Skeletal stages of the hand and wrist as indicators of the pubertal growth spurt

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Longitudinal data on adolescent growth in height and skeletal development of the hand and wrist were collected as part of a prospective study of the growth and development of 212 randomly selected Swedish urban children. The onset, peak and end of the pubertal growth spurt were defined on the unsmoothed incremental curve of height. The skeletal development was evaluated by studying the attainment of specified stages of the ulnar sesamoid of the metacarpophalangeal joint of the first finger, the epiphyses of the middle and distal phalanges of the third finger and the distal epihysis of the radius.

All growth events and skeletal stages occurred earlier in girls than in boys. At the peak of the pubertal growth spurt the skeletal development was more advanced in girls than in boys, but at the end of the spurt the girls had a less mature skeletal development than the boys.

The analysis of the relationship in time between the growth events and the skeletal stages showed that these stages kan be used to indicate which period of adolescent growth an individual has reached.

Key-words: Maturity indicators; orthodontic treatment timing; puberty; skeletal development

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The changes in the growth rate during the adolescent period can influence the course of orthodontic treatment (2, 6, 8). Owing to the close association in the timing of the maximum pubertal growth in body height and facial dimensions (1, 2, 29) longitudinal growth records of body height can be used in orthodontic treatment planning (2). However, in the clinical context growth records are seldom available and the clinician must base his judgement on single examinations. Even if sufficient records are available, it may be difficult to locate the pubertal growth spurt since it has been found that in about 30% of the girls and 2 – 3 % of the boys (12,27) the increase in growth rate during the spurt is too small (less than 20 mm) to be clinically discernible (22). Thus, additional information is necessary to estimate which period of the pubertal growth spurt has been reached. Such information can be found in the skeletal development of the hand and wrist, since the peak height velocity (PHV) and certain stages of skeletal development of the hand and wrist are closely associated (1, 2, 4, 7, 9, 20).

The aims of this study were:

- to determine the timing of ten speci-

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Table 1. *The skeletal stages in the present study and their equivalents in other studies*

Skeletal stages [a]	Defined in accordance to	
	ULNAR SESAMOID	
S	Björk (2) + ref. (4, 9, 13, 20, 21) Onset of ossification	
	3RD MIDDLE PHALANX (MP) AND DISTAL PHALANX (DP)	
MP3-F	Tanner et al. (25)	stage F
	Bowden (4)	MP: stage 6
	Helm et al. (9) + ref. (13)	MP 3 =
MP3-FG	Defined in present study	
MP3-G	Tanner et al. (25)	stage G
	Björk (2) + ref. (9, 13, 20)	MP3cap
	Bowden (4)	MP: stage 7
MP3-H	Tanner et al. (25)	stage H
	Bowden (4)	MP : stage 8
MP3-I	Tanner et al. (25)	stage I
DP3-I	Björk (2) + ref. (9, 13, 20)	MP3u, DP3u
	Bowden (4)	MP/DP:stage 9
	Stuart et al. (21)	completion
	RADIUS	
R-I	Tanner et al. (25)	stage I
R-IJ	Defined in present study	
R-J	Tanner & Whitehouse (24)	stage J
	Björk (2) + ref. (7)	Ru
	Stuart et al. (21)	completion

[a] For definition see figure 2–5

fied skeletal stages in a representative prospective longitudinal sample of Swedish children, and
- to describe the relationship in time between these ten skeletal stages and the pubertal growth spurt.

MATERIAL AND METHODS

Data on the skeletal development of the hand and wrist and the pubertal growth in height were obtained from 212 randomly selected Swedish urban children (90 girls and 122 boys) as part of a prospective longitudinal and interdisciplinary study of growth and development from birth to adulthood (10, 11). The children were born between 1955 and 1958. The method and the representativeness of the sample have been reported previously (10, 11). During the age period covered by this study the subjects were examined once a year up to the age of 18 years. After this age no radiographs were taken but height was also measured at the age of 20 – 22 years.

