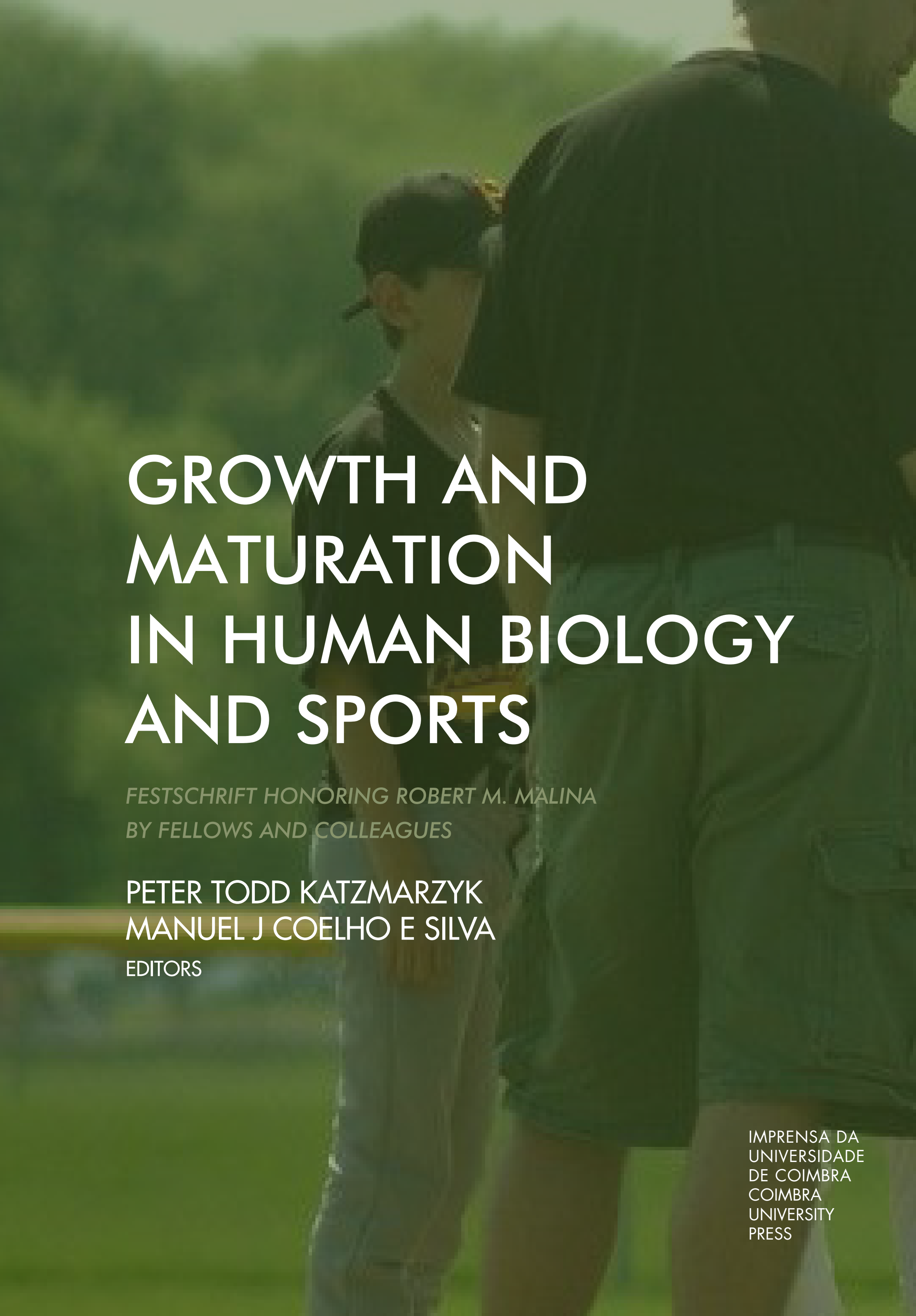

GROWTH AND MATURATION IN HUMAN BIOLOGY AND SPORTS

FESTSCHRIFT HONORING ROBERT M. MALINA BY FELLOWS AND COLLEAGUES

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THE TIMING AND SEQUENCE OF GROWTH SPURTS IN DIFFERENT BODY DIMENSIONS DURING ADOLESCENCE

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INTRODUCTION

The adolescent spurt is a hallmark of somatic growth and maturation. Longitudinal research designs are required in order to understand the biological changes that occur during adolescence and to identify the parameters of the growth spurt (Malina, 1978; Shuttleworth, 1937; Tanner, 1962). The primary indicators of the adolescent growth spurt are age at peak height velocity (PHV), or the timing of the maximum rate of growth in stature, and the magnitude of the spurt, or PHV (cm/yr). This spurt is universally present in normally developing males and females; however, the timing and magnitude vary considerably among individuals and between sexes. Females attain PHV near age 12.0, approximately two years before males (Tanner, 1971), but the spurt is of greater magnitude in males. Age at PHV is used as a reference point for comparisons of size attained and rate of growth in other dimensions rather than chronological age (Beunen *et al*, 1988; Malina *et al*., 1988; Malina *et al*. 2004; Shuttleworth, 1937). Age at peak weight velocity (PWV) generally occurs approximately 0.3-0.9 years after PHV in females and 0.2-0.4 years after PHV in males (Beunen and Malina, 1988).

