The development of aerobic power in young athletes

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BAXTER-JONES, A., H. GOLDSTEIN, AND P. HELMS. *The development of aerobic power in young athletes.* J. Appl. Physiol. 75(3): 1160–1167, 1993.—Previous studies investigating the effects of training in children have been hampered in their interpretation by the confounding effects of growth and development. We followed the development of maximal aerobic power ($\dot{V}O_{2\,max}$) in 453 athletes drawn from soccer, swimming, gymnastics, and tennis. Study design was of a mixed longitudinal type with five age cohorts (8, 10, 12, 14 and 16 yr) followed for 3 consecutive years. A multilevel regression modeling procedure was used to identify the independent effects of predictor variables while accounting for the effects of growth, such as changes in body size. When age, height, and weight were controlled for, $\dot{V}O_{2\,max}$ in males significantly increased with pubertal status, indicated by the coefficient value of 0.15 l/min being greater than its associated SE of 0.07 l/min. Females showed a similar pattern, with a coefficient value of 0.13 ± 0.07 l/min, although the significant increase in $\dot{V}O_{2\,max}$ ($P < 0.05$) found in males in the latter stages of puberty was not shown in females. Swimmers had the highest $\dot{V}O_{2\,max}$ values ($P < 0.001$) at all ages.

maximum oxygen uptake; puberty; training; longitudinal repeated measures; statistical modeling

THE EFFECT THAT TRAINING has on the development of maximal aerobic power ($\dot{V}O_{2\,max}$) during childhood and adolescence continues to be a subject of great interest to physiologists and sports scientists (6, 7, 11, 13). Most studies have been cross sectional, and because of this the effects of growth, development, and maturation may have masked or may have been greater than those brought about by training (15). Longitudinally gathered data are essential to clearly identify the relative contributions from growth, maturation, and training on the development of aerobic power (16).

A comprehensive review (12) of previously published data has concluded that, in normal children, $\dot{V}O_{2\,max}$ increases proportionally to body size and mass in both sexes. When $\dot{V}O_{2\,max}$ is "normalized" in this way, it remains stable in males throughout childhood and adolescence while decreasing in females. Although the use of ratio standards, such as $\dot{V}O_{2\,max}$ per kilogram body mass, is an attractive and seemingly ideal method to control for the increase of $\dot{V}O_{2\,max}$ with growth, the use of such ratio standards has been criticized by Tanner (20) and more recently by Winter et al. (25), because this method of controlling for growth can produce spurious correlation, misinterpretation of data, and incorrect conclusions.

The purpose of the present study was to examine the relationship of $\dot{V}O_{2\,max}$ to chronological age at different stages of maturity and to separate the effects of training from those of growth. The data used were obtained from the Training of Young Athletes (TOYA) study, a 5-yr longitudinal investigation into the effects of training that ran from 1987 through 1991. We utilized a multilevel regression modeling procedure (MRMP) (8) that circumvented the problems associated with ratio standards and had been designed especially for longitudinal data sets such as those provided by the TOYA study.

METHODS

Design. The TOYA study set out to establish the distribution, frequency, and source of the positive and negative effects of intensive training within a population of young athletes, with specific reference to sports-related health and injury problems, growth, psychological development, and cardiorespiratory fitness, the latter being presented here. Four sports were selected: a racket sport (tennis), a contact team sport (soccer), a sport that requires cardiovascular and muscular endurance (swimming), and a sport that requires flexibility and explosive strength (gymnastics). These sports were also chosen because they all involved a large number of young athletes, training for them was often started before puberty, and they possessed organized systems of intensive training and standardized age groups for competition. A random sample of athletes was drawn from within a 250-mile radius of London, the study base. The basic criteria for inclusion were that all athletes were being intensively trained (thresholds provided by each sport's governing body) and/or that they had performance success to a specified level in the past or were expected to achieve it in the future. The study used a mixed longitudinal design to incorporate five age cohorts spanning prepubertal, pubertal, and postpubertal children.

Subjects. At the start of the study in 1987 there were 453 subjects, 222 females and 231 males, in five age cohorts (8, 10, 12, 14, and 16 yr); by the end of 1990, 126 females and 145 males remained (59.8%; Table 1). A total of 182 subjects left the study; 58 were excluded because they retired from their sport, another 34 were excluded because they were not training intensively (i.e., they had fallen below the thresholds given by the sporting bodies or they were no longer achieving performance success), and 90 (19.9% of the total sample) withdrew themselves. With the exception of soccer and gymnastics, the sample was evenly distributed across genders (Table 1). Many

TABLE 1. *Subject by age cohort, gender, and sport at beginning and end of TOYA study*

