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REVIEW ARTICLE

The Development of Aerobic and Anaerobic Fitness with Reference to Youth Athletes

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Abstract

Purpose To challenge current conventions in paediatric sport science and use data from recent longitudinal studies to elucidate the development of aerobic and anaerobic fitness, with reference to youth athletes.

Methods (1) To critically review the traditional practice of ratio scaling physiological variables with body mass and, (2) to use multiplicative allometric models of longitudinal data, founded on 1053 (550 from boys) determinations of 10–17-year-olds' peak oxygen uptake (VO_2) and 763 (405 from boys) determinations of 11–17-year-olds' peak power output (PP) and mean power output (MP), to investigate the development of aerobic and anaerobic fitness in youth.

Results The statistical assumptions underpinning ratio scaling of physiological variables in youth are seldom met. Multiplicative allometric modelling of longitudinal data has demonstrated that fat free mass (FFM) acting as a surrogate for active muscle mass, is the most powerful morphological influence on PP, MP, and peak VO_2. With FFM appropriately controlled for, age effects remain significant but additional, independent effects of maturity status on anaerobic and aerobic fitness are negated.

Conclusions Ratio scaling of physiological variables with body mass is fallacious, confounds interpretation of the development of anaerobic and aerobic fitness, and misleads fitness comparisons within and across youth sports. Rigorous evaluation of the development of anaerobic and aerobic fitness in youth requires longitudinal analyses of sex-specific, concurrent changes in age- and maturation-driven morphological covariates. Age and maturation-driven changes in FFM are essential considerations when evaluating the physiological development of youth athletes.

Keywords Age · Growth · Maturation · Multiplicative allometric modelling · Peak oxygen uptake · Peak power output

Introduction

High levels of aerobic and/or anaerobic fitness are essential components of performance in many youth sports. Evaluation of the interplay between aerobic and anaerobic fitness in youth sport is, however, dependent not only on the intensity, frequency, and duration of exercise but also on developmental exercise physiology. Successful talent identification, long-term athlete development, physiological monitoring, and design of training programmes are founded on knowledge of the development of aerobic and anaerobic fitness. Yet, there are remarkably few rigorous studies which have analyzed the effects of concurrent changes in age-, growth-, and maturation-driven morphological covariates on physiological variables during youth. This paper will challenge current conventions in paediatric sport science and use data from recently published longitudinal studies to elucidate the development of aerobic and anaerobic fitness, with reference to youth athletes. The potential scope of the topic is huge and with journal limits on words and number of references, complementary reviews and tutorial papers are used to support the text where appropriate.

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Aerobic Fitness

Aerobic fitness defines the ability to deliver oxygen from the atmosphere to the muscles and to use it to generate energy to support metabolic demands during exercise. Peak oxygen uptake (VO_2), the highest rate of oxygen consumed during a progressive exercise test to exhaustion limits the capacity to perform aerobic exercise and is internationally recognized as the "gold standard" criterion measure of youth aerobic fitness [10, 49]. Although it is recognized that other variables contribute to aerobic fitness [2, 9] herein we will focus on peak VO_2 and use the terms peak VO_2 and aerobic fitness synonymously. Peak VO_2 is the most researched physiological variable in paediatric exercise physiology [36], but traditional data analyses have clouded understanding of its development in relation to growth and maturation and misled comparisons of aerobic fitness both within and between youth sports [3].

The rigorous assessment of youth peak VO_2 [25, 35] and the challenges associated with the physiological monitoring of youth athletes are well-documented [5, 24]. The importance of sport-specific ergometry is apparent in the physiological monitoring of youth swimmers where the requirement is for the determination of peak VO_2 to reflect the major muscle groups involved in propulsion [3, 47]. However, the developmental physiology issues addressed herein are common to both healthy youth and youth athletes across all sports, so for clarity and consistency we will focus on peak VO_2 using large muscle groups.

In paediatric sport science laboratories, peak VO_2 is routinely determined either running on a treadmill or pedalling on a cycle ergometer, but data from different ergometers should not be combined for analyses. Longitudinal analyses of 11–16-year-olds have reported age-related, mean treadmill values of peak VO_2 to be ~ 11%–14% higher than those determined on a cycle ergometer. However, as the total muscle mass activated during running or cycling is driven by sex-specific changes in growth and maturation, ergometer-driven differences in youth peak VO_2 within individuals vary in accord with their biological clocks [13]. It is therefore untenable to increase sample sizes by "correcting" for ergometer-driven differences in youth peak VO_2 through adding fixed percentages to cycle ergometer values, as has been common practice for decades (e.g. [43, 63]). Herein we will focus on the development of aerobic fitness rigorously determined on a treadmill.

Aerobic fitness and age

Peak VO_2 (in L/min) has been consistently reported to increase with age in both boys and girls. The mean peak VO_2 of boys is generally higher than that of similarly aged girls with the sex difference increasing with age [12]. Age-related paediatric "norms" are widely available and in common use to compare active and inactive, sporting and non-sporting, and healthy and unhealthy youth (e.g. [27]). Paediatric norms, however, only present average values of peak VO_2 from single moments in time ("snapshots") and provide few insights into the development of individuals' aerobic fitness.

