0·12	−0·15
HA	0·22*	0·05	0·01	0·71***	0·73***	0·88***	0·89***		0·54***	0·40***	0·11	−0·09	−0·12	−0·17
PV	−0·14	−0·42***	−0·50***	0·42***	0·46***	0·43***	0·32***	0·47***		0·37***	0·02	−0·16	−0·02	−0·16
MHV	−0·54***	−0·72***	−0·78***	0·30***	0·04	0·12	0·07	0·32***	0·57***		−0·01	−0·48***	−0·13	−0·48***
PHV	−0·30***	−0·36***	−0·30***	0·03	−0·13	0·04	0·22*	0·18	0·01	0·39***		0·88***	−0·21*	0·58***
PH	0·10	0·17	0·28***	−0·20*	−0·16	−0·04	0·17	−0·05	−0·42***	−0·35***	0·73***		−0·12	0·74***
PB	−0·29**	0·32***	0·45***	−0·39***	−0·64***	−0·29**	−0·11	−0·27**	−0·51***	−0·40***	−0·03	0·26**		0·56***
PAR	−0·04	0·24*	0·38***	−0·30***	−0·39***	−0·18	0·07	−0·14	−0·56***	−0·45***	0·57***	0·91***	0·59***	
	GIRLS													

*** $P<0{\cdot}001$; ** $P<0{\cdot}01$; * $P<0{\cdot}05$.

Table 3. Correlations between parameters

		H4	PV	MHV	PH	PB
AMHV	m	−0·25 **	−0·37 ***	−0·41 ***		
	f	−0·26 **	−0·28 **	−0·65 ***		
APHV	m	−0·38 ***	−0·40 ***	−0·54 ***		
	f	−0·40 ***	−0·50 ***	−0·78 ***		
AMHVR	m	−0·43 ***	−0·43 ***	−0·64 ***		
	f	−0·44 ***	−0·57 ***	−0·83 ***		
HMHV	m				−0·08	−0·85 ***
	f				−0·19 *	−0·67 ***

*** $P<0{\cdot}001$; ** $P<0{\cdot}01$; * $P<0{\cdot}05$.

Table 4. Conditional correlations given adult height (in boys).

in girls than in the Harpenden study (Tanner *et al.*, 1976). The reason for this difference may be that the age of minimal pre-spurt height velocity (AMHV) cannot be discerned accurately by fitting logistic curves to the growth spurt, but can only be estimated by eye as done by Tanner *et al.* (1976). However, it cannot be ruled out that our smoothing procedure may have slightly underestimated the age at which the spurt takes off. As a consequence of the earlier onset of the spurt all our parameters which depend on AMHV are somewhat different from those of the Harpenden study. The height at the onset of the spurt (HMHV) is 2·3 cm smaller in boys and 2·1 cm smaller in girls than in the Harpenden study. The adolescent gain in our children, defined as adult height minus height at minimal prespurt height velocity is 33·6 cm in boys and 29·0 cm in girls. This is 6·0 cm more, and 3·8 cm more respectively than in the Harpenden study. In addition to the earlier onset of the spurt this difference is a reflection of the greater adult height of 177·4 cm in boys and 164·8 cm in girls in our study.

In the analysis of the derived parameters, we were mainly interested in the following three questions: (1) How large is the individual variation in the adolescent spurt? (2) Which aspects of the growth spurt best characterize sex differences, and how do these relate to the sex difference in adult height? (3) Which parameters best define the adolescent spurt and what are the relationships between these parameters?

Besides the well-known wide variation in the age of the adolescent spurt, our data demonstrate that there is also a great variation in the duration and height of the peak. The peak basis, as a measure of the duration of the adolescent spurt, may be as short as 1·3 years in girls and 2·6 years in boys or may exceed 6 and 8 years respectively. Peak height, or the increase in height velocity during the growth spurt, may be as small as 0·7 cm/year in girls and 1·9 cm/year in boys or may be as large as 5·6 and 7·7 cm/year respectively.

In agreement with Deming (1957) and Tanner *et al.* (1976), our data show that the pubertal growth spurt is much more impressive in boys than in girls. A peak height of at least 4 cm/year, which means, in terms of peak height velocity (PHV), a doubling of the minimal pre-spurt velocity, is found in 70% of the boys and in only 11% of the girls.

According to Tanner *et al.* (1962, 1976) the adult sex difference in height is due to the later onset rather than to the more extensive spurt in boys. We found that the longer lasting prepubertal growth and the greater extent of the growth spurt in males both contribute 6 cm to the final sex difference in adult height. Furthermore, during the post-spurt period the girls show a larger gain in height than the boys. Thus, the maximum sex difference of 14 cm at the end of the spurt is reduced to the final difference in adult height of 12·6 cm.

This analysis of the contribution of the growth spurt to the sex difference in adult height can be confirmed by looking at the percentage of adult height attained at different ages. During the prepubertal period the boys have a lower percentage of adult height than the girls at the same chronological age. At the age of peak height velocity, both sexes have reached 91·3% of the adult height and at the end of the spurt the boys have reached 97·5% and the girls 96·5% of their respective adult heights. Thus, in boys the prepubertal period required to attain the same percentage of adult height is longer; there is more growth during the pubertal period and less in the post-spurt period than observed in girls. These findings coincide with the fact that in discriminant analysis peak height (PH) and age at peak height velocity (APHV) allow a good discrimination between boys and girls.

