

YOUTH SPORTS PARTICIPATION, TRAINABILITY AND READINESS

MANUEL J. COELHO E SILVA
ANTÓNIO J. FIGUEIREDO
MARIJE T. ELFERINK-GEMSER
ROBERT M. MALINA
EDITORS

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CHAPTER 10: TRAINABILITY OF VO_2max DURING CHILDHOOD AND ADOLESCENCE

Adriaan J Helmantel
Marije T Elferink-Gemser
Chris Visscher

INTRODUCTION

VO_2max develops just like other processes related to growth and maturation during childhood and adolescence. Longitudinal studies show an increase of absolute and relative VO_2max . Absolute VO_2max of untrained children and adolescents increases from about 1.0 l/min at the age of 6 to 2.0 and 2.8 l/min at the age of 15 for girls and boys, respectively. After this age, improvement of untrained boys continues, while VO_2max of untrained girls reaches a plateau (Krahenbuhl et al., 1985). VO_2max relative to body mass shows a different pattern in untrained children. It improves in boys and girls until about 10 years; subsequently, VO_2max remains at a plateau in boys and declines in girls (Krahenbuhl et al., 1985; Bar-Or, 1986; Rowland, 1996).

Although VO_2max is partly determined by genotype, it can be improved with systematic training it is also trainable. Much research has been done with adults and improvements up to 30% have been recorded (Powers and Howley, 2003). The responsiveness of VO_2max to training is also partly determined by genotype (Bouchard et al., 1997). In contrast to adults, less research has been conducted on the responsiveness of VO_2max to training in children and adolescents. The available research also shows variation in results (Baquet et al., 2003; Thompson and Baxter-Jones, 2002), ranging from no significant changes (e.g., Gilliam and Freedson, 1980) to improvements reaching 15% (e.g., Stansky et al., 1979).

The focus of this review is the trainability of VO_2max in children and adolescents. The review is set within the context of three stages of sport development that characterize childhood and adolescence (Côté and Hay, 2002) which are set within the deliberate practice model of expertise (Ericsson, 2003; Ericsson et al., 1993). The first stage covers the sampling years (6-12) during which there is high frequency of deliberate play and a low frequency of deliberate practice. The second stage is the specializing years (13-15) which are characterized by similar amounts of deliberate play and deliberate practice. The third stage, the investment years (16+) is dominated

by deliberate practice with low frequency of deliberate play. Relevant questions are the following: Are changes in VO_2max due only to growth and maturation or are they also due to training? Do changes in VO_2max occur in each of the sport developmental stages? What is the magnitude of change in VO_2max in each of the stages?

METHODS

The focus of this review is literature over the past 15 years (since 1993). Articles were collected by means of computer search through relevant data bases (Web of Science, PubMed, and Google Beta). The search items were as follows: "maximal oxygen uptake", " VO_2max ", "endurance training", "aerobic training", "anaerobic training" "effects of training", "physical training", "trainability" and "cardiovascular system". The results were then refined for "children", "adolescents", "young athletes", "youth", "teenagers", "pubertal" and "prepubertal". Articles were selected based on abstract reading. Only studies of healthy, non-obese children and adolescents were included.

Selected articles were reviewed with a focus on the following: number of participants and sex, chronological age, characteristics of the training intervention (content, duration, intensity, frequency, length), presence or absence of control group, absolute and/or relative values for VO_2max at the beginning and end of the training program, percentage change and significance of the change.

VO_2max is the most commonly used term for maximal achieved oxygen uptake. However, VO_2max in children and adolescents is characterized by a plateau and a real maximal value is not always attained. The highest level of VO_2 is used is expressed as peak VO_2 . Although peak VO_2 is generally treated as equivalent to VO_2max in children and adolescents (Rowland 1993), the term VO_2max is used in this review.

RESULTS

VO_2max without a training intervention

Studies of VO_2max without a training intervention in children and adolescents are summarized in Table I. Studies of VO_2max of trained and untrained children and adolescents should be noted. Untrained youth generally show lower levels of VO_2max compared to trained youth with relative values ranging from 35.2 to 48.0 ml/kg/min in boys and from 35.8 to 41.7 ml/kg/min

in girls. Absolute VO_2max for untrained boys and girls 9 to 16 years are also lower (Dencker et al., 2006, 2007; Gursel et al., 2004; Impertone et al., 2006; Pate et al., 2007; Rowland et al., 2000; Vinet et al., 2003). Two studies investigated relative VO_2max across several age-categories spanning childhood and adolescence. Between 5 and 13 years of age, relative VO_2max increased by 36% in boys and by only 10% in girls (Gursel et al., 2004), while between 12 and 19 years, relative VO_2max increased by 6.7% in boys and decreased by 5.5% in girls (Pate et al., 2007).

Trained boys 10 to 18 years generally show a relative VO_2max between 50 and 70 ml/kg/min (Cleuziou et al., 2002; Cubero et al., 2000; Eisenman et al., 2001; Noury et al., 2004; Thevenet et al., 2007; Tolfrey et al., 2006). Only study of trained boys reported a relative VO_2max <50 ml/kg/min (Cubero et al., 2000). In this study, 17 year old male soccer player had a mean relative VO_2max of 48.0 ml/kg/min, whereas cyclists and canoeists had, respectively, values of 57.0 and 53.0 ml/kg/min. The highest relative VO_2max in boys was observed in 17 year old elite distance runners, 67.5 ml/kg/min (Eisenmann et al., 2001). Girls in the latter study had relative VO_2max of ~55 ml/kg/min, which was considerably higher than 40.2 ml/kg/min in trained prepubertal children (Noury et al., 2004).

Only a few studies report absolute VO_2max in trained children and adolescents. Levels up to 2.50 l/min were reported in boys up to about 12 years which increased to 4.39 l/min in boys 18 years of age. Girls show levels of 1.31 to 2.28 l/min to about 12 years and of 2.89 l/min at 17 years (Eisenman et al., 2001; Noury et al., 2004; Tolfrey et al., 2006).

VO_2max values with a training intervention

a) Sampling years (about 6-12 years)

An overview of results are reported in Table 2. Given the variation in study designs and protocols, it is most effective to consider studies separately.

In a study of 14 prepubertal girls, 5 (9.3 ± 0.5 years) participated in a swim training program of about one year duration whereas the control group of 9 girls (9.3 ± 0.4) had no additional training (Obert et al., 1996). The experimental group trained 5 times per week for 2 hours, spread over 2 sessions a day. Training consisted of various activities to improve swimming technique and physiological capacity. All girls were tested on a swim ergometer (only arms involved) at the beginning and after one year. Both experimental and control groups increased significantly in absolute VO_2max by

39% and 13%, respectively, from 0.79 ± 0.12 to 1.10 ± 0.17 l/min and from 0.69 ± 0.10 to 0.78 ± 0.12 l/min. The experimental group showed significant improvement of relative $\dot{V}O_{2\max}$ from 26.2 ± 4.4 to 33.8 ± 5.0 ml/kg/min (+29%) while that of the control group remained stable at about 24.7 ml/kg/min.

