Endurance training and aerobic fitness in young people.

Georges Baquet, Emmanuel van Praagh, Serge Berthoin

Endurance Training and Aerobic Fitness in Young People

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

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

Running title: Aerobic training in young people

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

Table of Contents

Abstract

In adults, training-induced adaptations in aerobic fitness have been extensively studied and some exercise scientists have recommended similar training programs for young people. However, the subject of children and adolescents' responses to aerobic training 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 analyzed the procedures applied to protocol design and training methods to highlight the real impact of aerobic training on healthy children and adolescents' peakVO_2. 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 peakVO_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 peakVO_2 with training are discussed here. From 51 studies reviewed, 22 were finally retained. In most of the studies, there was a considerable lack of research papers 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 peakVO_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 analyzed to establish their respective potential influence on peakVO_2 changes. In general, aerobic training leads to a mean improvement of 5-6% in children or adolescents' peakVO_2. When only studies, which reported significant training effect, were taken into account, the mean improvement in peakVO_2 rose to 8-10%. Results suggested that intensities higher than 80% of maximal heart rate are necessary to expect a significant

improvement in peakVO_2. Finally, there is clearly a need for longitudinal or cross-sectional studies, which investigate the relationship between maturity and training with carefully monitored programs. Further research is also needed to compare interval training and continuous training.

1. Introduction

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 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 maximal oxygen uptake (VO_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 VO_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 VO_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 oxygen uptake achieved during a test to voluntary exhaustion as peak oxygen uptake (peakVO_2) rather than VO_2max, which implies that a plateau in VO_2 has been demonstrated.[10] However, many controversies exist between studies about the effects of training on children's peakVO_2. Longitudinal studies in children[11,12] have shown that training had no effect on peakVO_2 before puberty. This suggests that there is a maturational threshold below which children are not able to increase their peakVO_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. Thus, this review will examine how study design and training methods influence changes in peakVO_2, which result from aerobic exercise training in children and adolescents.

2. *Methodological considerations*

In accordance with previously published reviews on trainability in youngsters[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] studies with no peakVO_2 measurements.[24,40-46] From fifty-one studies, twenty-two were finally retained.[47-68] However, other factors such as maturity status, gender effect, group constitution, initial peakVO_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 studies validity. In the first part of the manuscript, each of these items is considered, and possible associations with changes in peakVO_2 from training are discussed.

2.1 *Maturity status*

Over the last twelve years, following recommendations provided in literature reviews,[16,18,69] children's maturity status has been assessed in most studies. However, of twenty-two papers reviewed, maturity status was reported in only eleven 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 subject's maturity status cannot be identified. One study compared the training responses of children and adolescents subjected to the same training program.[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 peakVO_2 relative to body mass, while significant improvement occurred in prepubertal and post-pubescent 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, in order to determine if there is a critical stage of maturity during which training enhances maximal gain in peakVO_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 to 14 years (mean age 12.4±1.9 years), were classified as circumpubertal. According to this classification, the number of studies in each subgroup is shown in table I.

When males and females were pooled, the average peakVO_2 improvement was 5.2% for prepubertal and 5.3% for circumpubertal subjects. However, as recommended by Rowland[13], when only studies showing significant improvements in peakVO_2 were included, the average improvement was 10.1% for prepubertal and 8.8% for circumpubertal individuals. According to gender, average improvements in peakVO_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%[72] or 10%[16], while a 14%[13] change was reported when only studies showing a significant increase in peakVO_2 were included. In prepubertal boys, peakVO_2 enhancement (6.1%) was slightly lower than that observed in the circumpubertal subjects (+7.6%). Nevertheless, the latter finding has to be interpreted with caution as prepubertal and circumpubertal males were not compared using the same training program, and only one study was conducted on circumpubertal males. Only one study has investigated adolescent girls.[65] In this study, no significant peakVO_2 improvement was reported. Any possible influence of maturity on peakVO_2 remains obscure, as few studies have compared response to training with regard to maturity status. There is a clear need to analyze the response of training of prepubertal and circumpubertal individuals when subjected to the same aerobic training program.

2.2 *Gender effect*

Six studies compared boys and girls.[47,59,60,64,67,68] In these studies, designed for prepubertal subjects, similar improvements in peakVO_2 were reported according to gender. Changes ranged from 0.7 to 19.4% in girls and were similar to those of boys, -1.6 to 20.5%, (table II). No study has been designed to compare the responses of adolescents according to gender. 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.

2.3 *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-randomized. When the authors failed to specify a random assignment, the studies were classified as non-random. According to this classification, the mean improvements in peakVO_2 according to group assignment are shown in table III. In both groups, similar improvements in peakVO_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 subjects 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.

Of the 22 studies listed, sample sizes ranged from 7 to 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.

2.4 Initial peakVO_2 and physical activity levels

Young people tend to have higher initial peakVO_2[73] and to be more physically active than adults[74]. A high initial peakVO_2 was proposed to explain no or lower changes in peakVO_2 in children after training compared with adults.[17] Table V shows the training induced changes in peakVO_2 as a function of initial peakVO_2. Circumpubertal males have a lower initial mean relative peakVO_2 level (39.0 $ml.kg^{-1}.min^{-1}$) than prepubertal ones (44.7 $ml.kg^{-1}.min^{-1}$). Only one study reported an initial peakVO_2 higher than 50 $ml.kg^{-1}.min^{-1}$ in girls.[62] In the different subgroups, significant improvements in peakVO_2 were observed. In prepubertal individuals with high initial aerobic fitness, the mean improvement in peakVO_2 (+2.7 %) was lower than for those with low initial aerobic fitness (+5.9 %). This result supports the results reported by Tolfrey et al.[64] and Mandigout et al.[67] The latter observed significant inverse relationships between differences in peakVO_2 and initial peakVO_2 values. However, the relationship accounted for only 9% of the variance in peakVO_2 over time.[64] Initial peakVO_2 seems to be related to the magnitude of the peakVO_2 differences induced by the training programs. It was not a major determinant, while for subjects with relatively low initial peakVO_2 (39.3 $ml.kg^{-1}.min^{-1}$) no significant improvement in peakVO_2 was found,[64] whereas significant improvement was observed in subjects with high pretraining peakVO_2 (55.9 $ml.kg^{-1}.min^{-1}$).[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 peakVO_2 values.[75,76] In adolescents, Rowland and Boyajian[59] reported a weak but significant relationship between the level of physical activity and percentage increase in peakVO_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 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.

