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# Endurance Training and Aerobic Fitness in Young People

*Georges Baquet*,[1] *Emmanuel Van Praagh*[2] and *Serge Berthoin*[1]

1 Faculty of Sports Sciences and Physical Education, University of Lille 2, Ronchin, France
2 Faculty of Sports Sciences, Blaise Pascal University, Clermont-Ferrand, France

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## Abstract

Training-induced adaptations in aerobic fitness have been extensively studied in adults, and some exercise scientists have recommended similar training programmes for young people. However, the subject of the response to aerobic training of children and adolescents is controversial. The effects of exercise training on prepubertal children are particularly debatable. The latter may be partly explained by different training designs, which make comparisons between studies very problematic.

We have analysed the procedures applied to protocol design and training methods to highlight the real impact of aerobic training on the peak oxygen uptake ($\dot{V}O_2$) of healthy children and adolescents. In accordance with previously published reviews on trainability in youngsters, research papers were rejected from the final analysis according to criteria such as the lack of a control group, an unclear training protocol, inappropriate statistical procedures, small sample size, studies with trained or special populations, or with no peak $\dot{V}O_2$ data. Factors such as maturity, group constitution, consistency between training and testing procedures, drop out rates, or attendance were considered, and possible associations with changes in peak $\dot{V}O_2$ with training are discussed.

From 51 studies reviewed, 22 were finally retained. In most of the studies, there was a considerable lack of research regarding circumpubertal individuals in general, and particularly in girls. The results suggest that methodologically listed parameters will exert a potential influence on the magnitude of peak $\dot{V}O_2$ improvement. Even if little difference is reported for each parameter, it is suggested that the sum of errors will result in a significant bias in the assessment of training effects. The characteristics of each training protocol were also analysed to establish their respective potential influence on peak $\dot{V}O_2$ changes. In general, aerobic training leads to a mean improvement of 5–6% in the peak $\dot{V}O_2$ of children or adolescents. When only studies that reported significant training effect were taken into account, the mean improvement in peak $\dot{V}O_2$ rose to 8–10%. Results suggested that intensities higher than 80% of maximal heart rate are necessary to expect a significant improvement in peak $\dot{V}O_2$.

There is clearly a need for longitudinal or cross-sectional studies that investigate the relationship between maturity and training with carefully monitored programmes. Further research is also needed to compare interval training and continuous training.

Aerobic fitness not only determines performance in a wide range of activities, but it is also a health-related parameter. In a performance context, aerobic training aims to increase maximal oxygen uptake ($\dot{V}O_{2max}$) or other indices of aerobic fitness (e.g. lactate/ventilatory threshold, exercise efficiency). In children, it has been demonstrated that parameters such as cholesterol or fat mass are related to $\dot{V}O_{2max}$.[1,2] Consequently, for young people of low aerobic fitness, there are advantages to improve their aerobic power. In this population, short-term effects of training are expected in terms of performance or to reach health-related standards for aerobic fitness.[3] Long-term effects of aerobic training may also be expected. Some authors have reported that children, with a higher level of physical activity, or who have been trained during childhood, showed a higher level of physical activity and aerobic fitness in young adulthood.[4-6]

Aerobic fitness can be related to many measured or estimated parameters obtained in various exercise conditions. As $\dot{V}O_{2max}$ is the most commonly used parameter to investigate the functional state of the oxygen transport system, the present review will only focus on this topic. In the majority of children, the absence of the oxygen uptake ($\dot{V}O_2$) plateau at maximal exercise raises questions as to whether the values elicited are truly maximal. As a result of several studies[7-9] it has become more usual and appropriate to define the highest $\dot{V}O_2$ achieved during a test to voluntary exhaustion as peak $\dot{V}O_2$ rather than $\dot{V}O_{2max}$, which implies that a plateau in $\dot{V}O_2$ has been demonstrated.[10] However, many controversies exist between studies about the effects of training on children's peak $\dot{V}O_2$. Longitudinal studies in children[11,12] have shown that training had no effect on $\dot{V}O_2$ before puberty. This suggests that there is a maturational threshold below which children are not able to increase their peak $\dot{V}O_2$. However, some other authors reported positive training effects in prepubertal children.[13-18] Discrepancies between studies seem, in part, due to different procedures in protocol design and training methods. Therefore, this review will examine how study design and training methods influence changes in peak $\dot{V}O_2$, which result from aerobic exercise training in children and adolescents.

## 1. Methodological Considerations

In accordance with previously published reviews on trainability in young people[16-19] the following criteria were used to eliminate research papers from the final analysis: no control group;[20-26] an unclear training protocol description;[11,27-30] inappropriate statistical procedures or small samples;[31-33] studies with trained or special populations;[34-39] and studies with no peak $\dot{V}O_2$ measurements.[24,40-46]

From 51 studies, 22 were finally retained.[47-68] However, other factors such as maturity status, sex effect, group constitution, initial peak $\dot{V}O_2$ and physical activity level, consistency between training and testing procedure, control of training intensity/duration, drop out rate or attendance can lead to a methodological bias, without casting doubt on the validity of the studies. In the first part of the manuscript, each of these items is considered, and possible associations with changes in peak $\dot{V}O_2$ from training are discussed.

### 1.1 Maturity Status

Over the last 12 years, the maturity status of children has been assessed in most studies following recommendations provided in literature reviews.[16,18,69] However, of 22 papers reviewed, maturity status was reported in only 11 studies.[50,54,58-62,64,65,67,68] In the remaining studies, only chronological age was reported. In such conditions, the association between the response to training and the individual's maturity status cannot be identified. One study compared the training responses of children and adolescents subjected to the same training programme.[33] In a cross-sectional study with twins, the authors investigated the influence of developmental stages on trainability. They demonstrated that during the circumpubertal period there was no increase in peak $\dot{V}O_2$ relative to body mass, while significant improvement occurred in prepubertal and postpubescent periods. Thus, the authors suggested that a decreased sensitivity to training occurred in the circumpubertal period compared with the years surrounding it. However, this study is unique and their conclusions have been strongly challenged.[70] These results highlight the need for longitudinal data to determine if there is a critical stage of maturity during which training enhances maximal gain in peak $\dot{V}O_2$.

