Growth processes leading to a large or small adult size

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Summary. *Background*: The way in which a large size in anthropometric variables is achieved is a longstanding problem, since the pubertal spurt shows statistically and clinically little association with adult size (mostly studied for height). By analysing longitudinal growth of groups of subjects with a large or a small adult size separately for height, leg and sitting height, and bihumeral and biiliac width, we studied this problem in some detail. Of interest are growth patterns specific for these variables and for boys or girls.
Methods: The data consist of 120 boys and 112 girls followed longitudinally from 4 weeks until adulthood. Statistically, structural average velocity curves were computed for each variable and each subgroup separately for comparison. This velocity curve represents the average intensity and the average tempo of growth. Since the area under the velocity curve is adult size, differences in the growth process can be visualized.
Results: Both sexes show similar patterns in reaching a small or large adult size. The different variables, however, show marked differences. Only for legs is the pubertal spurt delayed for the large groups (with additional gains in prepubertal years). For sitting height and biiliac width, a slightly elevated velocity all along development (after 2 years) leads to a larger size and for bihumeral width the size of the pubertal peak is decisive.
Conclusions: The steering of growth to a certain target size is qualitatively similar for boys and girls, but quite different for different anthropometric variables. This leads to questions about endocrinological control for various parts of the body and differential bone growth in development.

1. Introduction

In the auxological literature, it has long been a matter of debate as to how and when tall subjects reach on average their greater adult height than small subjects. In principle, this could be achieved by a prolonged growth period, by a higher prepubertal growth velocity or by a stronger pubertal spurt (PS), or a mixture of these factors. An intriguing fact is that the timing and intensity of the PS—the most prominent growth process after infancy—does not show sizeable correlations with adult size (Tanner, Whitehouse, Marubini *et al.* 1976, Largo, Gasser, Prader *et al.* 1978, Sheehy, Gasser, Molinari *et al.* 2000). Since the timing of the PS is closely related with the total period of growth, this finding is surprising.

In a methodological contribution Gasser, Kneip, Ziegler *et al.* (1990) introduced structural average growth curves (in terms of distance, velocity and acceleration) as a statistical technique for understanding the whole growth process. As an illustration of the method, subjects with a large or small adult height were compared with respect to their velocity curves (figure 9 in Gasser *et al.* 1990). The idea being that in this way, one could gain insight into how and when the difference in adult height is generated. It turned out that most of the adult variation in adult height is due to the prepubertal velocity level, in a rather homogeneous way over the years, whereas the PS has little influence. The same idea and the same statistical technique was applied successfully in a study dealing with the accumulation of overweight in childhood and adolescence (Gasser, Kneip, Ziegler *et al.* 1994).

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In this study, we extend this to the variables leg height, sitting height, bihumeral width and biiliac width. A simple strategy would be to form subgroups with a large or a small adult size in height, this being the most important anthropometric variable in paediatrics. However, we have decided to form these subgroups separately for each variable, since due to the variation in morphology, a group of tall subjects does not necessarily coincide with a group of broad subjects. Thus, one-third of the subjects with the largest adult size—separately for each variable—is selected and similarly one-third with the smallest values. In previous investigations it turned out that different parts of the body grow in markedly different ways in normal samples of boys and girls (Gasser, Kneip, Binding *et al.* 1991a, Gasser, Kneip, Ziegler *et al.* 1991b, Sheehy, Gasser, Molinari *et al.* 1999, Sheehy *et al.* 2000). It is then of some interest to investigate how a large size in each of the anthropometric variable is achieved.

This paper differs from a previous one (Sheehy *et al.* 2000) where the adult size reached was to be explained by regression and correlation methods: there, we tried to find biological mechanisms working consistently at an individual level, and leading then to a large or small adult size. Here, more modestly, we want to explain average differences between a large or a small adult size by visualizing average differences in velocity curves (note that the area under the velocity curve—its integral in mathematical terms—is exactly the adult size).

2. Subjects and methods

2.1. Subjects

In an internationally co-ordinated study (Falkner 1960), initiated in 1954, participation of 321 children could be obtained for the Zurich sample. Those children with rather complete measurements from infancy to adulthood ($n = 112$ girls and $n = 120$ boys) are the basis of this analysis. For further details the reader may consult Gasser *et al.* (1990) or Sheehy *et al.* (1999). For each of the five variables studied two different subgroups were formed: one-third of the subjects with a large adult size was chosen for comparison with one-third of the subjects with a small adult size. This led to 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 at least until age 20.