Thirty-eight boys, 11.5 years of age, participated in a sport-specific training study over 18 months (Vamvakoudis et al., 2007). Of this group, 20 boys formed The experimental group ($n=20$) had 2 years of basketball experience while the control group ($n=18$) had no sport experience and participated in normal physical education at school, 2 or 3 times a week for 40 minutes during the course of the study. The experimental group had 6 mixed basketball-related training sessions of different intensities per week each 90 minutes in duration. The boys were tested every 6 months with an incremental treadmill running test. The experimental group had significantly higher absolute and relative $\dot{V}O_{2\max}$ at the beginning and end of the training period. Both the control and experimental groups improved significantly in absolute $\dot{V}O_{2\max}$. The control group increased in absolute $\dot{V}O_{2\max}$ by 24.2% from 2.11 ± 0.34 to 2.62 ± 0.30 l/min and in relative values by 8.1% from 42.2 ± 5.3 to 45.6 ± 6.4 ml/min/kg. The experimental group improved in absolute $\dot{V}O_{2\max}$ by 34.6% from 2.31 ± 0.41 to 3.11 ± 0.50 l/min and in relative values by 8.6% from 51.4 ± 3.9 to 55.8 ± 4.1 ml/min/kg. Of interest, the relative gain in $\dot{V}O_{2\max}$ per unit body mass was virtually identical in the control and experimental groups, ~8%.

An experimental group (6 girls, 6 boys, 10.4 ± 0.3 years) trained for 13 weeks, 3 times per week for 1 hour. The protocol involved interval training (running at 90% HR max), continuous training (running at 80% HR max) and other aerobic activities including soccer, basketball and swimming (Mandigout et al., 2002). The control group (3 girls, 4 boys, 10.7 ± 0.5 years) participated in regular activities. $\dot{V}O_{2\max}$ was measured with an incremental bicycle ergometer test. After 13 weeks, the experimental group increased significantly in relative $\dot{V}O_{2\max}$, 41.3 ± 8.3 to 47.9 ± 10.7 ml/kg/min (+16.0%), while the control group showed no improvement in relative $\dot{V}O_{2\max}$ although their mean value, 45.9 ml/kg/min was rather high compared to those in the experimental training program. Unfortunately, absolute values and differences between boys and girls were not reported.

Comparable results were noted in a study 7 boys and 11 girls (10.0 ± 0.8 years) who were randomly divided into experimental and control groups (Noury et al., 2005). The experimental group had a training program of 8 weeks which included normal physical education lessons and the two sessions per week of 30 minutes high intensive running. The control group had normal physical education with no additional training. All children did an

incremental test on a bicycle ergometer at the beginning and end of the study. Relative $\dot{V}O_{2\max}$ of the experimental group improved significantly from 37.4 ± 7.3 to 43.2 ± 7.6 ml/min/kg (+15%), while relative $\dot{V}O_{2\max}$ of the control group remained the same over the 8 weeks, 38.8 ml/kg/min. Unfortunately, neither absolute values nor sex differences were reported.

A sample of 19 children (10 girls, 9 boys) 10-11 years followed a 13-week training program of continuous (>80% HR max) and interval (>90% HR max) activities for 1.0-1.5 hours per session, 3 times per week, while 16 children (7 girls, 9 boys) of the same age served as a control group (Obert et al., 2003). All children performed an incremental cycle ergometer test before and after the program. Relative $\dot{V}O_{2\max}$ increased significantly in the experimental group, 40.9 ± 8.9 to 44.2 ± 8.4 ml/min/kg in girls and 44.1 ± 6.1 to 50.9 ± 6.1 ml/min/kg in boys, 8.1% and 15.4%, respectively. This means an improvement of $\dot{V}O_{2\max}$ of respectively 8.1% and 15.4%. Relative $\dot{V}O_{2\max}$ of the control group, on the other hand, did not change, 42.4 and 51.5 ml/kg/min in girls and boys, respectively, after 13 weeks. Absolute values were not reported.

Using a 7 week training program, 13 boys and 20 girls (9.5 ± 0.9 years) participated in normal physical education lessons plus 2 additional training sessions per week (Baquet et al., 2002). The latter consisted of 30 minutes of short high intermittent exercise (10 and 20 second sprints). Ten boys and 10 girls (9.9 ± 0.4 years) comprised a control group which had only normal physical education lessons. $\dot{V}O_{2\max}$ was estimated with a graded field running test. The experimental group improved significantly in absolute $\dot{V}O_{2\max}$, 1.54 ± 0.35 to 1.68 ± 0.36 l/min, and in relative $\dot{V}O_{2\max}$, 43.9 ± 6.2 to 47.5 ± 7.2 ml/min/kg (+9.1% and +8.2%, respectively). The control group did not change in either absolute or relative $\dot{V}O_{2\max}$, 1.62 l/min and 46.2 ml/kg/min, respectively. Sex differences were not reported.

Comparable results were obtained in a study of 40 girls (9.1 ± 0.1 years) attending a summer camp (Eliakim et al., 2001). An experimental group (n=20) followed 2 training sessions of 45 minutes per day, 5 days per week over 5 weeks. The sessions consisted of endurance activities, 50% running activities and 50% ball sports. All activities were performed as games and intensity levels were not reported. The remaining girls (n=20) served as a control group who did not have special training sessions. $\dot{V}O_{2\max}$ was measured with an incremental bicycle ergometer test. The experimental group increased significantly in relative $\dot{V}O_{2\max}$ (+9.5%). Post-training $\dot{V}O_{2\max}$ was 1.45 l/min and 45 ml/min/kg in the experimental group. Exact values, pre-training values and values for the control group were not reported.

Using a 13 weeks protocol, 17 girls (10.5 ± 0.4 years) and 18 boys

(10.7±0.4 years) trained 3 times per week in 1.0-1.5 hour sessions of interval training (90% HR max), continuous training (75-85% HR max) and several aerobic activities, while 22 girls (10.5±0.9) and 28 boys (10.5±0.5 years) formed a control group which has no special training (Mandigout et al., 2001). An incremental bicycle ergometer test was used. Experimental girls improved significantly in both absolute (1.30±0.2 to 1.57±0.2 l/min, +20.8%) and relative (38.6±4.4 to 41.9±4.6 ml/min/kg, +8.5%) VO₂max. Corresponding improvements in experimental boys were somewhat less but significant, 1.70±0.3 to 1.84±0.3 l/min (+8.2%) in absolute and 47.2±7.9 to 49.2±7.1 ml/min/kg (+4.2%) in relative VO₂max. The control group also improved in absolute VO₂max (girls +6.9%, 1.40 to 1.50 l/min, boys +6.3%, 1.60 to 1.70 l/min) whereas relative VO₂max did not change, 39.6 ml/kg/min in girls and 46.1 ml/kg/min in boys.