2.5 Consistency between training and testing procedures

Differences in peak oxygen uptake 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 program and the testing procedure used the same mode of exercise, peakVO_2 improvement was found much higher than when different modes of exercise were achieved.[77-79] Two studies tested children on a cycle ergometer while they were trained in running[67,52] 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 peakVO_2 improvement. In the study by Williams et al.[66] a group trained continuously on a cycle ergometer and was tested on a motorized treadmill. In the study by Gilliam and Freedson,[52] the training was based on physical fitness program conducted during PE classes (mainly locomotor exercises) and peakVO_2 was measured on a cycle ergometer. In most of the studies reviewed, peakVO_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 in short duration (≤20s) shuttle running exercises and peakVO_2 was directly measured by use of a portable gas analyzer (K4b^2, Cosmed^R, Rome, Italy) during the 20-m shuttle run test.[80] These different results suggest that children's peakVO_2 improvement was higher when the testing mode was consistent with the training protocol.

2.6 *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 percentage of maximal heart rate (HRmax). If expressed as absolute value (beats per minute), it is assumed that a selected HR value represents the same intensity for all subjects. However, children are characterized by large interindividual variability in HRmax, and the same absolute HR may be associated with a great difference in percentage of HRmax. In most of the studies conducted in field conditions, the heart rate was not systematically monitored.[49,50,59-61,66,67] Some flaws in exercise intensity monitoring are also observed when HRmax is measured during a maximal exercise on a cycle ergometer and when exercise intensity is monitored for weight-bearing activities, such as HRmax measured during a cycle exercise is lower than that measured during a treadmill one.[81] 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 done by Savage et al.[54] children had to cover the same distance (from 2.4 to 4.8 km) 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 peakVO_2 to be elicited during a graded test,[82] could be calculated from physiologically determined parameters (peakVO_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.[83,84] The test is performed on a track marked with cones placed every 25 m. A pre-recorded soundtrack indicates with some brief sounds the instant when the subject 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 $km.h^{-1}$ and increased by 1 $km.h^{-1}$ per stage of 2 min. The test is finished when the subject is not able to maintain the imposed running speed. The speed at the last completed stage is kept as the MAV ($km.h^{-1}$). It is assumed that percentages of MAV are equivalent to percentages of peakVO_2. When exercises were proposed during time trials at relative velocities (%MAV), it was expected that all subjects perform the same relative exercise (intensity and duration), independently of their aerobic fitness level. Moreover, in contrast to heart rate, the MAV allows velocities at intensities near or higher than peakVO_2 to be carefully monitored.

Literature reviews showed that the range of differences in peakVO_2 between pre- and post-training values was rarely reported. Large interindividual differences between pre- and post-training peakVO_2, from –3% to +21%[59] or from -10 to +30%[67] were observed. These differences in the peakVO_2 training response may partly be explained by an inadequate exercise-training program 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 subject.

2.7 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 subjects or selecting highly motivated individuals does not provide an accurate representation of the impact of training.

2.8 *Summary*

Independently of gender or pubertal status, mean peakVO_2 improvement was around 5-6%. When only studies, which reported significant training effect, were taken into account, the mean improvement in peakVO_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 peakVO_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 peakVO_2 from training is compared to the approximately 5.6% day-to-day biological variations in peakVO_2 determination.[85]

3 Training design

The magnitude of peakVO_2 increase resulting from endurance training depends on the training programs used. Training design is determined by: exercise intensity and duration and recovery, length of the training program, frequency of sessions, or initial fitness.[86] 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 PE sessions[50,52,59,60,62,65,67].

3.1 Frequency and duration

The average frequency of the training protocol was 3-4 sessions per week (80 % of studies) with a range from 1 to 6 (table VIII). Only two sessions might be sufficient to increase peakVO_2.[68] In prepubertal and circumpubertal children, the gain in peakVO_2 was improved by increasing the number of sessions per week. With a comparable number of sessions per week, the variation in peakVO_2 was independent of pubertal status.

The duration of the sessions ranged from 5 min[51] to 90 min[67] (table IX). Eighteen studies had a session length inferior or equal to 30 min.[47-49,51,52,55-66,68] Three or four sessions from 30 min to one hour seemed to be the best option to improve peakVO_2. With a comparable session duration, the variation in peakVO_2 was independent of pubertal status. Both session frequency and session duration appears to be a key factor in training programs done on children.

3.2 Length of the program

The length of the training programs ranged from 4 weeks[55] to 18 months[63] (Table X). Sixteen studies lasted from one to three 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 program on peakVO_2 improvement. For example a 19% improvement of peakVO_2 wad observed with a 18-month program[63], while a 18% gain was found after a 4-week program.[55] Consequently, in the reviewed studies, the length of the programs does not appear to be a decisive factor in obtaining a significant gain in peakVO_2.

3.3 Intensity

The protocols addressing the trainability of children and adolescents are mainly based on continuous exercises at intensities lower than those associated with peakVO_2.[48,50-54,57-66] In these studies were included those that were based on PE 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 to peakVO_2[47,49,55,61,66,68]. In two studies the training program consisted in continuous and intermittent exercises[56,67] In most studies, exercise intensity of exercise is commonly defined in terms of percentages of HRmax. Table XI shows that for a same relative training intensity circumpubertal demonstrated higher changes in peakVO_2 than prepubertal. For prepubertal, compared to continuous or intermittent exercises, all-out exercises lead to higher peakVO_2 improvements.