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.

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). A cross-sectional average velocity curve would not lead to valid results, since it would, for example, 'smear out' the pubertal velocity peak due to the large variation in the timing of the pubertal spurt. The structural average velocity curve takes into account the different tempo of growth: the individual growth curves, evidently recorded at chronological ages, are transformed on the age scale in order to conform to the average tempo of growth. This is done by shifting, for example, the individual location of the pubertal velocity peak to its average location by a nonlinear age-transformation to an average maturation (see also Shuttleworth 1937, for an early account of the problem).

3. Results

Table 1 shows the means of the subgroups ($n = 40$ each for boys and $n = 37$ each for girls) at adulthood and table 2 at 4 weeks for the variables analysed. The percentage difference at adulthood between group is most pronounced for biiliac width, followed by legs, whereas relative differences are more modest for the trunk and the shoulder. As can be seen from table 2, the differences go consistently in the same direction already at 4 weeks. They are, however, statistically significant only for biiliac width of boys ($p = 0.02$, whereas $p = 0.06$ for girls) and for height of girls ($p = 0.02$).

Figure 1 gives average structural velocity curves of height for the two groups. Tall adults gain their additional centimetres mainly via a constantly higher basic velocity in prepubertal years. A small additional gain comes from a slightly later and broader—but not higher—PS, in particular for girls. (Due to a higher prepubertal velocity level, peak height velocity is higher in the tall group, but not size of the peak rising above the prepubertal level. The latter variable reflects better the intensity of the PS.) Figures 2 and 3 give an explanation for the results for height in terms of the development for the legs and the trunk (also average velocity curves): those subjects with long legs grow also consistently more prepubertally, due to a higher velocity level, but in both sexes, the PS is also clearly delayed, leading to a further gain in leg size. The trunk, on the other hand, shows no delay in the PS for those with a large

Table 1. Means of adult sizes for subgroups with a large or a small size at adulthood ($n = 40$ boys with a large or small adult size, and $n = 37$ girls with a large or small adult size).

Sex	Group	Height	Leg height	Sitting height	Bihumeral width	Biiliac width
m	large	186.2	89.5	97.7	44.6	29.9
	small	170.8	79.4	90.2	40.7	25.0
f	large	171.2	81.6	91.0	39.4	29.6
	small	158.6	72.8	84.8	35.9	25.8

Table 2. Means of sizes at 4 weeks for subgroups with a large or a small adult size ($n =$ 40 boys with a large or small adult size, and $n =$ 37 girls with a large or small adult size).

Sex	Group	Height	Leg height	Sitting height	Bihumeral width	Biiliac width
m	large	54.1	19.9	34.4	13.2	9.1
	small	52.2	18.9	33.0	13.1	8.7
f	large	53.2	19.8	33.6	14.0	8.8
	small	51.3	18.5	32.4	13.1	8.4

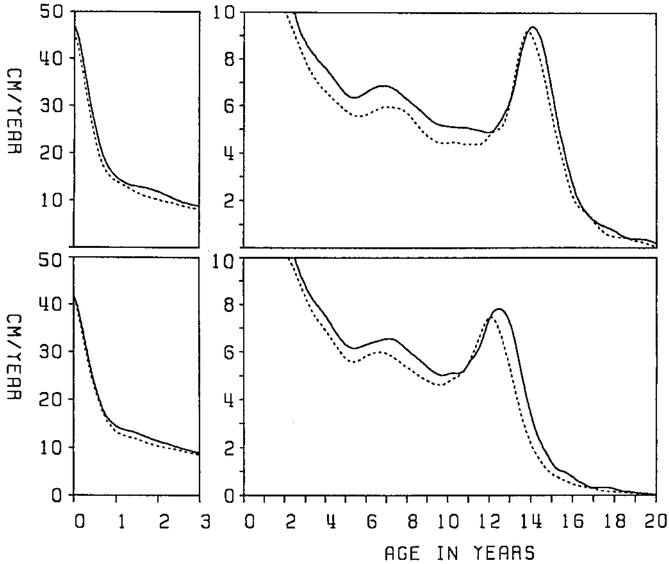

Figure 1. Structural average velocity curves for height for children with a large (solid line) and small (dashed line) adult size. Boys ($n = 40$) above, girls ($n = 37$) below. First 3 years on separate scale.