	Soccer	Gymnastics		Swimming		Tennis	
Year of Birth	M	M	F	M	F	M	F
1971	12 (2)	7 (4)	13 (3)	10 (5)	14 (8)	12 (7)	14 (7)
1973	25 (14)	10 (3)	18 (4)	14 (9)	16 (10)	15 (11)	17 (9)
1975	28 (16)	10 (5)	18 (12)	15 (11)	15 (11)	18 (15)	19 (12)
1977		6 (4)	15 (11)	15 (13)	15 (10)	19 (17)	20 (11)
1979		5 (2)	17 (12)			10 (7)	11 (6)
Totals	65 (32)	38 (18)	81 (42)	54 (38)	60 (39)	74 (57)	81 (45) = 453 (271)

Values are nos. of subjects in 1987, when Training of Young Athletes (TOYA) study began, with nos. of subjects in 1990, at end of study, in parentheses. M, males; F, females.

more females than males take part in gymnastics in the UK, and the sample of 80 females and 38 males was thought to reflect current participation rates.

Measurements. Body height, weight, pubertal development, and $\dot{V}\mathrm{O}_{2\,\max}$ were measured annually for 3 consecutive years. As part of a self-report questionnaire, average weekly training hours were recorded. Subjects were grouped into three pubertal stages to ensure adequate cell sizes within each sport: prepubertal (PP), midpubertal (MP), and late-pubertal (LP). Puberty was determined by assessment of stages of breast development in females and genitalia in males with Tanner's criteria (21), where PP is Tanner's *stage 1*, MP is Tanner's *stages 2–3*, and LP is Tanner's *stages 4–5*. $\dot{V}\mathrm{O}_{2\,\max}$ was measured with the subject running on a motor-driven treadmill (PK Morgan Instruments, Rainham, UK) and in an air-conditioned laboratory, temperature 20–22°C, relative humidity 45–60%. Subjects ran at an individually predetermined rate on a 3.4% grade for 1 min followed by increments of 0.5 km/h every minute until exhaustion (3, 4). Measures of gas exchange were obtained by standard open-circuit techniques. Subjects breathed through a Speak-Easy II face mask (Respironics, Monroeville, PA), and ventilation was measured through a turbine volume transducer attached to a control unit with digital display. Analysis of expired O_2 and CO_2 was carried out by paramagnetic analyzers (model nos. QA 500D and 801D, respectively, Morgan Instruments, Rainham, UK). This equipment was interfaced with a Sperry/Unisys Micro IT (286) computer. Gas concentration data were averaged every 10 s, with subsequent calculation of O_2 uptake ($\dot{V}\mathrm{O}_2$), CO_2 output, expired ventilation, and respiratory exchange ratio by use of Wyvern software (Morgan Instruments). The system was calibrated before each session with standard gases of known O_2 and CO_2 concentration. Heart rate was continuously recorded during exercise. The highest $\dot{V}\mathrm{O}_2$ was accepted as $\dot{V}\mathrm{O}_{2\,\max}$ if either a plateau occurred (an increase <2 ml/kg with an increase in work load) or if one of the following criteria was met: a heart rate of >95% of the predicted maximum corrected for age or a respiratory exchange ratio >1.1 (4).

Statistics. Descriptive statistics (means ± SD) were applied to all variables. Analysis of variance (ANOVA) and Fisher's least significant difference (LSD) procedure were used to determine whether significant differences existed between compared groups. Measures of $\dot{V}\mathrm{O}_{2\,\max}$ were adjusted for growth (height and weight) and maturation (pubertal staging) by the use of an MRMP (8). Separate equations were fitted for each sex, and predicted values of $\dot{V}\mathrm{O}_{2\,\max}$ (l/min) were then calculated from their age, height, weight, sport, and level of maturation. All analyses other than the modeling procedure were performed with the Statistical Analysis System Program (19), and $P < 0.05$ was considered significant.

Modeling. The ideal method of analysis of longitudinal repeated-measures data involves some form of multilevel analysis (8). Multilevel analysis has been found useful in extending understanding of biological processes beyond that which can be obtained through single-level linear modeling. The term multilevel refers to a hierarchical or nested membership relationship among units in a system. Research on human growth has benefited from the formulation of two-level models for repeated measurements on individual models because fewer restrictions are placed on the data than in earlier types of analysis (8). When this type of modeling is used, coefficients in a linear model of a process occurring at one level of a hierarchical system can be viewed as variables of interest that are functions of characteristics of units at another level. Furthermore, the variances and covariances of these coefficients are often of direct interest, and coefficients of within-unit relations among variables are generally estimated better than they would be if a single-level analysis were conducted for each group. The more appropriate model specification also resolves the problem of misestimated precision inherent in single-level analysis of hierarchically structured data. Furthermore, inasmuch as longitudinal data have nested structure-measurements within individuals, multilevel analysis permits individuals to have their own growth curves. Multilevel analysis was performed with the program Multilevel Models Project ML3 (17) using age, anthropometric variables, pubertal stage, and sport as covariates to identify those factors with the most influence on the outcome variable $\dot{V}\mathrm{O}_{2\,\max}$. The models produced used all the available data to produce individual growth trajectories (Fig. 1). Each line represents the predicted change in $\dot{V}\mathrm{O}_{2\,\max}$ with age for an individual; this is *level 1* of the modeling procedure and represents within-individual variation. Comparisons between these regression lines represents *level 2* of the model, variations between individuals. These predicted individual regression lines use not only the individual's own data but also information from the whole sample. Multilevel modeling effectively captures the feature that the variance of the observations increases with time, and because each individual has his or her own slope and intercept, it provides the opportunity to determine the effects on slope and intercept of each