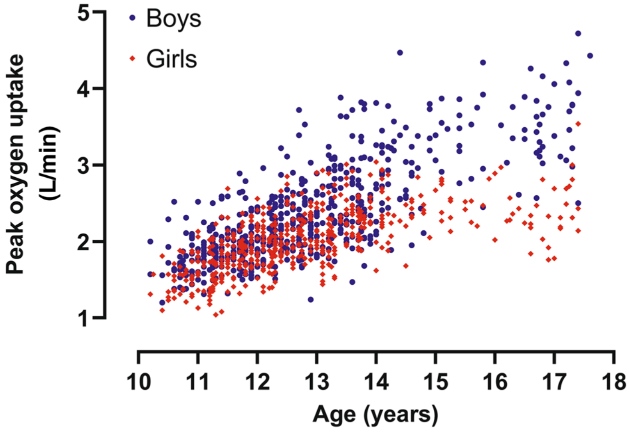

Fig. 1 Aerobic fitness in relation to age in 10–17-year-old boys and girls. Figure drawn from data reported in Armstrong and Welsman [14] and founded on 1053 determinations of peak oxygen uptake (550 from boys and 503 from girls)

Figure 1 illustrates 1053 (550 from boys) longitudinal measures of 10–17-year-olds' peak VO_2 [14]. In accord with the extant literature; the data indicate that boys' mean peak VO_2 increases from 10 to 17 years with girls' values increasing from 10 to 13 years of age before tapering off. Boys' mean peak VO_2 almost doubles from 10 to 17 years with girls' mean peak VO_2 increasing by ~ 50% over the same time period. Boys' mean peak VO_2 is ~ 11% higher than that of girls at age 10 years and the difference increases to ~ 50% by age 17 years. However, the wide individual variations in age-related peak VO_2 and the overlap of 10–13-year-old boys' and girls' data, clearly expose the limitations of mean age-related "snapshot" comparisons within and between sexes and within and across sports.

Cross-sectional analyses have consistently reported that youth athletes of both sexes, particularly those participating in endurance sports, typically present higher peak VO_2 values than their non-athlete peers [3, 8]. This may be partially due to appropriate training [4, 47] or genetics [60] but there is a marked variation among individual youth in the timing and tempo of biological maturation which confounds age-related comparisons [45]. Some longitudinal data suggest a spurt in aerobic fitness aligned with the time of peak height velocity (PHV) [38]. But age at PHV ranges from 9.0 to 15.0 years in girls and 11.1–17.3 years in boys and it has been reported, for example, that 12–13-year-old male football players span the spectrum from prepuberty to biological maturity [45]. The aerobic fitness of a prepubertal 12–13-year-old footballer cannot be meaningfully compared with that of a biologically mature footballer of similar chronological age. These issues are a major problem in establishing a level playing field in age-group sport [3, 45].

Development of Aerobic Fitness with Growth and Maturation

Cross-Sectional Studies and the Fallacy of Ratio Scaling

In the first laboratory study of boys' "physical fitness", Robinson [56] recognised that his VO_2 data were related to body size as well as age. Without providing a rationale he divided VO_2 (in mL/min) by body mass (in kg) and presented his data in ratio with body mass as mL/kg/min. In the second laboratory study of boys' aerobic fitness, Morse et al. [50] only reported VO_2 data in ratio with body mass. In the first study to include girls, Åstrand [21] commented that VO_2 should be scaled to active muscle mass rather than body mass. But as he was unable to measure active muscle mass, he suggested that VO_2 should be interpreted in relation to fat free mass (FFM) which can be determined indirectly. He did not, however, pursue this empirically and discussed his data in ratio with body mass. Collectively, these pioneers initiated the scientific study of the exercising child but also introduced a means of "controlling" physiological variables for growth and maturation which has confused understanding of paediatric sport science ever since.

Tanner [65] unequivocally demonstrated that ratio scaling of physiological variables was fallacious but the vast majority of published paediatric sport science papers persist in reporting peak VO_2 and other physiological variables (e.g. muscle strength, pulmonary ventilation, cardiac output) in ratio with body mass. This is probably because it is recognised as "the most convenient and traditionally accepted way" [23] and journal editors and reviewers seldom (if ever) require authors to provide a scientific rationale or statistical justification for its use.

Welsman and Armstrong [74] explained from first principles the statistical assumptions underpinning ratio scaling and empirically verified that they were not met in 20 years of cross-sectional studies from their laboratory, involving ~ 1000 determinations of the peak VO_2 of children and adolescents. In brief, if ratio scaling effectively controls for body mass then the product-moment correlation coefficient between peak VO_2 (in mL/kg/min) and body mass (in kg) will be not significantly different from zero. This statistical assumption was tested using data at the onset of the study illustrated in Fig. 1. Significant ($P<0.001$) negative correlations of $r=-0.52$ and $r=-0.54$, for girls and boys, respectively, between peak VO_2 (in mL/kg/min) and body mass (in kg) were calculated, demonstrating unequivocally the failure of ratio scaling to create a size-fee variable. Numerous reviews and tutorial papers have confirmed both theoretically and empirically the fallacy of ratio scaling of peak VO_2 and compellingly argued that with cross-sectional data, allometric scaling with multiple covariates based in log-linear regression is the method of choice when exploring the development of youth fitness (see [71–74] for discussion of scaling paediatric data from first principles). Analyzing the data at the onset of the study illustrated in Fig. 1 with an allometric (log-linear) scaling model, revealed a mass exponent of 0.68 and correlations between allometrically scaled peak VO_2 (i.e. mL/kg$^{0.68}$/min) and body mass (kg) of $r=0.07$ and $r=-0.13$, for girls and boys, respectively, which were not significantly different from zero. Peak VO_2 was therefore effectively controlled for body mass, with allometric scaling creating a size-free variable (see [3] pp 167–170 for analytical detail).