3.3.1 Continuous training

Of sixteen studies including continuous exercises, nine reported a significant increase in peakVO_2.[48,50,53,54,57-59,61,63] When intensity was lower or equal to 80%HRmax[48,52,54,57,58,62-65] peakVO_2 was improved in only three studies[57,58,63]. In the two studies by Yoshizawa et al.[57,63] on 4-6 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 peakVO_2[57] or a 19.4% increase.[63] In the latter study, a significant rise (+8.2%) in peakVO_2 was also observed in the control group. These results, obtained on very young children, are somewhat surprising, and may challenge the study validity. In the study, by Rowland et al.[58], the initial peakVO_2 of the circumpubertal was very low (30.3 $ml.kg^{-1}.min^{-1}$) which may explain why a low training stimulus (<80% HRmax) induce a significant improvement in peakVO_2. In two studies, subjects were submitted to the same training program carried out at different training intensities.[48,54] In these studies, only children involved in the high intensity training groups demonstrated significant improvement in peakVO_2. Massicotte and McNab[48] compared children who trained 12-min, 3 times a week for 6 weeks at 66-72%, 75-80% or 88-93% HRmax. Only the group who trained at 88-93% HRmax (170-180 bpm) significantly improved peakVO_2. Savage et al.[54] observed a significant increase in the children who trained at 85% of HRmax, while no significant change was found when training intensity represented 70% of HRmax. With intensities between 80 and 100% of HRmax, most studies[48,50,53,54,59,61] reported a significant improvement in peakVO_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 program was 14 weeks, but these durations included holiday's periods, that ranged from one to three months. The inclusion of long detraining period (holidays) in the training program may explain why no significant change in peakVO_2 was observed. Williams et al.[66], reported a 5.1% non significant improvement in peak VO_2, with exercises intensities close to 80% of HR max (a mean intensity of 160-170 $beat.min^{-1}$ for children with HRmax equal to 204 $beats.min^{-1}$). With a same training protocol, Mc Manus et al.[61] showed that girls with lower initial peakVO_2 (45 $ml.kg^{-1}.min^{-1}$) showed a significant improvement in peakVO_2 (7.2%).

In both children and adolescents, intensity higher than 80% of HRmax 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 program.[64] However, this is difficult goal to obtain in a school context and might explain that often no improvement in peakVO_2 was found, even if additional physical education sessions have been added.[87,88] Indeed, Stratton (1996)[89] observed that in most physical education sessions subjects failed to achieve elicits heart rate at a sufficient level to achieve the ACSM[90] guidelines in terms of intensity. This underlines the necessity to intensify school-based intervention programs.[91]

3.3.2 Interval training

All studies with intermittent exercises were conducted on prepubertal children. In three studies peakVO_2 was improved[55,61,68], while in the other non significant improvement was obtained[47,49,66]. Stewart and Gutin[49] failed to obtain significant improvement in peakVO_2 with a protocol which was based on a 5 min run as a warm-up, immediately followed by 3 series of 3 min at a paced velocity (90% HRmax) or "all-out" running with 1 min 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 peakVO_2. Bar-Or and Zwiren[47] also reported no improvement in schoolchildren’s peakVO_2 when children performed 145-m all out runs. In this study the children performed about six 145-m run in 40 s at the beginning of the training program, while eight to ten runs were performed in 35 s during the last session. In this study, the results of children who had 2, 3 or 4 sessions a week were pooled, which may induce several biases. When monitoring children’s physical activity patterns, Bailey et al.[92] reported that only 5% of their high intensity activities (i.e.: activities that elicited a VO_2 value higher than 24.5 $ml.kg^{-1}.min^{-1}$ or higher than lactic acidosis threshold) lasted more than 15s. Recent papers have tried to include such types of exercises in children's training programs.[61,66,68] Baquet et al.[68] showed that the compromise between short bursts of exercise (10s or 20s) and short periods of recovery (10s or 20s), allowed subjects to elicit a high level of peakVO_2 (from 66 to 78% of VO_2 between set 1 and set 5) and finally to reach peakVO_2. As for continuous running, the repetition of short bouts of exercise at high intensities (near or higher than peakVO_2), alternated with a short recovery time, allows subjects to reach high level of VO_2 and even to elicit peakVO_2.[68,93] After 7 weeks of such exercises, Baquet et al.[68] reported a significant improvement (8.2%) in peakVO_2. With "all out" runs of short duration (10s and 30s), Williams et al.[66] failed to improve boys' peakVO_2, while McManus et al.[61] demonstrated a significant improvement with an identical training protocol conducted on girls. A higher initial peakVO_2 in boys than in girls (55 versus 48 $ml.kg^{-1}.min^{-1}$, respectively) could partly explain these conflicting results. Finally, with the repetition of 20s "all-out" isokinetic exercises at low resistance-high velocity or high resistance-low velocity, Docherty et al.[55] obtained significant improvements in peakVO_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 peakVO_2. However, the impact of the exercises modes depends on many parameters (exercise intensity, exercise duration, recovery intensity, recovery duration, number of sets, number of series) that have to be precisely specified.

3.3.3 Mixed training

Two studies[56,67] included mixed training (continuous and intermittent exercises) at a mean intensity higher than 80 %HRmax. Mandigout et al.[67] reported significant improvements in peakVO_2, 8.5% and 4.2% in girls and boys, respectively. In this study, children had one continuous session (15-20 min, 1500-4500m at 90 %HRmax), one session (from 1h to 1h30) dedicated to aerobic activities (soccer, swimming, basketball) and intermittent exercises (10x10m, 6x200m, 4x600m at 80%HRmax). In adolescents, Mahon and Vaccaro[56] reported a mean improvement of 7.6% in peakVO_2 with 2 sessions of continuous exercises (20-30min at

70-80 %HRmax) and 2 sessions of intermittent exercises (100-200-800 m at intensities higher than 90%peakVO_2). However, with a mixed program the real impact of each exercise on peakVO_2 improvement cannot be identified accurately.

3.4 Summary

Significant improvements in peakVO_2 were reported independently of training frequency, duration and training 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 HRmax is needed to obtain significant increase in peakVO_2.