Many longitudinal analyses of adolescent growth and maturation are limited to the timing and magnitude of the growth spurts in stature and weight. Most body dimensions also exhibit growth spurts within about a two-year period. The timing and the magnitude of the spurts differ (Shuttleworth, 1937; Beunen *et al*, 1988; Malina *et al*., 2004; Satake *et al*., 1993, 1994), and there is considerable interindividual variability in the sequence in which the spurts in different dimensions occur (Stolz and Stolz, 1951; Satake *et al*., 1994). Studies of the sequence of spurts in several body dimensions are relatively few (Stolz and Stolz, 1951; Bielicki and Welon, 1973; Roche, 1974; Lindgren, 1978; Welon and Bielicki, 1979; Cameron *et al*., 1982; Satake et al., 1994), as are studies that have included aerobic capacity, particularly submaximal aerobic capacity or power output. Physical work capacity (PWC), or workload, at a heart rate of 170 bpm, or PWC_{170} is a common marker of submaximal aerobic capacity (Nudel, 1989), and is highly correlated with VO_2max (r=0.85 for adolescent males, mean age 14.2±0.9 years, Franz *et al*., 1984). Most of the limited, longitudinal data on submaximal work capacity have been treated in a cross-sectional manner, and there are fewer data available in females than in males (Armstrong and Welsman, 1994; Cunningham *et al*., 1984; Vanden Eynde *et al*., 1984).

The purpose of this study was to describe the timing and tempo of somatic growth and maturation, and PWC_{170} of Polish adolescents followed longitudinally from approximately 11 to 18 years of age. Objectives were: 1) to mathematically fit curves to individual data for anthropometric dimensions and PWC_{170} in order to estimate ages at PV and PVs for each dimension by sex; and 2) to examine mean and modal sequences among peak velocities by sex.

METHODS

Description of Subjects and Data Collection

The data are collected in a longitudinal study of Polish school children, organized in part by Dr. Robert M. Malina. Dr. Barbara Woynarowska, the attending physician at the schools and the director of school medicine of the National Institute of Mother and Child, Warsaw, Poland, collected the data along with Pawel Gorinsky between 1974 and 1982, and made the data available to Dr. Malina. Subjects were recruited and informed consent was completed following the procedures of the National Institute of Mother and Child.

Subjects

The 105 subjects (53 males and 52 females) were of Polish ancestry from Warsaw and all were healthy. On average, the subjects were 11.2±0.4 years of age at the time which data collection began (range=10.5 to 12.7 years at first measurement), and 18.2±1.6 years at the last data collection (range=14.0 to 20.1 years at last measurement).

Data Collection

Subjects were measured at three-month intervals from approximately age 10 or 11 to age 15 and annually thereafter until age 17 or 19. Complete data were not available for every subject and some attrition occurred during the course of the study (Table 1). The total sample size at 18+ years was 73 (37 males, 36 females) or 69.5% of the initial sample).

Weight, stature, four skeletal lengths (estimated arm length: estimated leg length: stature - symphyseal height, estimated sitting height: stature – symphyseal height, trunk length: suprasternal height – sympyhyseal height), three skeletal breadths (biacromial, bicristal, and chest breadths), chest depth, and six circumferences (chest, relaxed arm, estimated arm muscle, forearm, thigh, and calf circumferences) were assessed. Anthropometry was done according to the procedures of Martin (1956). Similar instrumentation and methods of measurement have been used in other European longitudinal studies of growth and maturation during adolescence.

Age at menarche was obtained prospectively for females as a measure of sexual maturity status. Submaximal power output, or PWC_{170}, was measured at approximately six-month intervals or yearly as part of the school health and fitness program. An average of 10 measurements of PWC_{170} (range=7-12) were taken on each subject. PWC_{170} was calculated from measurements of heart rate (ECG) and workload during a three-stage, graded submaximal test on a Monark bicycle ergometer, with workload increased with each stage in order for the subject to achieve a heart rate of ≥170 bpm (HR_{170}). Heart rate (by ECG) and revolutions per minute (rpm) were recorded at the end of each minute of cycling, and values for power output were plotted against heart rate on a graph, with power output at HR_{170} estimated by linear interpolation (Woynarowska and Kaminska, 1988) and recorded in kpm. The data were converted to Watts and expressed per unit body weight (Watts/kg) for the purposes of analysis.