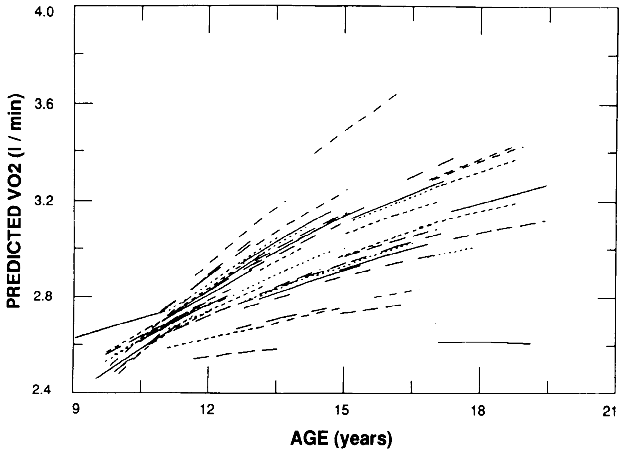

FIG. 1. Predicted individual maximal aerobic power ($\dot{V}O_{2\,max}$) growth curves for 70 male tennis players by use of multilevel modeling technique (8, 17). Each line represents regression of aerobic power ($\dot{V}O_2$) on age from 2–3 annual data points for each subject, with data from both individuals and whole sample. Alinearity was allowed for by including age^2 as a term.

predictor variable and its significance by relating the observed effects to the respective SEs. Thus group effects larger than within-individual variation can be identified.

To improve accuracy of calculation, age was measured around an origin of 12 yr, and for the same reason height and weight measures were adjusted around an origin of their respective means. Although the quadratic terms of age squared and height squared were not found to be significant, they were left in the model because they were the best estimates available to allow for the nonlinear relationship between $\dot{V}O_{2\,max}$ and age. Because swimmers had the highest $\dot{V}O_{2\,max}$ values, swimming was chosen as the base sport, and the other sports were compared with reference to it. In graphic representations of the model, height and weight were predicted at the age of 12 yr (our chosen origin) by regressing the variable on age and age squared, thereby allowing for the variation in height and weight of our sample at that age.

RESULTS

Over the 3-yr testing period, 1,065 exercise tests were performed, and of these 789 (74.1%) were accepted as having reached $\dot{V}O_{2\,max}$ and are reported here. As expected, the physical characteristics of age, weight, and height tended to increase with advancing sexual development (Tables 2 and 3), although this was not always the case. Soccer players (Table 3) had overlapping physical characteristics between pubertal stages.

$\dot{V}O_{2\,max}$ (Tables 2 and 3) tended to rise with increased pubertal development, although again, in soccer, there was overlapping between stages. However, in female athletes (Table 2), no increase in $\dot{V}O_{2\,max}$ with advancing sexual development was observed when $\dot{V}O_2$ was expressed as milliliter per kilogram per minute; in fact, in gymnasts the trend was reversed, with the mean value in MP (48.2 ± 4.3 $ml \cdot kg^{-1} \cdot min^{-1}$) being significantly greater ($P < 0.05$) than that in LP (44.7 ± 5.1 $ml \cdot kg^{-1} \cdot min^{-1}$). In male athletes (Table 3), with the exception of gymnasts, $\dot{V}O_{2\,max}$ ($ml \cdot kg^{-1} \cdot min^{-1}$) increased in the latter stages of puberty. In tennis and soccer players, duration of training per week increased with advancing sexual development, although there were no differences in training hours between puberty stages in gymnasts and swimmers.

Tables 4 and 5 summarize the results from the multilevel models. As previously stated, individual "growth" rates ("slopes") were evaluated following the approach of Goldstein (8) by the use of multifactorial analysis of covariance. Standard errors of estimate (SEE) were used as covariates for individual variability (within and between sporting and sexual development groups). The random variables (coefficients; Tables 4 and 5) show the covariance matrix (correlations) for the male and female models of $\dot{V}O_{2\,max}$ with growth. In males (Table 4) the within-individual variation (*level 1*) showed that the estimated $\dot{V}O_{2\,max}$ (mean value 0.0584) was greater than its associated SE (0.0048), indicating that $\dot{V}O_{2\,max}$ was increasing significantly with time. Also shown is the covariance matrix for *level 2*, the variance at age 12 yr, the intercept (constant/constant 0.0127 ± 0.0056), the covariance correlations between the slope and the intercept at that age (constant/age 0.0056 ± 0.0013), and the slope (age/age 0.0007 ± 0.0009). Although the variations of the intercept and the correlation of slope and intercept are significant, the high SE should be noted, a consequence of the fact that the analysis technique was designed to study populations rather than predict individual values. The positive correlation between intercepts indicates that there are differences between individuals, and the positive correlation between slope and intercept indicates that the higher the $\dot{V}O_{2\,max}$, the greater the change with age. The random variables in the female model (Table 5) show similar results.