A similar 13 week protocol was used to compare training programs of 3 and 2 times per week in 10-11 year old children (mean ages were not reported, Mandigout et al., 2002). The first experimental group (18 boys, 18 girls) did interval training (90% HR max), continuous training (80% HR max) and a mixed training with several aerobic activities like basketball and other games 3 times per week, while the second experimental group (10 boys, 10 girls) trained in the same manner but without the mixed session only 2 times a week. All training sessions lasted one hour. A control group (15 boys, 13 girls) were not involved in extra training activities. An incremental bicycle ergometer test was used. The first experimental group of girls increased significantly both absolute and relative VO₂max by 14.6% (1.37±0.20 to 1.57±0.19 l/min) and 8.6% (38.2±4.4 to 41.5±4.6 ml/min/kg), respectively. Boys in the first experimental group gained in absolute VO₂max by 6.4% (1.71±0.32 to 1.82±0.39 l/min) and in relative VO₂max by 5.1% (46.9±7.9 to 49.3±7.1 ml/min/kg). Children in the second experimental group made smaller gains in absolute VO₂max, +4.2% in girls (1.44 to 1.50 l/min) and +2.4% in boys (1.66 to 1.70 l/min); relative VO₂max improved only in girls, +1.2% (40.1 to 40.6 ml/kg/min) but not in boys (stable at 45.5 ml/kg/min). The control group also improved in absolute VO₂max, +6.9% in girls (1.45 to 1.55 l/min) and +1.8% in boys (1.69 to 1.72 l/min), while relative VO₂max did not change, girls 41.1 ml/kg/min and boys 46.6 ml/kg/min.

In contrast to the preceding studies which utilized a variety of activities to make training more attractive, others have utilized a more controlled training protocol (McManus et al., 1997, 2005). VO₂max of boys in continuous (n=10, 10.4±0.5 years) and interval (n=10, 10.4±0.3 years) training groups and a control group (n=15 boys, 10.5±0.4 years) were compared after 8 weeks. Both experimental groups trained 3 times per week for 20 minutes, while the control group had no training. The continuous training protocol involved 20 minutes per session on a cycle ergometer at heart rate between

160 and 170 bpm, while the interval training protocol called for 7 maximal sprints of 30 seconds each during the 20 minute session. Boys rested between sprints by cycling at low speed. After 8 weeks, both training groups increased significantly in VO_2max on an incremental bicycle ergometer test. Best results were achieved by the interval training group. Absolute VO_2max increased by 11.4% (1.76 ± 0.20 to 1.96 ± 0.22 l/min) and relative VO_2max increased by 11.4% (45.5 ± 3.4 to 50.7 ± 3.7 ml/min/kg). The continuous training group had smaller gains in absolute and relative VO_2max , respectively, 1.65 ± 0.16 to 1.72 ± 0.17 l/min (4.2%) and 47.0 ± 6.5 to 50.7 ± 6.9 ml/min/kg (7.9%). The control group, in contrast, improved in relative VO_2max by 1.6% (44.7 to 45.4 ml/kg/min), while absolute VO_2max remained rather stable at 1.59 l/min after 8 weeks.

The second study included 12 girls (9.3 ± 0.5 years) who participated in a cycle ergometer training protocol 3 times per week for 20 minutes at a heart rate of 160 to 170 bpm and 11 girls (9.8 ± 0.4) who participated in sprint running for 8 weeks. The running protocol called for maximal sprints of 10 and 30 seconds; the number of sprints increased from 3 of each duration in the first week to 6 sprints of each duration in week 8 (McManus et al., 1997). A control group had no formal training. VO_2max was assessed with an incremental treadmill test. Both experimental groups improved significantly in absolute VO_2max , cycling group by 10% (1.30 ± 0.19 to 1.43 ± 0.20 l/min) and running group by 8.4% (1.54 ± 0.24 to 1.67 ± 0.22), while the control group did not change in absolute VO_2max (1.49 l/min) after 8 weeks.

Also using a laboratory protocol, an experimental group (12 boys, 14 girls) trained for 12 weeks on 3 sessions per week of 30 minutes continuous (80% of HR max) cycling on an ergometer (Tolfrey et al., 1998). A control group (10 boys, 9 girls) had no additional training. Mean age of the total group was 10.5 ± 0.7 years. An incremental cycling test was used to estimate VO_2max . The experimental group increased absolute VO_2max by 3.8% in boys (1.60 to 1.66 l/min) and 13.2% in girls (1.36 to 1.54 l/min); variance statistics were not reported. Relative VO_2max increased by 1.3% in boys (46.6 to 47.2 ml/kg/min) and 7.9% in girls (39.3 to 42.4 ml/kg/min). Although there was a trend for improved performance, the changes were not significant. The control group did not change in relative VO_2max , 44.7 ml/kg/min in girls and 50.7 ml/kg/min in boys, after 12 weeks, while absolute VO_2max increased slightly in boys, 1.62 to 1.65 l/min (+1.9%) but not in girls, 1.52 l/min.

Several studies did not include a control group. To deal with this problem, subjects were followed for a period of no formal training prior to the onset of a training protocol. For example, 37 youth 11-13 years of age (24 girls, 13 boys) were followed for 12 weeks before training began; subsequently, trained for 12 weeks, 3 sessions per week on an aerobic circuit,

running and training with various ball sports (Rowland and Boyajian, 1995). Training was targeted at a heart rate between 165 and 175 bpm. Subjects were tested at the three time points with an incremental treadmill protocol. There was little change in both absolute (1.96 ± 0.32 to 2.02 ± 0.35 , +3.6%) and relative (44.3 ± 5.8 to 44.7 ± 5.8 l/min/kg, +0.9%) VO_2max after 12 weeks of non-training. After 12 weeks of aerobic training absolute and relative VO_2max increased significantly to 2.24 ± 0.38 l/min (+10.9%) and 47.6 ± 6.4 ml/min/kg (+6.5%). Sex-specific results were not reported.

In related study (Rowland et al., 1996), 31 children (20 girls, 9 boys, 11.8 ± 0.5 years) had a baseline period of no formal training for 13 weeks (except for formal physical education 2 times per week) which was followed by 13 weeks of aerobic training which replaced the physical education classes. Training occurred 3 times per week for 30 minutes and involved several aerobic exercises (HR 170 to 180 bpm). An incremental cycle ergometer test was used to estimate VO_2max at the three time points. Among girls absolute VO_2max increased from 1.76 ± 0.24 to 1.81 ± 0.28 to 1.97 ± 0.34 across the three testing moments while relative VO_2max changed only slightly, 43.7 ± 6.3 to 43.9 ± 6.8 to 46.1 ± 7.7 ml/kg/min. After 13 weeks of aerobic training, absolute and relative VO_2max improved by 8.8% and 5.0%, respectively. Corresponding values in boys at the three testing moments were, respectively, were 2.08 ± 0.31 , 2.15 ± 0.31 and 2.29 ± 0.30 l/min for absolute VO_2max and 45.3 ± 9.2 , 45.4 ± 8.8 and 48.2 ± 9.4 ml/kg/min for relative VO_2max . Improvements after 13 weeks of training approximated 6.5% and 6.2%, respectively. A significance ($p=0.06$) for relative VO_2max is girls and boys combined was reported.