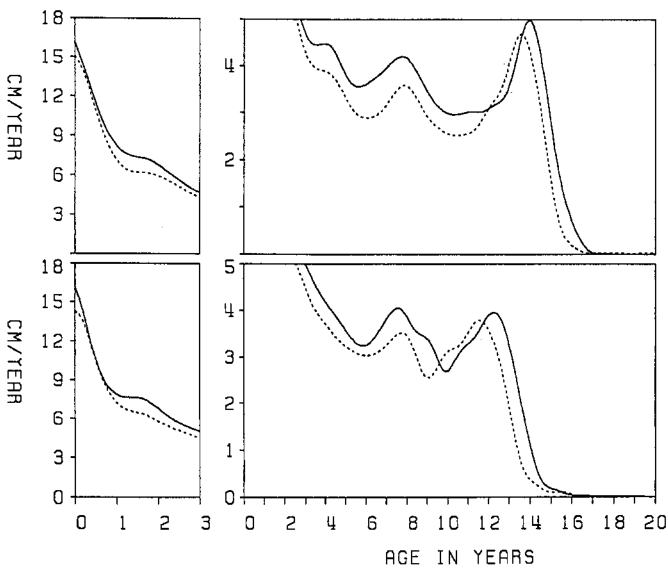

Figure 2. Structural average velocity curves for leg height for children with a large (solid line) or small (dashed line) adult size. Boys ($n = 40$) above, girls ($n = 37$) below. First 3 years on separate scale.

adult size; rather, the velocity is slightly elevated all along the growth period in a rather homogeneous way (remember that the differences between subgroups are relatively small for the trunk, table 1).

A large or small adult size is determined by different mechanisms in different variables, as can be seen from figures 4 and 5 for the two widths, despite some evident random variability in the velocity curves: biiliac width shows an elevated velocity all along development (beyond 2 years) for those with a large adult size,

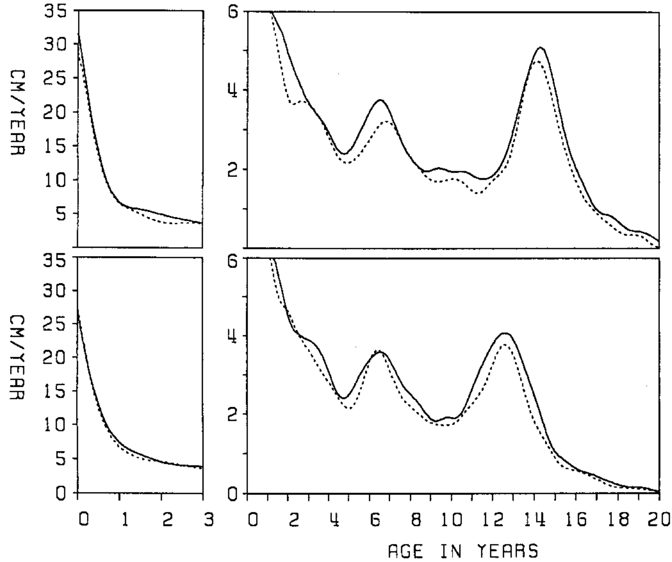

Figure 3. Structural average velocity curves for sitting height for children with a large (solid line) and small (dashed line) adult size. Boys ($n = 40$) above, girls ($n = 37$) below. First 3 years on separate scale.

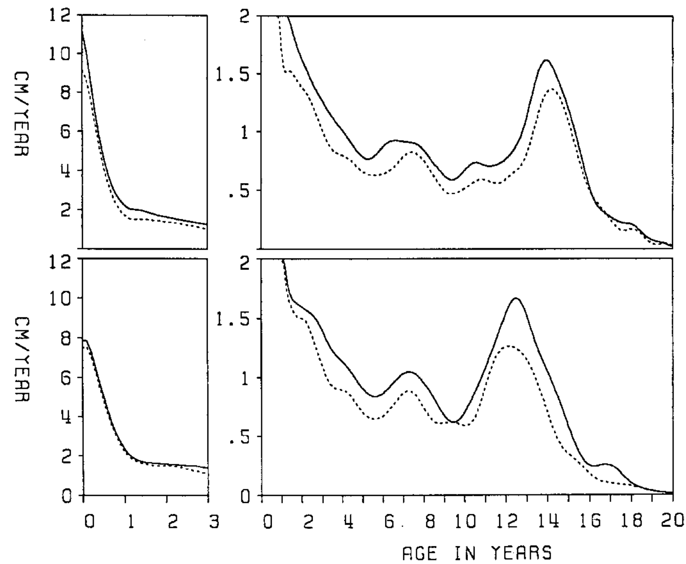

Figure 4. Structural average velocity curves for biiliac width for children with a large (solid line) and small (dashed line) adult size. Boys ($n = 40$) above, girls ($n = 37$) below. First 3 years on separate scale.