After each explanatory variable was adjusted for covariables and other explanatory variables (Tables 4 and 5), it can be seen that age, height, and weight had significant effects on $\dot{V}O_{2\,max}$, inasmuch as the slope coefficients of the regression of $\dot{V}O_{2\,max}$ on age for all these variables were greater than their respective SEs. Although age squared and height squared were of marginal significance, they were the best estimates available to allow for the nonlinear relationship between $\dot{V}O_{2\,max}$ and age. In males (Table 4), swimmers had higher levels of $\dot{V}O_{2\,max}$ than participants in the other three sports ($P < 0.001$), and $\dot{V}O_{2\,max}$ increased significantly during the transition from MP to LP ($P < 0.05$). In females (Table 5) age, height, and weight all had significant effects on $\dot{V}O_{2\,max}$ and, like male swimmers, female swimmers had significantly higher values of $\dot{V}O_{2\,max}$ than the other athletes. Females differed from males, however, in that there was no significant difference in $\dot{V}O_{2\,max}$ between pubertal stages.

The model was then used to predict $\dot{V}O_{2\,max}$ (l/min) for each sport at each stage of pubertal development. Before these predictions were made, weight, height, and height squared were first controlled for by predicting them at age 12 (our origin) by regressing the variables on age and age squared, thus making allowance for their variation at this age. The results are shown in Figs. 2 and 3, where the significantly higher $\dot{V}O_{2\,max}$ in males can be seen for all sports. For males (Fig. 2) the increase in $\dot{V}O_{2\,max}$ with age can also be seen in soccer players, swimmers, and at a

TABLE 2. *Physical and performance characteristics of female subjects*

	n	Age, yr	Weight, kg	Height, cm	$\dot{V}O_{2\,\max}$		Training Duration, h/wk
					l/min	$\mathrm{ml \cdot kg^{-1} \cdot min^{-1}}$	
Gymnastics							
PP	29	10.6±1.2	30.2±4.8	137.0±7.3	1.46±0.24	48.4±8.0	13.7±5.4
MP	35	12.7±1.5*	37.5±4.2*	147.7±5.1*	1.81±0.23*	48.2±4.3	12.8±5.1
LP	53	16.0±1.5*	52.5±6.4*	160.6±5.3*	2.33±0.30*	44.7±5.1*	13.4±6.6
Swimming							
PP	7	11.3±0.6	27.8±1.2	135.4±4.1	1.45±0.17	52.2±3.9	12.5±5.6
MP	25	12.8±1.6	42.0±6.4*	154.9±7.1*	2.16±0.44*	51.7±8.0	10.2±5.4
LP	72	15.1±3.9*	56.0±7.6*	164.8±5.1*	2.86±0.45*	51.1±6.3	10.5±5.9
Tennis							
PP	18	10.7±0.8	33.5±4.3	142.2±7.2	1.58±0.27	47.4±5.8	5.5±2.1
MP	41	12.0±1.0*	40.5±5.7*	150.8±7.9*	1.97±0.33*	48.6±5.3	7.6±4.7
LP	101	15.5±1.9*	58.1±6.8*	165.5±6.0*	2.72±0.37*	47.1±5.3	9.2±5.1

Values are means ± SD (all visits); *n*, no. of subjects. $\dot{V}O_{2\,\max}$, maximal aerobic power; PP, MP, and LP, pre-, mid-, and late-pubertal stages, respectively. * Significant difference from preceding state ($P < 0.05$) by Fisher's least significant difference (LSD) comparisons.

lower rate of increase in tennis players, with a plateau in gymnasts at ~12 yr. At all stages of pubertal development, swimmers had higher values than the other athletes. In females there was a smoother transition, and the nonsignificant differences between pubertal stages demonstrated in Table 5 can be clearly seen. Female swimmers increased their $\dot{V}O_{2\,\max}$ with age, whereas gymnasts showed a decrease from the age of 8–9 yr, and tennis players maintained a constant level with growth.

