Changes in Aerobic Fitness in Boys and Girls Over a Period of 25 Years: Data From the Amsterdam Growth and Health Longitudinal Study Revisited and Extended

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In the Amsterdam Growth And Health Longitudinal Study (AGAHLS), a group of approximately 650 12- to 14-year-old boys and girls was followed in their growth, and development of their health their lifestyle including diet, physical activity and smoking. One of the main interests was the change in their aerobic fitness. From 12 to 36 years of age in total, eight repeated measurements were performed to measure peak oxygen uptake (peak VO2). In this study the data of peak VO2 are revisited and extended: We made use of all collected data as a mixed longitudinal design including cross-sectionally measured subjects as well as longitudinally measured subjects. This led to the availability of 1,194 boys and 1356 girls. With generalized estimating equations (GEE) the longitudinal changes with chronological age and differences between boys and girls were analyzed. Teenage boys and girls increased their peak VO2 (ml/min) significantly \( (p < .001) \) until age 14 in girls and until age 17 in boys. However peak VO2 relative to bodyweight (peak VO2/BW) had significantly \( (p < .001) \) decreased over the whole age range from 12 to 36 in both sexes. Vigorous physical activity (VPA) also showed a decrease and was significantly \( (p < .001) \) related with lower peak VO2/BW (Beta = 0.001). This relation was stronger in boys than in girls. Because at the start of AGAHLS no fast responding metabolic instruments were available, future longitudinal studies about aerobic fitness should include also measurement of VO2 kinetics.

Introduction

In 1989 the Amsterdam Growth and Health Longitudinal Study (AGAHLS) research group published in the first volume of *Pediatric Exercise Science* a study with the
results of 10 years of longitudinal changes of aerobic fitness in male and female adolescents, from 12 to 23 years old (17).

The purpose of this study was to answer the following questions: (a) Does aerobic fitness decrease during the teenage period? (b) Is there a difference between males and females? (c) To what extent can daily physical activity explain this development?

It is now 25 years later, and one of the reprints on yellowed paper is on my desk. Reading the 14 printed pages with nine figures brings us back to the first longitudinal results of measurement of maximal aerobic power with direct measurement of peak VO₂, measured on a treadmill in a mobile laboratory.

The AGAHLS study, with five repeated measurements between the ages of 12 and 21, was extended with three follow-up measurements at the age of 27, 32, and 36 years.

Looking back at the 1989 publication, we used strictly longitudinally collected data of peak VO₂. In this present study we revisited the AGAHLS database adding cross-sectional data collected from a comparable control group. This control group was used to correct for possible testing and/or learning effects (16). From age 32 onwards this control group was also measured longitudinally.

The purpose of this study is (a) to compare the earlier pure longitudinal peak VO₂ data with the current mixed-longitudinal data and to analyze age- and sex-related trends over the whole age range from 12 to 36 years of age and (b) to analyze the longitudinal relationship between peak VO₂ and habitual physical activity, applying advanced statistical analyses.

**Methods**

**Subjects**

The subjects in this study were pupils from two secondary schools in the region of Amsterdam. All boys and girls in the first and second class grade of these schools (age range between 12 and 14 years) were invited to participate. School authorities invited the parents to be involved with their children to take part in the longitudinal measurements that were completed during normal school hours. The pupils were from three birth cohorts: 1962, 1963, and 1964. At baseline (1976), written informed consent was given by parents and pupils. At the time ethical approval was not needed.

**Measurements**

The initial measurements took place in front of the schools in a mobile laboratory. The participating boys and girls came individually to this laboratory. After school age the boys and girls were invited to the same mobile laboratory on the campus of the University in Amsterdam.

The mobile laboratory (10x3x2 m) combined an exercise unit with anthropometric materials (spring balance (SECA,NL), wall-mounted digital stadiometer, skinfold and, bone diameter caliper, Harpenden, UK). Maximal aerobic fitness (the maximal rate of delivery of oxygen by the cardiovascular and respiratory system and utilization by the skeletal muscles) was measured by a direct method using
a progressive protocol. Running at a constant speed of 8 kph was performed on a treadmill (Quinton, model 18–54). We used a procedure from Bar-Or et al. (8) with a submaximal test preceding a maximal test. The submaximal test consisted of three 2-min runs, with slopes of 0%, 2.5%, and 5% (in that order). During the warm-up for this submaximal test, the subjects were familiarized with running on the treadmill with a mouthpiece and nose clip.