Ratio scaled data offer a different picture of youth aerobic fitness from that when absolute values (in L/min) are presented. Ratio scaling "over-scales", disadvantages heavier youth (e.g. early maturers) and advantages lighter youth (e.g. later maturers). In several sports, body mass plays an important role in the selection of youth athletes and their retention in elite training programmes but youth athletes may be either penalised (e.g. rugby forwards) or favoured (e.g. artistic gymnasts) in ratio-scaled comparisons of fitness across sports. Moreover, the size of the real difference in aerobic (or anaerobic) fitness between youth athletes in different sports and their non-active peers is obscured in comparative studies of ratio-scaled data.

On average, instead of increasing with age, boys' ratio-scaled peak VO_2 remains unchanged from 10 to 17 years whereas girls' values decline, particularly in adolescence as they accumulate more body fat. Ratio-scaled data also suggest that when body mass is controlled for, changes in maturity status have no additional or independent effect on aerobic fitness [11]. In contrast, with body mass appropriately controlled for using allometry boys' peak VO_2 has been demonstrated to increase from 10 to 17 years with girls' peak VO_2 increasing at least from 10 to 13 years before levelling-off rather than declining [75]. Moreover, allometrically scaled data have showed that maturity status exerts significant and positive effects on peak VO_2 in both sexes, in addition to and independent of body mass and age [19].

Longitudinal Studies and Multiplicative Allometric Modelling

Some longitudinal studies have made seminal contributions to aspects of paediatric health and exercise science (e.g. [42, 48]) but to elucidate the development of physiological variables rigorous analyses of the effects of concurrent changes in age-, growth-, and maturation-driven morphological covariates are required. Longitudinal studies of aerobic fitness generally consist of a series of reports of annual analyses of absolute peak VO_2 and peak VO_2 in ratio with body mass. Data are consistent and reflect those from cross-sectional studies but provide few additional insights into the development of aerobic fitness.

Janz et al. [41] determined allometric scaling factors for a cohort of children and concluded that FFM was more appropriate than body mass to "normalise" peak VO_2 when investigating physiologic changes during growth and maturation. It is, however, the emergence [1] and on-going refinement [54] of multilevel allometric modelling which has provided an elegant approach to the study of developmental exercise physiology. Nevill et al. [51] introduced multiplicative allometric modelling to paediatric sport science and with the present authors [20] demonstrated that it enabled the effects of age, maturity status, body mass, and FFM on the development of aerobic fitness to be partitioned concurrently within an allometric framework.

Using multiplicative allometric modelling, Armstrong and Welsman [13–15, 17] investigated the longitudinal development of the peak VO_2 of the 10–17-year-olds described in Fig. 1, with the following baseline model where y is the physiological variable, in this case peak VO_2,

$$y = \text{mass}^k \times \exp\left(a_j + b \times \text{age} + c \times \text{age}^2\right)\varepsilon_{ij}.$$

log transformation linearized the model to form the starting point for analysis,

$$\log_e y = k \times \log_e \text{mass} + a_j + b \times \text{age} + c \times \text{age}^2 + \log_e\left(\varepsilon_{ij}\right).$$

All parameters were fixed with the exception of the constant (a) which was allowed to vary randomly at level 2 (between individuals) and the multiplicative error ratio (ε) which also varied randomly at level 1 (within individuals) as denoted by the subscripts i (level 1 variation) and j (level 2 variation). Age was centred on the group mean. From the baseline model of age, age^2, and body mass, additional explanatory variables such as sum of skinfolds were explored (see original papers for details of the analyses).

In addition to sex-specific models, the original papers explored the magnitude of sex differences in the development of aerobic fitness using the indicator variable boys = 0 and girls = 1 which sets the boys' constant as the baseline from which the girls' parameter is allowed to deviate. It was demonstrated that with age and body mass controlled for there was a sex difference of ~ 15% which decreased to ~ 9% when FFM replaced body mass in the models. In the 11–13-year-olds, the introduction of maximal cardiovascular covariates into models reduced the sex difference further but an unexplained ~ 4% sex difference remained [17].

As competition in youth sport is sex-specific, the primary focus herein is on single sex multiplicative allometric models to clarify the role of concurrent changes in age- and maturation-driven morphological covariates in the development of aerobic fitness. Analytical details and experimental procedures are comprehensively described in the original papers and all statistical significances were set at $P < 0.05$ [13–15, 17].

Tables 1 and 2 illustrate the multiplicative allometric models for boys and girls, respectively. The positive age terms in Model 1.1 (boys) and Model 2.1 (girls) show that (in conflict with ratio-scaled data), with body mass appropriately controlled for, aerobic fitness increases with age. The negative age^2 term in each model indicates that the size of the age effect decreases in both sexes as the rate of change in growth slows. The introduction of maturity status as the stages of pubic hair described by Tanner [66] into Models 1.2 (boys) and 2.2 (girls), showed maturity status in both sexes to have an incremental, additional effect on aerobic fitness, independent of age and body mass. Again, this is in direct conflict with the ratio-scaled interpretation of peak VO_2 and shows clearly the limitations of age-related comparisons of data ratio-scaled with body mass [14].

