ANNALS OF HUMAN BIOLOGY, 2001, VOL. 28, NO. 3, 328–336

Growth of early and late maturers

T. GASSER†, A. SHEEHY†, L. MOLINARI‡ and R. H. LARGO‡

† Universität Zürich, Zurich, Switzerland
‡ Kinderspital Zürich, Zurich, Switzerland

Received 28 March 2000; accepted 23 August 2000

Summary. *Background*: This is a study on the growth of subgroups of normal children, maturing early or late, in the variables height, leg and sitting height, arm length, biiliac and bihumeral width. While a longer growth period affects adult height only marginally, less is known about the other variables. It is also of interest to see in what way a shorter growth period is compensated by a higher velocity.
Methods: Out of 120 boys and 112 girls followed from 4 weeks until adulthood, subgroups of 40 boys and 37 girls were formed with respect to the average timing (across variables) of the pubertal spurt as an indicator of maturity.
Results: Only leg height shows a smaller adult size for early maturers. The shorter growth period is compensated by a higher prepubertal velocity and a higher level in pubertal years. The pubertal peak is a little larger for early maturing boys but not for girls.
Conclusions: There is an inherent pacemaker for growth that leads to the same adult size for a shorter growth period via a higher basic intensity. Legs are an exception since late maturers have, on average, longer legs as adults.

1. Introduction

In this paper we study growth from infancy until adulthood of early and late maturing normal children in terms of height, sitting and leg height, arm length and biiliac and bihumeral width. The maturity stage has been defined anthropometrically based on the age of peak velocity. Since there is only one puberty it does not make sense to define the maturational stage for each variable separately. We have, therefore, used the average age of peak velocity across the six variables studied, thereby also reducing the inevitable random variability when extracting age of peak velocity from noisy data. *A priori* one would expect late maturing children to have larger sizes as adults, due to the longer growth period. Most studies have, however, not found any difference in final height in either sex (Bayley 1956, Tanner 1962, Lindgren 1978). It is quite clear that early maturers have to be taller around the age of their pubertal growth spurt (PS) compared to late maturers at the same chronological age. Hägg and Taranger (1991) found the late maturing boys to be significantly taller as adults, but this was not true for girls. While most papers are based on pubertal peak velocity as an index of maturity (as is ours), a paper by Frisancho and Housh (1988) is based on bone age as index of maturity: from infancy till age 16, early maturing boys were significantly taller, girls only till age 12. We will reconsider this problem for height, and investigate it for the other five variables not studied previously.

Early maturing children, in our definition, start their PS about 1.5 (girls) or almost 2 years (boys) earlier than late maturers. They gain, therefore, a smaller increment in prepubertal years, due to a smaller growth period. Given that there are no or only small differences in adult size, the question then arises whether early maturers compensate this 'loss' by more intense growth in infancy, in childhood or in adolescence.

Annals of Human Biology ISSN 0301–4460 print/ISSN 1464–5033 online
http://www.tandf.co.uk/journals
DOI: 10.1080/0301446001000463 8

2. Subjects and methods

2.1. Subjects

In a prospective multicentre study (Falkner 1960) started in 1954, 321 children from Zurich participated in the Swiss cohort. For the longitudinal analysis we rely on $n = 112$ girls and $n = 120$ boys with essentially complete measurements from 4 weeks to 20 years (see Gasser, Kneip, Ziegler *et al.* 1990 or Sheehy, Gasser, Molinari *et al.* 1999 for details). All subjects were measured regularly until age 18, and most boys had measurements until age 20 or beyond ($n = 24$ at age 21, $n = 30$ at age 22, $n = 14$ at age 23, $n = 5$ at age 24 or 25). The last measurement was defined to be adult size. Subgroups of one-third of the children who matured early or late were formed in the following way: the age of peak velocity during the pubertal spurt (PS) was determined for each child and each anthropometric variable. The average of these six timings was then used as an indicator of individual maturity. One-third of the children with the lowest values was assigned to the early maturers, and one-third with the largest values to the late maturers. This resulted in subgroups of size $n = 40$ for boys and $n = 37$ for girls.