4. Conclusions

This review of factors influencing aerobic trainability during growth and development is an update of a quite similar assessment of this issue performed by Pate and Ward in 1990[16]. Since the last decade, most of the training studies observed their recommendations[18] experiment designs. In the literature, the trainability of prepubertal children has been studied more often than circumpubertals (19 *vs* 3 studies). Aerobic training leads to a mean improvement of 5-6% in children or adolescents' peakVO_2. When only studies that reported significant training effect were taken into account, the mean improvement in peakVO_2 rose to 8-10%. However, this expected improvement in young people remained lower than that generally reported for adults.[86] 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 HRmax, while training effects are assessed though peakVO_2 measurement. To analyze the effects of training on

$peakVO_2$, 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, which investigate the relationship between maturity and training with carefully monitored programs

References

1. Andersen LB, Haraldsdottir J. Changes in CHD risk factors with age: a comparison of Danish adolescents and adults. Med Sci Sports Exerc 1994; 26: 967-72

2 Malina RM, Beunen GP, Claessens AL, et al. Fatness and physical fitness of girls 7 to 17 years. Obes Res 1995; 3: 221-31

3. Bell RD, Macek M, Rutenfranz J, et al. Health indicators and risk factors of cardiovascular diseases during childhood and adolescence. In: Rutenfranz J, Mocellin R, Klimt F, editors. Children and exercise XII. Champaign (Ill): Human Kinetics: 1986

4 Telama R, Yang X, Laasko L, et al. Physical activity in childhood and adolescence as predictor of physical activity in young adulthood. Am J Prev Med 1997; 14: 317-23

5. Trudeau F, Laurencelle L, Tremblay J, et al. A long-term follow-up of participants in the Trois-Rivières semi-longitudinal study of growth and development. Ped Exerc Sci 1998; 10: 366-77

6. Janz KF, Dawson JD, Mahoney LT. Increase in physical fitness during childhood improves cardiovascular health during adolescence: the Muscatine study. Int J Sports Med 2002; 23: S15-S21

7. Cunningham DA, Van Waterschoot BM, Paterson DH, et al. Reliability and reproducibility of maximal oxygen uptake measurement in children. Med Sci Sports Exerc 1977; 9: 104-8

8. Rowland TW, Cunningham LN. Oxygen uptake plateau during maximal treadmill exercise in children. Chest 1992; 101: 485-9

9. Rivera-Brown AM, Rivera MA, Frontera WR. Reliability of VO_2max in adolescent runners: a comparison between plateau achievers and nonachievers. Ped Exerc Sci 1995; 7: 203-10

10. Armstrong N, Welsman J. Assessment and interpretation of aerobic fitness in children and adolescents. Exerc Sports Sci Rev 1994; 22: 435-76

11. Kobayashi K, Kitamura K, Miura M, et al. Aerobic power as related to body growth and training in Japanese boys: a longitudinal study J Appl Physiol 1978; 44: 666-72

12. Mirwald RL, Bailey D, Cameron N, et al. Longitudinal comparison of aerobic power in active and inactive boys aged 7.0 to 17.0 years. Ann Hum Biol 1981; 8: 405-14

13. Rowland TW. Aerobic response to endurance training in prepubescent children: a critical analysis. Med Sci Sports Exerc 1985; 17: 493-7

14. Sady SP. Cardiorespiratory exercise training in children. Clinics in Sports Med 1986; 5(3): 493-514

15. Vaccaro P, Mahon A. Cardiorespiratory responses to endurance training in children. Sports Med 1987; 4: 352-63

16. Pate RP, Ward DS. Endurance exercise trainability in children an youth. In Garcia WA, Lombardo JA, Stone JA, editors. Advanced in Sports Medicine and Fitness. Chicago year book Medical Publishers, 1990: 3, 37-55

17. Shephard RJ. Effectiveness of training programmes for prepubescent children. Sports Med 1992; 13(3): 194-213

18. Pate RR, Ward DS. Endurance trainability of children and youths. In: Bar-Or O (ed). The child and the adolescent athlete. Oxford: Blackwell Sciences, 1996: 130-137

19. Payne VG, Morrow JR. Exercise and VO_2max in children: A meta-analysis. Res Q Exerc Sport 1993; 64: 305-13

20. Cumming GR, Goulding D, Baggley G. Failure of school physical education to improve cardiorespiratory fitness. Can Med Ass J 1969; 101: 69-73

21. Daniels J, Oldridge N. Changes in oxygen consumption of young boys during growth and running training. Med Sci Sports 1971; 3: 161-5

22. Koch G, Eriksson BO. Effect of physical training on pulmonary ventilation and gas exchange during submaximal and maximal work in boys. Scand J Clin Lab Invest 1973; 31: 88-94

23. Mocellin R, Wasmund U. Investigation of the influence of a running-training program on the cardiovascular and motor performance capacity in 53 boys and girls of a second and third primary school class. Pediatric Work Physiology. Proc. 4th Symposium Wingate Institute, Israel 1973; 279-88

24 . Fournier M, Ricci J, Taylor AW, et al. Skeletal muscle adaptation in adolescent boys: sprint and endurance training and detraining. Med Sci Sports Exerc 1982; 14: 453-6

25. Benedict GJ, Vaccaro P, Hatfield BD. Physiological effects of an eight week precision jump rope program in children Am Cor Therapy Journal 1985; 39: 108-11

26. Haffor AA, Harrison AC, Catledge-Kirk PA. Anaerobic threshold alterations caused by interval training in 11-year-olds. J Sports Med Phys Fitness 1990; 30(1): 53-6

27. Eisenman PA, Golding LA. Comparison of effects of training on VO_2max in girls and young women. Med Sci Sports 1975; 7: 136-8

28. Stransky AW, Mickelson RJ, VanFleet C, et al. Effects of a swimming regimen on haematological cardiorespiratory and body composition changes in young females. J Sports Med Phys Fitness 1979; 19: 347-54

29. Rotstein A, Dotan R, Bar-Or O, et al. Effect of training on anaerobic threshold, maximal aerobic power and anaerobic performance of preadolescent boys. Int J Sports Med 1986; 7(5): 281-6