Body mass includes both fat mass and FFM where fat mass is largely metabolically inert [39]. In sports which involve transporting body mass fat acts as "deadweight" to be carried with a negative effect on performance, but it does not influence aerobic fitness. In this context, early maturing girls are disadvantaged as, on average, fat mass increases by ~ 50% in the 3 years post-PHV compared with ~ 12% in boys [26]. Girls' muscle mass as a percentage of total body mass remains stable at ~ 43%–44%, from 10 to 17 years whereas boys' muscle mass increases from ~ 46% to 54% of body mass over the same time period [46]. FFM includes tissues not involved in exercise, but in paediatric sport science FFM is well-established as a non-invasive surrogate for active muscle mass (e.g. [30, 41]).

Ideally FFM would be directly determined on each test occasion but this is not currently feasible in large studies involving several hundred assessments, moreover, "direct" measures of body fat on the same young people have been shown to vary widely across established laboratory techniques [37]. In paediatric exercise studies, FFM is commonly estimated from the youth-specific equations of Slaughter et al. [62]. It has, however, been compellingly argued that researchers should use the sum of triceps and subscapular skinfolds in conjunction with body mass as a surrogate of FFM, rather than rely on predictions from equations likely to be population-specific [57].

The introduction in Models 1.3 (boys) and 2.3 (girls) of the sum of triceps and subscapular skinfolds resulted in negative exponents with large increases in the body mass

Table 1 Multiplicative allometric models of peak oxygen uptake in 10–17-year-old boys

Response	Model 1.1 $\log_e$ peak VO_2	Model 1.2 $\log_e$ peak VO_2	Model 1.3 $\log_e$ peak VO_2	Model 1.4 $\log_e$ peak VO_2
Fixed part				
Constant	−1.864 (0.121)	−1.695 (0.126)	−2.276 (0.099)	−2.304 (0.114)
$\log_e$ body mass	0.714 (0.032)	0.656 (0.034)	0.964 (0.031)	–
Age	0.051 (0.005)	0.034 (0.006)	0.023 (0.004)	0.025 (0.005)
Age^2	−0.004 (0.001)	ns	−0.003 (0.001)	−0.003 (0.001)
PH stage 2	–	0.027 (0.011)	ns	ns
PH stage 3	–	0.059 (0.014)	ns	ns
PH stage 4	–	0.088 (0.017)	ns	ns
PH stage 5	–	0.092 (0.023)	ns	ns
$\log_e$ skinfolds	–	–	−0.185 (0.013)	–
$\log_e$ FFM				0.876 (0.032)
Random part				
Level 2				
Variance (constant)	0.007 (0.001)	0.006 (0.001)	0.003 (0.000)	0.004 (0.001)
Level 1				
Variance (constant)	0.005 (0.000)	0.004 (0.000)	0.004 (0.000)	0.005 (0.000)
Units: level 2	213	210	213	213
Units: level 1	550	477	550	550
−2*loglikelihood	−1085.256	−952.297	−1235.545	−1152.460

Models 1.1, 1.3, and 1.4 founded on 550 determinations of peak oxygen uptake. Model 1.2 founded on 477 determinations of peak oxygen uptake. Data from Armstrong and Welsman [14]

Values are model estimates (standard error), *PH* pubic hair, *FFM* fat free mass estimated from youth-specific equations [62], *ns* not significant ($P > 0.05$), – not entered

exponents and maturity status becoming non-significant. The positive age terms remained significant with negative age^2 terms indicating that the size of the age effect decreases as growth slows. Collectively, skinfolds and body mass act as a surrogate for FFM and increases in the body mass exponents can be attributed to the effect that fat mass has on increasing body mass without an increase in peak VO_2 [70]. The replacement in Models 1.4 (boys) and 2.4 (girls) of body mass and skinfold thicknesses with FFM estimated from the equations of Slaughter et al. [62] resulted in very similar models to 1.3 and 2.3. As determined by the models' significantly smaller −2*loglikelihoods the models with the best statistical fit were those where body mass and sum of skinfolds acted as a surrogate for FFM (i.e. Models 1.3 and 2.3) [14].

Models 1.3 and 2.3 reveal the powerful influence of FFM on the development of aerobic fitness. FFM doubles in boys from age 10–17 years and increases by ~ 60% in girls over the same time period. Sex-specific increases in FFM mask independent effects of maturation in the models as changes in FFM are strongly related to the timing and tempo of maturation. Percentage changes in FFM are at their peak around the time of PHV with boys' values increasing by ~ 80% over a 4-year period centred on PHV and girls' FFM increasing by ~ 30% from 1 year pre-PHV to 1 year post- PHV before tapering-off in accord with the development of peak VO_2 [3].

Peak VO_2 is a function of oxygen delivery to the muscles and oxygen utilisation by the muscles. As a surrogate of active muscle mass, increases in FFM augment oxygen delivery through the peripheral muscle pump which enhances venous return and increases maximal stroke volume (SV) and therefore maximal cardiac output ($\dot{Q}$) [58]. Armstrong and Welsman [15, 17] demonstrated through multiplicative allometric modelling of the data from the 11–13-year-olds described in Fig. 1, the powerful influence of increases in FFM on the development of maximal SV and maximal $\dot{Q}$, in both sexes. Moreover, with FFM controlled for, there were no sex differences in maximal cardiovascular variables. Intra-muscular oxygen utilisation during exercise is enhanced by increases in active muscle mass through factors such as age and maturation- driven changes in muscle structure [46], muscle fibre activation [32], and muscle metabolism [7]. However, detailed exploration of the integrated development of intra-muscular activity during aerobic exercise awaits the ethical application of appropriate non-invasive technology.