2.2. Measurements

Measurements were obtained at 1, 3, 6, 9, 12, 18 and 24 months and annually afterwards until age 9 for girls and age 10 for boys. Then followed half yearly measurements until the age when the annual increment in height was less than 0.5 cm, when yearly measurements started again. Measurements were continued until at least age 18, but most children were measured until age 20. It should be noted that measurements of bihumeral width started only at around age 2 for a small number of the children, reducing the number of children for whom early growth phases can be assessed in all six variables ($n = 29$ early maturing girls, $n = 24$ early boys, $n = 30$ late girls and $n = 32$ late boys).

Bihumeral and biiliac width were measured to the nearest millimetre with callipers, standing and sitting height were taken with a Harpenden stadiometer, and leg height was defined to be the difference of these measurements. Arm length was measured with a tape and the result was rounded to whole centimetres.

2.3. Statistical methods

The structural average growth curve for distance, velocity and acceleration is described in Gasser *et al.* (1990) and for the mathematically oriented reader in Kneip and Gasser (1992). Increments have been computed until age 1.5 years, from 1.5 to 6 years and from 6 years to the onset of the PS. The adolescent increment has been subdivided into an increment due to the spurt (the velocity peak above the prepubertal level) and one due to the level (the approximate contribution if prepubertal growth had continued at the same pace during puberty). See Sheehy, Gasser, Molinari *et al.* (2000) or Gasser, Sheehy and Largo (2001) for an exact definition. Relative increments were obtained by dividing by adult size. Each relative increment was submitted to a repeated measures analysis of variance (ANOVA) with the two between group factors 'early/late' and 'boys/girls' one within group factor 'variables'. It is of primary importance to test for the significance of differences between early and late maturers; significant interactions would indicate that some differences are specific to certain variables or to one sex. Further details on the method may be found in Sheehy *et al.* (1999).

3. Results

Tables 1 and 2 give means and standard deviations at adulthood and at 4 weeks. Differences are small and inconsistent at 4 weeks. As adults, late maturers have longer legs than early maturers and this difference is significant for girls ($p = 0.03$). As a consequence, height is also different, but not significantly. Arm length is the only other variable where small, statistically insignificant differences can be found for both sexes.

Figure 1 shows the growth of the legs and the trunk for the early and late maturers. For sitting height, early maturers have consistently higher values from an early age onwards. The difference becomes large when they enter their PS, but there is a complete convergence towards adulthood and this is true for both sexes. For legs, the differences are not as accentuated, due to the less intense PS compared to the trunk, and late maturers overtake early maturers during the late phase of their PS.

Structural average velocity curves for height for late and early maturers can be seen in figure 2. The velocity curve is a little lower for late maturers in childhood and prepubertal years (see in particular the girls' curves). Their later PS is roughly of the same intensity and the same duration as the one for early maturers, and this is also true for other variables. The fading out of the velocity curve is, however, more abrupt for the late maturers. Based on our definition, late maturers experience their PS close to 2 years later than early maturers across the six variables and in both sexes.

As a next step, we compared the percentage (or relative) increments for different growth phases for early and late maturers. As expected, late maturers gained more in prepubertal years, from 6 years till the onset of the PS (figure 3). This difference is

Table 1. Means ($\bar{x}$) and standard deviations (SD) of adult size for subgroups of early and late maturing boys ($n = 40$ boys and $n = 37$ girls).

Sex	Group		Standing height	Leg height	Arm length	Sitting height	Biiliac width	Bihumeral width
m	early	$\bar{x}$	177.6	83.8	79.4	93.8	28.0	42.9
		SD	6.5	4.5	3.5	3.2	1.8	1.6
	late	$\bar{x}$	178.8	85.2	80.2	93.7	27.8	42.2
		SD	6.8	4.5	3.3	3.4	1.7	1.8
f	early	$\bar{x}$	164.1	76.0	72.2	88.1	27.6	37.3
		SD	5.1	3.5	2.9	2.5	1.8	1.8
	late	$\bar{x}$	166.3	78.2	73.6	88.1	27.9	37.9
		SD	7.1	4.8	3.5	3.2	1.8	1.6

Table 2. Means ($\bar{x}$) and standard deviations (SD) for size at 4 weeks for subgroups of early and late maturing boys ($n = 40$) and girls ($n = 37$).