Three periods, defined as prepubertal (children), circumpubertal (adolescents) and postpubertal, are generally taken into consideration when maturity status was not assessed.[71] In the present review, this classification has been used to compare the effect of training in relation to maturity status. In contrast with Pate and Ward,[16] females under 11 years were classified as prepubertal. In Mahon and Vaccaro's study,[56] boys aged 10–14 years (mean age 12.4 ± 1.9 years), were classified as circumpubertal. According to this classification, the number of studies in each sub-group is shown in table I.

When males and females were pooled, the average peak $\dot{V}O_2$ improvement was 5.2% for prepubertal and 5.3% for circumpubertal individuals. However, as recommended by Rowland,[13] when only studies showing significant improvements in

**Table I.** Number of studies, according to sex and pubertal status. As some studies included boys and girls, the total number of references is greater than 22

| | Prepubertal | | | Circumpubertal | | |
|---|---|---|---|---|---|---|
| | age (y) | no. of studies | references | age (y) | no. of studies | reference |
| Males | <13 | 11 | 47-49,53-55,57,60,64,66,67 | 13–18 | 1 | 56 |
| Females | <11 | 7 | 47,60-64,67 | 11–16 | 1 | 65 |
| Mixed | | 5 | 50-52,59,68 | | 1 | 58 |

 

**Table II.** Peak oxygen uptake difference (Δpeak $\dot{V}O_2$) in boys, girls and mixed populations (boys and girls) according to pubertal status

| | Prepubertal | | Circumpubertal | |
|---|---|---|---|---|
| | Δpeak $\dot{V}O_2$ (%) [range] | references | Δpeak $\dot{V}O_2$ (%) | reference |
| Males | 6.1 [−1.6 to +20.5] | 47-49,53-55,57,60,64,66,67 | 7.6 | 56 |
| Females | 6.9 [0.7 to +19.4] | 47,60-64,67 | −1.5 | 65 |
| Mixed | 1.5 [−7.6 to +8.2] | 50-52,59,68 | 9.9 | 58 |

peak $\dot{V}O_2$ were included, the average improvement was 10.1% for prepubertal and 8.8% for circumpubertal individuals. According to sex, average improvements in peak $\dot{V}O_2$ at prepubertal and circumpubertal stages are reported in table II. The mean improvement corresponds to previously published reviews that reported mean values of 5%[19] or 10%,[16] while a 14%[13] change was reported when only studies showing a significant increase in peak $\dot{V}O_2$ were included. In prepubertal boys, peak $\dot{V}O_2$ enhancement (6.1%) was slightly lower than that observed in the circumpubertal individuals (+7.6%). Nevertheless, the latter finding has to be interpreted with caution as prepubertal and circumpubertal males were not compared using the same training programme, and only one study was conducted on circumpubertal males. Only one study has investigated adolescent girls.[65] In this study, no significant peak $\dot{V}O_2$ improvement was reported. Any possible influence of maturity on peak $\dot{V}O_2$ remains obscure, as few studies have compared response to training with regard to maturity status. There is a clear need to analyse the response of training of prepubertal and circumpubertal individuals when subjected to the same aerobic training programme.

### 1.2 Sex Effect

Six studies compared boys and girls.[47,59,60,64,67,68] In these studies, designed for prepubertal individuals, similar improvements in peak $\dot{V}O_2$ were reported according to sex. Changes ranged from 0.7–19.4% in girls and were similar to those of boys, −1.6–20.5% (table II). No study has been designed to compare the responses of adolescents according to sex. Based on these limited results, it seems that boys and girls demonstrate similar responses to aerobic training, and no conclusion can be drawn with respect to adolescents.

### 1.3 Group Constitution

The groups were generally based on school classes.[47-52,57-63,65-68] If the groups were constituted of entire classes, it could be assumed that the individuals were randomly assigned.[20] Conversely, when groups were constituted of schoolchildren who volunteered, it was assumed that the groups were non-randomised. When the authors failed to specify a random assignment, the studies were classified as non-random. According to this classification, the mean improvements in peak $\dot{V}O_2$ according to group assignment are shown in table III. In both groups, similar improvements in peak $\dot{V}O_2$ were observed. These data did not support the assumption made by Rowland[9] in a previous review, who suggested that the failure to address the problem of non-compliant individuals might seriously affect the study by selecting data of only motivated individuals. It should be noted that no study conducted on adolescents was based on randomly constituted groups.

**Table III.** Peak oxygen uptake difference (Δpeak $\dot{V}O_2$) according to pubertal status and individual assignment

| | Prepubertal | | Circumpubertal | |
|---|---|---|---|---|
| | Δpeak $\dot{V}O_2$ (%) [range] | references | Δpeak $\dot{V}O_2$ (%) [range] | references |
| Random assignment | 5.0 [−1.6 to +20.5] | 47,53,54,61,62,66,68 | | |
| Non-random assignment | 5.3 [−7.6 to +19.4] | 48-51,53,55,57,59,60,63,64 | 5.3 [−1.5 to +9.9] | 56,58,65 |

**Table IV.** Sample size in studies reviewed

| Sample size | Experimental group | | Control group | |
|---|---|---|---|---|
| | no. of studies | references | no. of studies | references |
| <11 | 5 | 48,54-56,63 | 8 | 48,50,54-56,61,63,64,68 |
| 11–20 | 13 | 49,50,52,58,60-62,64,65,67 | 11 | 49,51-53,55,58,60,62,65,66,68 |
| 21–30 | 2 | 47,51 | 2 | 47,67 |
| 31–40 | 2 | 59,68 | 1 | 59 |

Of the 22 studies listed, sample sizes ranged from 7–37 with an average of 16 individuals for the experimental and 14 for the control group (table IV). In some studies, there was a size difference in one of the two groups.[50,51,61,67,68] In these studies, the power of statistical data may be altered by the effect of sample size, inducing a type 2 error.