30. Mero A, Kauhanen H, Peltola E, et al. Physiological performance capacity in different prepubescent athletic groups. J Sports Med Phys Fitness 1990; 30: 57-66

31. Ekblom B. Effect of physical training in adolescent boys. J Appl Physiol 1969; 27: 350-5

32. Klissouras V, Weber G. Training, growth and heredity. In: Bar-Or O, editor. Pediatric Work Physiology. Proceedings of the Fourth International Symposium; 1973; Tel-Aviv. Technodaf 1973: 338-44

33. Weber G, Kartodihardjo W, Klissouras V. Growth and physical training with reference to heredity. J Appl Physiol 1976; 40: 211-5

34. Brown CH, Harrower JR, Deeter MF. The effects of cross-country running on preadolescent girls. Med Sci Sports 1972; 4: 1-5

35. Vaccaro P, Clarke DH. Cardiorespiratory alterations in 9 to 11 year-old children following a season of competitive swimming. Med Sci Sports Exerc 1978; 10: 204-7

36. Sundberg S, Elovainio R. Cardiorespiratory function in competitive endurance runners aged 12-16 years compared with ordinary boys. Acta Paediatr Scand 1982; 71(6): 987-92

37. Hagberg JM, Goldring D, Ehsani AA, et al. Effect of exercise training on the blood pressure and hemodynamic features of hypertensive adolescents. Am J Cardiol 1983; 52: 763-8

38. Conn CA, Schemmel RA, Smith BW, et al. Plasma and erythrocyte magnesium concentrations and correlations with maximum oxygen consumption in nine- to twelve-year-old competitive swimmers. Magnesium 1988; 7: 27-36

39. Obert P, Courteix D, Blonc S, et al. Evaluation de l'effet d'une pratique sportive intensive sur le potentiel aérobie de la fille prépubère: nécessité d'une spécificité de l'épreuve de laboratoire. Sci Sports 1996; 11: 113-9

40. Gatch W, Byrd R. Endurance training and cardiovascular function in 9- and 10-year-old boys. Arch Phys Med Rehabil 1979; 60: 574-7

41. Adeniran SA, Toriola AL. Effects of continuous and interval running programmes on aerobic and anaerobic capacities in schoolgirls aged 13 to 17 years. J Sports Med Phys Fitness 1988; 28: 260-6

42. Zakas A, Mandroukas K, Karamouzis M, et al. Physical training, growth hormone and testosterone levels and blood pressure in prepubertal, pubertal and adolescent boys. Scand J Med Sci Sports 1994; 4: 113-8

43. Blessing DL, Keith RE, Williford HN, et al. Blood lipid and physiological responses to endurance training in adolescents. Ped Exerc Sci 1995; 7: 192-202

44. Berthoin S, Mantéca F, Lensel-Corbeil G, et al. Effect of a 12-week training programme on maximal aerobic speed (MAS) and running time to exhaustion at 100% of MAS in school students aged 14 to 17-years. J Sports Med Phys Fitness 1995; 35: 251-6

45. Obert P, Mandigout S, Vinet A, et al. Effect of aerobic training and detraining on left ventricular dimensions and diastolic function in prepubertal boys and girls. Int J Sports Med 2001; 22: 90-6

46. Baquet G, Berthoin S, Van Praagh E. High-intensity aerobic training during a 10 week one-hour physical education cycle: effects on physical fitness of adolescents aged 11 to 16. Int J Sports Med 2001; 22: 295-300

47. Bar-Or O, Zwiren L. Physiological effects of increased frequency of physical education classes and of endurance conditioning on 9 to 10 year-old girls and boys. In Bar-Or O, Editor. Pediatric Work Physiology IV; 1973; Wingate Institute: Natanya, Israel. 1973: 190-208

48. Massicotte DR, Macnab RB. Cardiorespiratory adaptations to training at specified intensities in children. Med Sci Sports 1974; 6(4): 242-6

49. Stewart KJ, Gutin B. Effects of physical training on cardiorespiratory fitness in children. Res Quart 1976; 47(1): 110-20

50. Lussier L, Buskirk ER. Effects of an endurance training regimen on assessment of work capacity in prepubertal children. Ann N Y Acad Sci 1977; 30: 734-47

51. Yoshida T, Ishiko I, Muraoka I. Effect of endurance training on cardiorespiratory functions of 5-year-old children. Int J Sports Med 1980; 1: 91-4

52. Gilliam TB, Freedson PS. Effects of a 12 week school physical fitness program on peakVO_2, body composition and blood lipids in 7 to 9 year old children. Int J Sports Med 1980; 1: 73-8

53. Becker DM, Vaccaro P. Anaerobic threshold alterations caused by endurance training in young children. J Sports Med 1983; 23: 445-9

54. Savage MP, Petratis M, Thomson WH. Exercise training effects on serum lipids of prepubertal boys and adults men. Med Sci Sports Exerc 1986; 18: 197-204

55. Docherty D, Wenger HA, Collis ML. The effects of resistance training on aerobic and anaerobic power of young boys. Med Sci Sports Exerc 1987; 19: 389-92

56. Mahon AD, Vaccaro P. Ventilatory threshold and VO_2max changes in children following endurance training. Med Sci Sports Exerc 1989; 21: 425-31

57. Yoshizawa S, Honda H, Urushibara M, et al. Effects of endurance run on circulorespiratory system in young children. J Hum Ergol 1990; 19: 41-52

58. Rowland TW, Varzeas MR, Walsh CA. Aerobic responses to walking training in sedentary adolescents. J Adolescent Health 1991; 12(1): 30-4

59. Rowland TW, Boyajian A. Aerobic response to endurance training in children. Pediatrics 1995; 96(4): 654-8

60. Rowland TW, Martel L, Vanderburgh P, et al. The influence of short-term aerobic training on blood lipids in healthy 10-12 year old children. Int J Sports Med 1996; 17(7): 487-92

61. McManus, Armstrong N, Williams CA. Effect of training on the aerobic power and anaerobic performance of prepubertal girls. Acta Paediatr 1997; 86: 456-9