Height was recorded with the stretching up technique as proposed by Tanner (30). Increments were calculated using measurements taken at even ages. Each

Table 2. *Probit analysis of age at attainment of various adolescent maturity indicators in girls and boys*

	Sex	Mean	SD	Adjustment to probit line (Chi^2) [a]	df	Range	Sex difference [b] in years
Pubertal spurt							
ONSET	G	10.04	1.26	3.03	7	6.5–13.5	2.04
	B	12.08	1.20	3.83	6	9.5–15.5	
PHV	G	11.98	1.02	9.41	6	9.5–15.5	2.09
	B	14.07	1.08	2.53	6	11.5–17.5	
END	G	14.82	0.88	1.19	5	13.3–17.3	2.23
	B	17.05	0.98	1.32	5	14.5–19.5	
Skeletal development							
S	G	10.73	1.03	3.48	4	8.5–12.5	2.39
	B	13.12	1.12	3.86	6	10.5–16.5	
MP3–F	G	9.15	1.06	0.47	6	6.5–12.5	2.15
	B	11.66	1.26	3.71	6	8.5–14.5	
MP3–FG	G	11.34	0.95	1.57	4	9.5–13.5	2.35
	B	13.69	1.00	2.95	5	11.3–16.5	
MP3–G	G	12.42	1.02	3.08	4	10.5–14.5	2.20
	B	14.62	0.99	4.06	6	11.7–17.5	
MP3–H	G	13.45	0.96	3.34	5	11.5–16.3	2.10
	B	15.55	1.07	2.43	4	13.5–(18.5) [c]	
MP3–I	G	14.32	0.99	2.27	4	12.5–16.7	1,97
	B	16.29	1.02	2.93	4	14.5–(19.5) [c]	
DP3–I	G	13.33	0.91	7.14	5	11.5–16.5	2.28
	B	15.61	1.06	2.33	4	13.5–(18.5) [c]	
R–I	G	14.79	1.09	1.64	5	12.5–17.5	1.75
	B	16.54	0.95	6.21	4	14.5–(19.5) [c]	
R–IJ	G	15.79	1.06	3.59	5	13.5–(18.5)	1.79
	B	17.58	0.80	3.22	4	15.7–(20.5) [c]	
R–J	G	16.73	1.19	7.50	5	14.5–(20.5) [c]	1.28
	B	18.01	0.92	3.02	4	16.5–(22.5) [c]	

[a] No value of Chi^2 is statistically significant ($p > 0.10$)
[b] All sex differences are highly significant: $p < 0.001$.
[c] Value within brackets is extrapolated

measurement was adjusted to exactly specified target ages (11). The incremental growth curve was analysed graphically without any smoothing (27), a procedure which can be used in clinical routine work.

In the present study three growth events were used representing the onset (ONSET), peak (PHV) and end (END) of the pubertal growth spurt (Figure 1). (For details see reference 27.)

From the time prior to puberty 92.5 per cent of the original 212 subjects were regulary followed. At the end of the spurt 86.3 per cent of the subjects remained in the study.

The skeletal development of the right hand and wrist was assessed on radiographs obtained each year by a standardized procedure (26).

During the pubertal spurt radiographs of the hand and wrist were available from 78 girls and 97 boys, i.e. 82.5 per cent of the original sample. The bones to be used as indicators of the skeletal development were chosen according to Björk (2): the *ulnar sesamoid* of the metacarpophalangeal joint of the first finger, the epiphysis of the *middle and distal phalanges of the third finger* and the distal epiphysis of the *radius*. The assessments were made with one bone visible at a time (18) by using a magnifying viewer (14). In the present study ten skeletal stages were used (Figs. 2 – 5). Eight stages have been defined by others and two new stages (MP3-FG and R-IJ) were defined and used by the authors of the present study. (Table 1, for details see Figs. 4, 5). All skeletal stages were termed according to the TW-method (25).

The analysis of the radiographs were carried out by one examiner (U.H.). To evaluate the methodological error all available radiographs of 25 subjects were assessed by both authors. Identical ratings were found in more than 95 per cent of the assessments and none of the age differences was greater than one year.