Table 2 Multiplicative allometric models of peak oxygen uptake in 10-17-year-old girls

Response	Model 2.1 Log$_e$ peak VO$_2$	Model 2.2 Log$_e$ peak VO$_2$	Model 2.3 Log$_e$ peak VO$_2$	Model 2.4 Log$_e$ peak VO$_2$
Fixed part				
Constant	−1.701 (0.119)	−1.657 (0.127)	−2.004 (0.117)	−2.215 (0.142)
Log$_e$ body mass	0.631 (0.031)	0.609 (0.034)	0.815 (0.038)	–
Age	0.035 (0.004)	0.024 (0.006)	0.020 (0.005)	0.022 (0.005)
Age^2	−0.010 (0.001)	−0.008 (0.001)	−0.007 (0.001)	−0.006 (0.001)
PH stage 2	–	0.038 (0.013)	ns	ns
PH stage 3	–	0.046 (0.015)	ns	ns
PH stage 4	–	0.052 (0.018)	ns	ns
PH stage 5	–	0.055 (0.023)	ns	ns
Log$_e$ skinfolds	–	–	−0.129 (0.018)	–
Log$_e$ FFM	–	–	–	0.824 (0.040)
Random part				
Level: 2				
Variance (cons)	0.006 (0.001)	0.006 (0.001)	0.004 (0.001)	0.005 (0.001)
Level: 1				
Variance (cons)	0.004 (0.000)	0.004 (0.000)	0.004 (0.000)	0.004 (0.000)
Units: Level 2	207	206	207	207
Units: Level 1	503	456	503	503
−2*loglikelihood	−1060.443	−951.197	−1107.768	−1052.430

Models 2.1, 2.3, and 2.4 founded on 503 determinations of peak oxygen uptake. Model 2.2 founded on 456 determinations of peak oxygen uptake. Data from Armstrong and Welsman [14]

Values are model estimates (standard error), *PH* pubic hair, *FFM* fat free mass estimated from youth-specific equations [62], *ns* not significant ($P > 0.05$), – not entered

Anaerobic Fitness

Anaerobic fitness describes the ability to generate and sustain energy through non-oxidative pathways to support metabolic demands during maximal intensity exercise. Ethical and technological constraints prevent direct measurement of intramuscular energy flux during maximal intensity exercise and current knowledge of the development of anaerobic fitness is largely founded on analyses of external power output. Unlike aerobic exercise there is no “gold standard” criterion measure of anaerobic fitness. There is a plethora of both field- and laboratory-based performance tests but paediatric research has primarily focused on external power output during the Wingate anaerobic test (WAnT) [76]. The WAnT is an “all-out” cycling test in which the determination of maximal pedalling cadence against a fixed braking force allows the assessment of external peak power output (PP) and mean power output (MP). Power output is recorded each second and PP is reached within a few seconds of the onset of the test. MP is recorded as the total power output averaged over the 30 s test.

Within studies, the WAnT is a reliable test of external power output [40] but comparisons of paediatric data across studies are problematic as several laboratories have introduced modifications to the WAnT, including a rolling start, the use of toeclips, variations in the time over which PP is determined (1 s, 3 s, or 5 s), and adaptations of cycle crank length in relation to leg length [76]. Some laboratories have factored into their calculations the internal resistance of the ergometer and the inertia of the flywheel [28]. Others have focused on the Force–Velocity test (F–VT), a variant of the WAnT which optimises the braking force to determine optimised PP (e.g. [59]). However, if the braking force is increased to optimise PP it is likely to be too high to optimise MP. Increasing fatigue reduces the pedal cadence, affects the power-to-velocity ratio, and results in a lower MP. The ability to sustain power output as estimated by MP is an important component of success in many youth sports. Although the primary energy source of MP is anaerobic, its development in youth is a function of interplay between aerobic and anaerobic metabolism which is discussed later in this paper. Despite a range of methods precluding confident comparisons of the magnitude of individual WAnT data across studies, trends within studies are consistent and much of our understanding of the development of anaerobic fitness in youth is founded on data from the WAnT.

The optimum braking force for PP varies significantly with age [29] and physiologists using variants of the WAnT in long-term development programmes of youth athletes are advised to monitor anaerobic fitness through F–VTs (for PP) with separate customised 30 s tests for MP [3]. Data from unmodified WAnTs are, however, currently in regular use to monitor the development of anaerobic fitness in youth athletes whose sport requires very different muscle recruitment and motor patterns to those in cycling [3]. Correlations of WAnT data with high-intensity sport-related activities are low to moderate ($r = 0.2–0.7$) with trained youth athletes and not high enough to predict sport performance with confidence [3]. Youth sports involving running-related activities are more common than cycling and well-controlled maximal sprint running tests are more appropriate than cycling tests to estimate sports-related anaerobic fitness where body mass is transported rather than supported.