DISCUSSION

Aerobic power in trained and untrained children has been frequently measured, and in untrained males and females it has been shown to increase with chronological age (12). When trained and untrained subjects of both genders are compared, the values of aerobic power in the trained subjects are higher at all ages, with the greatest differences found during adolescence (2, 3). In the present study swimmers, soccer players, and tennis players had higher values of aerobic power (assessed as $\dot{V}O_{2\,\max}$ in $\mathrm{ml \cdot kg^{-1} \cdot min^{-1}}$) at all stages of pubertal development compared with a normal untrained population of British children (Fig. 4), who had been measured at a similar time and under experimental conditions similar to those in this study (2). The most commonly cited cause for the fall in $\dot{V}O_{2\,\max}$ ($\mathrm{ml \cdot kg^{-1} \cdot min^{-1}}$) in females is that they have a greater accumulation of subcutaneous fat during and after puberty (2, 10). In a review of maturity-associated variation in $\dot{V}O_{2\,\max}$, Krahenbuhl et al. (12) concluded that weight was probably the best general index for controlling the effects of maturation. It was argued that the changes with chronological age were not taken into account when the effects of weight, height, and biological age were used to control for the effects of maturation.

TABLE 3. *Physical and performance characteristics of male subjects*

	n	Age, yr	Weight, kg	Height, cm	$\dot{V}O_{2\,\max}$		Training Duration, h/wk
					l/min	$\mathrm{ml \cdot kg^{-1} \cdot min^{-1}}$	
Soccer							
PP	13	13.1±0.7	41.3±4.9	152.5±5.1	2.30±0.29	55.7±3.7	3.5±2.5
MP	27	13.7±0.9	44.0±6.6	154.8±4.9	2.44±0.31	55.7±4.0	3.7±3.0
LP	77	15.9±1.4*	62.8±10.1*	172.7±7.7*	3.85±0.60*	61.5±4.9*	7.5±5.8*
Gymnastics							
PP	12	11.4±1.2	31.2±4.7	137.0±6.2	1.71±0.35	54.5±4.4	14.8±6.0
MP	11	14.0±0.9*	41.9±4.6*	152.7±8.3*	2.35±0.32*	56.0±3.3	15.8±4.0
LP	25	16.1±1.3*	58.5±7.1*	167.2±5.5*	3.20±0.55*	54.7±5.3	13.9±7.7
Swimming							
PP	18	11.7±0. 8	37.8±6.4	147.2±5.7	2.16±0.35	57.7±7.5	8.5±4.7
MP	17	12.8±0.7*	44.2±6.6*	155.1±6.7*	2.57±0.42*	58.1±5.4	9.3±3.9
LP	59	16.1±1.7*	66.6±10.5*	176.4±7.3*	4.16±0.70*	62.7±6.8*	10.8±6.6
Tennis							
PP	41	11.6±1.3	36.7±6.1	147.0±6.4	1.98±0.35	54.1±5.2	7.8±3.2
MP	39	13.0±1.2	43.0±6.0	155.9±7.4	2.47±0.38	57.6±5.6	11.1±5.5
LP	69	16.2±1.7	64.8±9.7	176.5±7.2	3.86±0.72	59.5±6.1	12.3±7.7

Values are means ± SD (all visits); *n*, no. of subjects. * Significant difference from preceding stage ($P < 0.05$) by Fisher's LSD comparisons.

In the initial analysis of our results (Tables 2 and 3), it was found that $\dot{V}O_{2\,max}$ in both males and females tended to increase with advancing pubertal development. However, in female athletes no difference was found in $\dot{V}O_{2\,max}$ between groups when it was expressed relative to body weight. It could therefore be suggested that the increased $\dot{V}O_{2\,max}$ is caused by an increase in body mass rather than actual increases in metabolic capacity and that training before puberty was having little if any effect on aerobic power. Although no single assessment of maturation (e.g., secondary sex characteristics, skeletal maturity, or peak height velocity) provides a complete description of maturity, it has been recently argued that these indicators are sufficiently interrelated to indicate a general maturity factor during adolescence (14), and Tanner (22) has reported a high concordance of sexual maturity rating with skeletal age.

Although intergroup comparisons of aerobic power have commonly been based on differences in the ratio of maximum O_2 concentrations to body weight, Tanner (20) pointed out that the use of such ratio standards was "theoretically fallacious and, unless in exceptional circumstances, misleading," suggesting that such comparisons should be based on regression standards. More recently, this criticism has been confirmed by Winter et al. (25). To avoid the problems associated with comparisons of ratio standards, this study carried out a secondary analysis of the data by use of a linear modeling procedure. This particular modeling procedure was chosen because it allowed not only for within-individual variability, derived from three consecutive yearly visits, but also for variability between individuals. With this method it was also possible to determine contributions of growth and developmental variables to changes in $\dot{V}O_{2\,max}$ over time. This type of model has several advantages over other procedures for describing and analyzing growth data. It provides a means of studying general hypotheses about factors influencing the pattern of growth, whereas single curve-fitting procedures are not well suited to such tasks. Furthermore all the available data can be used for estimation, even if only one or two measurements are present for some individuals. This is a feature not shared by other parametric or nonparametric models, although the parametric models are somewhat more efficient in this respect than the nonparametric ones. The modeling procedure we used also provides population growth velocities, together with between-subject variability and a description of how these interact with other factors (8, 9).