### 1.4 Initial Peak Oxygen Uptake and Physical Activity Levels

Young people tend to have higher initial peak $\dot{V}O_2$[72] and tend to be more physically active than adults.[73] A high initial peak $\dot{V}O_2$ was proposed to explain no or lower changes in peak $\dot{V}O_2$ in children after training compared with adults.[17] Table V shows the training-induced changes in peak $\dot{V}O_2$ as a function of initial peak $\dot{V}O_2$. Circumpubertal males have a lower initial mean relative peak $\dot{V}O_2$ level (39.0 mL/kg/min) than prepubertal ones (44.7 mL/kg/min). Only one study reported an initial peak $\dot{V}O_2$ higher than 50 mL/kg/min in girls.[62] In the different subgroups, significant improvements in peak $\dot{V}O_2$ were observed. In prepubertal individuals with high initial aerobic fitness, the mean improvement in peak $\dot{V}O_2$ (+2.7%) was lower than for those with low initial aerobic fitness (+5.9%). This supports the results reported by Tolfrey et al.[64] and Mandigout et al.[67] The latter observed significant inverse relationships between differences in peak $\dot{V}O_2$ and initial peak $\dot{V}O_2$ values. However, the relationship accounted for only 9% of the variance in peak $\dot{V}O_2$ over time.[64] Initial peak $\dot{V}O_2$ seems to be related to the magnitude of the peak $\dot{V}O_2$ differences induced by the training programmes; however, it was not a major determinant. For individuals with relatively low initial peak $\dot{V}O_2$ (39.3 mL/kg/min), no significant improvement in peak $\dot{V}O_2$ was found;[64] whereas significant improvement was observed in individuals with high pretraining peak $\dot{V}O_2$ (55.9 mL/kg/min).[54]

The level of physical activity during prepubertal and circumpubertal periods may also interfere with training even if a habitually high physical activity level is not necessarily associated with high peak $\dot{V}O_2$ values.[74,75] In adolescents, Rowland and Boyajian[59] reported a weak but significant relationship between the level of physical activity and percentage increase in peak $\dot{V}O_2$ from training. However, in the training studies on youngsters, there is generally a lack of information concerning their level of physical activity. The level of physical activity was assessed in four studies, by self questionnaire[58,67] or parent questionnaire.[59,60] Tolfrey et al.[64] showed that, after training, children increased their level of physical activity. To overcome

**Table V.** Average initial peak oxygen uptake (peak $\dot{V}O_2$) and peak oxygen uptake difference (Δpeak $\dot{V}O_2$) according to pubertal status and initial peak $\dot{V}O_2$

| Initial peak $\dot{V}O_2$ | Prepubertal | | | Circumpubertal | | |
|---|---|---|---|---|---|---|
| (mL/kg/min) | peak $\dot{V}O_2$ (mL/kg/min) | Δpeak $\dot{V}O_2$ (%) [range] | references | peak $\dot{V}O_2$ (mL/kg/min) | Δpeak $\dot{V}O_2$ (%) [range] | references |
| <50 | 44.7 | 5.9 [−7.6 to +20.5] | 47-49,51-53,55,57 59-64,67,68 | 39.0 | 5.3 [−1.5 to +9.9] | 56,58,65 |
| ≥50 | 53.6 | 2.7 [−1.6 to +6.8] | 47,50,54,62,66 | | | |

**Table VI.** Differences in peak oxygen uptake (Δpeak $\dot{V}O_2$) according to pubertal status and consistency between training and testing procedures

| | Prepubertal | | Circumpubertal | |
|---|---|---|---|---|
| | Δpeak $\dot{V}O_2$ (%) [range] | references | Δpeak $\dot{V}O_2$ (%) [range] | references |
| Consistency between training and testing | 5.7 [−7.6 to +20.5] | 47-51,53-55,57,59-64,66,68 | 5.3 [−1.5 to +9.9] | 56,58,65 |
| No consistency between training and testing | 3.0 [−1.6 to +8.5] | 52,61,62,66,67 | | |

a possible interaction between the effects of training and physical activity patterns during training, the assessment of physical activity before, during and after training seems necessary.

### 1.5 Consistency Between Training and Testing Procedures

Differences in peak $\dot{V}O_2$ according to pubertal status and consistency between training and testing procedures are presented in table VI. Studies in adults have shown that when the training programme and the testing procedure used the same mode of exercise, peak $\dot{V}O_2$ improvement was found to be much higher than when different modes of exercise were achieved.[76-78] Two studies tested children on a cycle ergometer while they were trained in running[52,67] and three studies tested children on a treadmill while they were trained on a cycle ergometer.[61,62,66] In studies presenting no consistency between training and testing, only Gilliam and Freedson[52] and Williams et al.[66] failed to show peak $\dot{V}O_2$ improvement. In the study by Williams et al.[66] a group trained continuously on a cycle ergometer and was tested on a motorised treadmill. In the study by Gilliam and Freedson,[52] the training was based on physical fitness programme conducted during physical education classes (mainly locomotor exercises) and peak $\dot{V}O_2$ was measured on a cycle ergometer. In most of the studies reviewed, peak $\dot{V}O_2$ was measured in a laboratory setting using a treadmill or a cycle ergometer with an open-circuit spirometer. In one study, special attention was paid to the consistency between training and testing;[68] it consisted of short duration (≤20 seconds) shuttle running exercises and peak $\dot{V}O_2$ was directly measured by use of a portable gas analyser (K4b2, Cosmed®[1], Rome, Italy) during the 20m shuttle run test.[79] These different results suggest that children's peak $\dot{V}O_2$ improvement was higher when the testing mode was consistent with the training protocol.