Analyses

The data as recorded on the original data sheets were screened for completeness, recording errors, and outliers, variable by variable for each individual by Robert M. Malina and the author. Some missing values were interpolated over short intervals. Data were entered and analyzed via SAS. Individual data for stature, weight, and selected body dimensions and for several derived measures were mathematically fitted with curves using a kernel regression program (adapted from Guo, 1989). The program fitted distance curves to individual longitudinal data for various dimensions, and then calculated the first derivative of the distance curve, yielding velocity curves and estimates of age at PV and PV. Based on these criteria, visual comparisons of the fits of the curves to stature for several individuals of both sexes produced by the kernel regression to the actual data, and recommendations of researchers who had previously utilized kernel regression with growth data (Gasser *et al*., 1984; Guo, 1989; Guo *et al*., 1992), a 5^{th} degree polynomial, a bandwidth of 3.0 years, and an interval of 8 (8 estimates/yr) were chosen for the curve-fitting of all variables. RMSEs for stature in this sample were 0.55 for males and 0.48 for females, and were deemed acceptable based on the criterion of Guo *et al.* (1992) of an RMSE<1.5 for stature data fit with kernel regression. Data for each individual and each of 16 body dimensions and PWC_{170} were submitted to kernel regression analysis in order to obtain ages at PV and PVs for each dimension and submaximal power output for each subject. RMSEs for body dimensions other than stature were more variable: RMSEs ranged from 0.22 to 1.22 for males and from 0.22 to 1.12 for females, except for PWC_{170} in Watts, RMSE=7.85 for males and 5.57 for females. RMSEs were higher for PWC_{170} than growth measures due to greater variability in the performance data compared to growth data and to six-monthly measurements of PWC_{170} compared to quarterly measurements of body dimensions (i.e., fewer PWC_{170} data points available for curve fitting).

In addition to individual estimates for age at PV and PV for each body dimension and PWC_{170}, mean ages at PV and mean PVs were calculated for each dimension and PWC_{170} by sex. The prevailing order of occurrence of PVs was also examined relative to PHV and PWV (i.e., prior to, coincident with, or following PHV and PWV, respectively) after Beunen *et al*. (1988) Coincident was defined as a difference of <0.25 years (or ±0.125 years) between ages at PV.

Sequence of growth spurts

The sequence of growth spurts in various body dimensions was determined for each sex in two ways: by comparing the mean ages at PV calculated from kernel estimates (mean sequence of spurts), and by determining the modal sequence of spurts in selected body dimensions (stature, weight, sitting height, biacromial and bicristal breadths, plus estimated arm length and chest circumference or symphyseal height and thigh circumference) for comparison with the literature. The modal sequence of spurts was determined by documenting the sequence of spurts for each individual (after Satake *et al*., 1994; Stolz and Stolz, 1951), and determining the frequencies with which the spurt in each dimension occurred at a given position within the sequence of growth spurts and the cumulative frequencies (of occurrence) at each position within the sequence. The dimension with the greatest cumulative frequency in first position within the sequence was considered first in the modal sequence; of the remaining dimensions, the dimension with the greatest cumulative frequency in the second position within the sequence was considered second in the modal sequence, and so on. This is an equivalent approach to spurt sequence determination to that used by Stolz and Stolz (1951). Mean and modal sequences were then compared to each other and to the literature (Stolz and Stolz, 1951; Marubini *et al*., 1972; Tanner *et al*., 1976; Welon and Bielicki, 1979; Beunen *et al*., 1988; Buckler, 1990; Gasser *et al*., 1991; Satake *et al*., 1994).

RESULTS

Representativeness of the sample with regard to body size

Means and standard deviations for various body dimensions were calculated by sex for the age groups and compared to reference data for Warsaw youth (collected from 1976-1980 on 1460 adolescents, 772 M, 688 F), ages 10-18 years (Kurniewicz-Witczakowa *et al*., 1983). The sample in this study was generally representative of the greater population of Warsaw adolescents (i.e., within ±1 SD of the reference means).

Timing and tempo of the growth spurts

Mean ages at PV, PVs, and RMSEs for all dimensions to which curves were fit are shown by sex in Table 1. Mean ages at PHV and PHVs were 13.5±1.1 years and 9.1±1.3 cm/yr in males and 11.9±0.7 years and 7.5±1.6 cm/yr in females. PHV occurred, on average, 1.5 years earlier in females than in males, and females had a lower PV than males by 1.5 cm/yr. In addition to age at PV and PV in stature, sex differences were apparent in the timing and tempo of all dimensions, measured or derived. Mean ages at PV for various body dimensions ranged from 12.6 to 14.4 years in males and from 11.7 to 13.2 years in females. Females' ages at PV were, on average, earlier than males' ages at PV in every body dimension. However, males exhibited an earlier mean age at PV in absolute PWC_{170}. The intensity of the growth spurt in PWC_{170} and all body dimensions was greater in males than in females, with the exception of estimated trunk and arm lengths, bicristal breadth, arm circumference, and estimated arm muscle circumference.

The spurt in absolute PWC_{170} occurred, on average, at 13.2±1.0 years in males, slightly earlier than PHV (13.5±1.1 years) and more than one-half year earlier than PWV (13.8±1.5 years). The spurt in absolute PWC_{170} occurred at 13.2±0.8 years in females, the last in the sequence of ages at PV, 1.1 years after PHV (11.9±0.7 years) and 0.72 years after PWV (12.5±1.4 years). There was no sex difference in the timing of the spurt in PWC_{170}.