Sex	Group		Standing height	Leg height	Arm length	Sitting height	Biiliac width	Bihumeral width
m	early	$\bar{x}$	53.6	19.6	21.5	34.0	9.0	13.2
		SD	2.1	1.1	1.3	1.7	0.5	1.5
		late	53.0	19.4	21.6	33.5	8.7	13.7
		SD	2.2	1.1	1.5	1.4	0.5	2.4
f	early	$\bar{x}$	52.3	19.2	21.2	33.1	8.7	13.1
		SD	2.1	1.1	1.4	1.5	0.5	1.6
	late	$\bar{x}$	52.6	19.3	21.2	33.4	8.7	13.6
		SD	1.7	1.4	1.5	1.0	0.4	1.9

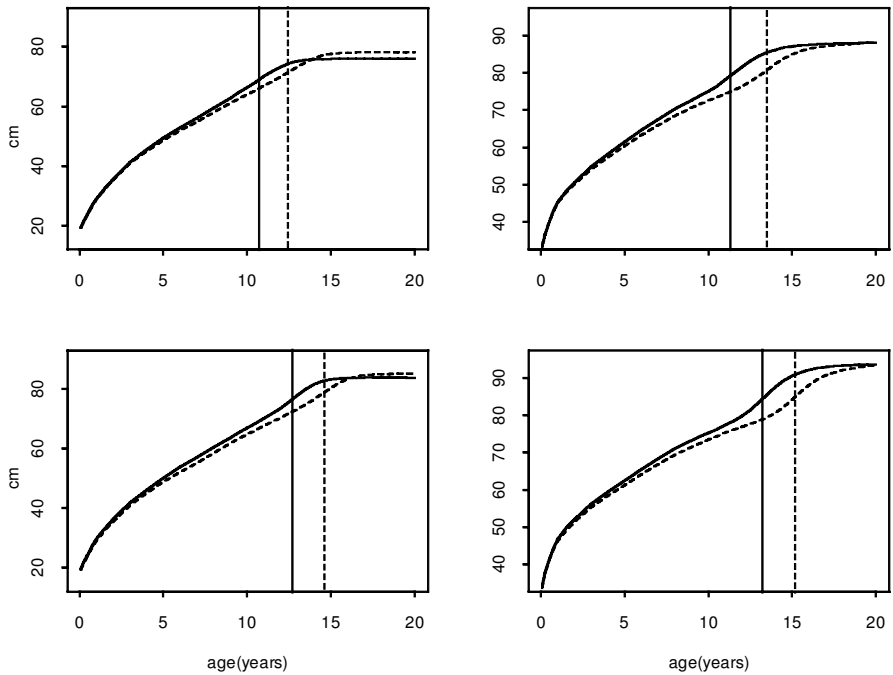

Figure 1. Distance curves for legs (left side) and for sitting height (right side) for subgroups of early and late maturing girls (above, $n = 37$) and of early and late maturing boys (below, $n = 40$). Solid lines are early maturers, dashed lines late maturers. Horizontal lines are ages of peak velocities.