While most studies indicate an improvement in VO_2max with training, there are exceptions. An 8 week program of interval run training of 10 and 30 second maximal sprints (12 boys, 10.1 ± 0.3 years) and continuous cycling for 20 minutes at 160-170 bpm (13 boys, 10.1 ± 0.2 years), 3 sessions per week resulted in no significant changes in VO_2max (Williams et al., 2000). A control group (14 boys, 10.1 ± 0.3 years) had no training. VO_2max was measured with an treadmill incremental test. Absolute VO_2max showed a non-significant increase (1.84 ± 0.2 to 1.91 ± 0.3 l/min, +3.8%) while relative VO_2max decreased slightly (54.8 ± 5.1 to 53.9 ± 7.8 ml/min/kg, -1.6%) in the sprint interval running group. The continuous group improved, though not significantly, in both absolute (1.80 ± 0.3 to 1.93 ± 0.3 l/min, +7.2%) and relative (54.7 ± 9.7 to 57.5 ± 7.0 ml/min/kg, +5.1%) VO_2max . The control group showed a small gain in absolute VO_2max (1.92 ± 0.2 to 1.97 ± 0.2) l/min, +2.6%) but no change in relative VO_2max (56.4 ml/kg/min).

b) *Specializing years (about 13-15 years)*

Most studies of the sampling years did not use samples of not specifically trained children. The influence of a 4-week training pre-season program on VO_2max was evaluated in 27 top basketball players (14.7 ± 0.5 years) divided into control ($n=7$), specialized training ($n=10$) and mixed training ($n=10$) groups (Bogdanis et al., 2007). The control group did not follow any training. The specialized group followed normal basketball training of variable intensities while the mixed group combined circuit training (20% of time) normal basketball training. Training sessions of 110-120 minutes occurred 5 days per week. An incremental treadmill test was used. Both experimental groups showed significant improvement in relative VO_2max ; absolute values were not reported. Improvements were 4.6% in both groups, 52.3 ± 1.0 to 54.7 ± 0.7 ml/kg/min for the specialized and 52.5 ± 1.3 to 54.9 ± 1.0 ml/kg/min for the mixed training protocols. The control group did not improve (49.8 ml/kg/min).

Two other studies in specialization age range did not observe significant training effects. Stoedefalke et al. (2000) found no significant increase in $\text{VO}_2\text{-max}$ measured during an incremental treadmill test after 20 weeks of training. In this experiment 38 girls were involved, Twenty girls (13.6 ± 0.3 years) completed a training program of 3 sessions per week for 20 weeks (Stoedefalke et al., 2000). Training sessions were 20 minutes at 80% HR max and consisted of running, cycling, rowing and dancing. A group of 18 girls (13.7 ± 0.2 years) served as a control and continued normal daily activities. Absolute VO_2max increased in the experimental group by 3.1%, 2.25 ± 0.30 to 2.32 ± 0.28 l/min, while the control group improved by 2.5%, 2.39 ± 0.36 to 2.45 ± 0.30 l/min; relative values were not reported.

In a co-twin control study of 9 male monozygotic twins 11-14 years, one twin did high speed running for 1.0-1.5 hours per session 3 days per week for 26 weeks while the other twin continued normal daily activities (Danis et al., 2002). VO_2max was tested on 3 occasions with an incremental treadmill test at the beginning, after 3 months and at the end 26 weeks. Both experimental and control twins improved in absolute and relative VO_2max . Mid-way in the program (13 weeks), the trained twins improved in both absolute (2.08 ± 0.43 to 2.23 ± 0.45 l/min, +7.2%) and relative (52.1 ± 3.6 to 53.9 ± 3.8 ml/min/kg, +3.5%) VO_2max , while the control twins increased in absolute but decreased in relative VO_2max . After 26 weeks, absolute VO_2max reached 2.37 ± 0.45 l/min and 57.5 ± 3.6 ml/min/kg in the experimental twins, reflecting further improvements of 6.3% and 6.7% in absolute and relative VO_2max , respectively. The overall improvement over 26 weeks was thus 13.9% in absolute and 10.4% in relative VO_2max . After 13 weeks, the control twins increased in absolute (2.10 ± 0.41 to 2.18 ± 0.43 l/min, +3.8%) but

decreased in relative VO_2max (54.0 ± 3.9 to 52.6 ± 3.8 ml/min/kg, -2.6%). Over the next 13 weeks, absolute VO_2max increased to 2.32 ± 0.47 l/min (+6.4%) and relative VO_2max increased to 55.4 ± 3.3 ml/min/kg (+5.3%) in the control twins. The control twins increased by 10.5% in absolute and by 2.6% in relative VO_2max over the 26 week interval. Mid-way during the program, improvements in VO_2max between experimental and control twins were significant but after 26 weeks they were not.

c) *Investment years* (about 16-18 years)

Eliakim et al. (1996) also investigated effects of training in 15-17 (no means were reported) years old girls. A summer school setting was used to evaluate the influence of an aerobic training program on girls 15-17 years of age (Eliakim et al., 1996). A sample of 44 girls were randomly divided into experimental and control groups. The former had 5, two hour training sessions per week for 5 weeks; sessions included 50% running, 25% team sports and 25% dancing (although no further specifics were indicated). Control subjects had no special activities other than a computer education program. An incremental cycle test was used. Experimental subjects significantly improved in absolute VO_2max by 12.1%, 1.48 ± 0.6 to 1.63 ± 0.5 l/min, whereas control subjects showed no change (1.57 l/min). Relative values were not reported.

VO_2max was measured before and after a competitive season (13 weeks) in a team of 9 male cross country runners (15.9 ± 1.0 years, 4.2 ± 2.1 years of experience) using an incremental test on a running ergometer (Plank et al., 2005). Training consisted of 6 sessions a week of about 1 hour duration using different running activities (continuous and interval running, competitive races. Both absolute and relative VO_2max increased significantly after 13 weeks, 3.73 ± 0.64 to 3.98 ± 0.62 l/min (+6.7%) and 61.6 ± 3.5 to 65.3 ± 2.9 ml/min/kg (+6.0%). No control group was included.

A sample of 16 late adolescent-young adults (4 boys, 12 girls, 19.5 ± 3.2 years) was included in a study comparing measurements of the CardioCoach with laboratory equipment (Vehrs et al., 2007). The focus was not training effects and no control group was included. Participants followed a 14 week program 3-5 sessions per week of 20-40 minutes of aerobic exercise at 65-85% HR max. Maximal graded exercise treadmill test were done before, after 7 weeks and at the end of the program. Relative VO_2max improved significantly from 44.4 ± 5.0 to 46.0 ± 5.2 (7 weeks) to 47.8 ± 5.6 ml/min/kg (14 weeks), an overall improvement of 7.7%. Absolute VO_2max and sex differences were not reported.