Table 1. Means (M) and standard deviations (SD) for age at peak velocity (Age at PV, yr) and peak velocity (PV, units/yr) by sex for various body dimensions. EAMC=estimated arm muscle circumference.

		Males				Females			
		Age at PHV		PV		Age at PHV		PV	
		M	SD	M	SD	M	SD	M	SD
Stature	cm	13.47	1.14	9.05	1.29	11.95	0.69	7.51	1.58
Weight	kg	13.83	1.51	9.14	3.62	12.52	1.36	7.55	2.18
Symphyseal ht	cm	13.04	1.16	5.59	1.14	11.92	0.90	5.12	2.60
Est. trunk length	cm	12.79	2.00	4.81	2.13	11.86	0.97	5.16	3.40
Est. sitting ht.	cm	13.22	1.76	5.27	1.62	12.10	0.97	5.03	2.07
Est. arm length	cm	12.84	1.47	5.23	1.74	11.73	0.69	5.28	2.42
Biacromial breadth	cm	13.39	1.36	2.44	0.53	12.05	0.78	2.08	0.65
Bicristal breadth	cm	13.23	1.53	1.82	0.55	12.73	1.08	2.22	0.86
Chest breadth	cm	12.85	1.22	2.17	0.96	12.42	1.41	1.70	0.83
Chest depth	cm	12.59	1.09	1.78	1.54	12.28	1.15	1.48	1.03
Chest circumference	cm	14.36	2.16	8.75	4.68	12.79	1.81	5.83	3.25
Arm circumference	cm	12.65	1.29	2.11	1.00	12.05	1.21	2.43	1.35
Forearm circumference	cm	13.56	1.87	2.20	0.86	13.15	2.02	1.52	1.48
Thigh circumference	cm	13.24	2.02	5.08	2.58	12.70	1.76	4.87	2.40
Calf circumference	cm	12.74	1.74	2.76	1.40	12.38	1.08	2.52	2.02
EAMC	cm	12.95	1.24	2.15	0.93	11.96	1.11	2.17	1.41
Absolute PWC_{170}	Watts	13.18	0.98	42.4	15.78	13.24	0.82	25.46	11.93

Timing of growth spurts relative to PHV and PWV

The prevailing order of occurrence of PVs relative to PHV and PWV (i.e., prior to, coincident with, or following PHV and PWV, respectively) is shown in Table 2. Growth spurts in nine dimensions preceded PHV in males, while those in weight, several upper body lengths and breadths, and chest and forearm circumferences follow PHV, and approximately equal numbers of individuals (i.e., within one case) exhibited spurts in thigh circumference before and after PHV. All body dimensions and PWC_{170} exhibited spurts before PWV in males, with the exception of chest circumference, which followed PWV. In females, the majority of body dimensions exhibited spurts after PHV and before PWV.

The exceptions were symphyseal height and estimated trunk and arm lengths, which attained PV coincident with PHV, and estimated sitting height and biacromial breadth, which had spurts which were evenly distributed (i.e., within one case each) before and after PHV. In addition, PVs in chest depth were evenly distributed before and after PWV, chest circumference spurts occurred coincidentally and after PWV (i.e., evenly distributed within one case), and PVs in bicristal breadth, forearm and calf circumferences and PWC170 occurred following PWV in females.

The PV in PWC_{170} tended to occur on either side of (i.e., both before and after) PHV in males (Table 2). It preceded PHV in 43.4%, was coincident with PHV in 22.6%, and followed PHV in 34.0%. In contrast, PV in PWC_{170} followed PHV in 86.5% of females, preceded PHV in 5.8% and was coincident with PHV in 7.7% (Table 2). Based on mean ages at PV, the spurt in absolute PWC_{170} occurred before PWV in males (64.2% before, 11.3% coincident, 24.5% following), and after PWV in females (17.3% both before and coincident, 65.4% following).

Table 2. Timing of growth spurts in various body dimensions and PWC_{170} relative to PHV and PWV based on the modal occurrence by sex from data for individuals (X=males, O=females), after Beunen *et al.* (1988). P=Prior to, C=Coincident with (PV within ±0.12 years), and F=Following; --=approximately equal numbers of cases (within one case). EAMC=estimated arm muscle circumference.