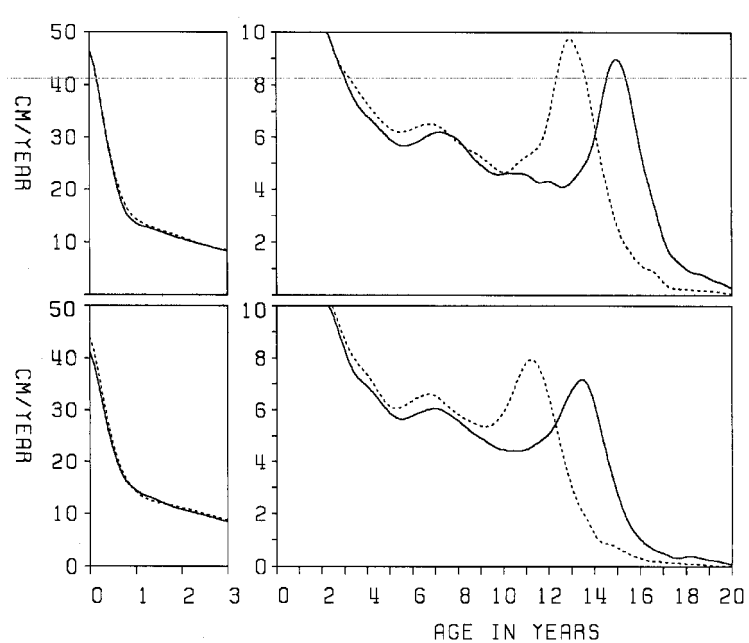

Figure 2. Structural average velocity curves for early maturers (dashed lines) and late maturers (solid lines) for subgroups of girls ($n = 37$), below, and for subgroups of boys ($n = 40$), above. First 3 years also on separate scales.

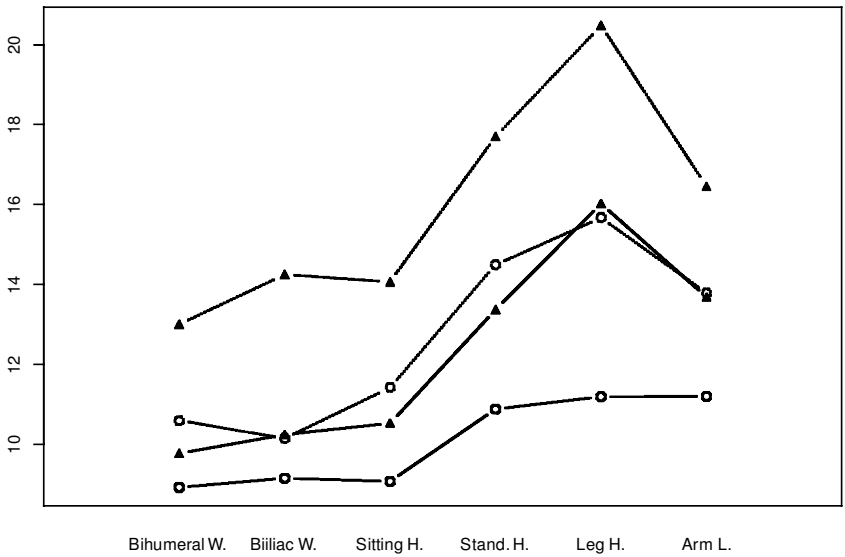

Figure 3. Means of relative increments from 6 years to the onset of the PS for early maturers (solid lines) and late maturers (dashed lines) and for boys (▲, $n = 40$) and girls (○, $n = 37$).

relatively homogeneous and highly significant ($p < 0.0001$). From the plot we also note substantial variation between different parts of the body ($p < 0.0001$), with a very large contribution in this period for legs. That girls have lower relative increments can be explained by their earlier onset to the PS. While the prepubertal increment is larger for late maturers, due to their later PS, the average velocity in this period is higher for early maturers in all variables and both sexes. This difference is largest for sitting height and smallest for legs and bihumeral width.

As a consequence, early maturers have to gain relatively more in some other period. The relative size achieved at 1.5 years (= the relative increment from conception till 1.5 years) differs already to some extent between early and late maturers and these differences are significant ($p = 0.0008$). However, the differences are low in practical terms (figure 4). Legs and arms are evidently totally different from the two widths. A substantial sex discrepancy arises for bihumeral width irrespective of the maturity stage. For bihumeral width and for the other variables, the higher relative increments for girls are simply due to the smaller average adult sizes compared to boys, and the same argument explains the approximate agreement for biiliac width. Early childhood, from 1.5 till 6 years, offers a straightforward picture (figure 5); early maturing children gain consistently a significantly larger percentage ($p < 0.0001$), and this difference is remarkably homogeneous across variables and the two sexes (figure 5). Not to our surprise, no interaction terms are statistically significant. It is, however, remarkable how large the relative gain is for legs, compared to the two widths and sitting height (differences between variables are significant with a $p < 0.0001$).