Correlations indicate that adult height does not depend either on the duration of growth or on the duration and height of the peak. Thus, a child does not become tall because of the late onset of a long lasting and high growth spurt. Furthermore, peak height, or increase in height velocity during the growth spurt, is independent of age and height of the child.

Partial correlations given adult height revealed two compensating mechanisms between the prepubertal and pubertal period. Firstly, a child with long-lasting growth, i.e. with a late growth spurt, tends to grow slower in the prepubertal period with respect to his adult height. Secondly, a child with a low prepubertal percentage of adult height has a longer-lasting but not higher spurt than a child with a higher prepubertal percentage of adult height.

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Zusammenfassung. Für 112 Knaben und 107 Mädchen der Zürcher Längsschnittstudie (1955–1976) wurden die Körperhöhen-Zuwachskurven zwischen 4,5 und 17,5 Jahren mit Hilfe glättender Splinefunktionen geschätzt. Die Parameter, die den Wachstumsvorgang charakterisieren, wie größter Körperhöhenzuwachs und Alter beim größten Körperhöhenzuwachs, wurden direkt aus den Kurven berechnet.

Die Variabilität der Parameter, die den jugendlichen Wachstumsschub beschreiben, ist groß, sowohl zwischen als auch innerhalb der Geschlechter. Größter Körperhöhenzuwachs, definiert als Körperhöhen-Geschwindigkeit während des Wachstumsschubes, und Alter beim höchsten Körperhöhenzuwachs charakterisieren den Geschlechtsunterschied im Wachstum hochsignifikant. Ein größter Körperhöhenzuwachs von mindestens 4 Zentimetern pro Jahr findet sich bei 70% der Knaben, aber nur bei 11% der Mädchen. Das Alter beim größten Körperhöhenzuwachs beträgt im Durchschnitt 12,2 Jahre bei Mädchen und 13,9 Jahre bei Knaben und hat die weite Spanne von 5,7 bzw. 3,8 Jahren.

Der Geschlechtsunterschied der erwachsenen Körperhöhe von 12,6 Zentimetern setzt sich aus folgenden 4 Faktoren zusammen: +1,6 cm durch stärkeres präpuberales Wachstum bei Knaben, +6,4 cm durch die Verzögerung des Wachstumsschubs bei Knaben, +6,0 cm durch den stärkeren Wachstumsschub bei Knaben und −1,4 cm durch stärkeres Wachstum der Mädchen nach dem Wachstumsschub.

Die Korrelationen zwischen den Parametern zeigen, daß die erwachsene Körperhöhe weder von der Dauer des Wachstums abhängt, noch von der Dauer und der Höhe des Gipfels. Der geringste Körperhöhenzuwachs vor dem Schub und der größte Körperhöhenzuwachs, nicht aber die Gipfelhöhe, hängen von Alter und Körperhöhe ab. Die Partialkorrelationen mit der erwachsenen Körperhöhe ergeben zwei Kompensationsmechanismen zwischen dem Wachstum in der präpuberalen und in der puberalen Phase. Geringe präpuberale Körperhöhe und geringer Körperhöhenzuwachs im Verhältnis zur erwachsenen Körperhöhe werden gefolgt von einem späten jugendlichen Schub und umgekehrt. Geringe Körperhöhe beim Einsetzen des Wachstumsschubes, im Verhältnis zur erwachsenen Körperhöhe, wird von einem länger andauernden, aber nicht stärkeren Schub gefolgt und umgekehrt.

Résumé. Des courbes de vitesse de croissance en taille de 4,5 à 17,75 ans ont été estimées á l'aide de fonction de lissage des irrégularités pour 112 garçons et 110 filles de l'Etude Longitudinale de Zurich (1955–1976). Des paramètres caractérisant le processus de croissance, tels que le pic de vitesse de croissance en taille et l'âge à ce pic, ont été calculés directement à partir des courbes.

La variabilité des paramètres décrivant la poussée de croissance à l'adolescence est grande, à la fois entre les sexes et dans chaque sexe. La hauteur du pic, définie comme l'augmentation de la vitesse de croissance en taille durant la poussée de croissance, et l'âge au pic de croissance en taille caractérisent tous deux la différence sexuelle de croissance de façon hautement significative. Une hauteur du pic d'au moins 4 cm par an est trouvée chez 70% des garçons, mais chez seulement 11% des filles. L'âge au pic de vitesse de la taille est en moyenne de 12,2 ans chez les filles et 13,9 ans chez les garçons avec une large amplitude de 5,7 ans et 3,8 ans respectivement.

La différence sexuelle de taille adulte, de 12,6 cm, est composée des quatre facteurs suivants: +1,6 cm causé par plus de croissance pré-pubertaire chez les garçons, +6,4 cm par le retard des garçons en poussée pubertaire, +6,0 cm par la poussée plus intense chez les garçons, et −1,4 cm par davantage de croissance aprés la poussée chez les filles.

Les corrélations entre les paramètres indiquent que la taille adulte ne dépend ni de la durée de la croissance ni de la durée et de la hauteur du pic. La vitesse de croissance minimale avant la poussée et la vitesse de pointe, mais non la hauteur du pic, dépendent de l'âge et de la taille.

Les corrélations partielles à taille adulte constante révèlent deux mécanismes compensatoires entre la croissance à la période pré-pubertaire et à la période pubertaire. Une petite taille pré-pubertaire et une basse vitesse de croissance en taille par rapport à la taille adulte sont suivis par une poussée pubertaire tardive et vice-versa. Une taille petite au début de la poussée par rapport à la taille adulte est suivie par une poussée durant plus longtemps, mais plus intense, et vice-versa.