	PHH			PWV		
	P	C	F	P	C	F
Stature				XO		
Weight			XO			
Symphyseal height	X	O		XO		
Estimated sitting height		O - -	XO	XO		
Estimated trunk length	X	O		XO		
Estimated arm length	X	O		XO		
Biacromial breadth		O - -	XO	X		O
Bicristal breadth			XO	XO		
Chest breadth	X		O	XO - -		- - O
Chest depth	X		O		O - -	XO
Chest circumference			XO	XO		
Arm circumference	X		O	X		O
Forearm circumference			XO	XO		
Thigh circumference	X - -		- - XO	X		O
Calf circumference	X		O	XO		
EAMC	X		O	X		O
PWC_{170}	X		O			

THE SEQUENCE OF GROWTH SPURTS IN DIFFERENT BODY DIMENSIONS AND PWC_{170}

Mean sequence of PVs by sex

Based on mean ages at PV (Table 3), the spurts in estimated trunk length and symphyseal height preceded the spurts in stature and weight, and that the spurts in weight, forearm circumference, and chest circumference followed the spurt in stature in the sequence in both sexes. Also, PHV and PWV occurred earlier in the sequence of spurts in females than in males. PHV occurred relatively early in the sequence of PVs in females (4^{th} out of 17 variables), whereas it occurred relatively late in the sequence of PVs in males (14^{th} out of 17 variables).

Table 3. Mean sequence of growth spurts in 16 dimensions and PWC_{170} by sex (EAMC=estimated arm muscle circumference).

Position	Males		Females	
	Variable	Mean Age at PV (yr)	Variable	Mean Age at PV (yr)
1	Chest depth	12.59	Arm length	11.73
2	Arm circumference	12.65	Trunk length	11.86
3	Calf circumference	12.74	Symphyseal height	11.92
4	Trunk length	12.79	Stature	11.95
5	Arm length	12.84	EAMC	11.96
6	Chest breadth	12.85	Arm circumference	12.05
7	EAMC	12.95	Biacromial breadth	12.05
8	Symphyseal height	13.04	Sitting height	12.10
9	PWC_{170}, Watts	13.18	Chest depth	12.28
10	Sitting height	13.22	Calf circumference	12.38
11	Bicristal breadth	13.23	Chest breadth	12.42
12	Thigh circumference	13.24	Weight	12.53
13	Biacromial breadth	13.39	Thigh circumference	12.70
14	Stature	13.47	Bicristal breadth	12.73
15	Forearm circumference	13.56	Chest circumference	12.79
16	Weight	13.83	Forearm circumference	13.15
17	Chest circumference	14.36	PWC_{170}, Watts	13.24

Modal sequence of PVs by sex

The modal order (the most frequently observed sequence in individuals) of PVs was determined for a set of selected body dimensions (Table 4) for comparison with the results of Stolz and Stolz (1951). PHV occurs later in the mean sequence than in the modal sequences in males, and earlier in the mean sequence than in the modal sequences in females. Ten males exhibited complete asynchrony of PVs in these dimensions and none showed complete synchrony. Two females exhibited complete asynchrony in PVs and no one individual was completely synchronous; however, females showed a greater tendency toward synchronicity in PVs than males.

Table 4. Modal sequence of ages at growth spurts in selected body dimensions by sex.

Position	Males	Females
1	Thigh circumference	Symphyseal height
2	Symphyseal height	Stature
3	Stature	Thigh circumference
4	Bicristal breadth	Biacromial breadth
5	Biacromial breadth	Sitting height
6	Weight	Weight
7	Sitting height	Bicristal breadth

DISCUSSION

Timing and tempo of the growth spurts in stature and weight

Although the timing of the growth spurt, or estimated age at peak height velocity (PHV), varies among studies, there is relatively little variation in the sex-specific estimates of age at PHV given the variety of analytical procedures used and populations studied. In this sample of Polish adolescents, age at PHV estimated by kernel regression was 13.5±1.1 years in males with a PV of 9.1±1.3 cm/yr, and age at PHV in females was 11.9±0.7 years with a PV of 7.5±1.6 cm/yr. Females in this sample experienced their adolescent growth spurt in stature 1.6 years earlier than males in this sample, but males had a greater tempo or maximum rate of growth than females by 1.5 cm/yr.

The mean age at PHV for males in this study was somewhat early compared to all but one non-parametric analysis (Satake *et al*., 1993) and several of the parametric analyses (Deming, 1957; Thissen *et al*., 1966; Bock *et al*., 1973; Johnston *et al*., 1973; Shohi and Sasaki, 1987; Berkey *et al*., 1994). The mean age at PHV for boys in the present study was also early compared to that for boys in the Wroclaw Growth Study, 14.0±1.2 years (Malina and Bielicki, 1992). The results suggest that this group of males might have been early maturers compared to those in other samples (range=12.6-14.7 years). In contrast, the mean PHV for males in this study was comparable to mean PVs estimated for other samples of males (range=6.9-11.9 cm/yr).

Mean age at PHV and mean PHV for females in this study compared closely with results of other studies (range for age at PHV=11.0-12.6 years, range for PHV=6.4-11.0 cm/yr). The results thus suggested that the girls in this study were average in their maturity status, which is consistent with their mean age at menarche, 13.1±0.8 years (range=10.9-15.0 years). The mean age at menarche for this sample is consistent with those reported for Polish girls (Koniarek, 1971: 13.0±0.9 years; Bielicki, 1975,1976: 13.1±1.0 years; Bielicki *et al*., 1977: 13.0±1.1 years; Welon and Bielicki, 1979: 13.1±0.9 years; Laska- Mierzejewska *et al*., 1982, Warsaw: 12.7±1.1 years, rural: 13.4 years) and those reported for other European populations (range=12.1 to 13.5 years).