The percentage contribution in adolescence was subdivided into a component due to the velocity level prevailing prepubertally and continued into adolescence, and one due to the pubertal velocity peak, the typical feature of the PS (see section 2). The increment due to the level was for early maturing children significantly higher ($p < 0.0001$) as a main effect, i.e. over all variables and both sexes combined

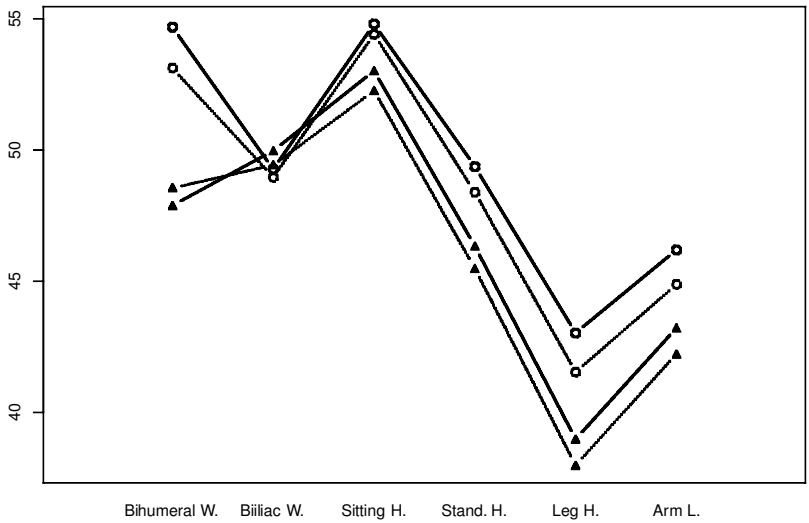

Figure 4. Means of relative increments from conception to 1.5 years for early maturers (solid lines) and late maturers (dashed lines) and for boys (▲, $n = 40$) and girls (○, $n = 37$).

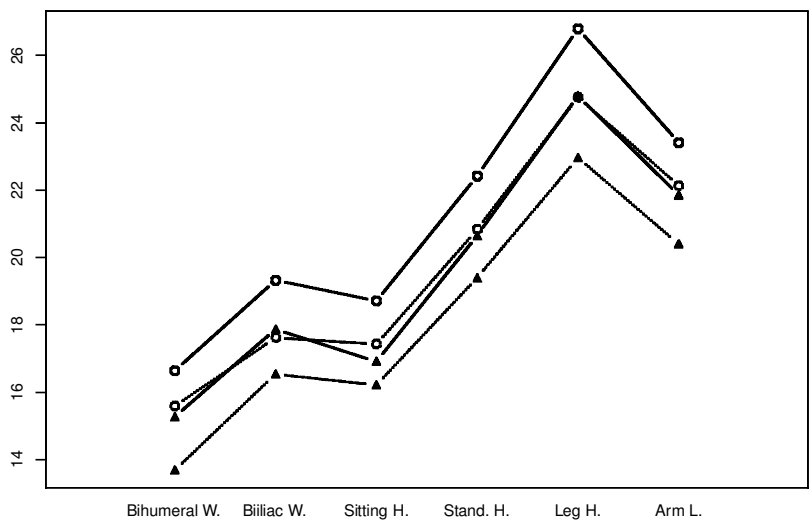

Figure 5. Means of relative increments from 1.5 to 6 years for early maturers (solid) and late maturers (dashed) and for boys (▲, $n = 40$) and girls (○, $n = 37$).

(figure 6). The difference is sizeable—and consistent—for height, leg height and sitting height, and small or inconsistent for the widths, leading to a significant interaction term variable × maturity stage ($p = 0.0009$). As in prepubertal years, we note a relatively large contribution for the legs, compared to other variables.

The contribution due to the spurt (i.e. due to the pubertal velocity peak) shows an accentuated discrepancy across variables and for boys and girls. Early maturing boys have somewhat higher gains due to the spurt than late maturers, and this difference is substantial for bihumeral width. Since this is not true for girls, a significant interaction maturity stage × sex arises, but no significant main effect for the maturity stage.