similar to sitting height. For bihumeral width, on the other hand, the prepubertal velocity is low in both groups, and not much different; a broad shoulder is, on average, mainly due to a PS of high intensity and long duration. In both variables of width there is no appreciable difference in the timing of the PS.

When comparing a subgroup of tall girls with a subgroup of small boys in such a way that their average adult height was about the same, an interesting pattern emerged (figure 6): in puberty we see qualitatively the classical sex differences,

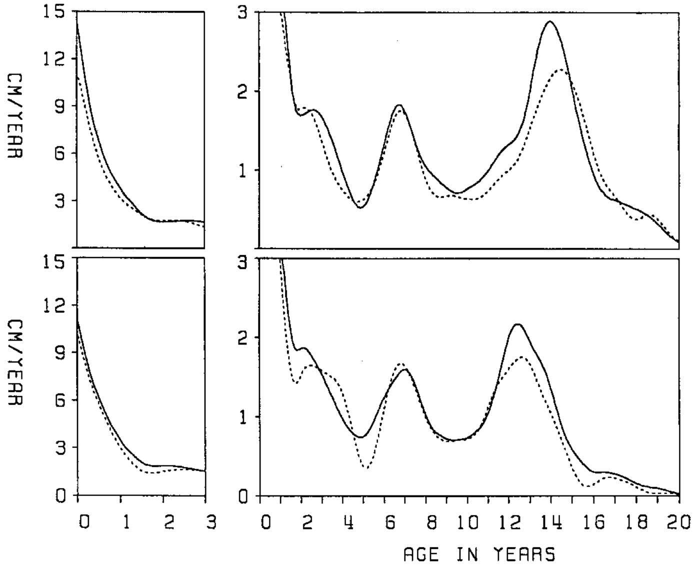

Figure 5. Structural average velocity curves for bihumeral width for children with a large (solid line) and small (dashed line) adult size. Boys ($n = 40$) above, girls ($n = 37$) below. First 3 years on separate scale.

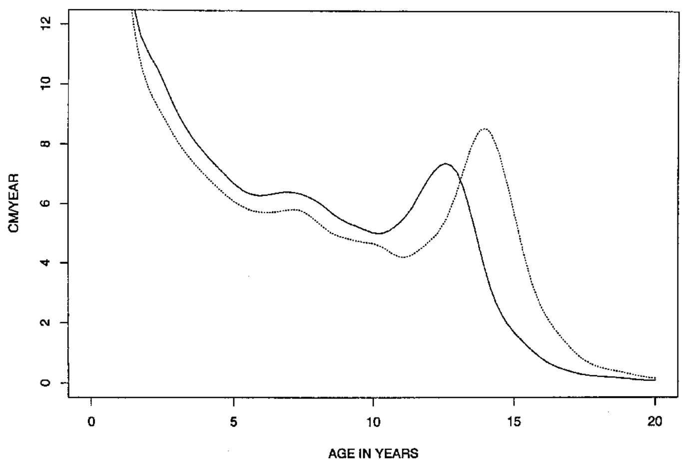

Figure 6. Structural average velocity curves of height for girls (solid line) and boys (dotted line) with a similar adult height.

namely a later and more intense spurt for boys. Therefore, beyond the age of onset of the PS for girls, boys have a larger gain in height. This is compensated for the girls by a constantly higher prepubertal velocity, in much the same way as in the comparison of tall and small boys (figure 1).

4. Discussion

It is not surprising that subjects who reach a large adult size in some variable have in the mean a larger size at 1 month, due to the strong genetic regulation of growth. Since, on the other hand, an infant gets on his/her genetic trajectory only within the first year (Smith, Truog, Rogers *et al.* 1976), this allows the conclusion that a maturational pacemaker is active quite early. (In what follows, we will not discuss height in detail since it is a composite of two heterogeneous variables, i.e. legs and trunk, which are studied separately.)

