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The influence of training and maturity status on girls' responses to short-term, high-intensity upper and lower body exercise

Melitta A. McNarry[1], Joanne R. Welsman[1] and Andrew M. Jones[1]

[1] School of Sport and Health Sciences, St. Luke's Campus, University of Exeter, Heavitree Road, Exeter EX1 2LU, United Kingdom

Correspondence to:

Melitta A. McNarry

School of Sport and Health Sciences

St. Luke's Campus

University of Exeter

Heavitree Road

Exeter

EX1 2LU

United Kingdom

M.A.Winlove@exeter.ac.uk

Abstract

A maturational threshold has been suggested to be present in young peoples' responses to exercise, with significant influences of training status only evidenced above this threshold. The presence of such a threshold has not been investigated for short term, high intensity exercise. To address this, we investigated the relationship between swim-training status and maturity on the power output, pulmonary gas exchange and metabolic responses to upper (UP) and lower body (LO) Wingate Anaerobic Test (WAnT). Girls at three stages of maturity: pre-pubertal (Pre: 8 trained (T) 10 untrained (UT)); pubertal (Pub: 9 T, 15 UT); and post-pubertal (Post: 8 T, 10 UT) participated. At all maturity stages, T exhibited higher peak power (PP) and mean power (MP) during UP (PP: Pre, T, 163±20 vs. UT, 124±29; Pub, T, 230±42 vs. UT, 173±41; Post, T, 245±41 vs. UT, 190±40 W; MP: Pre, T, 130±23 vs. UT, 85±26; Pub, T, 184±37 vs. UT, 123±38; Post, T, 200±30 vs. UT, 150±15 W; all $P<0.05$) but not LO exercise, whilst the fatigue index was significantly lower in T for both exercise modalities. Irrespective of maturity, the oxidative contribution, calculated by the area under the $\dot{V}O_2$ response profile, was not influenced by training status. No interaction was evident between training status and maturity, with similar magnitudes of difference between T and UT at all three maturity stages. These results suggest there is no maturational threshold which must be surpassed for significant influences of training status to be manifest in the 'anaerobic' exercise performance of young girls.

Keywords

Wingate; fatigue index; peak $\dot{V}O_{2;}$ oxidative contribution; NIRS; exercise modality

Introduction

The short-term, high-intensity nature of the Wingate Anaerobic test (WAnT) is highly relevant to the habitual activity and play patterns of young people (Bailey et al. 1995). Nonetheless, relatively few studies have examined children's physiological response to short-term, high-intensity exercise and, consequently, the influences of growth, maturation and training status on 'anaerobic' exercise performance in young people remain poorly understood (Williams 2008). There is a particular dearth of such information in young girls. Therefore, although a significantly higher peak power (PP) and mean power (MP) and lower fatigue index (FI) have been reported in trained young boys (Counil et al. 2003; Grodjinovsky et al. 1981; Ingle et al. 2006; Rotstein et al. 1986), it remains to be resolved whether similar influences of training status are present in young girls.

Training status has been reported to significantly influence the physiological responses to exercise in pre-pubertal girls (Bencke et al. 2002; McManus et al. 1997), although these effects may be confined to PP (McManus et al. 1997) or to the sport investigated (Bencke et al. 2002). In contrast, for adolescent girls no influence of training status on WAnT test performance has been reported (Seigler et al. 2003). This latter finding might be considered surprising given the significant effects of training status found in women during anaerobic tests (Liljedahl et al. 1996; Serresse et al. 1989). Furthermore, this finding contradicts the notion of a 'maturational threshold', below which significant physiological adaptations to training cannot occur (Katch 1983). This concept has been debated for many years with regard to aerobic exercise responses, with some studies supporting the concept (Kobayashi et al. 1978; Mirwald et al. 1981) and others refuting it (Danis et al. 2003; Weber et al. 1976).

The possibility that a maturational threshold for training status exists in the physiological response to short-term, high-intensity exercise has not been investigated.

The WAnT was originally devised as an anaerobic test but recent studies have reported a significant contribution of oxidative phosphorylation to ATP resynthesis during the test in both adults (e.g. Bediz et al. 1998; Calbet et al. 1997; Granier et al. 1995) and children (Chia 1997; 2006). Furthermore, this oxidative contribution has been reported to be greater in trained adults compared to their untrained counterparts (Granier et al. 1995), an effect that may be related to the faster $\dot{V}O_2$ kinetics of trained adults (e.g. Figueira et al. 2008; Koppo et al. 2004; Powers et al. 1985). The influence of training status on the oxidative contribution to the WAnT in young people has yet to be investigated.

The purpose of the present cross-sectional study was to investigate the influence of training status on the responses to upper-body (arm crank) and lower-body (cycle) WAnT in pre-pubertal, pubertal and post-pubertal girls. We hypothesised that the trained girls would exhibit a significantly higher PP, MP and oxidative contribution and a lower FI, with the difference between trained and untrained girls increasing with maturity. We also hypothesised that the differences associated with training status would be more pronounced during upper than lower-body exercise due to the predominantly upper body nature of swimming (Ogita et al. 1996).

Methods

Participants

In total, 18 pre-pubertal (8 trained, 10 untrained), 24 pubertal (9 trained, 15 untrained) and 18 post-pubertal (8 trained, 10 untrained) girls participated in this study. The trained girls (T) were all regional, national or international level swimmers. The pre-pubertal girls had been training for a mean of 2.5 (± 1) years and reported a mean training volume of 14 (± 3) $hrs \cdot wk^{-1}$. The pubertal and post-pubertal girls had been training 5 (± 1.5) years and 8 (± 2) years respectively, with training volumes of 18 (± 4) and 22 (± 3) $hrs \cdot wk^{-1}$, respectively. The training programme was predominantly aerobic although short, high intensity repetitions were also completed. In accordance with the long-term athlete development programme, the younger maturity groups were completing non-specific swimming training programmes whilst the post-pubertal swimmers were at the early stages of tailoring their training for specific swimming events. There was no bias amongst this group towards sprint, middle or long distance swimming events. The untrained (UT) group comprised volunteers from local schools who did not participate in any form of organised sport outside the national curriculum. Sexual maturity was assessed by self-report using the indices of pubic hair described by Tanner (1962). Age to peak height velocity was estimated to provide an additional indicator of physical maturity according to the equations of Mirwald *et al*. (2002), which are based on the measurement of standing and seated height, weight, and date of birth as described below.