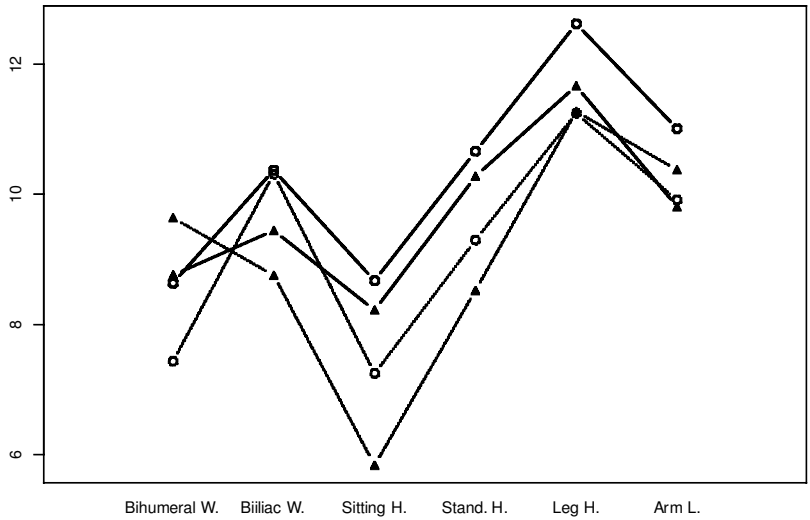

Figure 6. Means of relative increments due to the basic velocity level in adolescence for early maturers (solid lines) and late maturers (dashed lines) and for boys (▲, $n = 40$) and girls (○, $n = 37$).

4. Discussion

Most studies have found no difference in adult height between early and late maturers, as outlined in the Introduction. In the study by Hägg and Taranger (1991), late maturing boys achieved a larger adult height but this was not true for girls. They pointed out the importance of measuring late maturing boys to a sufficiently mature age (beyond 18 or 20 years, the oldest ages in most studies). While we agree with this point of view we have to stress that late growth in height is mostly due to the trunk and not to the legs, a distinction rarely made.

In our study, late maturing girls have significantly longer legs compared to early maturing girls. As a consequence height is also larger, but the difference is no longer statistically significant. For boys, we find also longer adult legs for late maturers but the difference is smaller and not significant. Thus, we see a modest, statistically insignificant difference in height. That legs are a little longer for late maturers is not implausible since prepubertal growth is decisive for the legs, when compared to pubertal growth or compared to other variables and also with respect to sex differences (Gasser, Kneip, Binding *et al.* 1991a, Gasser, Sheehy, Molinari *et al.* 2000). The longer growth period favours therefore specifically the legs. It is also notable that there is absolutely no difference between early and late maturers in adult sitting height in both sexes. Our data give clear evidence that late maturers show only a modest and statistically insignificant difference in height. This cannot be attributed to missing late growth which is anyhow due only to the trunk, since growth of the legs stops abruptly (Gasser *et al.* 1991a). Most of our girls have measurements until age 19 or 20 when even late growth has stopped. Given the fact that 73 of our 120 boys had their last measurement between 21 and 25 (see section 2), there is no time for much further growth in the trunk.

Early and late maturers do not differ in the adult size of biiliac or bihumeral width. The small difference in favour of late maturers for arm length is consistent with the finding for legs, since the growth of both variables is due to the growth of long bones.

The structural average velocity curves indicate that early maturing children compensate for their shorter duration of growth mainly by a higher basic velocity level in childhood and in pre-adolescence. This holds also for the basic velocity level in adolescence when continuing the prepubertal level into adolescence (Gasser *et al.* 2001). The pubertal spurt, on the other hand, is roughly of a similar intensity and duration for both early and late maturing children. That the PS is not a decisive factor for adult size is in line with clinical findings: in hypogonadism there is no PS, but a slowly decaying velocity trend leading to an adult size which even is somewhat higher compared to normal growth (Prader 1984, Uriarte, Baron, Garcia *et al.* 1992). This is due to the growth of the legs, similar to the late normal variant of growth. As always, the comparison of variants of normal growth with pathological growth has to be made with some caution.