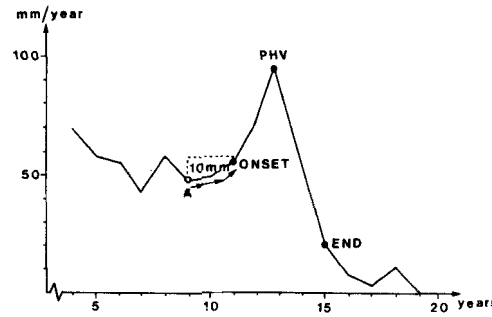

Fig. 1. The pubertal growth spurt.
Onset of the spurt (ONSET) is the smallest annual increment from which there is a significant continuous increase in growth rate to PHV. ONSET is found by locating the smallest annual increment (A) from which there is a continuous increase in growth rate to PHV. The curve is then followed towards PHV until growth rate has accelerated 10 mm. ONSET will be represented by the annual increment which is next below or coincides with this growth rate.
Peak height velocity (PHV) is the greatest annual increment during puberty.
The end of the spurt (END) is the first annual increment after PHV below 20 mm.

Statistical methods

The age of a subject at the attainment of any stage was defined as the midpoint of the age interval during which the change occurred. If more than one stage was attained the intervals were divided into appropriate equal parts. The individual ages were used to analyse the relationship in time between the skeletal stages and the pubertal growth events and in the correlation analysis. The mean ages at the occurence of the various stages were calculated by probit analysis (5) in such a way that an unbiased estimate of the mean value eas obtained (23). The cumulative percentages (Tables 3, 4, 6, 7 and 8) were calculated on the raw figures of the probit analysis.

RESULTS

The means and ranges of the ages at the occurrence of the growth events and the

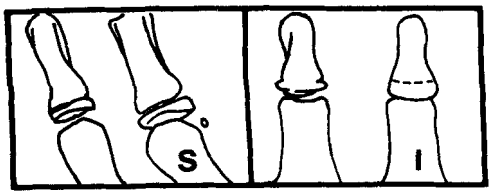

Fig. 2. The ulnar sesamoid (S) of the metacarpophalangeal joint of the first finger before and after ossifying.

Fig 3. The distal phalanx of the third finger (DP3) before and after stage I: fusion of the epiphysis and metaphysis is completed.

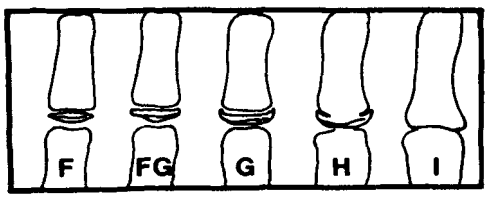

Fig. 4. The middle phalanx of the third finger (MP3):
- stage F: the epiphysis is as wide as the metaphysis.
- stage FG: the epiphysis is as wide as the metaphysis and there is distinct medial and/or lateral border of the epiphysis forming a line of demarcation at right angles to the distal border.
- stage G: the sides of the epihysis have thickened and also cap its metaphysis, forming a sharp edge distally at one or both sides.
- stage H: fusion of the epiphysis and metaphysis has begun.
- stage I: fusion of the epiphysis and metaphysis is completed.

Table 3. *Cumulative percentage of girls who had attained various adolescent maturity indicators at the end of each age interval*

Age interval in years	Pubertal spurt			Skeletal stage									
	ONSET	PHV	END	S	MP3-F	MP3-FG	MP3-G	MP3-H	MP3-I	DP3-I	R-I	R-IJ	R-J
6 – 7	1.2				1.3								
7 – 8	3.7				7.7								
8 – 9	21.0			6.5	29.9								
9 – 10	49.4	1.2		26.0	69.3	10.4							
10 – 11	79.0	19.8		53.9	92.2	33.8	11.7						
11 – 12	95.0	46.9		89.6	98.7	75.3	32.9	5.3		6.8			
12 – 13	97.5	88.8	1.2	100.0	100.0	95.9	67.2	36.8	10.1	35.7	6.9		
13 – 14	100.0	97.5	17.3			100.0	94.7	69.9	38.4	79.7	24.7	6.8	
14 – 15		98.7	61.7				100.0	95.9	77.8	97.3	54.3	23.9	13.4
15 – 16		100.0	90.1					98.6	93.2	98.7	86.1	50.0	24.6
16 – 17			98.8					100.0	100.0	100.0	98.6	90.0	50.7
17 – 18			100.0								100.0	98.6	87.3
18 – 19												–	–