The PWV for this sample of Polish males occurred at an earlier mean age (13.8±1.5 years) than those reported by the majority of studies by approximately one-half year, which range from 13.6 years (Johnston *et al*., 1973; Satake *et al*., 1993) to 14.6 years (Beunen *et al*., 1988). On the other hand, females in this study exhibited a growth spurt in weight that was consistent with the literature in timing and magnitude, and consistent with their average maturity status as indicated by mean ages at PHV and menarche. In both sexes, PWV occurred approximately 0.5 year after PHV, within the range of 0.1 year to approximately 1.0 year between mean ages at PHV and PWV reported in other studies.

Differences among studies in ages at PHV, PWV, and menarche may be due, in part, to population differences, as populations of southern European ancestry tend to mature earlier than those of northwestern or central European ancestry (Eveleth and Tanner, 1990). Differences in ages at PHV and PWV may also be due to different frequencies of measurement and the use of different analytical procedures. For example, the mean ages at PHV and PWV for the Polish sample in this study are closest to those for Japanese adolescents reported by Satake *et al*. (1993), who derived estimates from spline functions, a curve-fitting procedure similar to kernel regression.

Mean ages at PV for various body dimensions

Ages at PV ranged from 12.6 to 14.4 years (1.8 years) in males and from 11.7 to 13.2 years (1.5 years) in females (Table 5). The range of ages at PVs for this sample (time from earliest PV to latest PV) is consistent with ranges previously reported in other studies (Stolz and Stolz, 1951: 0.5-2.0 years; Bielicki and Welon, 1978: 1.9 years; Satake *et al*., 1993, 1994: 1.2-1.6 years). Sex differences were apparent in the timing (age at PV) and tempo (PV) of growth in all body dimensions, measured or estimated. On average, females had earlier mean ages at PV than males in every dimension; however, the intensity of the growth spurt was greater in males than in females in the majority of body dimensions. These findings are consistent with the literature, except for a couple of reports, which noted a greater PV in bicristal breadth in females than in males (Takai and Shinoda, 1991; Tanner *et al*., 1976).

Ages at PV and PVs of different body dimensions have been estimated by a number of methods (graphic, logistic, Gompertz logistic, splines, and kernel regression) for various samples studied longitudinally. Similar to comparisons of ages at PHV and PWV, the ages at PV for symphyseal height (estimated leg length), sitting height, trunk length, and biacromial and bicristal breadths for males in the present study were earlier relative to most of the comparative data, while mean PVs were generally greater than or equal to those reported in the literature. In females, both mean ages at PV and mean PVs for these dimensions were consistent with the literature.

Timing of growth spurts relative to PHV and PWV

Growth spurts in nine dimensions preceded PHV in males, while those in weight, upper body lengths and breadths, and chest and forearm circumferences followed PHV (Table 2). The timing of PVs in body dimensions for males relative to PHV was consistent with that in Belgian males (Beunen *et al*., 1988); however, relative to PWV, males in the Polish sample exhibited growth spurts in every body dimension prior to PWV except for chest circumference, while in Belgian males, PVs in biacromial and chest breadths and thigh and flexed arm circumferences were coincident with PWV. Comparisons of the timing of PVs in body dimensions to PHV and PWV have not been made for females.

Sequences of growth spurts in various body dimensions

In the present study, the mean sequence of spurts was determined from PVs derived from kernel estimates and the modal sequence of spurts was determined for two sets of selected body dimensions for comparison with the results of Stolz and Stolz (1951) and Satake *et al*. (1994).

Mean sequence of growth spurts

Differences between mean ages at PV for body dimensions and PWC_{170} were quite small, on the order of hundredths of a year in adjacent ages at PV in some cases, and smaller than those previously reported between ages at PV in selected dimensions. For example, several studies have reported a difference of approximately 1.0 year between mean ages at PV in estimated leg length and trunk length (Shuttleworth, 1937; Tanner, 1962; Bielicki and Welon, 1973). In the present study, spurts in estimated leg and trunk lengths occurred 0.25 years apart in males and 0.18 years apart in females. Differences between the results of this study and those of other studies may be due to different ways in which leg and trunk lengths and other skeletal lengths yield variable estimates for ages at PV. Population variability may be an additional factor.

In the majority of individuals of both sexes, spurts in two or more dimensions were synchronous, i.e., they occurred simultaneously (ages at PV were <0.25 years apart). However, spurts in body dimensions tended to be asynchronous, on average (Marshall and Tanner, 1986), i.e., different parts of the body achieved their maximum rates of growth at different times. The frequency of synchronous PVs in the present study may be related to the large number of dimensions (16 body dimensions and PWC_{170}) for which ages at PV were estimated.