Table 1. Results of studies without a training program (studies are listed by first author only although all papers have multiple authors)

	Training status	n	Age (yrs)	VO ₂ max (l/min)		VO ₂ max (ml/min/kg)	
				Boys	Girls	Boys	Girls
Gursel 2004	U	90	5-6	*		35.2	36.7
			7-8		38.1	37.4	
			9-10		43.8	39.0	
			11-12		46.3	41.4	
			13		48.0	40.5	
Dencker 2006	U	228	10	*		42.0	36.0
Dencker 2007	U	248	10	1.42	1.21	41.4	35.8
Vinet 2003	U	35	11	1.80	1.42	47.9	41.7
Rowland 2000	U	25	12	1.98	1.84	47.2	40.4
Pate 2007	U	3287	12-13	*		44.6	39.7
			14-15		47.1	38.3	
			16-17		46.9	38.9	
			18-19		47.6	37.5	
Impertone 2006	U	1783	15	*		46.6	38.8
Eisenmann 2001	T	124	9-10	1.94	1.81	62.7	56.3
			11	2.11	1.95	63.6	57.9
			12	2.47	2.28	63.3	57.1
			13	2.63	2.44	60.8	54.8
			14	3.07	2.69	63.5	56.9
			15	3.64	2.84	62.7	56.2
			16	3.88	2.85	64.8	54.3
			17	4.25	2.89	67.5	51.8
			18	4.39	-	67.3	-
Noury 2004	T	24	9-11	1.79	1.31	51.4	40.2
Tolfrey 2006	T	15	12	2.23	-	* U: 38.7 T: 52.4	
Cleuziou 2002	T&U	20	13	*			
Cubero 2000	T	64	15	*		53.0 can.	-
			16			57.0 cycl.	
			17			48.0 soc.	
Thevenet 2007	T	8	16	*		56.9	-

T: trained subjects, U: untrained subjects, *: no results, can: canoeist, cycl: cycling, soc: soccer.

Samples of 75 male and 49 female elite distance runners 9-19 years were followed in a mixed-longitudinal design (Eisenmann et al., 2001). The age range thus spans the three sport development stages used in this review. The subjects ran about 35 km a week or more and some were followed up to 5 years. VO₂max was measured annually with an incremental treadmill test. The mixed-longitudinal data were pooled yielding observations for 139 males and 105 females. Over the duration of the study, absolute VO₂max of the runners

increased significantly with age from 1.93 ± 0.22 l/min at 9 years to 4.39 ± 0.66 l/min at 18 years in boys and from 1.81 ± 0.18 to 2.89 ± 0.39 l/min in girls over the same ages. Relative VO_2max remained relatively stable (~ 62.5 ml/kg/min) between 9 and 15 years in male runners, but increased >67.0 ml/kg/min between 16 and 19 years (investment years). Nevertheless, the improvement was not significant. Relative VO_2max was also stable in female runners (~ 56.0 ml/kg/min) across the sampling and specializing years but declined to ~ 52.0 ml/kg/min in the investment years; the change, however, was not significant.

Table 2. Characteristics of training studies (studies are listed by first author only although all papers have multiple authors)

	Training status	Mean age (yrs), n	Length (wks), # sessions per week	Content, Intensity, Training time (min)	VO_2max Before Training (l/min)
Sampling years					
Eliakim 2001	U	9.1 40	5 10	Run + Ball, *, 90	EG G: * CG G: *
McManus 1997	U	9.5 30	8 3	Int/Con, Max/165bpm, 20	ITG G: 1.54 CTG G: 1.30 CG G: 1.49
Baquet 2002	U	9.7 53	7 2	Int, *, 30	EG B&G: 1.54 CG B&G: 1.62
Noury 2005	U	10.0 18	8 2	Int, *, 30	EG B&G: * CG B&G: *
Williams 2000	U	10.1 39	8 3	Int/Con, Max/165bpm, 20	ITG B: 1.84 CTG B: 1.80 CG B: 1.92
Mandigout 2002	U	10.5 19	13 3	Int, Con, Mxd, 90%, 80%, 60	EG B&G: * CG B&G: *
McManus 2005	U	10.5 35	8 3	Int/Con, Max/165bpm, 20	ITG B: 1.76 CTG B: 1.65 CG B: 1.59
Tolfrey 1998	U	10.5 45	12 3	Con, 80%, 30	EG G: 1.36 EG B: 1.66 CG G: 1.52 CG B: 1.62

(continues)

	VO ₂ max after training (l/min)	Increase absolute VO ₂ max	VO ₂ max before training (ml /kg/min)	VO ₂ max after training (ml /kg/min)	Increase relative VO ₂ max
Sampling years					
Eliakim 2001	1.45 *	*	*	45.0 *	9,5%
McManus 1997	1.67 1.43 1.46	8.4% 10.0% -	*	*	*
Baquet 2002	1.68 1.62	9.1% -	43.9 46.2	47.5 45.3	8.2% -
Nourry 2005	*	*	37.4 36.8	43.2 36.6	15.5% -
Williams 2000	1.91 1.93 1.97	3.8% 9.3% 2.6%	54.8 54.7 56.4	53.9 57.5 56.7	- 5.1% -
Mandigout 2002	*	*	41.3 45.9	47.9 45.1	16.0% -
McManus 2005	1.96 1.72 1.57	11.4% 4.2% -	47.0 45.5 44.7	50.7 50.7 45.4	7,9% 11,4% 1,6%
Tolfrey 1998	1.54 1.66 1.52 1.65	13.2% 3.8% - 1.9%	39.9 46.6 44.7 50.7	42.4 47.2 43.0 50.3	7.9% 1.3% - -

(continues)

	Training status	Mean age (yrs), n	Length (wks), # sessions per week	Content, Intensity, training time (min)	VO ₂ max Before Training (l/min)
Mandigout 2001	U	10.5 85	13 3	Int, Con, Mxd, 90%, 80%, 60	EG G: 1.30 EG B: 1.70 CG G: 1.40 CG B: 1.60 *
Obert 2003	U	10.6 35	13 3	Int, Con, 90%, 80%, 60	*
Mandigout 2002	U	10-11 84	13 3&2	Int, Con, (Mxd), 90%, 80%, 60	EG1 G: 1.37 EG2 G: 1.44 EG1 B: 1.71 EG2 B: 1.66 CG G: 1.45 CG B: 1.69
Rowland 1996	U	11.8 29	13 3	Mxd, 175bpm, 30	G: 1.81 B: 2.08 CG: -
Rowland 1995	U	11-13 37	12 3	Mxd, 170bpm, 30	EG B&G: 2.02 CG: -
Obert 1996	T	9.3 14	52 10	Mxd swim tr, *, 120	EG G: 0.79 CG G: 0.69
Vamvakoudis 2007	T	11.5 38	78 6	Mxd basket tr, *, 90	EG B: 2.31 CG B: 2.11

(continues)