An early maturation reduces the time available for growing (by about 1.5–2 years in the subgroups studied here and this has to be compensated by a higher growth intensity in certain phases of growth). Despite a higher velocity in prepubertal years from 6 years to the onset of the PS, the percentage increment for this period is significantly smaller for early maturers due to the shorter growth period. This effect can be seen consistently for both sexes and for all variables. Also due to the higher velocity level from 1.5 to 6 years early maturers gain substantially compared to late maturers. However, already the percentage of size achieved at 1.5 years is slightly greater for early maturers, indicating that there is an inherent pacemaker in the growth process acting long before puberty. Differences exist also in puberty, but they are of minor importance compared to prepubertal years. A modest relative gain for early maturers is due to a higher basic velocity level prevailing in puberty and conceptualized by us as a continuation of a prepubertal velocity level into puberty (Gasser *et al.* 2001). The contribution due to the pubertal velocity peak is somewhat higher for early maturing boys but not for early maturing girls which is qualitatively in line with the greater role played by the pubertal spurt for boys.

It is striking that there is a tremendous difference between variables with respect to the gains achieved in various growth phases. Partly, these relative gains are also quite specific for boys or for girls or for different variables—in particular the two widths. This is in line with our previous studies (Gasser *et al.* 1991a, Gasser, Kneip, Ziegler *et al.* 1991b, Sheehy *et al.* 1999) indicating a high specificity of growth processes in different anthropometric variables and in the two sexes.

Acknowledgements

This work was supported by the Swiss National Science Foundation (Project no. 3200-045829.95/2)

References

Bayley, N., 1956, Growth curves of height and weight by age for boys and girls, scaled according to physical maturity. *Journal of Pediatrics*, **48,** 187–194.

Falkner, F., (ed.) 1960, *Child Development: an International Method of Study* (Basel: Karger).

Frisancho, A. R., and Housh, C. H., 1988, The relationship of maturity rate to body size and body proportions in children and adults. *Human Biology*, **60,** 759–770.

Gasser, T., Kneip, A., Ziegler, P., Largo, R. H., and Prader, A., 1990, A method for determining the dynamics and intensity of average growth. *Annals of Human Biology*, **17,** 459–574.

Gasser, T., Kneip, A., Binding, A., Prader, A., and Molinari, L., 1991a, The dynamics of linear growth in distance, velocity and acceleration. *Annals of Human Biology*, **18,** 187–205.

Gasser, T., Kneip, A., Ziegler, P., Largo, R. H., Molinari, L., and Prader, A., 1991b, The dynamics of growth of width in distance, velocity and acceleration. *Annals of Human Biology*, **18,** 449–461.

Gasser, T., Sheehy, A., Molinari, L., and Largo, R. H., 2000, Sex dimorphism in growth. *Annals of Human Biology*, **27,** 187–197.

Gasser, T., Sheehy, A., and Largo, R. H., 2001, Statistical characterization of the pubertal growth spurt. *Annals of Human Biology* (in press).

Hägg, U., and Taranger, J., 1991, Height and height velocity in early, average and late maturers followed to the age of 25: a prospective longitudinal study of Swedish urban children from birth to adulthood. *Annals of Human Biology*, **18,** 47–56.

Kneip, A., and Gasser, T., 1992, Statistical tools to analyze data representing a sample of curves. *Annals of Statistics*, **20,** 1266–1305.

Lindgren, G., 1978, Growth of school children with early, average and late ages of peak height velocity. *Annals of Human Growth*, **5,** 253–267.

Prader, A., 1984, Biomedical and endocrinological aspects of normal growth and development. In *Human Growth and Development*, edited by J. Borms, R. Hauspie, A. Sand, C. Susanne and M. Hebbelinck (New York: Plenum), pp. 1–22.

Sheehy, A., Gasser, T., Molinari, L., and Largo, R. H., 1999, An analysis of variance of the pubertal and midgrowth spurts for length and width. *Annals of Human Biology*, **26,** 309–331.

Sheehy, A., Gasser, T., Molinari, L., and Largo, R. H., 2000, Contribution of growth phases to adult size. *Annals of Human Biology*, **27,** 281–298.

Tanner, J. M., 1962, *Growth at Adolescence* (Oxford: Blackwell Scientific).