After a short period of rest (10–15 min) running was continued for the maximal test. In this maximal test the slope was increased every 2 min by 2.5 or 5%, depending on the heart rate. This maximal test was continued until complete exhaustion had been reached. Each subject was encouraged verbally to exercise to his or her maximum. Heart rate was monitored telemetrically (Telecust 36, and Sirecust BS 1, Siemens NL) at rest, sitting on a chair, before the exercise test, and throughout the test. It was derived from the mean of 15 R-R intervals, measured in the last minute of each 2-minute period and in the last minute of the maximal test.

Expired air was measured by a 10 L high speed, low resistance dry-gas meter (Parkinson Cowan CD4, IA USA) via a two-way low resistance breathing valve.

We calculated respiratory rate (FR), Ventilation volume (VE, BTPS) and Tidal volume (VT). Oxygen uptake (VO$_2$) and Carbon dioxide production (VCO$_2$) was measured each minute throughout the exercise test, using the open-circuit method with samples of mixed expired air. The fractional concentration of oxygen was analyzed by paramagnetic analyzer (Servomex BV) and for carbon dioxide by infrared analyzer (Mijnhardt BV, NL). The gas meter, and the two gas analysers were integrated in an Ergoanalyzer (Mijnhardt, BV, NL). Measurement of VO$_2$ with the Ergoanalyzer has proven to be comparable to the classical method of collecting expired air in Douglas Bags and analyzing CO$_2$ and O$_2$ with Scholander technique (13). The maximal oxygen uptake during the exercise test was used as the peak VO$_2$ of that subject and the measurement was expressed as the mean value in ml per minute.

The exercise test was performed in all 8 years of measurements in the same mobile laboratory, on the same treadmill with the same metabolic unit, the same running protocol and with the same test leader (HCGK). This is an important procedure to avoid confounding effects in the longitudinal measurement of aerobic fitness over a total period of 25 years.

Daily physical activity was estimated by a standardized physical activity questionnaire/interview based on a validated questionnaire (27). At age 36 this standardized activity interview was computerized. This physical activity questionnaire/interview (PAQ) was retrospective and concerned the previous 3 months. It covered the following domains: (un)organized sports activities, active transportation to and from school, work etc., and work and home activities. Only those physical activities were taken into account, which had a duration of at least 5 min and a metabolic intensity level (MET) of more than four times the basal metabolic rate (>4 MET). Three metabolic levels of intensity were discerned: light intensity physical activity (LPA)(4–7 MET), moderate intensity physical activity (MPA; 7–10 MET) and vigorous intensity physical activity(VPA; >10 MET). The MET scores were taken from the compendium of physical activities from Ainsworth et al. (1). From that a total physical activity intensity score was calculated (TPA) as the product of the duration (min) and metabolic intensity scores (MET) per week (24). The vigorous intensity physical activity score (VPA) and the TPA scores are used in this paper.
Design

The AGAHLS was originally set up in 1974 to measure aerobic fitness in boys and girls during their adolescence and to evaluate how lifestyle (including physical activity and food intake) would change in relation to their development of health (15).

A multiple longitudinal design (33) with three birth cohorts was chosen, to control for cohort effects. Also a control group from another school with boys and girls from the same birth cohorts was included. However, these pupils were measured only once during the initial first four annual measurements. At this time it enabled us to control for eventually occurring test- or learning effects caused by repeated measurements (21,22,28). The control group was reinvited to join the study at the measurements at 32 and 36 years.

In the current study, all valid peak VO\(_2\) data of all subjects at all 8 years of measurements between 1977 and 2001 were used. Thus, in total 1,356 peak VO\(_2\) measurements in females and 1,194 peak VO\(_2\) measurements in males were included in the analysis. The subjects were arranged according their chronological age at all available time points of measurement (e.g., chronological age group 14 are all subjects with a chronological age between 13.5 and 14.5 at the time point of measurement).

Figure 1 shows the number of boys and girls in each chronological age group. The lowest number of teenagers (~100) was measured at chronological age 12 and at age 17. The numbers in other chronological age groups ranged from 200–400.

Statistical Analyses

With the development of (new) statistical techniques, such as generalized estimating equations (GEE) it has become possible to analyze longitudinal data and longitudinal relationships using all available longitudinal data, without summarizing the
longitudinal development of each subject into one value (23,34). With the GEE technique a correction is made for the dependency of the observations within one individual.

GEE was used to analyze the linear development over time for the different peak VO₂ and PAQ variables. Moreover, differences between boys and girls in the development of peak VO2 and physical activity over chronological age were analyzed by adding an interaction term between time and sex to the GEE model. Finally, GEE was also used to analyze the longitudinal relationship between the two variables peak VO₂ and VPA, measured at all data points, irrespective of the time-period between subsequent measurements.