TABLE 4. *Analysis of absolute $\dot{V}O_2$ related to age, sport, puberty stage, weight, and height for male subjects*

Random Variable	Constant	Age
Level 1 (within individuals)		
Constant	0.0584±0.0048	
Level 2 (between individuals)		
Constant	0.0127±0.0056	
Age	0.0056±0.0013	0.0007±0.0009

Explanatory Variable	Estimate ± SEE
Constant	2.9470±0.0616
Age	0.0994±0.0266
Age^2	−0.0036±0.0031
Weight	0.0363±0.0038
Height	0.0162±0.0041
Height^2	0.0002±0.0001
Gymnastics-Swimming	−0.2513±0.0686*
Soccer-Swimming	−0.2551±0.0725*
Tennis-Swimming	−0.1786±0.0481*
MP-PP	0.0218±0.0423
LP-PP	0.1529±0.0675†
Interaction	
Gymnastics × Age	−0.0587±0.0259‡
Soccer × Age	0.0126±0.0252
Tennis × Age	−0.0294±0.0199

Values are means ± standard errors of estimate (SEE). Absolute $\dot{V}O_2$ was expressed in l/min. For statistical accuracy age is measured about an origin of 12.0 yr. Weight and height are measured about an origin of their respective means. Swimming is used as base measure and for statistical analysis other sports are compared with it. PP, prepuberty; MP, midpuberty; LP, late puberty. Significance of correlations: * $P < 0.001$; † $P < 0.05$; ‡ $P < 0.01$.

TABLE 5. *Analysis of absolute $\dot{V}O_2$ related to age, sport, puberty stage, weight, and height for female subjects*

Random Variable	Constant	Age
Level 1 (within individuals)		
Constant	0.0450±0.0043	
Level 2 (between individuals)		
Constant	0.0116±0.0050	
Age	0.0023±0.0013	0.0015±0.0007

Explanatory Variable	Estimate ± SEE
Constant	2.3010±0.0704
Age	0.0308±0.0147
Age^2	0.0011±0.0009
Weight	0.0292±0.0039
Height	0.0136±0.0036
Height^2	0.0001±0.0001
Gymnastics-Swimming	−0.2030±0.0528*
Tennis-Swimming	−0.1620±0.0471*
MP-PP	0.0582±0.0483
LP-PP	0.1350±0.0707
Interaction	
Gymnastics × Age	−0.0503±0.0197†
Tennis × Age	−0.0266±0.0177

Values are means ± SEE. Absolute $\dot{V}O_2$ was expressed in l/min. For explanation of variables, see Table 4 and text. Significance of correlations: * $P < 0.001$; † $P < 0.01$.

The results of this secondary analysis indicate, as might be expected, that in both sexes (Tables 4 and 5) age, height, and weight contribute significantly to changes in $\dot{V}O_{2\,max}$ over time. It was also found that the different sports and their associated training regimens had a significant influence, although the number of hours trained per week did not and was therefore not used in the model. However, it was found that changes in $\dot{V}O_{2\,max}$ with pubertal stage showed two distinct patterns between the sexes (Figs. 2 and 3). In males, there was a significant increase in aerobic power toward the end of puberty that was in direct contrast to the nonsignificant increase in aerobic power found in females during this time. On the basis of our comparison with normal untrained children (2), it would seem that training effectively increased aerobic power above the increases normally attributed to age and corresponding physical