### 1.6 Monitoring of Training Intensity/Duration

In training protocol design, it is of particular importance to accurately monitor exercise intensity. In the laboratory, this can be done when exercises are performed on treadmills or cycle ergometers. When training is conducted out of the laboratory, authors generally report intensity as a function of absolute heart rate (HR) or as a percentage of maximal heart rate ($HR_{max}$). If expressed as an absolute value (beats/minute), it is assumed that a selected HR value represents the same intensity for all individuals. However, children are characterised by large inter-individual variability in $HR_{max}$, and the same absolute HR may be associated with a great difference in percentage of $HR_{max}$. In most of the studies conducted in field conditions, HR was not systematically monitored.[49,50,59-61,66,67] Some flaws in exercise intensity monitoring are also observed when $HR_{max}$ is measured during a maximal exercise on a cycle ergometer and when exercise intensity is monitored for weight-bearing activities. For example, $HR_{max}$ measured during a cycle exercise is lower than that measured during a treadmill exercise.[80]

**1** The use of tradenames is for product identification purposes only and does not imply endorsement.

Exercise duration is a second key factor in the determination of training. In some studies, exercise intensity was well monitored, but exercise duration differed because some individuals of different aerobic fitness were instructed to run at their own pace but over the same distance.[54,56,63] For instance, in the study by Savage et al.,[54] children had to cover the same distance (from 2.4 to 4.8km) whether by walking, jogging or running. It is of particular importance that all individuals exercise at the same intensity over the same duration. To avoid this bias, several authors have proposed time trials at velocities expressed as percentages of maximal aerobic velocity (MAV).[44,46,68] This velocity, defined as the lowest velocity allowing peak $\dot{V}O_2$ to be elicited during a graded test,[81] could be calculated from physiologically determined parameters (peak $\dot{V}O_2$ and energy cost of running). In field test conditions, MAV can also be determined with a graded field test, the Université de Montréal Track Test.[82,83] The test is performed on a track marked with cones placed every 25m. A pre-recorded soundtrack indicates with some brief sounds the instant when the individual must pass near a cone to maintain a constant velocity. A longer sound marks the changes in stage. At the first stage, the speed is set at 8 km/hour and increased by 1 km/hour per stage of 2 minutes. The test is finished when the individual is not able to maintain the imposed running speed. The speed at the last completed stage is kept as the MAV (km/hour). It is assumed that percentages of MAV are equivalent to percentages of peak $\dot{V}O_2$. When exercises were proposed during time trials at relative velocities (%MAV), it was expected that all individuals perform the same relative exercise (intensity and duration), independently of their aerobic fitness level. Moreover, in contrast to HR, the MAV allows velocities at intensities near or higher than peak $\dot{V}O_2$ to be carefully monitored.

Literature reviews showed that the range of differences in peak $\dot{V}O_2$ between pre- and post-training values was rarely reported. Large inter-individual differences between pre- and post-training peak $\dot{V}O_2$, from –3% to +21%[59] or from –10 to +30%[67] were observed. These differences in the peak $\dot{V}O_2$ training response may partly be explained by an inadequate exercise-training programme that was not carefully adapted to each individual's potential. There is therefore a need, principally in field test design, to accurately check training intensity and duration of exercise for each individual.

### 1.7 Drop Out and Attendance

Only eleven studies[47,49,54,58-60,62,64-67] considered drop-out or attendance rates during testing procedures. Drop-out rates of 20%,[54] 15%,[62] 13%,[66] 11%[65] or 0%[59,65] were reported. Rowland and Boyajian[59] and Savage et al. [54] observed attendance values of 90–95%, and 96%, respectively. It is important to note that rejecting lowly motivated individuals or selecting highly motivated individuals does not provide an accurate representation of the impact of training.

### 1.8 Summary

Independently of sex or pubertal status, mean peak $\dot{V}O_2$ improvement was around 5–6%. When only studies that reported significant training effect were taken into account, the mean improvement in peak $\dot{V}O_2$ rose to 8–10%. There was a notable lack of studies conducted during the circumpubertal period, and particularly few done on girls. Current data suggest that methodologically listed parameters will exert a potential influence on the magnitude of peak $\dot{V}O_2$ improvement. Even if little difference is reported for each parameter, it is assumed that the sum of errors will result in a significant bias in the assessment of training effects. This is particularly important when the expected improvement in peak $\dot{V}O_2$ from training is compared with the approximately 5.6% day-to-day biological variations in peak $\dot{V}O_2$ determination.[84]

## 2. Training Design

The magnitude of peak $\dot{V}O_2$ increase resulting from endurance training depends on the training programmes used. Training design is determined by: exercise intensity, duration and recovery; length of the training programme; frequency of sessions; or initial fitness.[85] The question is: is there an ideal standard protocol for aerobic training in young people? The characteristics of each training protocol are shown in table VII. Individuals were involved in various activities such as: cycling;[48,53,61,62,64,66] running;[47,49,51,54,56-58,61,63,66,68] isokinetic exercises;[55] or a patchwork of aerobic activities or physical education sessions.[50,52,59,60,62,65,67]

### 2.1 Frequency and Duration

The average frequency of the training protocol was 3–4 sessions per week (80% of studies) with a range of 1–6 (table VIII). Only two sessions might be sufficient to increase peak $\dot{V}O_2$.[68] In prepubertal and circumpubertal children, the gain in peak $\dot{V}O_2$ was improved by increasing the number of sessions per week. With a comparable number of sessions per week, the variation in peak $\dot{V}O_2$ was independent of pubertal status.

The duration of the sessions ranged from 5 minutes[51] to 90 minutes[67] (table IX). Eighteen studies had a session length inferior or equal to 30 minutes.[47-49,51,52,55-66,68] Three or four sessions from 30 minutes to 1 hour seemed to be the best option to improve peak $\dot{V}O_2$. With a comparable session duration, the variation in peak $\dot{V}O_2$ was independent of pubertal status. Both session frequency and session duration appear to be key factors in training programmes for children.

### 2.2 Length of the Programme

The length of the training programmes ranged from 4 weeks [55] to 18 months[63] (table X). Sixteen studies lasted from 1–3 months.[47-50,52-56,58,59,61,62,64,66,68] As shown in table X, there was no clear influence of the length of the programme on peak $\dot{V}O_2$ improvement. For example a 19% improvement of peak $\dot{V}O_2$ wad observed with an 18-month programme,[63] while an 18% gain was found after a 4-week programme.[55] Consequently, in the reviewed studies, the length of the programmes does not appear to be a decisive factor in obtaining a significant gain in peak $\dot{V}O_2$.