The timing of the spurt (age at PV), and intensity of the spurt (PV), in each dimension were variable among individuals, which is consistent with other studies (Roche, 1974; Marshall, 1974; Cameron *et al*., 1982; Satake *et al*., 1994). Sequences of mean ages at PV also differ among longitudinal studies (Table 5), and present some problems in making comparisons, since different dimensions are included in the studies. Differences in sequences of mean ages at PV among studies may be due, in part, to individual variability in maturation rate and sequence of PVs, to the different analytical curve-fitting procedures or models used to estimate parameters of the spurt, to different measurement frequencies and study durations, and to sampling variation.

Based on mean ages at PV, the sequences of spurts occurred in males and females exhibited several commonalities: the spurts in estimated trunk length and symphyseal height (estimated leg length) preceded the spurts in stature and weight, and the spurts in weight and forearm and chest circumferences followed the spurt in stature in both sexes. Also, the PVs in chest dimensions occurred in the same order relative to each other in both sexes (chest depth, first; chest breadth, second; and chest circumference, third). Sex differences in the sequence of PVs, however, outnumbered the similarities, which is generally consistent with the literature, which indicates that the sequence of growth spurts in various dimensions generally varies by sex. For example, PV in bicristal breadth precedes that in biacromial breadth in males (Stolz and Stolz, 1951; Tanner *et al*., 1976; Welon and Bielicki, 1979; Buckler, 1990), while the opposite occurs in females (Tanner *et al*., 1976; Buckler, 1990; Satake *et al*., 1993). Other examples of reversed order include the timing of PVs in trunk and arm lengths (trunk before arm in males, arm before trunk in females), and PVs in bicristal and biacromial breadths and calf and thigh circumferences precede PHV in males and follow PHV in females. PHV also occurred earlier in the sequence of spurts in females than in males, as did PWV.

The sex difference in sequence of PVs found in this study is not uncommon, although only one study has tested the statistical significance of the similarity of the sequences between sexes. Satake *et al*. (1994) calculated Kendall's rank order correlations among average and individual sequences to determine whether or not there was significant agreement among growth gradients. The order of mean ages at PV in seven body dimensions was statistically similar in both sexes (Kendall's $r=0.62$, $p<0.05$). The sequence of mean ages at PV in this sample of Polish adolescents was not subjected to this type of statistical analysis; however, this might be considered in follow-up analyses.

Modal sequence of growth spurts

Modal sequences have been reported in only one other study (Stolz and Stolz, 1951). Of the 16 body dimensions in the present study, 7 were selected for modal sequence determination and for comparison with Stolz and Stolz (1951). Modal sequences in the present study differed by sex (Table 5); however, leg growth (symphyseal height and/or thigh circumference) exhibited a spurt prior to stature, followed by spurts in breadths, sitting height, and weight, not necessarily in that order. Similarities exist between the modal sequence of the present study and mean sequences of other studies (Table 5): the spurt in leg length generally precedes that in stature, spurts in sitting height and breadths follow the spurt in stature, and the spurt in weight tends to occur late in the sequence of spurts. Aside from these similarities, the modal sequence in the present study differs from the sequence of mean ages at PV in this and other studies. Besides the obvious difference between the methods used to determine the mean and modal sequences, differences between the modal and mean sequences in the present study are probably due to a number of factors already mentioned, including differences among analytical procedures and population variability.

The modal sequence for males in this study (thigh circumference, symphyseal height or estimated leg length, stature, bicristal breadth, biacromial breadth, weight, and sitting height) was reasonably similar to that described by Stolz and Stolz (1951) (leg length; thigh circumference; stem length or sitting height and stature, coincident with one another; bicristal breadth; biacromial breadth; and weight. The sequence was quite variable in the majority of individuals, both in the present study and in that by Stolz and Stolz (1951). In contrast to the findings of Stolz and Stolz (1951), however, no individual exhibited completely synchronous PVs in this set of 7 body dimensions, while 10 individuals exhibited complete asynchrony in the present study. In the study of Stolz and Stolz (1951), PVs were completely synchronous in two individuals and completely asynchronous in two individuals.

The modal sequence of PVs in Polish females in the present study was: symphyseal height (estimated leg length), stature, thigh circumference, biacromial breadth, sitting height, weight, and bicristal breadth. Two individuals exhibited complete asynchrony in PVs and none exhibited complete synchrony; however, females showed a greater tendency toward synchronicity in PVs than males. Finally, the modal sequence of spurts in the present study does not mirror any of the sequences of mean ages at PV from other studies. This is, perhaps, due to the fact that the beginning age at data collection in females was closer to the age at PHV in females than in males. There are no corresponding data for California adolescents; Stolz and Stolz (1951) studied only males. However, this modal sequence for females in the present study is consistent with that reported by Satake *et al*. (1994).