Since adult size is the integral (or sum) of the velocity curve across age, a mean difference in adult size has to be reflected in certain epochs of growth in differences for the average velocity curves, the question is when and to what degree. These differences explain how and when the larger average adult size for the 'large group' is accumulated, when compared to the 'small group'. Note that the mean differences in adult size for the subgroups considered are relatively large for biiliac width, intermediate for legs and less pronounced for sitting height and bihumeral width.

The structural average velocity curves of subgroups are inevitably more variable than those previously published for the whole sample (Gasser *et al.* 1991a, b). However, the patterns of differences seen can be assumed to be qualitatively reliable since they are similar in both sexes.

There are no discernible sex differences in the growth processes, leading eventually to a large or small adult size. This is plausible from clinical findings (see Prader 1984, for a good review): the PS is the main growth feature that is sex dependent. The occurrence or absence of a PS is, however, not critical for achieving normal adult height, and sex hormones are, therefore, not critical for achieving adult height. As our study shows, they are also not critical for the particular form of the growth process leading to a large or small size.

However, there are important differences for different variables for these growth processes. Since a delayed puberty is an important factor in determining the larger adult size for boys as compared to girls (Gasser, Sheehy, Molinari *et al.* 2000), it is notable that both those having relatively larger and those having relatively smaller adult size for sitting height, bihumeral and biiliac width have, on average, about the same timing for the PS. Legs are quite distinct since it is the only variable where the PS shows a modest delay for the 'large group'. This explains, however, only to a small extent the higher size for the 'large group'. More important is the higher prepubertal velocity level for explaining the variation in adult size (as for sitting height and biiliac width).

The pattern for the trunk and biiliac width is similar: the velocity for those with a large adult size is, on average, slightly elevated over prepubertal and pubertal years in a rather homogeneous way as if a small value had been added to the velocity of the small group for all relevant ages (or alternatively the intensity of growth—given by the velocity—multiplied by a factor). Since the adult difference for biiliac width is relatively large for the two subgroups, it is not surprising that the velocity pattern is rather distinct for biiliac width. For bihumeral width, on the other hand, the velocity level of prepubertal years has a modest influence on adult size, whereas the intensity and the duration of the PS is an important factor for this variable. This might have to do with the fact that shoulder width was measured as bihumeral width, which reflects also the growth of muscles and fat in puberty. Note that for bihumeral width, the pubertal spurt is an important factor for achieving adult size anyhow (Sheehy *et al.* 1999) which could explain its importance for explaining variation in adult size. Previous results in terms of correlations and regression models (Sheehy *et al.* 2000) are in line with these mean differences: for legs, the timing of the PS was the most influential variable among pubertal variables for adult size, whereas the contribution due to the PS was most important for the trunk and for biiliac and bihumeral width.

It would be desirable to have a biological explanation for the clear-cut findings of this study: no discernible sex differences and important differences between variables in the way a large or small adult size is achieved. Adult size is probably governed by multi-factorial genetic laws. The absence of a sex difference in the process to this differing adult size could imply that this process is regulated only under the influence of autosomal genes. Not enough is known about the differential growth of various bones to allow speculation on the biological cause of the differences seen (Bonjour and Tsang 1999).

Tall women, compared to small men, achieve height gains due to a higher pre-pubertal velocity level, in much the same way that tall men win their additional size when compared to small men. This illustrates that sex steroids do not have a decisive role in controlling the mechanism of how tallness is achieved. (It is well known that sex steroids do not influence adult size.) It is of interest to compare these results with those of Ratcliffe, Pan and McKie (1992, 1994): women with a genetic XXX disposition had a similar adult height and a similar growth velocity as women with XX genes. Men with an XYY disposition had an adult height about 13 cm higher than XY men, a difference similar to the one between men and women. This difference is due to a higher prepubertal velocity level—a mechanism responsible for normal variation in adult height—and also due to a more intense PS for XYY men, reminiscent of the sex difference in adolescent growth. Prader (1984) has speculated how the Y chromosome is responsible for the adult sex difference in size.