62. Welsman JR, Armstrong N, Withers S. Responses of young girls to two modes of aerobic training. Br J Sports Med 1997; 31: 139-42

63. Yoshizawa S, Honda H, Nakamura N, et al. Effects of an 18-month endurance run training program on maximal aerobic power in 4- to 6-year-old girls. Ped Exerc Sci 1997; 9: 33-43

64. Tolfrey K, Campbell IG, Batterham AM. Aerobic trainability of prepubertal boys and girls. Ped Exerc Sci 1998; 10: 248-63

65. Stoedefalke K, Armstrong N, Kirby BJ, et al. Effect of training on peak oxygen uptake and blood lipids in 13 to 14-year-old girls. Acta Paediatr 2000; 89: 1290-4

66. Williams CA, Armstrong N, Powell J. Aerobic responses of prepubertal boys to two modes of training. Br J Sports Med 2000; 34: 168-73

67. Mandigout S, Lecoq AM, Courteix D, et al. Effect of gender in response to an aerobic training programme in prepubertal children. Acta Paediatr 2001; 90: 9-15

68. Baquet G, Berthoin S, Dupont G, et al. Effects of high intensity intermittent training on peak VO_2 in prepubertal children. Int J Sports Med 2002; 23: 439-44

69. LeMura LM, Von Duvillard SP, Carlonas R, et al. Can exercise training improve maximal aerobic power (VO_2max) in children: a meta-analytic review. J Exerc Physiol (on line) 1999; 2(3): 1-22

70. Naughton G, Farpour-Lambert NJ, Carlson J, et al. Physiological issues surrounding the performance of adolescent athletes. Sports Med 2000; 30: 309-25

71. Kemper HCG, Van de Kop H. Entraînement de la puissance maximale aérobie chez les enfants prépubères et pubères. Sci Sports 1995; 10: 29-38

72. Payne VG and Morrow RJ. Exercise and VO_2max in children: a meta-analysis. Res Q Exerc Sport 1993;64: 305-13

73. Rowland TW. Developmental aspects of physiological function relating to aerobic exercise in children. Sports Med 1990; 10: 255-66

74. Siegel PZ, Brackbill RM, Frazier EL, et al. Behavioral risk surveillance, 1986-1990. Morbid. Mortal. Weekly Rep 1991; 40: 1-22

75. Armstrong N, Kirby BJ, McManus AM. Aerobic fitness of prepubescent children. Ann Hum Biol 1995; 22: 427-44

76. Falgairette G, Duché P, Bedu M et al. Bioenergetic characteristics in prepubertal swimmers. Comparison with active and non-active boys. In J Sports Med 1993; 14: 444-8

77. Magel JR, Foglia GF, McArdle WD, et al. Specificity of swim training on maximum oxygen uptake. J Appl Physiol 1975; 38: 151-5

78. McArdle WD, Magel JR, Delio DJ, et al. Specificity of run training on VO2 max and heart rate changes during running and swimming. Med Sci Sports 1978; 10(1): 16-20

79. Gergley TJ, McArdle WD, Dejesus P, et al. Specificity of arm training on aerobic power during swimming and running. Med Sci Sports Exerc 1984; 19: 49-54

80. Léger L, D Mercier, C Gadoury, et al. The multistage 20 metre shuttle run test for aerobic fitness. J Sports Sci 1988; 6: 93-101

81. Turley KR, Wilmore JH. Cardiovascular responses to treadmill and cycle ergometer exercise in children and adults. J Appl Physiol 1997; 83: 948-57

82. Billat V, Koralsztein JP. Significance of the velocity at VO_2max and time to exhaustion at this velocity. Sports Med 1996; 22: 90-108

83. Léger L, Boucher R. An indirect continuous running multistage field test: the Université de Montréal Track Test. Can J Appl Spt Sci 1980; 5: 77-84

84. Berthoin S, Baquet G, Rabita J, et al. Validity of the Université de Montreal Track Test to assess the velocity associated with peak oxygen uptake for adolescents. J Sports Med Phys Fitness 1999; 39: 107-12

85. Katch VL, Sady SS, Freedson P. Biological variability in maximum aerobic power. Med Sci Sports Exerc 1982; 14: 21-5

86. Wenger HA, Bell GJ. The interactions of intensity, frequency and duration of exercise training altering cardiorespiratory fitness. Sports Med 1986; 3: 346-56

87. Kemper HCG, Verschuur R, Ras KGA, et al. Effect of 5-versus 3-lessons-a-week physical education program upon physical development of 12 and 13-year old schoolboys. J Sports Med Phys Fitness 1976; 16(4): 319-26

88. Klausen K, Rasmussen B. Effect of five physical education lessons a week on some anthropometric and physiological variables in school children. In: Telama R et al., editors. Research in school physical education. The proceedings of the International Symposium on Research in School Physical Education; 1982 Nov 18-21; Jyvaskyla, Finland. Foundation for Promotion of Physical Culture and Health 1983: 203-9

89. Stratton G. Children's heart rate during physical education lessons: a review. Ped Exerc Sci 1996; 8: 215-33

90. American College of Sports Medicine. ACSM's guidelines for exercise testing and prescription. Baltimore: Williams and Wilkins, 1995

91. Baquet G, Berthoin S, VanPraagh E. Are intensified Physical Education sessions able to elicit heart rate at a sufficient level to promote adolescents physical fitness. Res Q Exerc Sport. 2002; 73(3): 282-8

92. Bailey RC, Olson J, Pepper SL, et al. The level and tempo of children’s physical activities: an observation study. Med Sci Sports Exerc 1995; 27: 1033-41

93. Dupont G, Blondel N, Lensel G, et al. Critical velocity and time spent at VO_2max for short intermittent runs at supramaximal velocities. Can J Appl Physiol 2002; 27(2): 103-15

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
Males	< 13 years-old	13-18 years-old
Studies number	11	1
[References]	[47-49,53-55,57,60,64,66,67]	[56]
Females	< 11 years-old	11-16 years-old
Studies number	7	1
[References]	[47,60-64,67]	[65]
Mixed		
Studies number	5	1
[References]	[50-52,59,68]	[58]

Table II. Peak oxygen uptake difference ($\Delta peakVO_2$) in boys, girls and mixed populations (boys and girls) according to pubertal status.