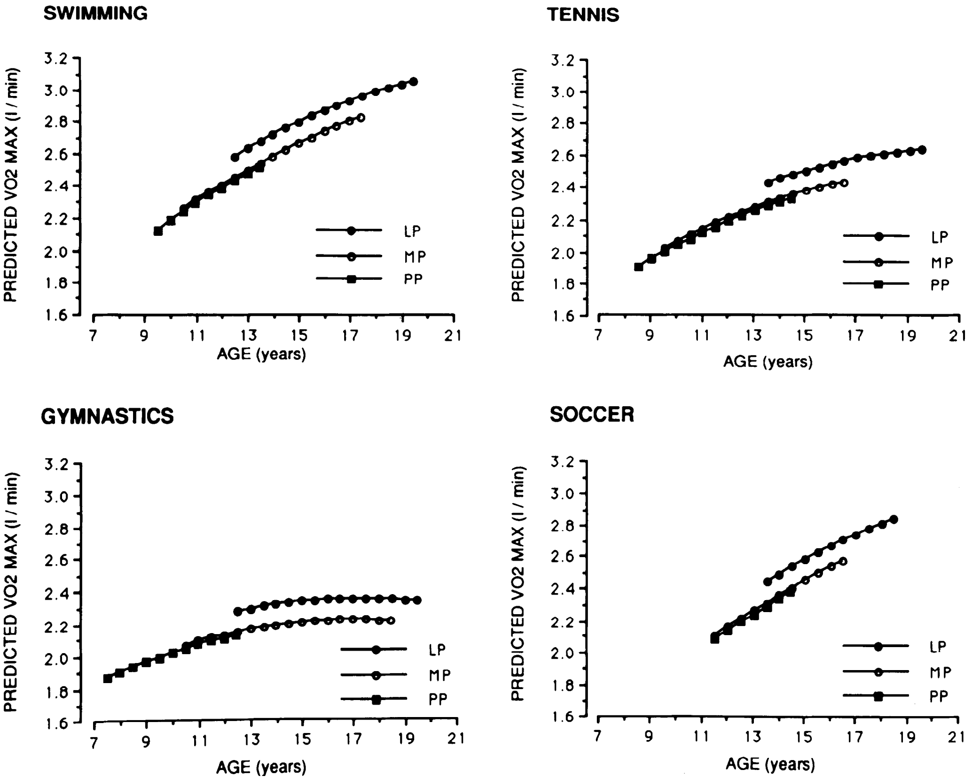

FIG. 2. Predicted $\dot{V}O_{2\,max}$ for male athletes at different ages in each pubertal group. Weight, height, and height^2 were controlled for by predicting them at age 12 by regressing variables on age and age^2. PP, prepubertal; MP, midpubertal; LP, late pubertal.

growth and maturation. In a more aerobic sport, such as swimming, this effect was more noticeable. It was also found that, contrary to other reports (11, 15), aerobic power was seen to increase with training even in the prepubertal years.

The question remains: how much of the increase in $\dot{V}O_{2\,max}$ is due to growth and biological maturity, and how much is a result of training (15). Using the MRMP, we were able to model not only the within-subject variation of $\dot{V}O_{2\,max}$ with time but also the variation between subjects while simultaneously accounting for other explanatory variables, such as age, height, weight, sport, and pubertal development, all of which have been shown to contribute to within-subject variation. The MRMP enabled us to separate the effects of maturation while avoiding the errors inherent when using ratio standards. At the

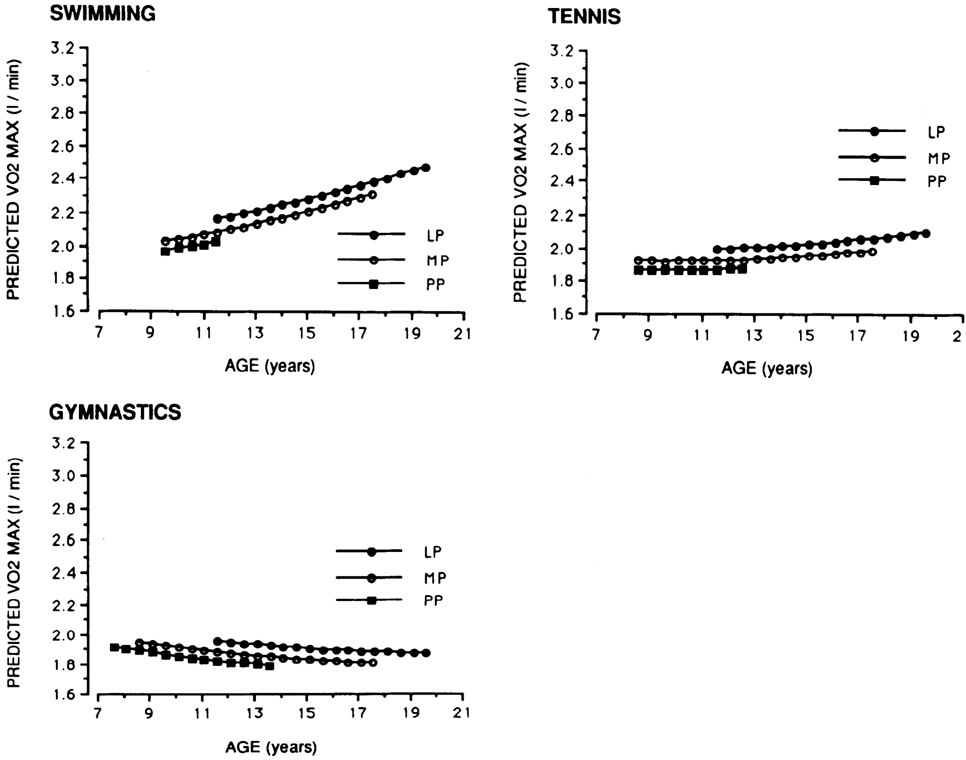

FIG. 3. Predicted $\dot{V}O_{2\,max}$ for female athletes at different ages in each pubertal group. Weight, height, and height^2 were controlled for by predicting them at age 12 by regressing variables on age and age^2.