Anthropometry

An anthropometrical evaluation was performed before the first test for all participants. Standing and seated height were measured to 0.1 cm using a Holtain stadiometer (Holtain, Crymych, Dyfed, UK) and body mass (BM) was determined using Avery beam balance scales to 0.05 kg (Avery, Birmingham, UK). Skinfold thickness was assessed three times at five sites on the body (bicep, triceps, subscapular, supra-iliac crest and thigh) by the same researcher for all participants using Harpenden callipers (Baty International, Burgess Hill, UK), accurate to the nearest 0.2mm. The mean of the three measurements was taken. Percentage body fat and fat free mass (FFM) were subsequently estimated based on the equations of Slaughter et al. (1988).

Participants were asked to arrive at the laboratory in a rested and fully hydrated state, at least 3 hours postprandial and to refrain from consuming caffeinated drinks in the 6 hours prior to the test. The methods employed during this study were approved by the institutional research ethics committee and all participants and their parents/guardians gave written informed consent and assent, respectively.

Experimental protocols and measures

The Wingate tests were conducted on two identical basket loaded cycle ergometers (Monark model 814 *E*), one of which was modified to allow upper body exercise. The seat height was adjusted to suit each participant, ensuring a slight flexion in the knee during the cycle WAnT and that the centre of the pedal crank was in line with the middle of the participants' glenohumeral joint during the upper body WAnT.

Each participant completed two WAnTs, one upper (UP) and one lower (LO) body, on separate days. The WAnT was preceded by a standardised 3 minute warm-up performed at a steady pace at the minimum ergometer resistance. This was interspersed at 1 min, 2 min and 2.5 minutes with a 3 s, all-out sprint against the actual test resistance to familiarise the participants with the test protocol. The resistance was set at 0.075 $kg \cdot kg^{-1}$ BM and 0.045 $kg \cdot kg^{-1}$ BM for the LO and UP WAnT, respectively, based on the guidelines of Bar-Or (1983). After a 2 minute rest, the WAnT itself commenced with 3 minutes sitting stationary on the ergometer for the assessment of baseline responses. Following this, participants were asked to accelerate the unloaded flywheel to 60 rpm and a 3 s countdown was given. On "GO!", the participants accelerated as fast as possible and the load basket was dropped. Participants were asked to pedal as fast as they could for the entire 30 s test and warned beforehand that signs of pacing would result in the test being repeated. Strong verbal encouragement was provided through-out the 30 s test.

Throughout the WAnT, gas exchange variables (Metalyser 3B Cortex, Biophysik, Leipzig, Germany) and heart rate (Polar S610, Polar Electro Oy, Kempele, Finland) were measured on a breath-by-breath basis and displayed online**.** Prior to each test the gas analyser was calibrated using gases of known concentration and the turbine volume transducer was calibrated using a 3-litre syringe (Hans Rudolph, Kansas City, MO). The delay in the capillary gas transit and analyser rise time were accounted for relative to the volume signal, thereby time aligning the concentration and volume signals.

Data analysis

Power output variables were corrected for flywheel inertia and internal resistance (Chia et al. 1997) and reported for each second of exercise. Peak power (PP) was defined as the highest 1-s value and mean power (MP) was defined as the mean power output over the entire test. The fatigue index (FI) was calculated as the change in power output relative to PP ((PP – end power / PP)*100).

Breath-by-breath data were interpolated to 1 s intervals and the peak $\dot{V}O_2$ was defined as the highest 3 s average. The relative contribution of oxidative phosphorylation to the total energy expenditure during the 30 s WAnT was calculated by determining the area under the curve of $\dot{V}O_2$ as a function of time, described by non-linear regression. This VO_2 was subsequently converted to the oxidative energy cost of exercise by multiplying by 20.92 $J \cdot mL \cdot O_2^{-1}$ and expressed relative to the total work done for the 30 s WAnT. Mechanical efficiency values of 13% (Kavanagh & Jacobs 1988) and 30% (Bar-Or 1996) were employed to allow comparison to previous paediatric studies (Chia et al. 1997).

To determine the kinetics of the $\dot{V}O_2$ response, the interpolated data were modelled using a mono-exponential function without a time delay, as reported by Calbet et al. (2003) (Graphpad Prism, Graphpad Software, San Diego, CA):

$$\Delta VO_{2(t)} = A \cdot \left(1 - e^{-\left(\frac{t}{\tau}\right)}\right)$$

Where $\Delta\dot{V}O_2$ is the increase in $\dot{V}O_2$ at time *t* above the baseline value (calculated as the mean $\dot{V}O_2$ from the first 45 s of the last minute of baseline), A and τ are the amplitude and time constant, respectively.

Statistical analyses

A two way ANOVA with repeated measures was used to analyse training status and exercise mode effects. Subsequent independent or paired samples t-tests were employed as appropriate to identify the specific location of significant effects. The interaction of training status and sexual maturity stage was investigated using a factorial ANOVA. The influence of body size was accounted for using analysis of covariance (ANCOVA) on log transformed data to determine the allometric relationship between body mass and peak $\dot{V}O_2$, PP and MP (Welsman et al. 2000). The allometric relationship was also determined between estimated fat free mass (FFM) and PP and MP. Log-linear ANCOVA identified common exponents for all participants at each maturity stage for peak $\dot{V}O_2$, PP and MP with BM and FFM. All data are presented as means ± SD. Statistical significance was accepted when $P < 0.05$.

Results

Anthropometric characteristics, presented in Table 1, did not differ significantly between trained and untrained girls within each maturity group. All the girls in the pre-pubertal group were self-characterised as Tanner stage 1, whilst the pubertal girls were stages 3 and 4 and post-pubertal were stage 5.

Influence of training status

The influence of training status on PP and MP was dependent on exercise modality in all maturity groups, with no influence evident during cycle ergometry but significantly higher values being present in the trained girls during upper body ergometry, as summarised in Table 2 and shown in Figure 1. These differences remained significant subsequent to ratio or allometric scaling with the exception of PP in the pre-pubertal girls. In contrast, irrespective of exercise modality, the trained girls in all maturity groups exhibited a lower fatigue index. During upper but not lower body ergometry, the trained girls in all three maturity groups demonstrated a significantly greater total work done (KJ; Pre: T, 3.9 ± 0.7 vs. UT, 2.6 ± 0.8; Pub: T, 5.5 ± 1.1 vs. UT, 3.7 ± 1.1; Post: T, 6.0 ± 0.9 vs. UT, 4.5 ± 1.2, all $P<0.05$).