All GEE analyses were performed with STATA (Version12; 32), and for all analyses a p-value <.05 was considered statistically significant.

Results

Figure 2 shows the mean values of peak VO₂ (ml/min) separately for girls and boys from age 12–36 years of age. During the teenage period (12–17 years) there was an increase in peak VO₂ for girls of ~10% and for boys of ~30%. Thereafter, from 21 to 32 years of age a small decrease occurred in both sexes. At the last measurement at age 36 both males and females showed an increase of ~10%. Mean peak VO₂ values were significantly (p < .001) higher in males than in females over the whole age period.

If peak VO₂ was related to bodyweight (peak VO₂/BW), as it is most often expressed in the literature, in both males and females (Figure 3), peak VO₂ (ml/kg-min) continuously decreasing from age 12 to age 32. The decrease was significantly (p < .001) greater in boys than girls until age 32. Boys showed significantly (p < .001) higher mean values than girls over the whole age range.

Figure 4 shows the mean values of peak VO₂ relative to bodyweight to the 2/3 power. This measure takes into account the same scaling factor of bodyweight as peak VO₂ (30). The decrease in peak VO₂ (ml/min·kg²/3) was less pronounced than for VO₂ (ml/kg·min); in boys there was no decrease during adolescence. From age 21 onwards both boys and girls showed a significant decrease until age 32.

Figure 5 shows the change in vigorous physical activity (VPA in METS/week). Mean VPA was significantly (p < .001) higher in boys compared with girls from age 12 until age 21. In boys, VPA decreased during their teens by ~50%. From age 21 years onwards differences between males and females disappeared.

The longitudinal relationship between VO₂peak (ml/min·kg) with VPA (METS/week) showed a highly significant (p < .001) and positive correlation.

Discussion

The editorial board of PES challenged the authors from the 1989 paper (17) to reflect on that paper and to indicate how far we have advanced in 25 years. This question has been taken literally by showing the longitudinal data that we collected since then (11,19,20). The peak VO₂ (ml/min) has stabilized from age 23 onwards in both boys and girls and only at the last measurement at age 36, there was a slight increase in both sexes. This increase was concomitant with an increase in the
Figure 2 — Mean values of peak VO$_2$ (ml/min) over the age range from 12 to 36 years, separate for boys and girls.

Figure 3 — Mean values of peak VO$_2$ relative to bodyweight (peak VO$_2$/BW in ml/kg.min) separately for boys and girls over the chronological age range from 12 to 36 years.
Figure 4 — Mean values of peak VO2 relative to bodyweight/2/3 (peak VO2 in ml/kg^{2/3}.min) separately for boys and girls over the chronological age range from 12 to 36 years.

Figure 5 — Mean values of vigorous physical activity levels (VPA) in Mets/week, separately for boys and girls over the chronological age range from 12 to 36 years.
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maximal slope reached at the end of the maximal treadmill test (data not shown) and also with an increase in VPA (see Figure 5). The latter suggests that in their thirties both men and women had adopted a more active lifestyle in combination with raising young children. Another explanation is the fact that at age 36 the PAQ was computerized and that this change may have led to the apparent increase in VPA. If we had taken total physical activity (TPA) as the measure of habitual physical activity (including also LPA and MPA), a tremendous increase from 3300 METS/week to 5000 METS/week (~50%) was manifested at age 36 in both sexes (see Figure 6). The same change in the PAQ methodology could have caused this confounding trend. More objective methods of measurements of physical activity, such as step counters and heart rate monitors, as used in the first four years of the AGAHLS, are therefore advised in future longitudinal studies (9).

Comparison of Aerobic Fitness During Adolescence in Cross-Sectional Pure and Mixed Longitudinal Data

Peak VO₂ during adolescence has been extensively documented by Armstrong et al. (2). A database with 5000 peak VO₂ values of 8–16 year olds showed an almost linear increase in boys’ peak VO₂. Girls’ data demonstrate a similar but less consistent trend with a tendency of peak VO₂ to plateau at about 14 years of age.

Our pure longitudinal data published in 1989 (17) follow this trend and the mixed longitudinal data (see Figure 2) are not different. The only striking difference is that the Dutch boys and girls have significantly higher mean absolute

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**Figure 6** — Mean values of total physical activity levels (TPA) in Mets/week, separately for boys and girls over the chronological age range from 12 to 36 years.
peak VO₂ values compared with the British boys and girls during the adolescent years.