It seems that the fewer the number of body dimensions measured and the longer the duration of the study, the more likely that PVs for different dimensions will be asynchronous, i.e., that they will show distinct and different ages at PV. In this study, there were a relatively large number of dimensions (17, including PWC_{170}, compared to 4-8 in most studies) to which curves were fit to estimate ages at PV and PVs; thus, there may have been a greater tendency towards synchronicity in PVs in this study than in others. These conditions may also underlie the small differences between ages at PV for different dimensions as reported by Satake *et al*. (1994), and smaller differences between ages at

PV for selected dimensions found in this study compared to those reported in other studies.

Table 5. Mean sequences of growth spurts by sex. Variables for which ages at PV were estimated in this study that are the same as variables included in other studies of sequence are shown in **bold** font.

Study, Method	Males	Females
NON-PARAMETRIC ANALYSES		
This study	chest depth	**arm length**
Kernel regression	arm circumference	**trunk length**
mean ages at PV	calf circumference	**leg length**
53 M, 52 F	**trunk length**	**stature**
	arm length	**EAMC**
	chest breadth	arm circumference
	EAMC	biacromial breadth
	leg length	**sitting height**
	sitting height	chest depth
	bicristal breadth	calf circumference
	thigh circumference	chest breadth
	biacromial breadth	**weight**
	stature	**thigh circumference**
	forearm circumference	**bicristal breadth**
	weight	**chest circumference**
	chest circumference	forearm circumference
Beunen *et al*. (1988)	leg length	
Non-smoothed polynomials	stature	
mean ages at PV	sitting height	
Leuven Growth Study	weight	
432 M	chest circumference	
	arm pull	
Satake *et al*. (1993)	stature	stature
Splines	biacromial breadth	arm span
mean ages at PV	arm span, bicristal breadth	sitting height, biacristal breadth
Kanagawa, Japan	sitting height	weight
16 M, 21 F	weight	bicristal breadth
	chest circumference	chest circumference

(to be continued)

(continuation of Table 5)

Study, Method	Males	Females
Gasser *et al.* (1991)	leg length (supine)	leg length
Kernel - structural average curves mean ages at PV Zurich Longitudinal Growth Study 120 M, 112 F	leg height (stature.-sitting height) arm length supine length, stature sitting height, crown-rump length	leg height arm length supine length, stature sitting height, crown-rump length
PARAMETRIC ANALYSES		
Stolz and Stolz (1951) Graphic California Adolescent Study 67 M	leg length thigh circumference stem length, stature bicristal breadth biacromial breadth	weight
Marubini et al. (1972) Gompertz and Logistic Harpenden Growth Study 23 M, 15 F	leg length stature sitting height biacromial breadth	leg length stature sitting height biacromial breadth
Tanner et al. (1976) Logistic Harpenden Growth Study 55 M, 35 F	stature bicristal breadth biacromial breadth sitting height	stature sitting height biacromial breadth bicristal breadth
Welon and Bielicki (1979) Graphic Wroclaw Growth Study 192 M, 250 F	leg length biiliac breadth biacromial breadth, weight stature, trunk length trunk length	leg length biiliac breadth biacromial breadth stature Weight

DISCUSSION

The specific aims of this study of somatic growth and maturation in 105 Polish adolescents were to mathematically fit curves to individual data for anthropometric dimensions and PWC_{170} in order to derive estimates of ages at PV and PVs for each dimension by sex; and, in addition, to examine the mean and modal sequences among peak velocities by sex.

The males in this study may have been advanced in maturity status relative to other samples based on a mean age at PHV that was somewhat early compared to other estimates; although mean PHV was comparable to values for other samples of males. The females in this study appeared to be average in maturity status because the mean age at PHV and mean PHV were consistent with estimates from other studies.

The PVs in body dimensions other than stature occurred within a relatively narrow time period (1.51 years in females to 1.77 years in males), and the ranges of PVs were consistent with ranges previously reported (0.5-2.0 years).

Sex differences were apparent in ages at PV and PVs. On average, females had earlier ages at PV in somatic dimensions than males, with the exception of PWC_{170}. The intensity of the growth spurt in PWC_{170} was greater in males than in females, and the same was true for the 12 of the 16 body dimensions (including stature) for which parameters were estimated, consistent with the literature.

When the timing of spurts in various body dimensions was compared to ages at PHV and PWV, the prevailing order of PVs showed that growth spurts in weight and upper body lengths and breadths followed PHV in males, while almost all body dimensions exhibited spurts after PHV in females and before PWV in both sexes. In the majority of the sample, a number of dimensions were synchronous in estimated age at PV, perhaps because ages at PV were estimated for more body dimensions than in any other study previously.

In both sexes, the growth spurt or PV in PWC_{170} occurred near both PHV and PWV; however, it occurred closer to PHV in males than in females, and PV in PWC_{170} tended to occur on either side of PHV and before PWV in males, while it tended to occur after both PHV and PWV in females.

There was a reasonably well-defined sequence of mean ages at PV in body dimensions as well as a reasonably clear modal sequence of spurts, and both mean and modal sequences differed by sex. There is some consistency with mean sequences reported in other studies; however, the modal sequence of PVs differed from that based on mean ages at PV and from sequences previously reported.

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