Trained girls achieved a significantly higher peak $\dot{V}O_2$ during upper body ergometry in all three maturity groups and during lower body ergometry in pubertal and post-pubertal girls, as shown in Table 3. The trained girls in all maturity groups had faster $\dot{V}O_2$ kinetics during the 30 s WAnT for both exercise modalities, as shown in Figure 2. Despite this, the oxidative contribution to total energy expenditure was only influenced by training status in the post-pubertal girls during lower body ergometry. The $\dot{V}O_2$ τ was significantly related to peak $\dot{V}O_2$ during upper body exercise in all three maturity groups (Pre, r = -0.73; Pub, -0.52; Post, -0.48; all $P<0.05$) and during lower body exercise in pubertal (r = -0.46; $P<0.05$) and post-pubertal girls (r = -0.66; $P<0.01$).

Interaction of training status with maturity

No interaction was evident between maturity and training status for the mechanical power or $\dot{V}O_2$ related parameters, with statistically similar differences between trained and untrained girls being evident at all three stages of maturity and for both modes of exercise (Tables 2, 3, 4).

Discussion

The main finding of the present study was that training status significantly influenced both the mechanical power and the $\dot{V}O_2$ responses of girls to short-term, high-intensity exercise across three stages of maturity. Moreover, the magnitude of these training status differences was not modulated by maturity. These data therefore suggest that there is no maturational threshold which must be surpassed for significant influences of training status to be manifest (Katch 1983).

Influence of training status

The current results broadly agree with previous studies reporting significant influences of training status in pre-pubertal girls (Bencke et al. 2002; McManus et al. 1997). The effects of training status were greater in our study compared to that of McManus et al. (1997), who reported effects on PP only, perhaps as a consequence of the more trained status of the present participants. Bencke et al. (2002) reported significant influences of swim-training status during lower body exercise, whilst we found significant influences during upper body exercise only. The explanation for this discrepancy is obscure.

In adolescent girls, no influence of training status on any mechanical power parameter has been reported (Siegler et al. 2003). These findings contrast with the current results for both pubertal and post-pubertal girls. Direct comparisons to this previous study are hindered by the absence of a maturity assessment of the ~ 16 year old girls, who may have been late-pubertal or post-pubertal. The discrepancy with the present findings may also be attributable to an insufficient training stimulus in the study of Siegler et al. (2003) since all participants were involved in regular football training with a subset undertaking additional resistance and plyometric training. Alternatively, or additionally, a discrepancy between the training modalities and the test modality (cycle) may explain the contradictory results (Grodjinovsky et al. 1981).

In contrast to the results of the present study, the FI has previously been reported to be unaffected by training status in girls (Bencke et al. 2002; Siegler et al. 2003). A lower FI in our trained participants indicates a superior ability to maintain power output near the peak power output as the test proceeds. These results suggest that whilst PP and MP may be influenced by both aerobic (Obert et al. 2001; Rotstein et al. 1986) and anaerobic (Grodjinovsky et al. 1981; Ingle et al. 2006) based training programmes, aerobic training is more effective at reducing the FI. The mechanistic basis for this is unclear but may be related to alterations in oxidative capacity and fatigue resistance in type II muscle fibres (Jones and Carter, 2000).

Before considering the possible mechanistic basis of the aforementioned training status related differences, it is appropriate to highlight the cross-sectional design of this study. A fundamental advantage of this design is that it allows the investigation of the physiological effects of long-term, intensive training programmes, the replication of which is very challenging using longitudinal intervention based studies. However, the compromise is that it precludes the elucidation of whether the training status differences are attributable to training *per se* or are a reflection of the participants' genotypes, or uncontrolled factors such as sampling bias or non-physiological learning effects.

The mechanistic basis of training-status related enhancements in the mechanical power indices of children remain unclear (Obert et al. 2001), although a number of putative mechanisms have been proposed including changes in muscle metabolism, muscle mass and/or muscle fibre type. Suggestions of an altered muscle metabolism are based on early muscle biopsy studies which reported increased concentrations of adenosine triphosphate, phosphocreatine (PCr) and muscle glycogen, along with an increased activity of several glycolytic enzymes in trained children (Cadefau et al. 1990; Eriksson et al. 1973; Fournier et al. 1982). However, more recent studies failed to find any influence of training status on intramuscular pH or the ratio of PCr to inorganic phosphate, both of which have been suggested to be indicators of glycolytic capacity (Kuno et al. 1995). Lower limb muscle mass is a major determinant of the mechanical power response to short-term, high-intensity cycle exercise in healthy, untrained children (Davies et al. 1972; Mercier et al. 1992; Santos et al. 2003). Whether upper body muscle mass is similarly influential in determining the mechanical power response to short term, high intensity upper body exercise is unknown. A potential role of muscle fibre type distribution and/or recruitment in determining training status related differences has been suggested on the basis of reports in adults suggesting an increased percentage of type I muscle fibres in trained participants (Russell et al. 2003; Saltin and Gollnick 1983). However, due to ethical constraints, no information is presently available in young people to corroborate or refute this possibility. Thus evidence regarding the mechanistic basis of training status related differences in the mechanical power indices of young people is inconclusive.

This is the first study to investigate the influence of training status on the oxidative contribution to short-term, high-intensity exercise in young people. In agreement with previous studies in both children (Chia et al. 1997; 2006) and adults (e.g. Bediz et al. 1998; Calbet et al. 1997; Granier et al. 1995), a significant oxidative contribution to the WAnT test was observed. However, contrary to our hypothesis and to previous findings in adults (Granier et al. 1995), the influence of training status was limited to lower body exercise in post-pubertal girls; no influence was evident in the oxidative contribution to either upper or lower body WAnT exercise in pre-pubertal or pubertal girls. This finding is surprising considering the significantly faster $\dot{V}O_2$ kinetics observed in the trained girls at all three stages of maturity, which one would anticipate would result in a greater oxidative contribution to meet the energy demands. The explanation for the apparent lack of training status on the oxidative contribution to the WAnT may be related to an equal influence of training status on both the oxidative (Eriksson et al. 1973; Fournier et al. 1982) and glycolytic components of energy provision (Cadefau et al. 1990; Eriksson et al. 1973; Fournier et al. 1982), such that the overall balance is not altered by training status. Further studies investigating the influence of training status on oxidative and glycolytic components of energy provision are required in young people.