skeletal stages are given in Table 2. The cumulative percentage of subjects who have attained a certain stage at the end of each age interval is given in Tables 3 and 4. The correlation coefficients between the occurrence of the growth events and the attainment of the skeletal stages are given in Table 5. The relationship in time between the growth events in the skeletal stages are given in Tables 6, 7 and 8.

Pubertal growth spurt

On an average, the pubertal growth spurt began (ONSET) at an age of about 10 years in girls and 12 years in boys. In

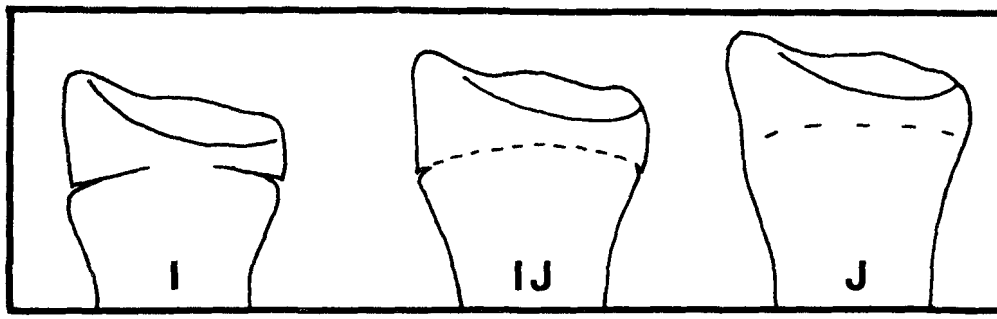

Fig. 5. The distal epiphysis of the radius:
– stage I: fusion of the epiphysis and metaphysis has begun. – stage IJ: fusion is almost completed but there is still a small gap at one or both margins. – stage J: fusion of the epiphysis and metaphysis is completed.

both sexes PHV occurred about two years after the onset of the spurt. The end of the spurt (END) was attained at the age of about 15 years in girls and 17 years in boys (27). The mean duration of the pubertal growth spurt was similar in girls and boys, i.e. 4.7 and 4.9 years respectively (27).

Skeletal development

The occurrence of the latest skeletal stage – the complete closure of the distal epiphysis of the radius (R-J) could be established in 54 (60.0 %) girls and 45 (36.9 %) boys, i.e. 46.7 % of the original sample. Two out of the ten skeletal stages, i.e. MP3-FG and R-IJ, were defined in the present study. Stage MP3-FG was observed in 70 out of 74 (94.5 %) of the girls and 80 out of 90 (88.9 %) of the boys. The new stage of radius (R-IJ) could be observed in 51 out of 62 (82.3 %) girls and in 19 out of 51 (37.3 %) boys.

Skeletal development at the beginning of the growth spurt (ONSET)

According to the mean values one of the skeletal stages (MP3–F) preceeded ONSET, while two of the stages (MP3–FG and S) occurred between ONSET and PHV (Table 2). Although statistically significant–, the values of the correlation coefficients between the occurrence of ONSET and these skeletal stages were low or moderate. (Table 5.) The first epiphyseal stage of the third middle phalanx (MP3–F) was attained before ONSET in about 40 % in both sexes, while the second stage (MP3–FG) was observed before ONSET in only two of the girls (2.6 %) and in none of the boys (Table 6). The ulnar sesamoid was ossified before ONSET in 14.3 % of the girls and 8.3 % of the boys.

