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Peak oxygen uptake in relation to growth and maturation in 11- to 17-year-old humans

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Abstract This study used multilevel modelling to examine peak oxygen uptake ($\dot{V}O_{2\text{peak}}$) during growth and maturation. Body mass, stature, triceps and subscapular skinfold thicknesses, blood haemoglobin concentration, and $\dot{V}O_{2\text{peak}}$ of boys and girls, [mean (SD)] aged 11.1 (0.4) years at the onset of the study, were measured at ages 11, 12, 13 and 17 years. Sexual maturation was assessed on the first three occasions and was assumed to be Tanner stage 5 at 17 years. The analysis was founded on 388 $\dot{V}O_{2\text{peak}}$ determinations from 132 children. The initial model revealed mass, stature and age as significant explanatory variables of $\dot{V}O_{2\text{peak}}$ with an additional positive effect for stage of maturity. Girls’ values were significantly lower than those of boys and a significant age-by-sex interaction described a progressive divergence in boys’ and girls’ $\dot{V}O_{2\text{peak}}$. The introduction of skinfold thicknesses produced a model with an improvement in fit. The stature term was negated and the mass exponent almost doubled. The sex and age-by-sex terms were reduced but remained significant. Many of the observed maturity effects were explained with stage 5 becoming non-significant. Blood haemoglobin concentration was a nonsignificant parameter estimate in both models. Fat-free mass was the dominant influence on the growth of $\dot{V}O_{2\text{peak}}$ but the multilevel regression models demonstrated that, with body size and fatness allowed for, $\dot{V}O_{2\text{peak}}$ increased with age and maturation in both sexes.

Keywords Aerobic fitness · Age · Fatness · Sex · Multilevel modelling

Introduction

Peak oxygen uptake ($\dot{V}O_{2\text{peak}}$), the highest oxygen uptake ($\dot{V}O_2$) elicited during an exercise test to exhaustion, is recognized as being the best single indicator of children’s and adolescents’ aerobic fitness. Cross-sectional data have consistently demonstrated an almost linear increase both in boys’ and girls’ $\dot{V}O_{2\text{peak}}$ (measured in litres per minute) with chronological age, with boys’ values being significantly higher than those of girls, at least from age 10 years (Armstrong and Welsman 1994). Longitudinal studies provide greater insights into the development of performance variables during growth but data drawn from substantial samples (n more than 20 male or female subjects) are sparse although, in general, they confirm the results of cross-sectional studies (Armstrong and Welsman 2000). However, during growth and maturation $\dot{V}O_{2\text{peak}}$ is highly correlated with body size, and for the independent effects of chronological age, maturation and sex on $\dot{V}O_{2\text{peak}}$ to be examined, the confounding influence of body size must be allowed for.

Conventionally, $\dot{V}O_{2\text{peak}}$ has been expressed relative to total body mass to account for body size differences, and the picture that has emerged shows boys’ $\dot{V}O_{2\text{peak}}$ to remain remarkably consistent over the age range 10–18 years whereas the values for girls show a progressive decline over the same period (Armstrong and Welsman 1994). Compelling arguments have been presented to refute the validity of expressing values relative to total body mass to remove the influence of body size from size-dependent performance variables (Packard and Boardman 1987; Winter 1992) and inappropriate statistical techniques might have clouded our understanding of the development of $\dot{V}O_{2\text{peak}}$ during growth and maturation (Armstrong and Welsman 2000).

Studies using scaling methods based on allometry have produced, in cross-sectional studies, results that challenge the conventional model (Welsman et al. 1996;
Armstrong et al. 1998). Welsman et al. (1996) used a log-linear analysis of covariance to remove the effects of body size from \( V_{O_2}\text{peak} \) in prepubertal, circumpubertal, and adult male and female subjects. In direct contrast to analyses employing values expressed relative to total body mass, the allometric approach revealed progressive increases in \( V_{O_2}\text{peak} \) across groups of males and, in females, an increase in \( V_{O_2}\text{peak} \) from prepuberty to circumpuberty with no decline in values with the progression into adulthood being evident. Armstrong et al. (1998) demonstrated, using a log-linear analysis of covariance to allow for effects of body size, a positive effect of maturation on \( V_{O_2}\text{peak} \), which in previous studies had been obscured through the use of an inappropriate means of normalizing values for differences in body mass.

The emergence (Aitkin et al. 1981) and refinement (Goldstein et al. 1998) of multilevel regression modelling has allowed a flexible and sensitive interpretation of longitudinal data in which, for example, body size, age, maturation and sex effects can be partitioned concurrently within an allometric framework.