Lakomy [44] was the first to estimate the anaerobic fitness of adult athletes through maximal sprint running on a non-motorised treadmill (NMT) but it was van Praagh et al. [69] who introduced the technique to youth athletes. van Praagh et al. [69] restricted performance to 10 s sprints, only published their research in abstract form, and stopped further development due to safety concerns. It was Sutton et al. [64] who developed a laboratory-based, paediatric NMT test station incorporating a safety harness, which enabled 8-year-old children to safely produce maximal sprint performances over a 30s period. The typical error of NMT test data 1 week apart was reported as 5% for MP and 6% for PP, which compares very favourably with data from WanTs [76]. The paediatric NMT test station has been used successfully with 8–16-year-olds not only in tests of PP and MP [18] but also in studies of repeated sprint ability [53], recovery profiles from maximal intensity work [55], and simulated sport-related performance [52], but more research is required to explore its full potential in the physiological assessment and monitoring of youth athletes' performance.

Anaerobic Fitness and Age

Cross-sectional studies of WAnT-determined anaerobic fitness are plentiful, at least over the age range 11–13-years, but the wide range of methodologies outlined earlier precludes confident comparisons of data across studies Age-related paediatric norms are available (e.g. [23]) but with the same flaws as those described for aerobic fitness. Youth athletes have been persistently reported to have higher anaerobic fitness than similarly aged non-athletes but as with aerobic fitness, this is likely to be through an amalgam of training [3, 8], genetics [61], and variation in the timing and tempo of biological maturation [45].

Collectively, cross-sectional studies are consistent in reporting age-related increases in PP in both sexes with little or no significant sex difference until ~ 13 years of age. Data on MP are less readily available but generally reflect the age- and sex-related trajectories of those for PP [23, 67]. To our knowledge there is only one published longitudinal study which reports the age-related PP and MP of both boys and girls, with at least three measures separated by time [16].

Duché et al. [33] published the first longitudinal study of PP and MP, but only reported data in ratio with body mass (i.e. in W/kg). In a mixed cross-sectional-longitudinal study, Falk and Bar-Or [34], reported the PP and MP of three groups of boys to increase with age over an 18 months period of study. Santos et al. [59] reported the optimised PP of 12-year-old boys and girls to increase with age over 18 months, with no significant sex difference. MP was not determined.

Figures 2 and 3 describe 763 (405 from boys) longitudinal measures of 11–17-year-olds' PP and MP, respectively [16]. Longitudinal data provide a more informative analysis of anaerobic fitness than cross-sectional studies

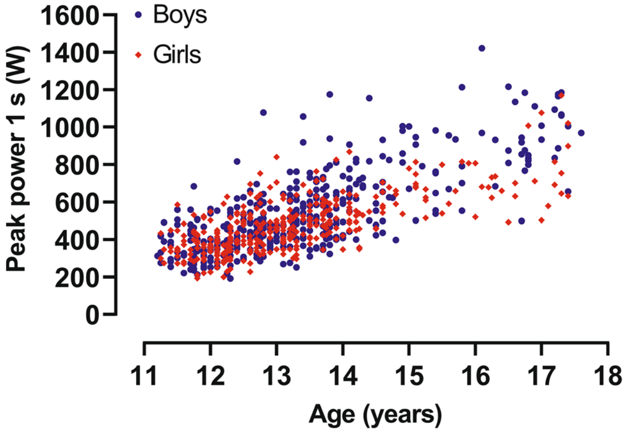

Fig. 2 Peak power in relation to age in 11–17-year-old boys and girls. Figure drawn from data reported in Armstrong and Welsman [16] and founded on 763 Wingate anaerobic tests (405 from boys and 358 from girls)

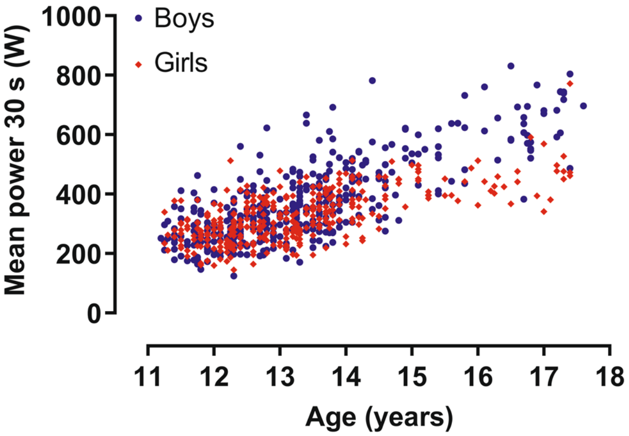

Fig. 3 Mean power in relation to age in 11–17-year-old boys and girls. Figure drawn from data reported in Armstrong and Welsman [16] and founded on 763 Wingate anaerobic tests (405 from boys and 358 from girls)

and show that PP and MP increase with age in both sexes. Boys' mean PP and MP increase by ~ 120% and ~ 115%, respectively, from 11 to 17 years. Girls' mean PP and MP increase by ~ 66% and ~ 60%, respectively, over the same age range. There is no significant sex difference at age 11 years in either PP or MP but girls' mean PP and MP data begin to level-off from ~ 14 years and by age 17 years the sex difference is ~ 30% in both PP and MP. However as noted with aerobic data from the same participants (Fig. 1), the wide individual differences in age-related PP and MP and the overlap of boys' and girls' data particularly from ~ 11 to 14 years, clearly show the marked limitations of making age-related comparisons within and between sexes and within and across sports.