Skeletal development at peak height velocity (PHV)

According to the mean values three of the skeletal stages (MP3-F, MP3-FG and S) preceeded PHV, while the remaining seven stages occurred after PHV (Table 2). The values of the correlation coefficients between the occurrence of PHV and the skeletal stages were moderate or high (Table 5).

The ulnar sesamoid (S) was ossified before or during the same annual interval as PHV occurred in all subjetcts, except in one boy. In this boy the ulnar sesamoid became visible during the first annual interval after PHV (Table 7).

The first stage of the epiphysis of the third middle phalanx (MP3-F) was attained before or at PHV in all subjects. At PHV the second stage (MP3–FG) was obtained by more than 90 % of the sub-

Table 4. *Cumulative percentage of boys who had attained various adolescent maturity indicators at the end of each age interval*

Age interval in years	Pubertal spurt			Skeletal stage									
	ONSET	PHV	END	S	MP3-F	MP3-FG	MP3-G	MP3-H	MP3-I	DP3-I	R-I	R-IJ	R-J
8 – 9					2.9								
9 – 10	5.3				10.3								
10 – 11	14.7			5.2	28.4								
11 – 12	51.4	1.9		12.5	58.9	3.1	1.0						
12 – 13	79.4	15.9		45.3	83.0	28.7	2.1						
13 – 14	92.5	51.4		78.5	99.0	60.6	31.2	6.6		5.4			
14 – 15	99.1	79.8	1.0	96.8	100.0	91.4	62.9	33.7	11.0	32.2	2.2		
15 – 16	100.0	96.2	15.2	99.0		97.9	92.6	66.3	43.5	64.8	36.6	1.1	
16 – 17		99.0	50.5	100.0		100.0	98.9	91.9	72.8	90.9	66.3	28.7	15.2
17 – 18		100.0	81.9				100.0	97.8	94.7	97.8	91.8	65.5	51.1
18 – 19			97.1					–	–	–	–	–	–
19 – 20			100.0										

Table 5. *Correlation coefficients between age at attainment of various adolescent maturity indicators in girls and boys*

Pubertal spurt		Skeletal stage									
		S	MP3–F	MP3–FG	MP3–G	MP3–H	MP3–I	DP3–I	R–I	R–IJ	R–J
ONSET	G	.56	.30	.61	.61	.60	.64	.70	.60	.56	.55
	B	.53	.28	.67	.66	.70	.73	.70	.54	.39	.25
PHV	G	.63	.50	.75	.79	.79	.79	.86	.76	.77	.75
	B	.73	.41	.81	.83	.85	.87	.85	.74	.55	.38
END	G	.69	.50	.76	.79	.81	.74	.83	.81	.82	.73
	B	.71	.46	.77	.82	.85	.83	.85	.64	.50	.48

Table 6. *Cumulative percentage of girls and boys who attained a certain skeletal stage in each annual interval in relation to the interval during which the onset (ONSET) of the spurt occurred*

Interval in years to ONSET	S		MP3–F		MP3-FG	
	G	B	G	B	G	B
−4				2.0		
−3		1.0	10.3	6.2		
−2	3.9	2.0	28.6	23.4	1.3	
−1	14.3	8.3	41.2	40.2	2.6	
ONSET	42.9	25.8	75.3	69.1	18.4	11.4
+1	76.3	63.4	92.1	89.8	67.1	42.4
+2	97.4	92.6	100.0	99.0	88.0	83.9
+3	100.0	99.0		100.0	98.7	97.9
+4		100.0			100.0	100.0

jects. The third stage (MP3-G) was observed before PHV in five out of 68 (7.4 %) girls and one out of 86 (1.2 %) boys. The last two stages of the middle phalanx (MP3-H and MP3-I) were attained after PHV in all subjects. The fusion of the epiphysis of the third distal phalanx was completed (DP3-I) after PHV in all subjects except in two girls (2.7 %), in whom the occurrence of the two events coincided.