If peak VO₂ is expressed as the simple ratio of peak VO₂ divided by body weight (ml/min/kg) a different picture emerges: In our pure longitudinal data set boy’s peak VO₂/BW is remarkably constant with a mean value of 59 ml/kg/min, but in the mixed longitudinal data set it decreases gradually to 53 ml/kg/min. Comparison with the Armstrong and Welsman database (5) reveals that British boys’ peak VO₂ /BW remains stable from 6 to 18 years at about 48 ml/kg/min with girls’ values showing a decline from 45 to 35 ml/kg/min. These mean values are however 10–15% lower than the Dutch data.

Comparison of aerobic fitness from our AGAHLS with a database that represent mean values from studies with samples from various sizes and different nations must be interpreted cautiously. Higher mean values of aerobic fitness in the Dutch population can be explained by higher habitual physical activity by commuter cycling to and from school (about 80% of boys and girls actively commute to school until age 16 years).

The mixed longitudinal data presented and analyzed in this paper created more longitudinal data points (six instead of four over the chronological age range from 12 to 17 years) with more subjects per chronological age (twice as much) than the pure longitudinal data published in 1989. This can explain why in boys a small decrease of 1 ml/min/kg per year in peak VO₂/BW could be demonstrated in their teens.

Relationship of Aerobic Fitness With Vigorous Physical Activity

The longitudinal relation between VPA (MET s/week) and aerobic fitness (peakVO₂/ BW in ml/kg/min) over the age range from 12 to 36 years revealed a positive and significant ($p < .001$) association. This is in contrast with studies stretching back over 35 years which show no meaningful relationship (6, 25). The difference with the current study is, that many of these studies did not monitor VPA over a sufficiently long duration and that our data extend over a longer age range, including young adulthood. The limitation of our data are that they came from a standardized interview, based on a questionnaire and not on objective physical activity measurements such as pedometry and heart rate monitoring. (27) However during the teenage period we checked the reliability and the validity of the Physical Activity Questionnaire (PAQ). Test-retest reliability was high ($r = .62$ in boys and $.75$ in girls). However, the validity compared with pedometer and 48-hr heart rate registration was relatively low ($r = .16$ and $.20$, respectively; 18).

VO₂max, Peak VO₂, and VO₂ Kinetics

We have to differentiate between VO₂max (the maximal oxygen uptake measured during an exercise test while reaching a VO₂ plateau) and peak VO₂ (the highest oxygen uptake during an exercise test). The reason is that in children and adolescents, an absolute leveling-off of VO₂ seldom occurs with increasing exercise intensity (3,12,26). Astrand (7) was the first to formulate that a rise of less than 150 ml in oxygen uptake can be assumed as a plateau. In the AGAHLS database during the adolescence period, 50% of the boys and 60% of the girls reached this
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plateau. More importantly, the comparison of boys and girls who demonstrated a VO₂ plateau with those who did not showed no significant higher peak VO₂ (14). The most commonly applied criterion for VO₂ plateau in children is a body mass-related requirement for an increase in VO₂ of less than 2.0 ml/kg-min for a 5–10% increase in exercise intensity (31). Two studies (4, 29) have experimentally demonstrated that peak VO₂, as defined above, can be accepted as maximal index of children’s aerobic fitness.

The development of rapid responding flow meters permit measurement of gas exchange data on breath-by-breath basis. This new technology, not available at the start of our AGAHLS in the seventies of the past century, enables present studies to measure not only youth’s peak VO₂, but also their VO₂ kinetics response to increasing exercise intensity (10). The primary time constant of the VO₂ kinetics response to moderate and vigorous intensity exercise decreases with chronological age and boys have a higher time constant than girls during the transition from rest to vigorous intensity exercise. The faster the response of VO₂ during increasing exercise intensity (from rest to moderate and from moderate to vigorous intensity exercise) should attribute to a better aerobic fitness. Therefore, it seems important in future longitudinal studies to monitor aerobic fitness not only based on changes in peak VO₂ but also on VO₂ kinetics. This is under the assumption that in children with the same peak VO₂, the ones with the fastest VO₂ kinetics will have the best aerobic fitness.

Conclusions

The most interesting findings of the current study were that peak VO₂ (expressed relative to body weight) was higher in boys compared with girls over the longitudinal period between 12 and 36 years of age and that for both genders a slight but significant decrease over time was observed. Furthermore, the difference in VPA between boys and girls during adolescence disappeared in young adulthood, mainly caused by a sharp decrease in VPA in males.

Moreover, this 25 years of longitudinal research in adolescence and young adulthood revealed that changes in instruments, procedures and of investigators can be an important confounder in detecting intraindividual changes in health and lifestyle.

Finally, general age and sex differences of relatively large teenage populations of purely longitudinal peak VO₂ and habitual physical activity data are not much different from mixed longitudinal data.

References