		Prepubertal	Circumpubertal
	$\Delta peakVO_2$ (%)	6.1	7.6
Males	(range)	(-1.6 to 20.5)	
	[References]	[47-49,53-55,57,60,64,66,67]	[56]
Females	$\Delta peakVO_2$ (%)	6.9	-1.5
	(range)	(0.7 to 19.4)	
	[References]	[47,60-64,67]	[65]
Mixed	$\Delta peakVO_2$ (%)	1.5	9.9
	(range)	(-7.6 to 8.2)	
	[References]	[50-52,59,68]	[58]

Table III. Peak oxygen uptake difference ($\Delta peakVO_2$) according to pubertal status and subject assignment.

Status		Random assignment	Non-random assignment
Prepubertal	$\Delta peakVO_2$(%)	5.0	5.3
	(range)	(-1.6 to 20.5)	(-7.6 to 19.4)
	[references]	[47,53,54,61,62,66,68]	[48-51,53,55,57,59,60,63,64]
Circumpubertal	$\Delta peakVO_2$ (%)		5.3
	(range)		(-1.5 to 9.9)
	[references]		[56,58,65]

Table IV. Sample size in studies reviewed.

	Sample size			
	<11	11≤ x≤ 20	21≤ x≤ 30	31≤ x≤ 40
Experimental group [references]	5 [48,54-56,63]	13 [49,50,52,58,60-62,64,65,67]	2 [47,51]	2 [59,68]
Control group [references]	8 [48,50,54-56,61,63,64]	11 [49,51-53,55,58,60,62,65,66,68]	2 [47,67]	1 [59]

Table V. Average initial peak oxygen uptake (peakVO_2) and peak oxygen uptake difference (ΔpeakVO_2) according to pubertal status and initial peakVO_2

		Initial peakVO_2	
		<50 $ml.kg^{-1}.min^{-1}$	≥50 $ml.kg^{-1}.min^{-1}$
Prepubertal	peakVO_2 ($ml.kg^{-1}.min^{-1}$)	44.7	53.6
	ΔpeakVO_2 (%)	5.9	2.7
	(range)	(-7.6 to 20.5)	(-1.6 to 6.8)
	[References]	[47-49,51-53,55,57,59-64,67,68]	[47,50,54,62,66]
Circumpubertal	peakVO_2 ($ml.kg^{-1}.min^{-1}$)	39.0	
	ΔpeakVO_2 (%)	5.3	
	(range)	(-1.5 to 9.9)	
	[References]	[56,58,65]	

Table VI. Differences in peak oxygen uptake (ΔpeakVO₂) according to pubertal status and consistency between training and testing procedures.

		Consistency between training and testing	No consistency between training and testing
Prepubertal	ΔpeakVO_2 (%)	5.7	3.0
	(range)	(-7.6 to 20.5)	(-1.6 to 8.5)
	[References]	[47-51,53-55,57,59-64,66,68]	[52,61,62,66,67]
Circumpubertal	ΔpeakVO_2 (%)	5.3	
	(range)	(-1.5 to 9.9)	
	[References]	[56,58,65]	

Table VII. Effects of training on peakVO$_2$ in during prepubertal and circumpubertal periods. Studies are classified by chronological order

Study	Sex	Age	N	Pubertal Status (P/A)	Exercise	Length	Intensity	Frequency (n/wk)	Duration	Test	VO$_2$ (ml.kg^{-1}.r pre/post/
Bar-Or and Zwiren [47]	M F	9-10 9-10	22 24	P P	Interval running	9 weeks	All-out	2-4	20-25 min, 145m with 1.5 min recovery between each repetition	T	50.2/49.4 44.2/46.1
	M F	9-10 9-10	22 24	P P	Control group				Calisthenics and games		50/49.3/ 45/43.8/
Massicotte and Mac Nab[48]	M	11-13	9	P	Cycling	6 weeks	88-93% HRmax	3	12min	E	46.7/51.8/-
	M	11-13	9	P			75-80% HRmax				47.4/48/-
	M	11-13	9	P			66-72% HRmax				46.6/48.2
	M	11-13	9	P	Control group						45.7/44.2
Stewart and Gutin[49]	M	10-12	13	P	Interval running	8 weeks	90% HRmax	4	5*1min and 3*3min paced or all out runs with 1min recovery between each repetition	T	49.8/49.5
	M	10-12	11	P	Control group						48.4/49.2
Lussier and Burskirk[50]	MF	10.3	16	P	Continuous running and various activities	12 weeks	92% HRmax	2 2	10 to 35min 45min	T	55.6/59.4/
	MF	10.5	10	P	Control group						53.1/53.9