Skeletal development at the end of the growth spurt (END)

According to the mean values all skeletal stages except the last two stages of the radius (R-IJ and R-J) preceeded END (Table 2). At END the fusion of the third distal phalanx was completed (DP3-I) in all subjects and that of the third middle phalanx (MP3-I) in all subjects except in four (6.4 %) girls (Table 8). The fusion of the distal radius began (R-I) before or at END in 52 out of 67 (78.3 %) girls and 64 out of 68 (94.4 %) boys. When fusion of the radius was almost completed (R-IJ) all subjects had reached or passed END.

DISCUSSION

The timing of the pubertal growth spurt and the skeletal stages of the hand was generally in agreement with other studies (Table 9). The marked difference in the timing of some of the skeletal stages and the pubertal growth might be more due to different sampling procedures than to population differences. In some studies the subjects have been sampled from orthodontic patients of varying ages (2, 9, 20). In the present prospective study the subjects were sampled before birth and followed up to adulthood. Thus the entire pubertal growth period could be observed. In nonrandomised samples (2, 9, 20), in which all subjects have not been followed during the same age period, there are less observations of early and late occurring stages. Due to the operational criteria the number of early and late maturers is probably too low in such studies. Furthermore early stages may already have occurred in early maturers when recruited and late stages may not have occurred at the last examination of late maturers. A number of withdrawals is inevitable. In many studies the impact of this was not taken into account in the statistics (2, 4, 7, 9, 20, 21). In the present

Table 7. *Cumulative percentage of girls and boys who attained a certain skeletal stage in each annual interval in relation to the interval during which the peak of the spurt (PHV) occurred*

Interval in years to PHV	S		MP3–F		MP3–FG		MP3–G		MP3–H		MP3–I		DP3–I		R–I		R–IJ		R–J	
	G	B	G	B	G	B	G	B	G	B	G	B	G	B	G	B	G	B	G	B
−6				1.1																
−5				4.3																
−4	1.3	1.4	19.2	16.7																
−3	10.4	3.3	46.4	42.2	1.3															
−2	35.5	18.5	80.0	74.4	7.8	2.1														
−1	79.2	66.7	96.3	90.4	59.2	38.2	6.7	1.1												
PHV	100.0	98.9	100.0	100.0	96.0	91.3	54.2	44.4	5.5	1.1			2.7							
+1		100.0			100.0	100.0	93.2	93.5	52.8	53.0	8.2	3.3	66.2	48.8	1.4	2.3				
+2							100.0	100.0	94.6	97.8	60.3	69.4	98.6	97.6	34.8	49.4	1.4	1.2		
+3									100.0	100.0	97.3	100.0	100.0	100.0	79.7	93.2	30.6	34.3	4.5	17.6
+4											100.0				100.0	100.0	82.8	93.8	30.3	72.2
+5																	100.0	100.0	75.4	100.0
+6																			100.0	

Table 8. *Cumulative percentage of girls and boys who attained a certain skeletal stage in each annual interval in relation to the interval during which the end of the spurt (END) occurred*

Interval in years to END	MP3–H		MP3–I		DP3–I		R–I		R–IJ		R–J	
	G	B	G	B	G	B	G	B	G	B	G	B
−3	3.9	5.7			2.7	2.2						
−2	38.6	44.2	5.4	11.1	47.9	39.6	1.3	6.9				
−1	95.8	100.0	49.3	60.9	98.6	97.6	22.2	43.9				
END	100.0		94.6	100.0	100.0	100.0	78.9	94.5	20.3	44.4	4.3	21.0
+1			100.0				100.0	100.0	81.6	92.1	25.8	79.2
+2									100.0	100.0	75.0	98.2
+3											98.2	100.0
+4											100.0	

study the percentage of withdrawals during the pubertal period was as low as 6.4 per cent and considered in the statistics.