As hypothesised, the influence of training status was significantly more pronounced during upper than lower body exercise, a finding most likely attributable to the predominantly upper body nature of swimming (Ogita et al. 1996). This finding, which agrees with previous reports in young boys (Grodjinovsky et al. 1981), highlights the importance of the exercise modality in revealing training status effects in the response to short-term, high-intensity exercise in biologically immature populations. A failure to account for disparities between the training and testing modalities may explain the absence of training status influences on the short-term, high-intensity exercise response of girls previously reported (McManus et al. 1997; Siegler et al. 2003).

Interaction of training status with maturity

The interaction between training status and maturity during short-term, high-intensity exercise in young populations has not previously been investigated. Contrary to our hypothesis, no interaction was found between the magnitude of training status related differences and maturity for any parameter during either lower or upper body exercise. This finding contrasts with the classic theory of Katch (1983) which suggests the presence of a maturational threshold below which significant physiological adaptations to training are not manifest. These findings have potentially important implications for youth training programmes, indicating that training benefits can be obtained even before puberty. Further research is required to elucidate whether these conclusions are specific to girls and/or swimming, as it may be anticipated that the changes in the hormonal milieu associated with the onset of puberty (Daly et al. 1998; Tsolakis et al. 2003; Zakas et al. 1994) would have a more significant impact in boys and/or in strength/power related sports. Furthermore, it must be determined if the manifestation of significant influences of training status during pre-puberty are associated with additional benefits during adulthood. It should be emphasised that any such benefit would need to be balanced with the increased chance of burnout or injury typically associated with intensive training at a young age (Baxter-Jones & Helms 1996; Hemery 1988; Hollander et al. 1995; Salguero & Gonzalez-Boto 2003; Starosta 1996).

In conclusion, this study has demonstrated significant influences of training status on the mechanical power indices during upper body WAnT, irrespective of maturity status in 11-17 year old girls. Specifically, PP and MP were both higher and the FI was lower in swim-trained pre-pubertal, pubertal and post-pubertal girls relative to their untrained counterparts during a 30 s all-out upper body exercise test. The dichotomy in the influence of training status between the upper and lower body highlights the importance of exercise modality in revealing training status influences. The present results indicate the presence of a significant oxidative contribution to energy provision during a WAnT test in girls. However, this oxidative contribution is not influenced by training status despite significantly faster $\dot{V}O_2$ kinetics in the trained girls. Finally, this study suggests that the influence of training status on short-term, high-intensity exercise performance is similar regardless of maturity stage, providing evidence against the concept of a maturational threshold in girls' responses to short-term, high-intensity exercise.

References

Bailey, R. B., Olson, J., Pepper, S. L., Porszasz, J., Barstow, T. J., and Cooper, D. M. 1995. The level and tempo of children's physical activities: an observational study. Med Sci Sport Exerc. **27**(7): 1033-1041.

Bar-Or, O. 1983. Pediatric sports medicine for the practitioner. New York: Springer-Verlag.

Bar-Or, O. 1996. Anaerobic performance. *In* Measurement in Pediatric Exercise Science. *Edited by* D. Docherty. Champaign, Il: Human Kinetics. pp. 161-182.

Baxter-Jones, A. D. G., and Helms, P. 1996. Effects of training at a young age: A review of the training of young athletes (TOYA) study. Pediatr. Exerc. Sci. **8**: 310-327.

Bediz, C. S., Gokbel, H., Kara, M., Ucok, K., Cikrikci, E., and Ergene, N. 1998. Comparison of the aerobic contributions to Wingate anaerobic tests performed with two different loads. J. Sports Med. Phys. Fit. **38**(1): 30-34.

Bencke, J., Damsgaard, R., Saekmose, A., Jorgensen, P., Jorgensen, K., and Klausen, K. 2002. Anaerobic power and muscle strength characteristics of 11 years old elite and non-elite boys and girls from gymnastics, team handball, tennis and swimming. Scandinavian Journal of Medicine & Science in Sports. **12**(3): 171-178.

Cadefau, J., Casademont, J., Grau, J. M., Fernandez, J., Balaguer, A., Vernet, M., and Urbanomarquez, A. 1990. Biochemical and histochemical adaptation to sprint training in young athletes. Acta Physiol. Scand. **140**(3): 341-351.

Calbet, J. A. L., Chavarren, J., and Dorado, C. 1997. Fractional use of anaerobic capacity during a 30- and a 45-s Wingate test. Eur. J. Appl. Physiol. Occup. Physiol. **76**(4): 308-313.

Calbet, J. A. L., De Paz, J. A., Garatachea, N., De Vaca, S. C., and Chavarren, J. 2003. Anaerobic energy provision does not limit Wingate exercise performance in endurance-trained cyclists. J. Appl. Physiol. **94**(2): 668-676.

Chia, M. 2006. Aerobic energy contribution to maximal exercise in children. Biol. Sport. **23**(2): 117-125.

Chia, M., Armstrong, N., and Childs, D. 1997. The assessment of children's anaerobic performance using modifications of the Wingate Anaerobic Test. Pediatr. Exerc. Sci. **9**(1): 80-89.

Counil, F. P., Varray, A., Matecki, S., Beurey, A., Marchal, P., Voisin, M., et al. 2003. Training of aerobic and anaerobic fitness in children with asthma. J. Pediatr. **142**(2): 179-184.

Daly, R. M., Rich, P. A., and Klein, R. 1998. Hormonal responses to physical training in high-level peripubertal male gymnasts. Eur. J. Appl. Physiol. Occup. Physiol. **79**(1): 74-81.

Danis, A., Kyriazis, Y., and Klissouras, V. 2003. The effect of training in male prepubertal and pubertal monozygotic twins. Eur. J. Appl. Physiol. **89**(3-4): 309-318.