Baxter-Jones et al. (1993) used a polynomial, additive approach to analyse \( V_{O_2}\text{peak} \) data from athletic youths in training. Nevill et al. (1998) re-modelled the data of Baxter-Jones et al. (1993) using a variety of techniques to assess model fit and demonstrated that a multiplicative allometric model presented a solution which was not only physiologically plausible but a much better statistical fit, required fewer fitted parameters than the original solution and appropriately allowed for the heteroscedastic data. They demonstrated that body mass, stature and age were independent, significant covariates of \( V_{O_2}\text{peak} \) both in boys and girls. Armstrong et al. (1999) used a multiplicative allometric analysis founded on 590 \( V_{O_2}\text{peak} \) determinations over three annual occasions and investigated chronological age, sex, and maturity-associated changes in \( V_{O_2}\text{peak} \), with body size allowed for, over the age range 11–13 years. Despite the narrow age range, they demonstrated with a representative sample of young people that body mass and skinfold thicknesses were significant covariates but, in conflict with the conventional view, additional significant positive effects for both age and maturation were evident. Girls’ \( V_{O_2}\text{peak} \) was lower than that of boys’ and the positive effects for age were larger in boys than in girls.

At 6 years after their initial visit, at mean age 17.0 (0.3) years, 63 of the subjects in the study of Armstrong et al. (1999) re-visited the laboratory and were re-tested using the same procedures and equipment as in the original investigation. This study uses these data to examine aerobic fitness from 11 to 17 years using a multilevel modelling approach to investigate the influences of sex and changes in age, body size, body fatness, and maturity-associated variables on \( V_{O_2}\text{peak} \). It was hypothesised that, in boys and girls, age and maturity-associated variables would influence \( V_{O_2}\text{peak} \) independent of body size and fatness.

## Methods

### Subjects

All children in year 6 (aged 10–11 years) attending the 15 state schools in the city of Exeter (UK) were invited to participate in a longitudinal study of habitual physical activity, physiological responses to exercise and body composition. There were 70% (n = 745) of this population who volunteered and provided written, informed consent signed by both the child and its parent or guardian. The experiments reported in this paper comply with the current laws of the United Kingdom. In an attempt to examine sample bias, the stature and body mass of the volunteers were compared with the non-volunteers. No significant differences (\( P > 0.05 \)) were obtained. From the volunteers, 25% of the eligible children in each school were randomly selected as participants. The study received approval from the District Health Authority Ethics Committee.

The children and adolescents completed a range of laboratory tests including determination of \( V_{O_2}\text{peak} \) on three occasions at approximately yearly intervals. In previous publications we have reported the \( V_{O_2}\text{peak} \) of these youngsters when prepubertal (Armstrong et al. 1995), in relation to sex and maturation at age 12 years (Armstrong et al. 1998) and examined longitudinally over the initial 3 years of the study (Armstrong et al. 1999). At age 17 years, the young people were invited back to the Research Centre to repeat the laboratory tests. There were 63 subjects who re-visited the laboratory and although it is impossible to ascertain whether this subsample was representative of the whole sample at age 17 years there was no significant difference (\( P > 0.05 \)) between their \( V_{O_2}\text{peak} \)

The data reported in this paper reflect the development of \( V_{O_2}\text{peak} \) over the age range 11–17 years and are drawn from the subjects for whom a complete longitudinal data set was available for the first three tests plus the data sets for those who returned on the fourth occasion. The total number of subjects involved was 132 and specific numbers are, for test 1 boys \( n = 71 \), girls \( n = 49 \), test 2 boys \( n = 60 \), girls \( n = 42 \), test 3 boys \( n = 56 \), girls \( n = 47 \), and test 4 boys \( n = 37 \) and girls \( n = 26 \).

### Procedure

Age was computed from date of birth and date of examination. Anthropometric apparatus was calibrated according to the manufacturers’ instructions. Stature was measured using a stadiometer (Holtain, Crymlyn, Dyfed, UK), body mass determined using beam balance scales (Avery, Birmingham, UK), and skinfold thicknesses over the triceps and subscapular regions measured using Holtain skinfold calipers (Holtain, Crymlyn, Dyfed, UK). All measurements were taken according to standard techniques (Weiner and Lourie 1981). On the first three occasions sexual maturity was visually assessed using the indices for pubic hair development described by Tanner (1962). As the mean or median age at which young people reach stage 5 for pubic hair development is 13.9–15.2 years in girls and 14.9–16.1 years in boys (Malina and Bouchard 1991), it was assumed that on the fourth occasion, at age 17 years, the subjects were at stage 5 for pubic hair development. Haemoglobin concentration was determined in duplicate from a fingertip blood sample which was immediately assayed using an HemoCue photometer (Clandon Scientific, Farnborough, UK).

The subjects were well habituated to the laboratory environment and to the specific test protocols prior to any formal tests. The \( V_{O_2}\text{peak} \) was measured during a progressive treadmill exercise test to voluntary exhaustion. Following a 3 min warm-up at 6 km h\(^{-1}\) and a brief rest, belt speed was increased to 7 km h\(^{-1}\) (test 1) or 8 km h\(^{-1}\) (tests 2–4) for the initial 3 min stage then increased by 1 km h\(^{-1}\) each stage until a speed of 10 km h\(^{-1}\) was attained. Belt speed was then held constant and further increments in intensity were achieved by 2.5% increases in gradient until the subjects said they were exhausted. Each exercise stage was separated by a 1 min