### 2.3 Intensity

The protocols addressing the trainability of children and adolescents are mainly based on continuous exercises at intensities lower than those associated with peak $\dot{V}O_2$.[48,50-54,57-66] These protocols included exercises that were based on physical education sessions[52] or circuit training,[59,60] which were assumed to be mainly continuous. Six studies were designed with intermittent exercises at intensities higher than that associated with peak $\dot{V}O_2$.[47,49,55,61,66,68] In two studies, the training programme consisted of continuous and intermittent exercises.[56,67] In most studies, intensity of exercise is commonly defined in terms of percentages of $HR_{max}$. Table XI shows that for a same relative training intensity circumpubertal demonstrated higher changes in peak $\dot{V}O_2$ than prepubertal. For prepubertal, compared with continuous or intermittent exercises, 'all-out' exercises lead to higher peak $\dot{V}O_2$ improvements.

#### *2.3.1 Continuous Training*

Of sixteen studies including continuous exercises, nine reported a significant increase in peak $\dot{V}O_2$.[48,50,53,54,57-59,61,63] When intensity was lower or equal to 80% $HR_{max}$[48,52,54,57,58,62-65] peak $\dot{V}O_2$ was improved in only three studies.[57,58,63] In the two studies by Yoshizawa et al.[57,63] on 4- to 6-year-old children, the intensity during training sessions was estimated from maximal velocity during treadmill tests and mean velocity during the training sessions. Using an identical protocol, the authors reported a 5.9% increase in peak $\dot{V}O_2$[57] or a 19.4% increase.[63] In the latter study, a significant rise (+8.2%) in peak $\dot{V}O_2$ was also observed in the control group. These results, obtained on very young

**Table VII.** Effects of training on peak $\dot{V}O_2$ in during prepubertal and circumpubertal periods. Studies are presented in chronological order

| Study | Sex | Age (y) | n | Pubertal status (P/C) | Exercise | Length | Intensity | Frequency (n/wk) | Duration | Test | $\dot{V}O_2$ (mL/kg/min) pre/post/Δ(%) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Bar-Or and Zwiren [47] | M | 9–10 | 22 | P | Interval running | 9 wks | All-out | 2–4 | 20–25 min, 145m with 1.5 min recovery between each repetition | T | 50.2/49.4/–1.6 |
| | F | 9–10 | 24 | P | | | | | | | 44.2/46.1/+4.3 |
| | M | 9–10 | 22 | P | Control group | | | | Calisthenics and games | | 50/49.3/–1.4 |
| | F | 9–10 | 24 | P | | | | | | | 45/43.8/–2.7 |
| Massicotte and Macnab[48] | M | 11–13 | 9 | P | Cycling | 6 wks | 88–93% $HR_{max}$ | 3 | 12 min | E | 46.7/51.8/+10.9* |
| | M | 11–13 | 9 | P | | | 75–80% $HR_{max}$ | | | | 47.4/48/+1.3 |
| | M | 11–13 | 9 | P | | | 66–72% $HR_{max}$ | | | | 46.6/48.2/+3.4 |
| | M | 11–13 | 9 | P | Control group | | | | | | 45.7/44.2/–3.3 |
| Stewart and Gutin[49] | M | 10–12 | 13 | P | Interval running | 8 wks | 90% $HR_{max}$ | 4 | 5 × 1 min and 3 × 3 min paced or all-out runs with 1 min recovery between each repetition | T | 49.8/49.5/–0.6 |
| | M | 10–12 | 11 | P | Control group | | | | | | 48.4/49.2/+1.7 |
| Lussier and Burskirk[50] | M & F | 10.3 | 16 | P | Continuous running and various activities | 12 wks | 92% $HR_{max}$ | 2 | 10–35 min | T | 55.6/59.4/+6.8* |
| | M & F | 10.5 | 10 | P | Control group | | | 2 | 45 min | | 53.1/53.9/+1.5 |
| Yoshida et al.[51] | M & F | 5 | 21 | P | Distance training 750–1500m | 7mo | 94% $HR_{max}$ | 1 | 5–10 min | T | 43.5/44.3/+1.8 |
| | M & F | 5 | 25 | P | | | | 5 | | | 42.1/42.8/+1.7 |
| | M & F | 5 | 11 | P | Control group | | | | | | 41.6/45.1/+8.4 |
| | M & F | 5 | 21 | P | Distance training 750–1500m | 14mo | | 1 | | | 43.5/41.6/–4.4 |
| | M & F | 5 | 25 | P | | | | 5 | | | 42.1/38.9/–7.6 |
| | M & F | 5 | 11 | P | Control group | | | | | | 41.6/42.8/+2.9 |
| Gilliam and Freedson[52] | M & F | 8.5 | 11 | P | Physical education lessons | 12 wks | 78% $HR_{max}$ | 4 | 25 min | E | 43.4/42.9/–1.2 |
| | M & F | 8.5 | 12 | P | Control group | | | | | | 40.5/40.9/+1.0 |
| Becker and Vaccaro[53] | M | 9.5 | 11 | P | Continuous cycle training | 8 wks | 85% $HR_{max}$ | 3 | 40 min | E | 39/46.99/+20.5* |
| | M | 9.9 | 11 | P | Control group | | | | | | 41.7/44/+5.51 |
| Savage et al.[54] | M | 8.5 | 8 | P | Walking, jogging, running | 12 wks | 68% $HR_{max}$ | 5 | From 2.4–4.8km per time | T | 52.2/54.6/+4.6 |