Davies, C. T. M., Barnes, C., and Godfrey, S. 1972. Body composition and maximal exercise performance in children. Hum. Biol. **44**(2): 195-&.

Eriksson, B. O., Gollnick, P. D., and Saltin, B. 1973. Muscle metabolism and enzyme activities after training in boys 11-13 years old. Acta Physiol. Scand. **87**(4): 485-497.

Figueira, T. R., Caputo, F., Machado, C. E. P., and Denadai, B. S. 2008. Aerobic fitness level typical of elite athletes is not associated with even faster VO_2 kinetics during cycling exercise. J. Sport. Sci. Med. **7**(1): 132-138.

Fournier, M., Ricci, J., Taylor, A. W., Ferguson, R. J., Montpetit, R. R., and Chaitman, B. R. 1982. Skeletal-muscle adaptation in adolescent boys - sprint and endurance training and detraining. Med. Sci. Sports Exerc. **14**(6): 453-456.

Granier, P., Mercier, B., Mercier, J., Anselme, F., and Prefaut, C. 1995. Aerobic and anaerobic contribution to wingate test-performance in sprint and middle-distance runners. Eur. J. Appl. Physiol. Occup. Physiol. **70**(1): 58-65.

Grodjinovsky, A., Inbar, O., Dotan, O., and Bar-Or, O. 1981. Training effect on the anaerobic performance of children as measured by the Winagte anaerobic test. *In* Children and Exercise IX. *Edited by* K. Berg & B. O. Eriksson. Baltimore, MD: Univeristy Park Press. pp. 139-145.

Hemery, D. 1988. Should a child specialise in just one sport? The pursuit of sporting excellence: A study of sport's highest achievers. Champaign, Il: Human Kinetics.

Hollander, E. B., Meyers, M. C., and LeUnes, A. 1995. Psychological factors associated with overtraining: Implications for youth sport coaches. J Sport Behav. **18**: 3-20.

Ingle, L., Sleap, M., and Tolfrey, K. 2006. The effect of a complex training and detraining programme on selected strength and power variables in early pubertal boys. J. Sports Sci. **24**(9): 987-997.

Jones, A. M., and Carter, H. 2000. The effect of endurance training on parameters of aerobic fitness. Sports Med. **29**(6): 373-86.

Katch, V. L. 1983. Physical conditioning of children. J. Adolesc. Health, **3**(4): 241-246.

Kavanagh, M. F., and Jacobs, I. 1988. Breath-by-breath oxygen consumption during performance of the Wingate Test. Can J Sports Sci. **13**: 91-93.

Kobayashi, K., Kitamura, K., Miura, M., Sodeyama, H., Miyashita, M., and Matsui, H. 1978. Aerobic power as related to body growth in Japanese boys: a longitudinal study. J. Appl. Physiol. **44**: 666-672.

Koppo, K., Bouckaert, J., and Jones, A. M. 2004. Effects of training status and exercise intensity on phase II VO_2 kinetics. Med Sci Sports Exerc. **36**(2): 225-232.

Kuno, S. Y., Takahashi, H., Fujimoto, K., Akima, H., Miyamaru, M., Nemoto, I., et al. 1995. Muscle metabolism during exercise using P-31 nuclear-magentic-resonance spectroscopy in adolescents. Eur. J. Appl. Physiol. Occup. Physiol. **70**(4): 301-304.

Liljedahl, M. E., Ingemar, H., Christer, S., and Eva, J. 1996. Different responses of skeletal muscle following sprint training in men and women. Eur. J. Appl. Physiol. **74**(4): 375-383.

McManus, A. M., Armstrong, N., and Williams, C. A. 1997. Effect of training on the aerobic power and anaerobic performance of prepubertal girls. Acta Paediatr. **86**(5): 456-459.

McNarry, M. A., Welsman, J., and Jones, A. M. 2010. Influence of training status and exercise modality on pulmonary O_2 uptake kinetics in pubertal girls. Eur. J. Appl. Physiol. doi: 10.1007/s00421-010-1681-6

McNarry, M. A., Welsman, J. R., and Jones, A. M. 2010. Influence of training and maturity status on the cardiopulmonary responses to ramp incremental cycle and upper body exercise in girls. J. Appl. Physiol. doi: japplphysiol.00988.02010.

Mercier, B., Mercier, J., Granier, P., Legallais, D., and Prefaut, C. 1992. Maximal anaerobic power - relationship to anthropometric characteristics during growth. Int. J. Sports Med. **13**(1): 21-26.

Mirwald, R. L., Bailey, D. A., Cameron, N., and Rasmussen, R. L. 1981. Longitudinal comparison of aerobic power in active and inactive boys aged 7.0 to 17.0 years. Ann Hum Biol. **8**(5): 405-414.

Mirwald, R. L., Baxter-Jones, A. D. G., Bailey, D. A., and Beunen, G. P. 2002. An assessment of maturity from anthropometric measurements. Med. Sci. Sports Exerc. **34**: 689-694.

Obert, P., Mandigout, M., Vinet, A., and Courteix, D. 2001. Effect of a 13-week aerobic training programme on the maximal power developed during a force-velocity test in prepubertal boys and girls. Int. J. Sports Med. **22**(6): 442-446.

Ogita, F., Hara, M., and Tabata, I. 1996. Anaerobic capacity and maximal oxygen uptake during arm stroke, leg kicking and whole body swimming. Acta Physiol. Scand. **157**(4): 435-441.

Powers, S. K., Dodd, S., and Beadle, R. E. 1985. Oxygen uptake kinetics in trained athletes differing in VO_2 max. Eur. J. Appl. Physiol. **54**: 306-308.

Rotstein, A., Dotan, R., Baror, O., and Tenenbaum, G. 1986. Effect of training on anaerobic threshold. maximal aerobic power and anaerobic performance of preadolescent boys. Int. J. Sports Med. **7**(5): 281-286.

Russell, A., Wadley, G., Snow, R., Giacobino, J. P., Muzzin, P., Garnham, A., et al. 2002. Slow component of VO_2 kinetics: the effect of training status, fibre type, UCP3 mRNA and citrate synthase activity. Int. J. Obes. **26**(2): 157-164.

Salguero, A., and Gonzalez-Boto, R. 2003. Identification of dropout reasons in young competitive swimmers. J. Sports Med. Phys. Fit. **43**(4): 530-534.