Development of Anaerobic Fitness with Growth and Maturation

Cross-Sectional Studies

Cross-sectional studies of PP and MP in ratio with body mass, report age-related increases in both sexes with the sex difference increasing with age [67, 76]. As explained in the complementary section on aerobic fitness, ratio-scaled data are fallacious and mislead understanding of developmental exercise physiology.

In two rigorously analysed cross-sectional studies. Doré et al. [30, 31] adopted an allometric model to investigate the contribution of morphological variables to the optimised PP of 605 (189 girls) 7–18-year-olds. They demonstrated that both estimated FFM and estimated lean leg volume (LLV) were more strongly related to PP than body mass in both sexes. They commented that FFM reflects the total active muscle mass including muscles (e.g. trunk muscles, arm muscles, gluteus maximus) which contribute to exercise performance in addition to muscles included in LLV, and recommended FFM as the preferred scaling factor in large investigations of anaerobic fitness.

Longitudinal Studies

As indicated earlier longitudinal studies of anaerobic fitness are sparse, two studies controlled for body mass using ratio scaling and, in accord with cross-sectional data reported boys' PP and MP to increase with age [33, 34]. Santos et al. [59] determined on four occasions 6 months apart, the optimised PP of 17 boys and 15 girls aged 12.3 years at study onset. They analysed their data using multiplicative allometric modelling and reported no significant sex differences with a model controlling for body mass and sum of triceps and subscapular skinfolds as the best statistical fit for the data.

Armstrong and Welsman [16] used multiplicative allometric modelling to analyse the data illustrated in Figs. 2 and 3. They demonstrated that with age and body mass controlled for, there was a sex difference of ~ 10% in PP and ~ 11% in MP which reduced to ~ 5% and ~ 7%, respectively, when the sum of triceps and subscapular skinfolds

Table 3 Multiplicative allometric models of peak power and mean power in 11–17-year-old boys

Response	Model 3.1 Log$_e$ PP	Model 3.2 Log$_e$ PP	Model 3.3 Log$_e$ MP	Model 3.4 Log$_e$ MP
Fixed part				
Constant	2.529 (0.231)	2.142 (0.211)	2.418 (0.202)	2.002 (0.185)
Log$_e$ body mass	0.961 (0.060)	1.219 (0.063)	0.889 (0.052)	1.155 (0.055)
Age	0.104 (0.010)	0.064 (0.008)	0.087 (0.007)	0.047 (0.008)
Age^2	−0.007 (0.003)	ns	ns	0.007 (0.002)
Log$_e$ skinfolds	–	−0.212 (0.028)	–	−0.212 (0.024)
Random part				
Level: 2				
Variance (cons)	0.021 (0.003)	0.015 (0.002)	0.020 (0.002)	0.014 (0.002)
Level: 1				
Variance (cons)	0.012 (0.001)	0.013 (0.001)	0.006 (0.001)	0.006 (0.001)
Units: level 2	198	198	198	198
Units: level 1	405	405	405	405
−2*loglikelihood	−342.35	−384.223	−514.033	−584.905

Models founded on 405 determinations of peak power and mean power. Data from Armstrong and Welsman [16]

Values are model estimates (standard error), *PP* peak power, *MP* mean power, *ns* not significant ($P > 0.05$), – not entered

Table 4 Multiplicative allometric models of peak power and mean power in 11–17-year-old girls

Response	Model 4.1 $\mathrm{Log_e}$ PP	Model 4.2 $\mathrm{Log_e}$ PP	Model 4.3 $\mathrm{Log_e}$ MP	Model 4.4 $\mathrm{Log_e}$ MP
Fixed part (SE)				
Constant	3.378 (0.249)	2.856 (0.245)	2.952 (0.219)	2.429 (0.235)
$\mathrm{Log_e}$ body mass	0.712 (0.064)	1.009 (0.079)	0.719 (0.057)	1.015 (0.076)
Age	0.101 (0.011)	0.077 (0.008)	0.055 (0.007)	0.033 (0.009)
Age^2	−0.007 (0.003)	ns	ns	0.007 (0.003)
$\mathrm{Log_e}$ skinfolds	–	−0.200 (0.039)	–	−0.199 (0.036)
Random part				
Level: 2				
Variance (cons)	0.015 (0.003)	0.013 (0.003)	0.017 (0.002)	0.015 (0.002)
Level: 1				
Variance (cons)	0.017 (0.002)	0.017 (0.002)	0.009 (0.001)	0.009 (0.001)
Units: level 2	190	190	190	190
Units: level 1	358	358	358	358
− 2*loglikelihood	−259.440	−281.088	−388.888	−418.833

Models founded on 358 determinations of peak power and mean power. Data from Armstrong and Welsman [16]

Values are model estimates (standard error); *PP* peak power, *MP* mean power, *ns* not significant ($P > 0.05$), – not entered

was introduced to the models as a surrogate for FFM. For our current purpose the sex-specific models are presented in Tables 3 and 4, for boys and girls, respectively.

In direct contrast with the development of aerobic fitness and in both sexes, once body mass and age had been controlled for [Models 3.1 and 3.3 (boys) and 4.1 and 4.3 (girls)] the introduction of maturity status had no significant effect on either PP or MP. In both sexes, models founded on FFM were superior to those with body mass as the sole morphological variable, with age exerting a significant, additional effect in all models. In all cases the introduction of body mass and sum of skinfolds as a surrogate for FFM produced a better statistical fit for the data than FFM estimated from youth-specific equations and for brevity only these models are presented herein [i.e. Models 3.2 and 3.4 (boys) and 4.2 and 4.4 (girls)]. As described earlier in the complementary section on aerobic fitness, the powerful influence of maturation-driven FFM masks any independent effects of maturity status.