Skeletal stages

Since maturity indicators of brief duration are more informative than those of long duration (19) it may be advantageous to introduce new intermediate stages. To improve orthodontic treatment planning two new skeletal stages were defined in this study. The new stage MP3–FG (Figure 4) was selected as an indicator of the acceleration period of the pubertal growth spurt and the new stage R-IJ (Figure 5) as an indicator of late adolescent growth. To be useful a maturity indicator must occur in every subject, that is, be universal (19). The stages MP3-FG were observed in about 90 per cent of the subjects, and stage R-IJ in more than 80 per cent of the girls and less than 40 per cent of the boys. Because of limitations in the schedule of serial radiographic examinations skeletal stages of brief duration may appear to be skipped in some subjects (19). The observed sex difference of stage R-IJ may be the result of a more rapid maturation in males at this stage (see further discussion below). The method error of the assessment of the new stages were similar to those of the other skeletal stages used in this study.

Other investigators have reported corresponding values of methodological error (9). In conclusion the two new skeletal stages are valid as maturity indicators.

In orthodontics there is need for indicators of late adolescent growth since – although the general growth rate is low during this period – late mandibular growth may cause crowding and occlusal disturbances (3, 16).

Since the complete fusion of the distal epiphysis of the radius (R-J) has been reported to be a useful indicator of growth termination (2) it might be valuable to follow the fusion of the radius more closely by using three stages (R–I, R-IJ, R-J). Stage R-J was excluded in the second version of the TW-method for the assessment of skeletal maturity since it was «excessively variable in timing» (25). As one of the main applications of the TW-2 method is the prediction of the adult height, it may be appropriate to exclude a skeletal stage representing a period when about 99 per cent of the adult height has been attained in most individuals.

Skeletal development in relation to the pubertal growth spurt

The ossification of the ulnar sesamoid preceeded ONSET in 14 per cent of the girls and in 8 per cent of the boys (Table 6). A similar figure has been reported in a study of Turkish girls (15).

At PHV the sesamoid was ossified in all subjects except in one boy. (Even when PHV was estimated by the measurements every three months the sesamoid was not ossified until the first annual interval after PHV.) In two Danish studies (9, 20) the sesamoid was ossified in both sexes while ossification after PHV has been reported in Australian aboriginal girls and Turkish girls (7, 15).

The new stage of the third middle phalanx (MP3-FG) was observed before ONSET in two girls (Table 6), who both had an extremely small peak of the growth spurt. This made the location of ONSET uncertain. Due to the definition of ONSET (Figure 1) the beginning of the growth spurt was probably determined too late in these two girls.

The fusion of the third distal phalanx (DP3-I) was completed after PHV in all subjects except two girls, in whom the complete fusion coincied with PHV. This was also found when PHV was estimated from measurements taken every three months. These two girls were the latest maturers in the female sample. A similar range of relation between DP3-I and PHV was observed in Danish girls (20).

Table 9. *The timing of peak height velocity (PHV) and skeletal stages in girls and boys in various samples*

		Girls Mean	SD	Boys Mean	SD
Peak height velocity					
PHV	Present study	12.0	1.02	14.1	1.08
	Denmark (9[a], 20[b])	12.3	0.93	14.2	0.9
	Australia (4)	11.7	1.01	13.9	0.96
Ulnar sesamoid					
S	Present study	10.7	1.03	13.1	1.12
	Denmark (9[a], 20[b])	11.5	1.02	13.2	1.1
	Iceland (13)	11.2	1.13	13.4	1.40
	Australia (4)	11.0	–	13.0	–
	USA (21)	10.7	0.86	12.6	1.14
3rd middle phalanx					
MP3–F	Present study	9.5	1.07	11.7	1.33
	Denmark (9[a])	–	–	12.9	1.3
	Iceland (13)	10.1	1.30	12.5	1.52
	Australia (4)	10.1	0.75	11.9	0.69
MP3–FG	Present study	11.3	0.95	13.7	1.00
MP3-G	Present study	12.4	1.02	14.6	0.99
	Denmark (9[a], 20[b])	12.5	0.88	14.5	1.0
	Iceland (13)	12.2	1.26	14.2	1.53
	Australia (4)	11.9	0.88	14.0	0.74
MP3–H	Present study	13.5	0.96	15.6	1.07
	Australia (4)	13.5	0.94	15.8	0.93
MP3–I	Present study	14.3	0.99	16.3	1.02
	Denmark (9[a],20[b])	14.2	0.84	16.5	0.9
	Iceland (13)	14.5	1.61	17.2	1.74
	Australia (4)	14.3	0.98	16.8	0.87
	USA (21)	13.9	1.00	16.0	1.08
3rd distal phalanx					
DP3–I	Present study	13.3	0.91	15.6	1.06
	Denmark (9[a], 20[b])	13.5	0.85	15.6	0.9
	Iceland (13)	13.4	1.24	15.8	1.59
	Australia (4)	13.4	0.88	15.8	0.83
	USA (21)	13.3	0.92	15.5	1.08
Radius					
R–I	Present study	14.8	1.09	16.5	0.95
R–IJ	Present study	15.8	1.06	17.6	0.80
R–J	Present study	16.7	1.19	18.0	0.92
	Denmark (2[a])	–	–	17.5[c]	–
	Australia (7)	16.5	1.2	17.3	0.7
	USA (21)	16.7	1.00	17.3	0.7