Yoshida et al.[51]	MF	5	21	P	Distance training 750 to 1500 m	7 months	94% HRmax	1	5-10 min	T	43.5/44.3/+1.8
	MF	5	25	P				5			42.1/42.8/+1.7
	MF	5	11	P	Control group						41.6/45.1/+8.4
	MF	5	21	P	Distance training 750 to 1500 m	14 months		1			43.5/41.6/-4.4
	MF	5	25	P				5			42.1/38.9/-7.6
	MF	5	11	P	Control group						41.6/42.8/+2.9
Gilliam and Freedson[52]	MF	8.5	11	P	PE lessons	12 weeks	78% HRmax	4	25min	E	43.4/42.9/-1.2
	MF	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 weeks	85% HRmax	3	40min	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 weeks	68% HRmax	5	From 2.4 to 4.8 km per time	T	52.2/54.6/+4.6
	M	8	12	P			85% HRmax				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 weeks	High velocity/low resistance (180°.s^{-1})	3	2 sets of 20s all-out effort with 20s rest (5min rest between each set)	E	46.2/54.7/+18.4*
	M	12.4	12	P			Low velocity/high resistance (30°.s^{-1})				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 weeks	80-95% HRmax	2 + 2	20-30 min 100 to 800m (from 1.5 to 2.5 km)	T	45.9/49.4/+7.6*
	M	12.3	8	C	Control group						45.4/45.9/+1.1
Yoshizawa et al.[57]	M	5 to 6	12	P	Running endurance	6 months	117-157 $m.min^{-1}$ (<80% HRmax)	6	One run of 915m	T	47.6/50.4/+5.9*
	M	5 to 6	12	P	Control group						
Rowland et al.[58]	MF	15.7	15	C	Walking	11 weeks	80 % HRmax	3	30 (1.8 mile)	T	30.3/33.3/+9.9*
	MF	15.7	15	C	Control group						30.7/30.3/-1.3
Rowland and Boyajia[59]	MF	10.9 to 12.8	13 24	P	Circuit training Distance running or walking Aerobic games	12 weeks	80-85% HRmax	3	20 to 30 min	T	44.7/47.6/+6.5*
	MF		13 24	P	Control group						44.3/44.7/+0.9
Rowland et al.[60]	M F	10.9 to 12.9	14 20	P	Aerobic dance, step aerobics, distance running and circuit activities	13 weeks	87.5 % HRmax	3	30 min	T	45.4/48.2/+6.1 43.9/46.1/+5
	M F		14 20		Control group						45.3/45.4/+0.2 43.7/43.9/+0.4

McManus et al.[61]	F	9.3	12	P	Cycle ergometer	8 weeks	80-85 %HRmax	3	20min	T	45/48.5/+7.2*
	F	9.8	11	P	Sprint running		All-out		3*10s with 30s rest and 3*30s with 90s 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 weeks	80 %HRmax	3	20min	T	51.8/52.2/+0.7
	F	9-10	17		Aerobics		75-80 %HRmax		20-25min		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	18 months	117-157 $m.min^{-1}$ (<80% HRmax)	6	One run of 915m	T	42.2/50.4/+19.4*
	F	4	8	P	Control group						42.4/45.9/+8.2*
Tolfrey et al. [64]	M F	10,6 10,6	12 14	P P	Continuous cycle training	12weeks	80 % HRmax	3	30 min	E	46.6/47.2/+1.3 39.3/42.3/+7.9
	M F	10,3 10,5	10 9	P P	Control group						50.7/50.3/-0.7 44.7/40.3/-3.8
Stoedefalke et al.[65]	F	13 to 14	20	C	Treadmill running, cycle and rowing ergometry, stair stepping	20 weeks	75-85 % HRmax	3	20 min	T	40.8/40.2/-1.5
	F	13 to 14	18	C	Control group						41.9/41.4/-1.3%

Williams et al.[66]	M	10.1	12	P	Sprint running	8 weeks	All-out	3	3*10s with 30s rest and 3*30s with 90s rest	T	54.8/53.9/-1.6
	M		13	P	Continuous cycle training		80-85 % HRmax		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 weeks	80-90 % HRmax	3	60 to 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]	MF	9.5	33	P	Interval running	7 weeks	80-95% HRmax	2	5 sets of 10*10s of run (30 min)	FT ($K4b_2$)	43.9/47.5/+8.2*
	MF	9.9	20	P	Control group						46.2/45.3/-1.9

M: males; F: females; MF: males and females; P; prepubertal subjects; C: circumpubertal subjects; HRmax: maximal heart rate; T: treadmill; C: cycle ergometer; FT: field test; $K4b_2$: Cosmed $K4b_2$ gas analyzer; PeakVO_2: maximal oxygen uptake.

Supprimé: ¶
¶
¶

Table VIII. Difference in peak oxygen uptake ($\Delta peakVO_2$) according to pubertal status and sessions frequency.

		Sessions frequency		
		< 3 sessions	3≤ and ≤ 4	> 4 sessions
Prepubertal	$\Delta peakVO_2$ (%)	0.8	5.7	5.3
	(range)	(-7.6 to 8.2)	(-1.6 to 20.5)	(-4.4 to 19.4)
	[References]	[51,68]	[47-50,52,53,55,59-62, 64,66,67]	[51,54,57,63]
Circumpubertal	$\Delta peakVO_2$ (%)		5.3	
	(range)		(-1,5 to 9.9)	
	[References]		[56,58,65]	

Table IX. Difference in peak oxygen uptake ($\Delta peakVO_2$) according to pubertal status and session duration.

		Session duration	
		≤ 30 min	> 30 min
Prepubertal	$\Delta peakVO_2$ (%)	4.5	8.2
	(range)	(-7.6 to 19.4)	(4.2 to 20.5)
	[References]	[47-49,51,52,55,57,59-63,64,66,68]	[50,53,54,67]
Circumpubertal	$\Delta peakVO_2$ (%)	5.3	
	(range)	(-1.5 to 9.9)	
	[References]	[56,58,65]	

Table X. Peak oxygen uptake difference ($\Delta peakVO_2$) according to pubertal status and session program duration

		Program duration	
		≤ 6 months	> 6 months
Prepubertal	$\Delta peakVO_2$ (%)	5.7	2.8
	(range)	(-1.6 to 20.5)	(-7.6 to 19.4)
	[References]	[47-50,52-55,59-62,64,66-68]	[51,57,63]
Circumpubertal	$\Delta peakVO_2$ (%)	5.3	
	(range)	(-1.5 to 9.9)	
	[References]	[56,58,65]	

Table XI. Difference in peak oxygen uptake ($\Delta peakVO_2$) according to pubertal status and exercise training intensity.

		≤80% of HRmax	Between 81 and 100%of HRmax	All-out or sprint
Prepubertal	$\Delta peakVO_2$(%)	4.5	4.7	7.8
	(range)	(-1.2 to 19.4)	(-7.6 to 20.5)	(-1.6 to 17.2)
	[References]	[48,52,54,57,62-64]	[48-51,53,54,59-61,66-68]	[47,55,61,66]
Circumpubertal	$\Delta peakVO_2$(%)	4.2	7.6	
	(range)	(-1.5 to 9.9)	(7.6)	
	[References]	[58,65]	[56]	