	VO ₂ max after training (l/min)	VO ₂ max absolute VO ₂ -max	VO ₂ max before Training (ml/min/kg)	VO ₂ max after training (ml/min/kg)	Increase Relative VO ₂ max
Mandigout 2001	1.57	20.7%	38.6	41.9	8.5%
	1.84	8.2%	47.2	49.2	4.2%
	1.50	7.1%	39.6	39.5	-
	1.70	6.3%	46.1	45.5	-
Obert 2003	*	*	EG G: 40.9	44.2	8.1%
			EG B: 44.1	50.9	15.4%
			CG G: 42.4	42.6	-
			CG B: 51.5	50.3	-
Mandigout 2002	1.57	14.6%	38.2	41.5	8.6%
	1.50	4.2%	40.1	40.6	1.2%
	1.82	6.4%	46.9	49.3	5.1%
	1.70	2.4%	45.5	45.2	-
	1.55	6.9%	41.1	40.1	-
Rowland 1996	1.72	1.8%	46.6	45.6	-
	1.97	8.8%	43.9	46.1	5.0%
	2.29	6.5%	45.4	48.2	6.2%
Rowland 1995	2.24	10.9	44.7	47.6	6.5%
Obert 1996	1.10	39.2%	26.2	33.8	29%
	0.79	14.5%	24.7	24.9	-
Vamvakoudis 2007	3.11	34.6%	51.4	55.8	8.6%
	2.62	24.2%	42.2	45.6	8.1%

(continues)

	Training status	Mean age (yrs), n	Length (wks), # sessions per week	Content, Intensity, training time (min)	VO ₂ max Before Training (l/min)
Specializing years					
Danis 2002	U	11-14	26	Run, *, 60	EG B: 2.08
		18	3		CG B: 2.10
Stoedefalke 2000	U	13-14	20	Mxd, 80%, 20	EG G: 2.25
		38	3		CG G: 2.39
Bogdanis 2007	T	14.7	4	Mxd basket, *, 110	*
		27	5		
Investment years					
Eliakim 1996	U	15-17	5	Mxd, *, 120	EG G: 1.48
		44	5		CG G: 1.57
Vehrs 2007	U	19.5	14	Mxd, 75%, 30	*
		16	3-5		
Plank 2005	T	15.9	13	Run, mxd, 60	EG B: 3.73
		9	5		CG: -

(continues)

	VO ₂ max after training (l/min)	Increase absolute VO ₂ -max	VO ₂ max before Training (ml/min/kg)	VO ₂ max after training (ml/min/kg)	Increase Relative VO ₂ max
Specializing years					
Danis 2002	2.37	13.9%	52.1	57.5	10.4%
	2.32	10.5%	54.0	55.4	2.6%
Stoedefalke 2000	2.32	3.1%	*	*	*
	2.45	2.5%			
Bogdanis 2007	*	*	EG1 B: 52.3 EG2 B: 52.5 CG B: 49.8	54.7 54.9 49.4	4.6% 4.6% -
Investment years					
Eliakim 1996	1.63	12.1%	*	*	*
	*	-			
Vehrs 2007	*	*	EG B&G: 44.4 CG: -	47.8	7.7%
Plank 2005	3.98	6.7%	61.6	65.3	6.0%

*No values reported, G: values for girls, B: values for boys, B+G: values for boys and girls separated, B&G: values of boys and girls not separated, ITG: Interval Training Group, CTG: Continuous Training Group, EG: Experimental Group, CG: Control Group, T: trained subjects, U: untrained subjects, Mxd: mixed training types, Run: running training, Int: interval training, Con: continuous training

DISCUSSION

Changes in absolute VO₂max associated with training vary from 2.4% to 39.2% with a slightly higher mean increase girls ($\pm 12.5\%$) than in boys ($\pm 10\%$). All studies except one (Williams et al., 2000) also show at least small increments in relative VO₂max with training and the mean increase was higher in girls ($\pm 10\%$) than in boys ($\pm 6.5\%$).

One of the goals of this study was to evaluate variation in trainability during three sport development stages proposed by Côté and Hay (2002). Accordingly, the focus shifts from sampling (~6-12 years) through specializing (~13-15 years) into investment years (~16+ years) on a continuum from deliberate play to deliberate practice. The goal of deliberate practice is to improve an aspect of performance. In the context of the present review, the performance focus is VO₂max. Most studies in the last 15 years concerned the trainability of VO₂max in the age range spanning the sampling years, while few studies considered the specializing (Bogdanis et al., 2007; Danis et al., 2002; Stoedefalke et al., 2000) and investment years (Eliakim et al., 1996; Plank et al., 2005; Vehrs et al., 2007) years. One study was spanned all three sport development stages (Eisenmann et al., 2001).

Figure 1a shows absolute VO₂max reported in all studies reviewed. Values from studies without a training program and at the beginning of a training program from the studies with an intervention are used to form a

baseline that probably reflect normal growth of VO_{2max} . Absolute VO_{2max} increases almost linearly to about 15 years after which girls appear to reach a plateau and boys continue to improve. This is consistent with earlier discussions (Krahenbuhl et al., 1985; Bar-Or, 1986; Rowland, 1996; Armstrong et al., 2000). Trained children and adolescents show higher values than untrained peers of both sexes, but there appears to be no difference in the manner of increase in VO_{2max} across age. This implies that starting training at younger age (sampling years) does not temper an increase in VO_{2max} at older ages (specializing and investment years). It is not possible, however, to state that starting training during the sampling years will give an advantage for the other stages and adulthood. The 10-year rule (Ericsson et al., 1993), however, proposes that deliberate practice is necessary to reach elite level so that starting at a younger age should have an advantage compared to starting at later age.

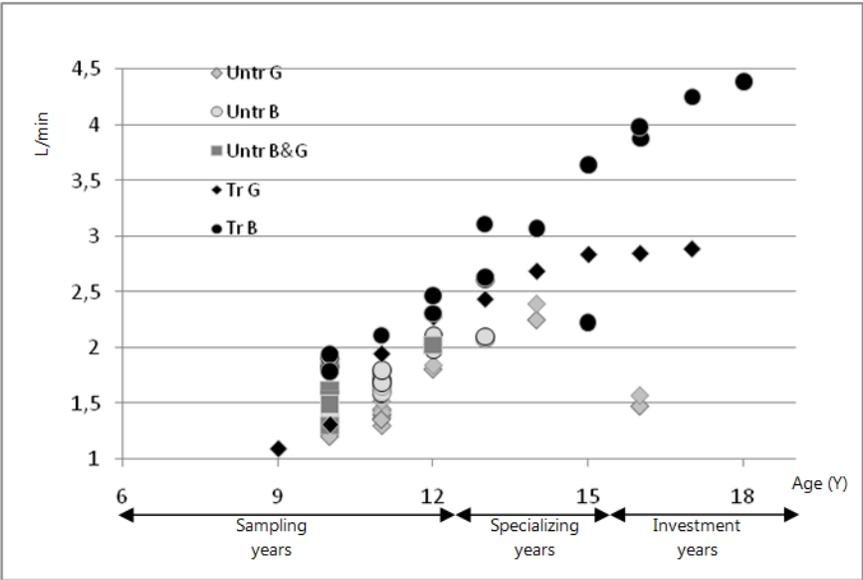


Figure 1a. Absolute VO_{2max} in l/min by age. Legend: [Untr] untrained; [Tr] trained; [G] girls; [B] boys, [B&G] boys&girls