[a] boys [b] girls [c] estimated value

Sex differences in skeletal development

The sex differences of skeletal development decrease with age (Table 2). The early skeletal stages were observed about 2.4 years earlier in girls while the sex differences at the final stage (R-J) had decreased to 1.3 years. This is in accordance with another study (28) where the fusion of the epiphysis of the third middle phalanx and the distal radius lasted longer in girls than in boys. In a study of the knee joint (17) the sex difference of modal ages at completion of epiphyseo-diaphyseal fusion of the femur, tibia and fibula was 1.1 – 1.4 years, while the sex difference of maturity indicators appearing at the age of 10 was about two years.

During the acceleration period of the pubertal growth spurt the sex differences were greater for the skeletal stages than for the growth events, while the reverse was true at the end of the spurt (Table 2). Consequently at PHV the skeletal development in the girls was more mature than in the boys, while at the end of the spurt the boys were more mature (Tables 7 and 8). However, this finding might have been influenced by the fact that radiographs were not taken after the age of 18. Since all subjects except 16 boys had reached END at the age of 18, the sex differences at END would probably be larger provided radiographs had been taken after this age. Even if it was assumed that none of the 16 boys would have attained a complete fusion (R-J) when END occurred there would still be a significant sex difference for a coincident occurrence of END and the final stage of radius (R-J) ($Chi^2 = 6.25$, $p < 0.02$). It is tempting to hypothesize that the more rapid skeletal maturation of the boys during the latter part of the pubertal growth spurt is caused by the increasing secretion of testosterone (31). Exogenous testosterone accelerates the skeletal maturation remarkedly, while the effect of estrogen is less marked (32). Due to the observed sex differences during the late adolescent period one would expect that girls grew longer and more during the postpubertal period. In an earlier report based on the same sample (27) it was found that the postpubertal period was nearly six months longer in girls, while the duration of the pubertal growth spurt was about the same in both sexes. In av Swiss study (12) the post-spurt growth was found to be 1.4 cm greater in girls than in boys.

CONCLUSIONS

The following findings concerning the relationship in time between the various events have been made:

Ulnar sesamoid (S)

- if the sesamoid is not ossified, PHV has not been reached. (However, in occasional subjects the ossification may begin just after PHV.)
- if the sesamoid has just become visible, most children are in the acceleration period of the pubertal spurt.

Third middle phalanx (MP 3)

- if stage F is not attained, neither is PHV.
- if stage FG is attained the subject is in the pubertal growth spurt, most probably in the acceleration period
- if stage G is attained, PHV is imminent or has been reached
- if stage H is attained the deceleration period of the growth spurt has begun.
- if stage I is attained, the end of the spurt is imminent or has just been reached.

Third distal phalanx (DP3)

- if stage it is not attained, neither is the end of the spurt.
- if stage I is attained, PHV has occurred.

Radius (R)

- if stage I is attained, the end of the spurt is imminent or has just been reached.
- if the new stage IJ is attained, the postpubertal period has begun.

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