135 (72 boys) of the participants described in Figs. 2 and 3 also had their PP and MP determined annually through maximal sprint running on an NMT. The study confirmed the NMT test as an appropriate method to investigate the development of both PP and MP with a methodology which is more ecologically valid for many youth sports than cycling. Absolute values of PP and MP (in W) were not comparable across ergometers but the multiplicative allometric models were remarkably similar with FFM being the most powerful morphological influence on both MP and PP in both sexes and on both ergometers, with age exerting a significant additional effect in all models [18].

The multiplicative allometric models consistently emphasise the importance of increases in FFM (representing increases in active muscle mass) in the development of both PP and MP. Active muscle mass varies with running and cycling and relative changes in magnitude have not been rigorously monitored and quantified through adolescence, although total muscle mass has been estimated to increase from 11 to 17 years by ~ 110% in boys and ~ 60% in girls [46]. Technological and ethical limitations have restricted intra-muscular investigations during maximal intensity exercise but the influence of age and maturation-driven increases in FFM on PP and MP encompass changes not only in active muscle mass but also in muscle structure, muscle metabolism, muscle fibre size, type, and activation, and neuromuscular coordination. These factors and their effects on the development of anaerobic fitness have been comprehensively reviewed elsewhere [7, 68, 76], as has their trainability in youth [3].

Anaerobic and Aerobic Fitness

Relationship Between the Development of Anaerobic and Aerobic Fitness

Coaches have noted for many years that during childhood and early adolescence, those who excel in predominantly "anaerobic" activities also excel in "aerobic" activities and Bar-Or [22] introduced the term "non-metabolic specialists" to describe the phenomenon. The present data suggest that this relationship is not one of non-metabolic specialism but can be explained by the strong, common influence of age and FFM on both aerobic and anaerobic fitness.

Peak VO_2, PP, and MP all increase during youth but despite their common relationship with FFM, their rate of development appears asynchronous. The data illustrated in Figs. 1, 2 and 3 are from the same young people and show that there is a greater percentage increase in anaerobic fitness than in aerobic fitness from 11 to 17 years, in both sexes. Appropriate intra-muscular data are sparse and often collected at rest rather than during high intensity exercise, but the balance of evidence indicates that several changes advantageous to anaerobic fitness occur later during growth and maturation than those promoting aerobic fitness. Changes include increases in muscle pennation angle, type 2 muscle fibre activation, muscle phosphocreatine stores, muscle glycogen stores, and intra-muscular anaerobic enzyme activity [3, 6, 7].

Interplay of Anaerobic and Aerobic Metabolism in Youth Sport

Performance in youth sport almost always involves an interplay between anaerobic and aerobic metabolism which depends upon the intensity and duration of the activity and the individual's developmental physiology, modulated by training status. The ability to quickly attain high power output and retain much of it for a sustained period is an important component of many youth sport-related activities. In many sports the contribution of different energy pathways to performance is complex and difficult to evaluate. However, MP determined over 30 s and conventionally classified as a measure of anaerobic fitness, provides a clear example of the interaction between anaerobic–aerobic energy interplay and developmental physiology.

To examine the anaerobic–aerobic interplay during high intensity exercise in youth, the peak VO_2 and MP of 135 (63 girls) of the 11–16-year-olds described in Figs. 1, 2 and 3 were determined annually on a cycle ergometer and a treadmill. Multiplicative allometric models confirmed FFM as the most powerful morphological influence on MP, regardless of whether MP was determined on a cycle ergometer or a treadmill. However, when ergometer-specific peak VO_2 was entered into the appropriate models it made a significant, additional contribution to FFM in explaining the development of MP, in both sexes, on both ergometers. The models including peak VO_2 presented a significantly better statistical fit to the data than FFM alone and clearly illustrated how developmental changes in peak VO_2 contribute to explaining developmental changes in MP [13, 18].

Conclusions

Understanding of the development of anaerobic and aerobic fitness in youth has been clouded by fallacious ratio scaling of physiological variables with body mass. A multiplicative allometric approach applied to longitudinal data has demonstrated that in both sexes peak VO_2, PP, and MP increase with age but the most powerful influence on the development of both anaerobic and aerobic fitness is FFM. Increases in FFM encompass the effects of maturation on anaerobic and aerobic fitness as changes in FFM are strongly related to the timing and tempo of maturation. The rate of development of anaerobic and aerobic fitness is asynchronous, probably due to intra-muscular changes which promote anaerobic fitness occurring later in development than those promoting aerobic fitness. Most sport-related activities are supported by an anaerobic–aerobic energy interplay which depends not only on the intensity and duration of the activity but also on the relative development of aerobic and anaerobic fitness.

Those involved with the identification, long-term development, performance, and physiological testing of youth athletes are strongly advised to reject ratio scaling of physiological variables with body mass and focus on appropriate analyses of the concurrent effects of age and maturation-related changes in FFM. FFM can be monitored through a combination of body mass and sum of triceps and subscapular skinfold thicknesses. The multiplicative allometric equations presented herein can be used to estimate the peak VO_2, PP, and MP of healthy youth for comparative purposes but similar longitudinal studies of sex-specific groups of elite youth athletes are required to better inform long-term athlete development programmes.

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