Tanner, J. M., Whitehouse, R. H., Marubini, E., and Resele, L. F., 1976, The adolescent growth spurt of boys and girls of the Harpenden Growth Study. *Annals of Human Biology*, **3,** 109–126.

Uriarte, M. M., Baron, J., Garcia, H. B., Barnes, K. M., Loriaux, D. L., and Cutler, G. B. Jr, 1992, The effect of pubertal delay on adult height in men with isolated hypogonadotropic hypogonadism. *Journal of Clinical Endocrinology and Metabolism*, **74,** 436–440.

Address for correspondence: Theo Gasser, University of Zurich, Biostatistics, ISPM, Sumatrastrasse 30, CH-8006 Zurich, Switzerland. email: tgasser@ifspm.unizh.ch.

Zusammenfassung. *Hintergrund:* Es handelt sich um eine Studie über das Wachstum von Untergruppen früh- oder spätreifender normaler Kinder bezüglich der Variablen Körperlänge, Beinlänge und Sitzhöhe, Armlänge, Beckenbreite und Ellbogenbreite. Während eine längere Wachstumperiode die Erwachsenenkörperhöhe nur unbedeutend beeinflusst, ist über die anderen Variablen wenig bekannt. Es ist daher interessant zu sehen, in welcher Weise eine kürzere Wachstumsperiode durch eine höhere Wachstumsgeschwindigkeit kompensiert wird.
Methodik: Aus einer Gruppe von 120 Jungen und 112 Mädchen, die vom Alter von 4 Wochen bis zum Erwachsenenalter untersucht wurden, wurden Untergruppen von 40 Jungen und 37 Mädchen gebildet. Dies erfolgte mit Bezug auf den durchschnittlichen Zeitpunkt (ermittelt aus allen Variablen) des puberalen Spurts als Reifungsindikator.
Ergebnisse: Nur die Beinlänge zeigt eine geringere Erwachsenengröße bei den Probanden mit früher Reife. Die kürzere Wachstumsperiode wird durch eine höhere präpuberale Geschwindigkeit und ein höheres Niveau in den Pubertätsjahren kompensiert. Der puberale Gipfel ist etwas größer bei den Jungen mit früher Reife, nicht dagegen bei den Mädchen.
Schlussfolgerungen: Es gibt einen inhärenten Schrittmacher für das Wachstum, welcher bei einer kürzeren Wachstumsperiode über eine höhere Basisintensität zur gleichen Erwachsenengröße führt. Die Beinlänge bildet eine Ausnahme, da die spät Reifenden im Durchschnitt als Erwachsene längere Beine haben.

Résumé. *Arrière plan*: il s'agit d'une étude sur la croissance de la la stature, hauteur de la jambe et de la taille-assis, de la longueur du bras et des largeurs bihumérale et biiliaque, chez des sous-groupes d'enfants normaux à maturation lente ou rapide. Alors qu'on sait qu'une plus longue période de croissance n'affecte la stature adulte que de façon marginale, peu de choses sont connues quant aux autres variables. Il est également intéressant de voir dans quelle mesure une période de croissance plus courte est compensée par une vélocité plus grande.
Méthode: à partir d'échantillons de 120 garçons et 112 filles suivis de l'âge de quatre semaines jusqu'à l'état adulte, on a formé des sous-groupes de 40 garçons et de 37 filles, selon la chronologie moyenne (calculée sur l'ensemble des variables) de la poussée pubertaire, considérée comme un indicateur de maturité.
Résultats: seule la hauteur de la jambe exprime une plus petite taille adulte chez les enfants à maturation rapide. La période de croissance plus courte est compensée par une vélocité prépubertaire plus élevée et un plus haut niveau pendant la puberté. Le pic pubertaire est un peu plus marqué pour les garçons à maturation précoce, mais non pour les filles.
Conclusions: il existe un régulateur inhérent au processus de croissance, qui conduit à une dimension adulte identique lorsque se raccourcit la période de croissance, via une intensité de base plus grande. Les jambes en sont une exception, car les enfants à maturation tardive ont en moyenne de plus longues jambes à l'état adulte.