Saltin, B., and Gollnick, P. D. 1983. Skeletal muscle adaptability: significance for metabolism and performance. *In* Handbook of Physiology *Edited by* ed. Bethesda, MD: Physiological Society. (pp. 555-631)

Santos, A. M. C., Armstrong, N., De Ste Croix, M. B. A., Sharpe, P., and Welsman, J. 2003. Optimal peak power in relation to age, body size, gender, and thigh muscle volume. Pediatr. Exerc. Sci. **15**(4): 406-418.

Serresse, O., Ama, P. F. M., Simoneau, J. A., Lortie, G., Bouchard, C., and Boulay, M. R. 1989. Anaerobic performances of sedentary and trained subjects. Can J Sport Sci. **14**(1): 46-52.

Siegler, J., Gaskill, S., and Ruby, B. 2003. Changes evaluated in soccer-specific power endurance either with or without a 10-week, in-season, intermittent, high-intensity training protocol. J. Strength Cond. Res. **17**(2): 379-387.

Slaughter, M. H., Lohman, T. G., Boileau, R. A., Horswill, C. A., Stillman, R. J., Vanloan, M. D., & et al. 1988. Skinfold equations for estimation of body fatness in children and youth. Hum. Biol. **60**(5): 709-723.

Starosta, W. 1996. Selection of children in sport. *In* Current Research in Sport Sciences: An International Perspective. *Edited by* V. Rogozkin & R. M. Maughan. London: Plenum Press. pp. 21-25.

Tanner, J. M. 1962. Growth of Adolescence (2nd edition ed.). Oxford: Blackwell Scientific.

Tsolakis, C., Vagenas, G., and Dessypris, A. 2003. Growth and anabolic hormones, leptin, and neuromuscular performance in moderately trained prepubescent athletes and untrained boys. J. Strength Cond. Res. **17**(1): 40-46.

Weber, G., Kartodihardjo, W., and Klissouras, V. 1976. Growth and physical-training with reference to heredity. J. Appl. Physiol. **40**(2): 211-215.

Welsman J and Armstrong N. 2000. Statistical techniques for interpreting body size-related exercise performance during growth. Pediatr. Exerc. Sci. **12:** 112-127.

Williams, C. A. 2008. Maximal intensity exercise. *In* Paediatric Exercise Science and Medicine. *Edited by* N. Armstrong & W. Van Mechelen. Oxford: Oxford University Press. pp. 227-241.

Winlove, M. A., Jones, A. M., and Welsman, J. 2010. Influence of training status and exercise modality on pulmonary O_2 uptake kinetics in pre-pubertal girls. Eur. J. Appl. Physiol. **108**(6): 1169-1179.

Zakas, A., Mandroukas, K., Karamouzis, G., and Panagiotopoulou, G. 1994. Physical training, growth hormone and testosterone levels and blood pressure in prepubertal, pubertal and adolescent boys. Scand J Med Sci Sports. **4**(2): 113-118.

Table 1. Participants' anthropometric characteristics

	Pre-pubertal		Pubertal		Post-pubertal	
	Trained	Untrained	Trained	Untrained	Trained	Untrained
	N = 8	N = 10	N = 9	N = 15	N = 8	N = 10
Age (y)	11.2 ± 1.0	11.9 ± 0.9	14.2 ± 0.8	14.2 ± 0.6	16.6 ± 0.6	16.7 ± 0.8
Stature (m)	1.48 ± 0.08	1.50 ± 0.06	1.66 ± 0.05	1.60 ± 0.06	1.67 ± 0.04	1.69 ± 0.06
Mass (kg)	43.2 ± 3.1	43.6 ± 6.6	56.9 ± 6.7	54.9 ± 7.0	59.4 ± 7.6	61.7 ± 6.7
Sum of skinfolds (mm)	67.0 ± 17.4	59.2 ± 13.2	63.6 ± 15.3	67.3 ± 18.6	54.3 ± 16.5	69.8 ± 32.3
Body fat (%)	26.7 ± 8.5	25.3 ± 5.9	29 ± 10	31 ± 9	24 ± 11	27 ± 9

Values are mean ± S.D.

* *Significant difference between pre-pubertal and pubertal girls within trained or untrained children (P<0.01)*

† *Significant difference between pubertal and post-pubertal girls within trained or untrained children (P<0.01)*

Table 2. Mechanical power indices in trained and untrained girls at 3 stages of maturity during a lower and upper body WAnT

	Pre-pubertal		**Pubertal**		**Post-pubertal**	
	Trained	Untrained	Trained	Untrained	Trained	Untrained
	N = 8	N = 10	N = 9	N = 15	N = 8	N = 10
			Cycle WAnT			
PP (W)	325 ± 41	359 ± 72	496 ± 90 #	454 ± 109 #	487 ± 106	541 ± 20
PP ($W \cdot kg^{-1}$BM)	7.3 ± 1.1	8.3 ± 1.6	8.9 ± 1.2	8.3 ± 1.5	8.5 ± 1.4	8.8 ± 1.3
PP ($W \cdot kg^{-1}$FFM)	9.5 ± 1.2	11.1 ± 2.2	12.4 ± 2.8	12.4 ± 1.7	10.2 ± 1.8	12.2 ± 1.6
MP (W)	258 ± 42	274 ± 70	400 ± 60 #	352 ± 77 #	388 ± 55	421 ± 35
MP ($W \cdot kg^{-1}$BM)	5.9 ± 0.9	6.3 ± 1.5	7.1 ± 1.0 #	6.4 ± 1.0	6.8 ± 0.8	6.9 ± 0.9
MP ($W \cdot kg^{-1}$FFM)	7.8 ± 0.8	8.4 ± 2.2	10.0 ± 2.0	9.6 ± 1.2	8.5 ± 1.3	9.4 ± 0.7
FI (%)	28 ± 11	42 ± 10 *	30 ± 13	42 ± 9 *	32 ± 8	44 ± 10 *
			Upper body WAnT			
PP (W)	163 ± 20 †	124 ± 29 *†	230 ± 42 †	173 ± 41 *†	245 ± 41 †	190 ± 40 *†
PP ($W \cdot kg^{-1}$)	3.8 ± 0.6 †	2.9 ± 0.7 *†	4.0 ± 0.4 †	3.4 ± 0.9 *†	4.1 ± 0.4 †	3.1 ± 0.8 *†
PP ($W \cdot kg^{-1}$FFM)	4.8 ± 3.9 †	3.9 ± 1.0 †	5.6 ± 0.9 †	4.5 ± 0.6 *†	5.7 ± 1.1 †	4.3 ± 0.9 *†
MP (W)	130 ± 23 †	85 ± 26 *†	184 ± 37 †	123 ± 38 *†	200 ± 30 †	150 ± 15 *†
MP ($W \cdot kg^{-1}$)	3.0 ± 0.5 †	2.0 ± 0.6 *†	3.2 ± 0.4 †	2.5 ± 0.9 *†	3.4 ± 0.3 †	2.5 ± 0.8 *†
MP ($W \cdot kg^{-1}$FFM)	3.8 ± 0.6 †	2.6 ± 1.0 *†	4.5 ± 0.9 †	3.3 ± 0.5 *†	4.6 ± 0.8 †	3.4 ± 0.9 *†
FI (%)	35 ± 12	50 ± 16 *	32 ± 14	46 ± 16 *	32 ± 6	44 ± 12 *