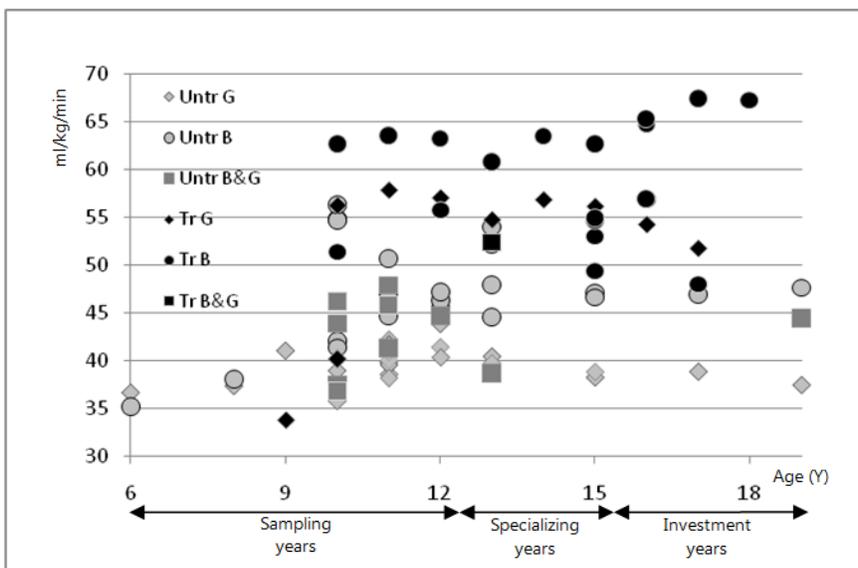


Figure 1b. Relative VO₂max in ml/kg/min by age. Legend: [Untr] untrained; [Tr] trained; [G] girls; [B] boys, [B&G] boys&girls

Figure 1b shows corresponding values for relative VO₂max. In general, trained children and adolescents have higher values compared to untrained peers. Only two results for trained girls were lower than expected. One study using a swim ergometer to measure VO₂max (Obert et al., 1996), while use of only upper body musculature gives lower results than use of lower body musculature (Al-Hazzaa et al., 1998). Relative VO₂max seems to improve during the sampling years but tends to remain stable during the subsequent stages in both sexes. This is not totally consistent with the literature (Krahenbuhl et al., 1985; Bar-Or, 1986; Rowland, 1996) which shows a decline in relative value in girls after about of 10 years of age. Although trained youth have higher values than the untrained, it appears to be difficult to improve relative VO₂max in trained children and adolescents. Limited data for the investment years show a slight increase in males but a small decrease in females. Hence, generalizations are not warranted.

To show an influence of training on improvement in VO₂max it is necessary to partition observations attributed to training from normal growth and maturation. Figures 2a and 2b show differences between experimental and control groups for all studies. Experimental groups trained 2 to 10 times per week for durations of 20 to 120 minutes over periods of 4 to 78 weeks. Improvements are divided into four categories; no improvement (less than 1%), low improvement (1-5%), moderate improvement (6-10%), and high

improvement (>10%). For both absolute and relative VO₂max 'no' improvement is observed largely within control groups. Only one experimental group shows 'no' improvement in relative VO₂max, while all experimental groups show at least low improvement in absolute VO₂max. The observation of 'no' improvement in relative VO₂max is consistent with a stable pattern during childhood and adolescence. While absolute VO₂max is more liable to growth and maturational effects, it is not surprising that some control groups show 'moderate' and even 'high' improvements. These results were found in studies of longer duration. Nevertheless, experimental groups showed higher improvements in absolute VO₂max in these studies that exceeded the effects of growth and maturation. Most experimental groups show moderate and high improvement for both absolute and relative VO₂max.

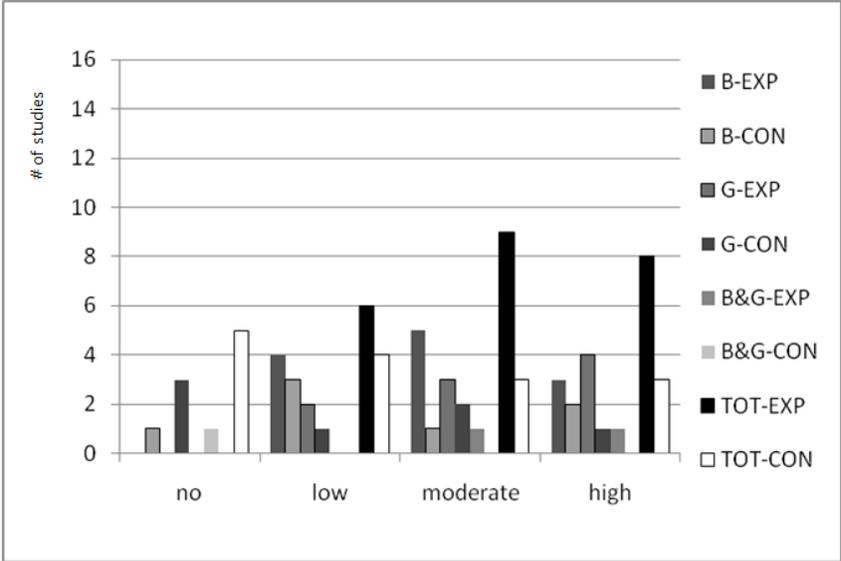


Figure 2a. Number of studies for each category of improvement of absolute VO₂max. Legend: [B] boys; [G] girls; [B&G] boys&girls; [Exp] experimental group; [Con] control group; [Tot] total

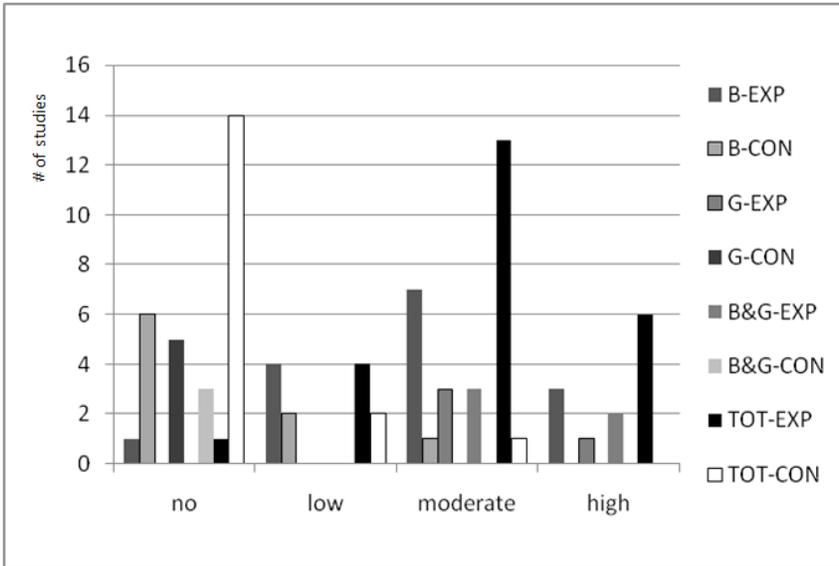


Figure 2b-number of studies for each category of improvement of relative $VO_2\max$. Legend: [B] boys; [G] girls; [B&G] boys&girls; [Exp] experimental group; [Con] control group; [Tot] total.