*Continued next page*

**Table VII.** Contd

| Study | Sex | Age (y) | n | Pubertal status (P/C) | Exercise | Length | Intensity | Frequency (n/wk) | Duration | Test | $\dot{V}O_2$ (mL/kg/min) pre/post/Δ(%) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | M | 8 | 12 | P | | | 85% $HR_{max}$ | | | | 55.9/58.5/+4.6* |
| | M | 10 | 10 | P | Control group | | | | | | 57/55.7/–2.2 |
| Docherty et al.[55] | M | 12.4 | 11 | P | Intermittent exercise | 4 wks | High velocity/ low resistance (180 °/sec) | 3 | 2 sets of 20 sec all-out effort with 20 sec rest (5 min rest between each set) | E | 46.2/54.7/+18.4* |
| | M | 12.4 | 12 | P | | | Low velocity/ high resistance (30 °/sec) | | | | 47/55.1/+17.2* |
| | M | 12.4 | 11 | P | Control group | | | | | | 47/49/+4 |
| Mahon and Vaccaro[56] | M | 12.4 | 8 | C | Continuous and interval running | 8 wks | 80–95% $HR_{max}$ | 2 + | 20–30 min | T | 45.9/49.4/+7.6* |
| | M | 12.3 | 8 | C | Control group | | | 2 | 100–800m (from 1.5–2.5 km) | | 45.4/45.9/+1.1 |
| Yoshizawa et al.[57] | M | 5–6 | 12 | P | Running endurance | 6mo | 117–157 m/ min (<80% $HR_{max}$) | 6 | One run of 915m | T | 47.6/50.4/+5.9* |
| | M | 5–6 | 12 | P | Control group | | | | | | |
| Rowland et al.[58] | M & F | 15.7 | 15 | C | Walking | 11 wks | 80% $HR_{max}$ | 3 | 30 (2.9km) | T | 30.3/33.3/+9.9* |
| | M & F | 15.7 | 15 | C | Control group | | | | | | 30.7/30.3/–1.3 |
| Rowland and Boyajian[59] | M & F | 10.9–12.8 | 13 | P | Circuit training, distance running or walking | 12 wks | 80–85% $HR_{max}$ | 3 | 20–30 min | T | 44.7/47.6/+6.5* |
| | | | 24 | | Aerobic games | | | | | | |
| | M & F | | 13 | P | Control group | | | | | | 44.3/44.7/+0.9 |
| | | | 24 | | | | | | | | |
| Rowland et al.[60] | M | 10.9–12.9 | 14 | P | Aerobic dance, step aerobics, distance running and circuit activities | 13 wks | 87.5% $HR_{max}$ | 3 | 30 min | T | 45.4/48.2/+6.1 |
| | F | | 20 | | | | | | | | 43.9/46.1/+5 |
| | M | | 14 | | Control group | | | | | | 45.3/45.4/+0.2 |
| | F | | 20 | | | | | | | | 43.7/43.9/+0.4 |
| McManus et al.[61] | F | 9.3 | 12 | P | Cycle ergometer | 8 wks | 80–85% $HR_{max}$ | 3 | 20 min | T | 45/48.5/+7.2* |

*Continued next page*

**Table VII.** Contd

| Study | Sex | Age (y) | n | Pubertal status (P/C) | Exercise | Length | Intensity | Frequency (n/wk) | Duration | Test | $\dot{V}O_2$ (mL/kg/min) pre/post/Δ(%) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | F | 9.8 | 11 | P | Sprint running | | All-out | | 3 × 10 sec with 30 sec rest and 3 × 30 sec with 90 sec rest | | 48/50.9/+6* |
| | F | 9.6 | 7 | P | Control group | | | | | | 44.6/43.1/–3.4 |
| Welsman et al.[62] | F | 9–10 | 18 | P | Cycle ergometer | 8 wks | 80% $HR_{max}$ | 3 | 20 min | T | 51.8/52.2/+0.7 |
| | F | 9–10 | 17 | | Aerobics | | 75–80% $HR_{max}$ | | 20–25 min | | 47/47.8/+1.7 |
| | F | 9–10 | 18 | P | Control group | | | | | | 46.2/45.9/–0.6 |
| Yoshizawa et al.[63] | F | 4 | 8 | P | Running endurance | 18mo | 117–157 m/min | 6 | One run of 915m | T | 42.2/50.4/+19.4* |
| | F | 4 | 8 | P | Control group | | (<80% $HR_{max}$) | | | | 42.4/45.9/+8.2* |
| Tolfrey et al.[64] | M | 10.6 | 12 | P | Continuous cycle training | 12 wks | 80% $HR_{max}$ | 3 | 30 min | E | 46.6/47.2/+1.3 |
| | F | 10.6 | 14 | P | | | | | | | 39.3/42.3/+7.9 |
| | M | 10.3 | 10 | P | Control group | | | | | | 50.7/50.3/–0.7 |
| | F | 10.5 | 9 | P | | | | | | | 44.7/40.3/–3.8 |
| Stoedefalke et al.[65] | F | 13–14 | 20 | C | Treadmill running, cycle and rowing ergometry, stair stepping | 20 wks | 75–85% $HR_{max}$ | 3 | 20 min | T | 40.8/40.2/–1.5 |
| | F | 13–14 | 18 | C | Control group | | | | | | 41.9/41.4/–1.3 |
| Williams et al.[66] | M | 10.1 | 12 | P | Sprint running | 8 wks | All-out | 3 | 3 × 10 sec with 30 sec rest and 3 × 30 sec with 90 sec rest | T | 54.8/53.9/–1.6 |
| | M | | 13 | P | Continuous cycle training | | 80–85% $HR_{max}$ | | 20 min | | 54.7/57.5/+5.1 |
| | M | | 14 | P | Control group | | | | | | 56.4/56.7/+0.5 |
| Mandigout et al.[67] | M | 10.7 | 18 | P | Interval and continuous running, aerobic activities | 13 wks | 80–90% $HR_{max}$ | 3 | 60–90 (10 × 100, 6 × 200, 4 × 600m, 1500–4500m) | E | 47.2/49.2/+4.2* |
| | F | 10.5 | 17 | P | | | | | | | 38.6/41.9/+8.5* |
| | M | 10.5 | 22 | P | Control group | | | | | | 46.1/45.5/–1.3 |
| | F | 10.5 | 28 | P | | | | | | | 39.6/39.5/–0.2 |
| Baquet et al.[68] | M & F | 9.5 | 33 | P | Interval running | 7 wks | 80–95% $HR_{max}$ | 2 | 5 sets of 10 × 10 sec of run (30 min) | FT ($K4b^2$) | 43.9/47.5/+8.2* |
| | M & F | 9.9 | 20 | P | Control group | | | | | | 46.2/45.3/–1.9 |

**C** = circumpubertal; **E** = cycle ergometer; **F** = females; **FT** = field test; **$HR_{max}$** = maximal heart rate; **$K4b^2$** = Cosmed® $K4b^2$ gas analyser; **M** = males; **P** = prepubertal; **$\dot{V}O_2$** = oxygen uptake; **T** = treadmill. * indicates significantly different from pretraining value at $p < 0.05$.