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Zusammenfassung. *Hintergrund:* Die Art, in der anthropometrische Variable die Erwachsenengröße erreichen, ist ein seit langer Zeit bestehendes Problem, da der puberale Spurt statistisch und klinisch nur geringe Assoziationen zur Erwachsenengröße zeigt (am häufigsten untersucht für die Körperhöhe). Wir untersuchten dieses Problem detailliert durch die Analyse des longitudinalen Wachstums von Probandengruppen mit großer oder geringer Erwachsenengröße jeweils für Körperhöhe, Beinlänge, Sitzhöhe sowie Ellbogenbreite und Beckenbreite. Dabei waren die Wachstumsmuster speziell für diese Variablen für Jungen und Mädchen von Interesse.
Methodik: Die Daten stammen von 120 Jungen und 112 Mädchen, die von der vierten Lebenswoche bis zum Erwachsenenalter longitudinal untersucht wurden. Statistisch wurden die strukturellen mittleren Kurven der Wachstumsgeschwindigkeit für jede Variable und zum Vergleich getrennt für jede Untergruppe berechnet. Diese Geschwindigkeitskurven stellen die mittlere Intensität und das mittlere Tempo des Wachstums dar. Da die Fläche unter der Geschwindigkeitskurve die adulte Größe darstellt, können auf diese Weise Unterschiede im Wachstumsprozess verdeutlicht werden.
Ergebnisse: Beide Geschlechter zeigen ähnliche Muster hinsichtlich des Erreichens einer geringen oder großen Erwachsenengröße. Die einzelnen Variablen weisen jedoch erhebliche Unterschiede auf. Nur bei der Beinlänge ist der puberale Wachstumsspurt in der Gruppe mit großer Endgröße verzögert (mit einem zusätzlichen Zuwachs in den präpuberalen Jahren). Bei der Sitzhöhe und der Beckenbreite führt eine geringfügig gesteigerte Geschwindigkeit während der gesamten Entwicklung (nach dem zweiten Lebensjahr) zu einer größeren Erwachsenengröße und bei der Ellbogenbreite ist die Höhe des puberalen Wachstumsgipfels ausschlaggebend.
Schlussfolgerungen: Die Steuerung des Wachstums hin zu einer bestimmten Zielgröße ist für Jungen und Mädchen qualitativ ähnlich, dagegen ziemlich unterschiedlich für verschiedene anthropometrische Variable. Daraus ergeben sich Fragen bezüglich der endokrinologischen Steuerung des Wachstums verschiedener Körperteile und eines unterschiedlichen Knochenwachstums während der Entwicklung.

Résumé. *Arrière plan*: Considérant qu'il y a peu d'association statistique et clinique entre la poussée pubertaire et le format adulte (surtout étudié pour la stature), la façon dont de grandes valeurs des dimensions anthropométriques sont atteintes, demeure un problème irrésolu. C'est à cela que s'attache ce travail, en procédant par l'analyse de la croissance longitudinale d'un groupe de sujets de format corporel adulte soit petit soit grand, pour lesquels sont considérées séparément, les dimensions de la stature, de la jambe, de la taille-assis, de la largeur bihumérale et de la largeur biiliaque. En particulier, s'est-on intéressé aux modalités spécifiques de croissance de ces variables chez les garçons et chez les filles.
Méthodes: Les données portent sur 120 garçons et 112 filles suivis longitudinalement de l'âge de quatre semaines jusqu'à l'état adulte. Des courbes statistiques de vélocité structurale moyenne ont été établies pour comparaison dans chaque sous-groupe séparément et pour chaque variable. Cette courbe de vélocité représente l'intensité moyenne et le tempo moyen de la croissance. L'aire située au-dessous de la courbe étant la taille adulte, des différences dans le processus de croissance peuvent ainsi être observées.
Résultats: Les deux sexes montrent des modalités similaires dans l'atteinte de la taille adulte, qu'elle soit petite ou grande. Les diverses variables montrent cependant des différences marquées. La poussée pubertaire n'est retardée que pour les jambes, dans le groupe de grand format (avec des gains additionnels pendant la période prépubertaire). Pour la taille-assis et la largeur biiliaque, une vélocité modérément élevée pendant l'ensemble du développement (après deux ans) conduit à une taille plus grande; pour la largeur bihumérale, on observe que l'importance du pic pubertaire est décisive.
Conclusions: le déroulement de la croissance jusqu'à atteindre une dimension projetée est qualitativement semblable pour les garçons et pour les filles, mais très différent suivant les variables anthropométriques concernées. Ceci conduit à s'interroger sur le contrôle endocrinologique de diverses parties du corps, ainsi que sur la croissance osseuse différentielle pendant le développement.