Values are mean ± S.D. PP, peak power; MP, mean power; FI, fatigue index; BM, body mass; FFM, fat free mass

* *Significant difference between trained and untrained children within a maturity group (P<0.05)*

\# *Significant difference compared to previous maturity stage within training status group (P<0.05)*

† *Significant difference between exercise modalities within training status and maturity status group (P<0.05)*

Table 3. Peak oxygen uptake and oxidative contribution to energy provision in trained and untrained girls at 3 stages of maturity during a lower and upper body WAnT

	Pre-pubertal		**Pubertal**		**Post-pubertal**	
	Trained	Untrained	Trained	Untrained	Trained	Untrained
	N = 8	N = 10	N = 9	N = 15	N = 8	N = 10
			Cycle WAnT			
Peak $\dot{V}O_2$ ($L \cdot min^{-1}$)	1.8 ± 0.3	1.6 ± 0.3	2.2 ± 0.3	1.8 ± 0.2 *	2.5 ± 0.2	2.2 ± 0.2 $^{*\#}$
Peak $\dot{V}O_2$ ($mL \cdot kg^{-1} \cdot min^{-1}$)	43 ± 6	38 ± 5	38 ± 7	34 ± 4 *	43 ± 4	35 ± 7 *
Oxidative 13% (%)	14 ± 3	14 ± 2	13 ± 3	12 ± 2	15 ± 2	10 ± 2 *
Oxidative 30% (%)	33 ± 7	32 ± 5	30 ± 6	27 ± 5	34 ± 4	23 ± 5 *
$\dot{V}O_2$ τ (s)	15 ± 6	20 ± 4	9 ± 5	17 ± 2 *	8 ± 3	18 ± 3 *
			Upper body WAnT			
Peak $\dot{V}O_2$ ($L \cdot min^{-1}$)	1.6 ± 0.2 †	1.1 ± 0.3 *†	2.1 ± 0.2 $^{\#}$	1.4 ± 0.2 $^{*\dagger\#}$	2.1 ± 0.4 †	1.5 ± 0.3 *†
Peak $\dot{V}O_2$ ($mL \cdot kg^{-1} \cdot min^{-1}$)	36 ± 7 †	25 ± 5 *†	36 ± 4	27 ± 7 *†	35 ± 6 †	23 ± 5 *†
Oxidative 13% (%)	21 ± 3 †	25 ± 6 †	20 ± 5 †	20 ± 7 †	16 ± 4	16 ± 2 †
Oxidative 30% (%)	49 ± 6 †	58 ± 13 †	46 ± 11 †	47 ± 15 †	37 ± 9	37 ± 5 †
$\dot{V}O_2$ τ (s)	12 ± 4	20 ± 4 *	10 ± 4	17 ± 3 $^{*\#}$	10 ± 3	19 ± 2 *

Values are mean ± S.D. $\dot{V}O_2$, oxygen uptake; Oxidative 13%, oxidative contribution assuming 13% mechanical efficiency; Oxidative 30%, oxidative contribution assuming 30% mechanical efficiency

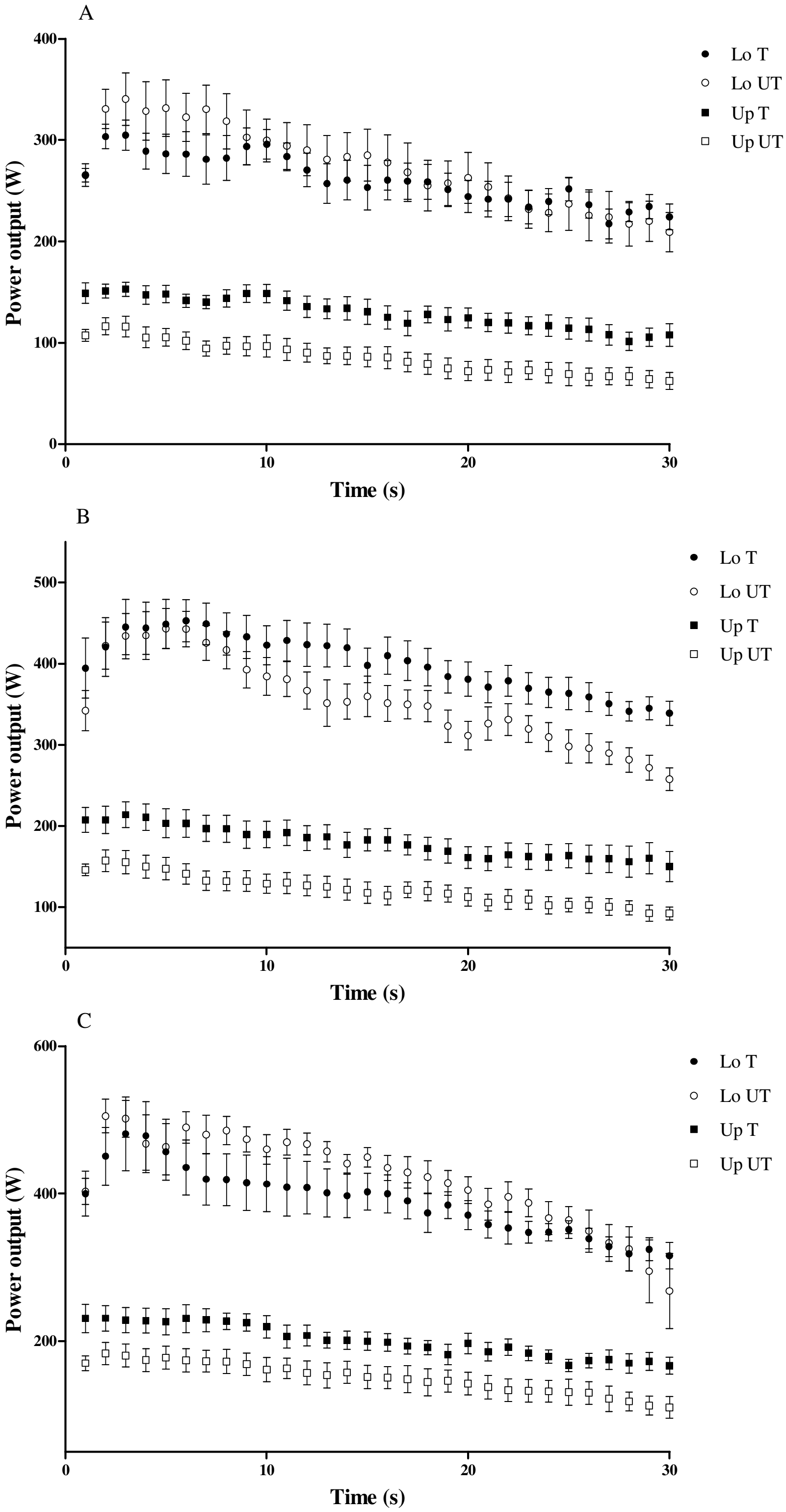
* *Significant difference between trained and untrained children within a maturity group (P<0.01)*