**Table VIII.** Difference in peak oxygen uptake (Δpeak $\dot{V}O_2$) according to pubertal status and session frequency

| Frequency | Prepubertal | | Circumpubertal | |
|---|---|---|---|---|
| (sessions/wk) | Δpeak $\dot{V}O_2$ (%) [range] | references | Δpeak $\dot{V}O_2$ (%) [range] | references |
| <3 | 0.8 [−7.6 to +8.2] | 51,68 | | |
| 3–4 | 5.7 [−1.6 to +20.5] | 47-50,52,53,55,59-62,64,66,67 | 5.3 [−1.5 to +9.9] | 56,58,65 |
| >4 | 5.3 [−4.4 to +19.4] | 51,54,57,63 | | |

children, are somewhat surprising, and may challenge the study validity. In the study by Rowland et al.,[58] the initial peak $\dot{V}O_2$ of the circumpubertal was very low (30.3 mL/kg/min), which may explain why a low training stimulus (<80% $HR_{max}$) induces a significant improvement in peak $\dot{V}O_2$. In two studies, individuals were subjected to the same training programme carried out at different training intensities.[48,54] In these studies, only children involved in the high-intensity training groups demonstrated significant improvement in peak $\dot{V}O_2$.

Massicotte and Macnab[48] compared children who trained for 12 minutes, three times a week for 6 weeks at 66–72%, 75–80% or 88–93% $HR_{max}$. Only the group who trained at 88–93% $HR_{max}$ (170–180 beats/min) significantly improved peak $\dot{V}O_2$. Savage et al.[54] observed a significant increase in the children who trained at 85% of $HR_{max}$, while no significant change was found when training intensity represented 70% of $HR_{max}$. With intensities between 80% and 100% of $HR_{max}$, most studies[48,50,53,54,59,61] reported a significant improvement in peak $\dot{V}O_2$, while no increase was achieved in three protocols.[51,60,66] Nevertheless, in the study by Yoshida et al.[51] the authors indicated that the length of the programme was 14 weeks; however, these durations included holiday periods that ranged from 1–3 months. The inclusion of a long detraining period (holidays) in the training programme may explain why no significant change in peak $\dot{V}O_2$ was observed. Williams et al.,[66] reported a 5.1% non-significant improvement in peak $\dot{V}O_2$, with exercise intensities close to 80% of $HR_{max}$ (a mean intensity of 160–170 beats/min for children with $HR_{max}$ equal to 204 beats/min). With the same training protocol, McManus et al.[61] showed that girls with lower initial peak $\dot{V}O_2$ (45 mL/kg/min) showed a significant improvement in peak $\dot{V}O_2$ (7.2%).

In both children and adolescents, intensity higher than 80% of $HR_{max}$ seems to be necessary to improve aerobic fitness. The major difficulty in a continuous protocol is children's attendance. They must be encouraged individually or monitored continually to ensure their adherence to the exercise programme.[64] However, this is difficult goal to obtain in a school context and might explain that often no improvement in peak $\dot{V}O_2$ was found, even if additional physical education sessions have been added.[86,87] Stratton[88] observed that in most physical education sessions, individuals failed to achieve elicit HR at a sufficient level to achieve the American College of Sports Medicine[89] guidelines in terms of intensity. This underlines the necessity to intensify school-based intervention programmes.[90]

#### 2.3.2 Interval Training

All studies with intermittent exercises were conducted on prepubertal children. In three studies, peak $\dot{V}O_2$ was improved,[55,61,68] while non-significant improvement was obtained in the other.[47,49,66] Stewart and Gutin[49] failed to obtain significant improvement in peak $\dot{V}O_2$ with a protocol that was

**Table IX.** Difference in peak oxygen uptake (Δpeak $\dot{V}O_2$) according to pubertal status and session duration

| Session duration | Prepubertal | | Circumpubertal | |
|---|---|---|---|---|
| (min) | Δpeak $\dot{V}O_2$ (%) [range] | references | Δpeak $\dot{V}O_2$ (%) [range] | references |
| ≤30 | 4.5 [−7.6 to +19.4] | 47-49,51,52,55,57,59-64,66,68 | 5.3 [−1.5 to +9.9] | 56,58,65 |
| >30 | 8.2 [+4.2 to +20.5] | 50,53,54,67 | | |

**Table X.** Peak oxygen uptake difference (Δpeak $\dot{V}O_2$) according to pubertal status and programme duration

| Programme | Prepubertal | | Circumpubertal | |
|---|---|---|---|---|
| duration (mo) | Δpeak $\dot{V}O_2$ (%) [range] | references | Δpeak $\dot{V}O_2$ (%) [range] | references |
| ≤6 | 5.7 [−1.6 to +20.5] | 47-50,52-55,59-62,64,66-68 | 5.3 [−1.5 to +9.9] | 56,58,65 |
| >6 | 2.8 [−7.6 to +19.4] | 51,57,63 | | |

based on a 5-minute run as a warm-up, immediately followed by three series of 3 minutes at a paced velocity (90% $HR_{max}$) or all-out running with 1 minute of rest. The intensity of the training was alternated every training session and was probably not sufficient (intensity and/or exercise duration) to elicit a high percentage of peak $\dot{V}O_2$. Bar-Or and Zwiren[47] also reported no improvement in schoolchildren's peak $\dot{V}O_2$ when children performed 145m all-out runs. In this study, the children performed about six 145m runs in 40 seconds at the beginning of the training programme, while eight to ten runs were performed in 35 seconds during the last session. In this study, the results of children who had two, three or four sessions a week were pooled, which may induce several biases.