Figures 3a and 3b show relative improvement (%) in $VO_2\max$ associated with training. During the sampling years improvements in absolute $VO_2\max$ are in a similar range for both trained and untrained children (3% to 20%). Only two studies reported improvements >30% in absolute $VO_2\max$ (Obert et al., 1996; Vamvakoudis et al., 2007). These studies spanned 52 and 78 weeks so that the larger improvements were due in part to growth and maturation since control groups showed high improvements, 14.5% and 24.2%, over the same periods. Improvements for trained youth tend to be lower during the specializing and investment years than during the sampling years though data are too limited for generalization.

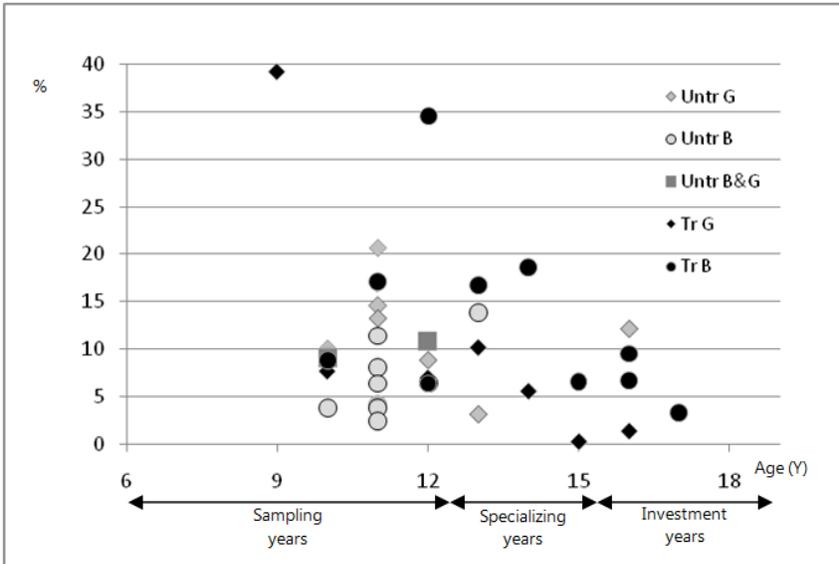


Figure 3a. Percentage improvement of absolute VO₂max due to training. Legend: [Untr] untrained; [Tr] trained; [G] girls; [B] boys; [B&G] boys&girls.

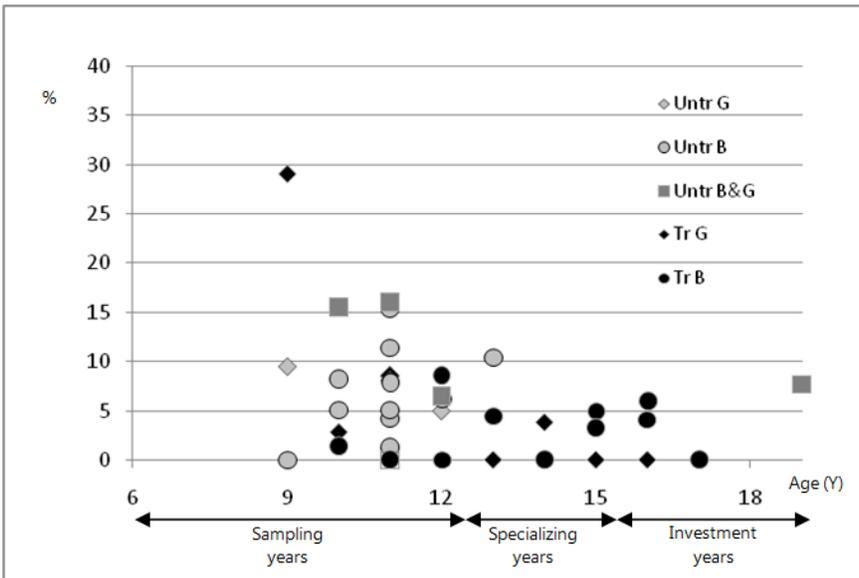


Figure 3b. Percentage improvement of relative VO₂max due to training. Legend: [Untr] untrained; [Tr] trained; [G] girls; [B] boys; [B&G] boys&girls.

A training program of 7 weeks with 3 sessions per week seems sufficient to improve VO_2max . Longer training periods do not show consistently better results, especially for relative VO_2max . Although highest improvements of absolute VO_2max were noted in studies with training periods >26 weeks, it is difficult to partition training from changes associated with normal growth and maturation.

More than 3 training sessions a week does not show consistently better results, whereas two sessions per week seem appear to be insufficient to improve VO_2max . Although two studies (Baquet et al., 2002; Nourry et al., 2005) used two sessions per week, the sessions were added to the normal physical education classes. In most studies training replaced at least one physical education class. With only two sessions a week, time between sessions seems to be too long for improvement to occur. This is consistent with training principles that a new impulse should occur close enough in time to bring about an effect.

The studies considered differed in training intensity and duration so that it is almost impossible to conclude which intensity is most effective. Studies generally used different training protocols during a week. One session usually consisted of interval (maximal sprints) training and another of continuous (80% of HR max or 160-180 bpm) training, while a third session included mixed activities such as ball sports and dancing. The few studies that compared interval training with continuous training showed no consistent results. Accordingly, it is not possible to conclude if one type of training is more effective than another to improve VO_2max in children and adolescents, but heart rate should be at least 160 bpm. It is also difficult to draw a conclusion on an effective training duration. Training sessions in the studies varied between 20 minutes and 2 hours. Longer sessions did not show higher improvements than shorter sessions. Moreover, training sessions of 20 minutes appear effective in improving VO_2max .

Although some results show reasonable consistency, the relatively small number of studies in combination with variation in sampling, numbers of subjects, design and protocols limits generalization. It is likely that training studies would not attract overweight and obese youth. Another confounder is failure to control for pubertal status and timing of the adolescent growth spurt. Absolute VO_2max shows its own growth spurt that occurs, on average, coincident with the growth spurt in height in both sexes (Malina et al., 2004). More comprehensive research designs are needed to better understand the influence of systematic training on growth of VO_2max at different ages during childhood and adolescence.

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