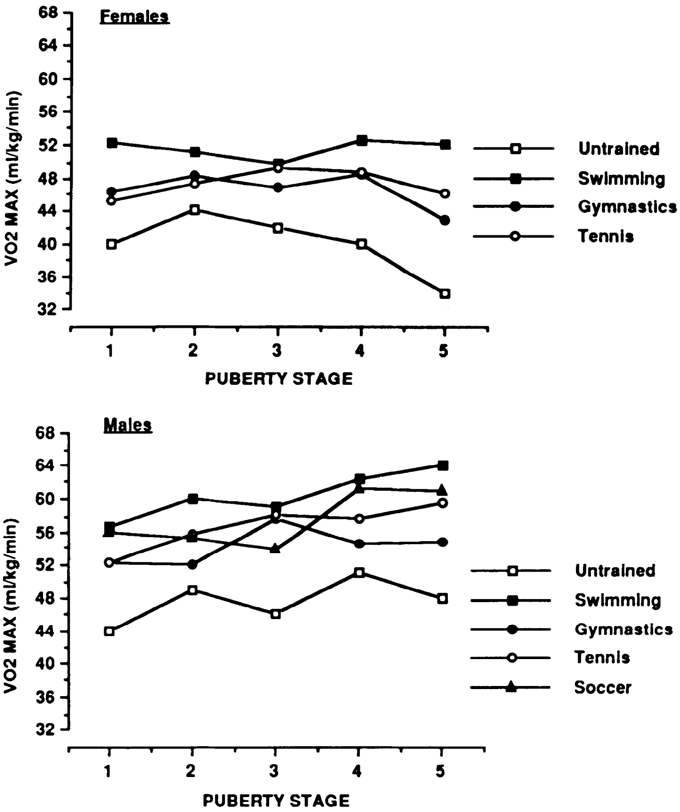

FIG. 4. $\dot{V}O_{2\,max}$ in trained and untrained children and adolescents in relation to gender and sexual maturity (as assessed by Tanner; see *Measurements* and Ref. 21). Results of present study were compared with those of a recent study (2) of a normal untrained population of British children.

same time we were also able to compare the effects of intensive training in four different sports on the growth of aerobic power. However, it should be emphasized again that this modeling procedure produces large SEs (Tables 4 and 5), a consequence of the fact that the analysis technique is designed to study populations and not to predict individual values.

A common issue in work with children is whether or not they obtain a true $\dot{V}O_{2\,max}$. Previous studies have found that only a minority of children produce a true $\dot{V}O_{2\,max}$ plateau (1, 12) and have suggested that the more appropriate term to use with children is peak $\dot{V}O_2$, which represents the highest $\dot{V}O_2$ elicited during an exercise test to exhaustion. However, it has been found that if children are sufficiently encouraged, they do approach the true limits of $\dot{V}O_{2\,max}$ without reaching a plateau in $\dot{V}O_2$ (5, 18). It is therefore possible that the significant increase in $\dot{V}O_{2\,max}$ with time (Table 4) could have been a reflection of true $\dot{V}O_{2\,max}$ tests being produced by the older children. Therefore, when interpreting these data, it is important to be aware that the large SEs produced by the model could also have been a consequence of the possible lack of a stable end point in $\dot{V}O_{2\,max}$.

The critical stage of maturity during which endurance training exerts its greatest influence on the cardiorespiratory system is still speculative (23). Mirwald et al. (15) found, in agreement with Kobayashi et al. (11), that in longitudinal studies of male subjects training did not appreciably improve aerobic power before the age of 12 yr. However, both studies supported the view that the adolescent growth period was the critical period for growth of aerobic power. This view has been opposed by Weber et al. (24), who found that there was no difference in rate of increase in aerobic power during this growth period, although the amount of training performed and the maturity indicator used have been criticized (15). In the present study we found a statistically significant increase in aerobic power during pubertal development in male athletes ($P < 0.05$), an increase that was most obvious toward the end of puberty.

Male swimmers were found to have significantly higher aerobic power at all stages of puberty than males participating in the other three sports ($P < 0.001$). This could have been a result of the training program, although a genetic predisposition cannot be ruled out. In female subjects, we found no significant difference in aerobic power between pubertal stages, and, like males, female swimmers had significantly greater aerobic power at all stages of puberty than participants in other sports.

In conclusion, growth in aerobic power was found to be significantly related to physical growth (age, height, and weight) and, in males, to pubertal development. Furthermore the different sports all showed different patterns of aerobic power with age, suggesting that the type of sports training was influencing aerobic power development. However, further research is needed to verify this, especially with groups of untrained children, so that the effects of selection can be controlled for. The high SEs obtained from the modeling procedure highlight not only the fact that the model should not be used to predict individual values but also the possible problem associated with measuring $\dot{V}O_{2\,max}$ in children. In contrast to previous reports (11, 15), we found that in sports with an aerobic content to their training, aerobic power did increase in the prepubertal years.

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