\# *Significant difference compared to previous maturity stage within training status group (P<0.05)*

† *Significant difference between exercise modalities within training status and maturity status group (P<0.05)*

Figure 1. Mean power output responses for (a) pre-pubertal, (b) pubertal and (c) post-pubertal girls during lower body (Lo) and upper body (Up) exercise. Trained girls are shown with closed and untrained girls with open symbols.

Figure 2. Mean $\dot{V}O_2$ responses for (a) pre-pubertal, (b) pubertal and (c) post-pubertal girls during lower bodo (Lo) and upper body (Up) exercise. Trained girls are shown with closed and untrained girls with open symbols.


A
Power output (W)
400
300
200
100
0
Time (s)
0
10
20
30
Lo T
Lo UT
Up T
Up UT
B
Power output (W)
500
400
300
200
100
Time (s)
0
10
20
30
Lo T
Lo UT
Up T
Up UT
C
Power output (W)
600
400
200
Time (s)
0
10
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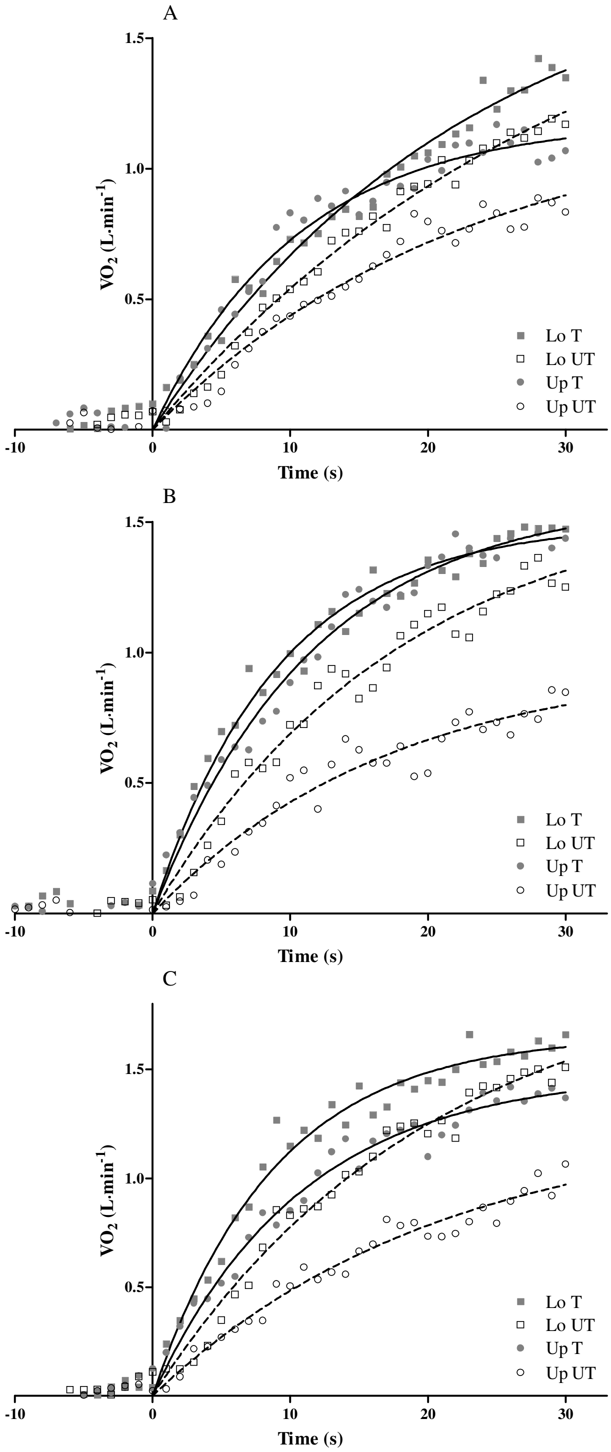
A
1.5
1.0
0.5
VO_2 ($L \cdot min^{-1}$)
-10
0
10
20
30
Time (s)
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Up T
Up UT
B
1.5
1.0
0.5
VO_2 ($L \cdot min^{-1}$)
-10
0
10
20
30
Time (s)
Lo T
Lo UT
Up T
Up UT
C
1.5
1.0
0.5
VO_2 ($L \cdot min^{-1}$)
-10
0
10
20
30
Time (s)
Lo T
Lo UT
Up T
Up UT