When monitoring children's physical activity patterns, Bailey et al.[91] reported that only 5% of their high-intensity activities (i.e. activities that elicited a $\dot{V}O_2$ value higher than 24.5 mL/kg/min or higher than lactic acidosis threshold) lasted more than 15 seconds. Recent papers have tried to include such types of exercises in children's training programmes.[61,66,68] Baquet et al.[68] showed that the compromise between short bursts of exercise (10 or 20 seconds) and short periods of recovery (10 or 20 seconds), allowed individuals to elicit a high level of peak $\dot{V}O_2$ (from 66–78% of $\dot{V}O_2$ between set 1 and set 5) and finally to reach peak $\dot{V}O_2$. As for continuous running, the repetition of short bouts of exercise at high intensities (near or higher than peak $\dot{V}O_2$), alternated with a short recovery time, allows individuals to reach a high level of $\dot{V}O_2$ and even to elicit peak $\dot{V}O_2$.[68,92] After 7 weeks of such exercises, Baquet et al.[68] reported a significant improvement (8.2%) in peak $\dot{V}O_2$. With all-out runs of short duration (10 and 30 seconds), Williams et al.[66] failed to improve boys' peak $\dot{V}O_2$, while McManus et al.[61] demonstrated a significant improvement with an identical training protocol conducted on girls. A higher initial peak $\dot{V}O_2$ in boys than in girls (55 versus 48 mL/kg/min, respectively) could partly explain these conflicting results.

Finally, with the repetition of 20-second all-out isokinetic exercises at low resistance/high velocity or high resistance/low velocity, Docherty et al.[55] obtained significant improvements in peak $\dot{V}O_2$ (18.4% with high velocity/low resistance exercises and 17.2% with low velocity/high resistance exercises). These results indicate that interval training could lead to significant increase in peak $\dot{V}O_2$. However, the impact of the exercise mode depends on many parameters (exercise intensity, exercise duration, recovery intensity, recovery duration, number of sets, number of series) that have to be precisely specified.

#### 2.3.3 Mixed Training

Two studies[56,67] included mixed training (continuous and intermittent exercises) at a mean intensity higher than 80% $HR_{max}$. Mandigout et al.[67]

**Table XI.** Difference in peak oxygen uptake (Δpeak $\dot{V}O_2$) according to pubertal status and exercise training intensity

| Exercise intensity | Prepubertal | | Circumpubertal | |
|---|---|---|---|---|
| | Δpeak $\dot{V}O_2$ (%) [range] | references | Δpeak $\dot{V}O_2$ (%) [range] | references |
| ≤80% of $HR_{max}$ | 4.5 [−1.2 to +19.4] | 48,52,54,57,62-64 | 4.2 [−1.5 to +9.9] | 58,65 |
| 81–100% of $HR_{max}$ | 4.7 [−7.6 to +20.5] | 48-51,53,54,59-61,66-68 | 7.6 | 56 |
| 'All-out' or sprint | 7.8 [−1.6 to +17.2] | 47,55,61,66 | | |

**$HR_{max}$** = maximal heart rate.

 

reported significant improvements in peak $\dot{V}O_2$, 8.5% and 4.2% in girls and boys, respectively. In this study, children had one continuous session (15–20 minutes, 1500–4500m at 90% $HR_{max}$), one session (from 1 hour to 1 hour 30 minutes) dedicated to aerobic activities (soccer, swimming, basketball) and intermittent exercises (10 × 10m, 6 × 200m, 4 × 600m at 80% $HR_{max}$). In adolescents, Mahon and Vaccaro[56] reported a mean improvement of 7.6% in peak $\dot{V}O_2$ with two sessions of continuous exercises (20–30 minutes at 70–80% $HR_{max}$) and two sessions of intermittent exercises (100, 200, and 800m at intensities higher than 90% peak $\dot{V}O_2$). However, with a mixed programme, the real impact of each exercise on peak $\dot{V}O_2$ improvement cannot be identified accurately.

### 2.4 Summary

Significant improvements in peak $\dot{V}O_2$ were reported independently of training frequency, duration and programme length. To the contrary, training intensity seems to be a key factor in training design. The presented results indicated that intensity higher than 80% of $HR_{max}$ is needed to obtain significant increase in peak $\dot{V}O_2$.

## 3. Conclusions

This review of factors influencing aerobic trainability during growth and development is an update of a similar assessment of this issue performed by Pate and Ward in 1990.[16] Since the last decade, most of the training studies observed recommended[18] experimental designs. In the literature, the trainability of prepubertal children has been studied more often than circumpubertal children (19 vs 3 studies). Aerobic training leads to a mean improvement of 5–6% in peak $\dot{V}O_2$ of children or adolescents. The mean improvement in peak $\dot{V}O_2$ rose to 8–10% when only studies that reported significant training effect were taken into account. However, this expected improvement in young people remained lower than that generally reported for adults.[85]

Surprisingly, there is a lack of studies reporting the outcomes of adolescent training. To our knowledge, no study has reported the effects of aerobic training from childhood to adolescence in a careful manner. Aerobic exercise often consists of regular and long-distance running, cycling or swimming at a moderate intensity, about 80–85% of $HR_{max}$, while training effects are assessed through peak $\dot{V}O_2$ measurement. To analyse the effects of training on peak $\dot{V}O_2$, it can be assumed that exercise at higher intensities is needed. Further research is needed to compare interval training and continuous training in children and adolescents. Finally, there is also clearly a need for longitudinal or cross-sectional studies that investigate the relationship between maturity and training with carefully monitored programmes.

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Correspondence and offprints: *Serge Berthoin*, Laboratoire d'Etudes de la Motricité Humaine, Faculté des Sciences du Sport et de l'Education Physique, Université de Lille 2, 9 rue de l'Université, F59790 Ronchin, France.
E-mail: berthoin@hp-sc.univ-lille2.fr