Maximal oxygen uptake versus maximal power output in children

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Abstract

Maximal oxygen uptake (VO_{2PEAK}) is considered the optimal method to assess aerobic fitness. Such measurements, however, require special equipment and training. Maximal exercise test with determination of maximum power output (max W) offers a more simple approach. This study explores the relationship between VO_{2PEAK} and max W in 247 children (139 boys and 108 girls), aged 7.9-11.1 years. VO_{2PEAK} was measured by indirect calorimetry during a maximal ergometer exercise test with an initial workload of 30 W and 15 W · min^{-1} increase. Also, maximal power output was measured. A sample (n=124) was used to calculate reference equation, which was then validated in another sample (n=123). Linear reference equation for both gender combined; VO_{2PEAK} (ml · min^{-1}) =96 + 10.6 · max W + 3.5 · body mass. Using this reference equation, estimated VO_{2PEAK} per body mass (ml · min^{-1} · kg^{-1}) calculated from max W correlated closely with direct measurement of VO_{2PEAK}, (r=0.91, P<0.001). Bland-Altman analysis concluded an average limit of agreement of 0.2±2.9 (ml · min^{-1} · kg^{-1}) (1 SD). This study implies that maximum power output serves as a good surrogate measurement for VO_{2PEAK} in population-studies of children aged 8-11 years.

Introduction

Maximal aerobic fitness, defined as maximal oxygen uptake (VO_{2PEAK}), is generally considered to be the best single marker for the functional capacity of the cardio respiratory system. In children low aerobic fitness, assessed by direct measurement of maximum oxygen uptake, has been associated with elevated levels of risk factors for cardiovascular disease (Eiberg *et al*., 2005). However, a wide range of methods are used to assess fitness in population-studies in children including sub-maximal and maximal cycle ergometer tests, sub-maximal and maximal treadmill tests and shuttle-run tests, with or without direct measurement of VO_{2PEAK} (Boreham *et al*., 1997; Tomkinson *et al*., 2003; Eisenmann *et al*., 2005; Ruiz *et al*., 2006; Tomkinson & Olds, 2007; Rizzo *et al*., 2007; Ruiz *et al*., 2007a,b,c). All indirect measures of VO_{2PEAK} introduce errors (Rowland, 1996) and therefore may dilute any existing relationship between fitness and the risk factor or parameter that is investigated. Moreover, the different methods make it difficult to compare studies and to evaluate secular trends in fitness. Direct measurement of VO_{2PEAK} during a maximal exercise test is considered the optimal method to assess aerobic fitness (Rowland, 1996). Measurements of VO_{2PEAK}, however, require special equipment (indirect calorimetry) and training. In addition, daily calibration of the measurement equipment is required. Maximal exercise tests with determination of only maximal power output (max W) on the other hand offer a considerably more simple approach. The hypothesis that maximum power output serves as a good surrogate measurement for VO_{2PEAK} is not new and this hypothesis has been evaluated in adolescents and adults (McArdle & Magel, 1970; Pedersen & Nielsen, 1984; Kuipers *et al.,* 1985; Andersen *et al.,* 1987; Andersen, 1995), also in children (Woynarowska, 1980; Binkhorst *et al.,* 1985; Hansen *et al.,* 1989). Different test protocols may yield different results and the purpose of this report was to re-evaluate the relationship between VO_{2PEAK} and max W in a population-based cohort of children aged 8-11 years.

Materials & Methods

Recruitment of the study cohort has been presented previously (Dencker *et al*., 2006a, b,c; Dencker *et al*., 2007). This cohort was recruited among children in four different schools in Malmö, Sweden. A total of 477 children received an invitation to participate in the study and 248 (140 boys and 108 girls), aged 8 to 11 years accepted the invitation. All schools were situated in socially homogeneous middle-class residential areas with inhabitants of non-immigrant origin. A questioner was used to exclude major illness that could influence the exercise capacity. Height and body mass of all invited children were retrieved from the general health data registered by the school nurses, in order to evaluate whether selection bias had occurred. The institutional ethics committee of the Lund University, Sweden, approved the study. Written informed consent was obtained from the parents of all participating children.

Anthropometric measures

Total body height and mass were measured in the laboratory with the child dressed in light clothing. Height was measured to the nearest cm using a fixed stadiometer (Hultafors AB, Hultafors, Sweden) and body mass was measured to the nearest kg with a standard scale (Avery Berkel model HL 120, Avery Weigh-Tronix Inc, Fairmont, MN, USA). Body mass index (BMI) was calculated as body mass in kilograms divided by height in meters squared ($kg \cdot m^{-2}$). Pubertal status was assessed by self-evaluation according to Tanner (Duke *et al*., 1980).

Measurement of Aerobic Fitness

Aerobic fitness was determined by a maximal exercise test that was performed on an electrically braked cycle ergometer (Rodby rhc, model RE 990, Rodby Innovation AB, Karlskoga, Sweden). Expired gas was sampled continuously via a mixing chamber and analysed for the concentration of O_2 and CO_2 (Sensor Medics 2900, SensorMedics Inc, Yorba Linda, CA, USA). Measurements were obtained every 20 s during two minutes at rest and during exercise to volitional exhaustion. All children, regardless of gender, fitness, height and weight, used the same protocol with an initial workload of 30 Watts (W) and an increase of 15 W · min^{-1} (1 W · 4 sec^{-1}), and were required to cycle at a rate of 53-64 revolutions · min^{-1}. Heart rate (HR) and respiratory exchange ratio (RER) were recorded and displayed throughout the test. Maximal power output in W (max W) from completed 20 second segment, maximum heart rate (max HR) and maximum RER (max RER) were recorded. Predicted max HR was considered to be 195 beats · min^{-1} (Armstrong & Welsman, 2000). VO_{2PEAK} was determined as the highest value recorded during the last minute of exercise. Both VO_{2PEAK} and max W were calculated per kilogram of body mass and also per (kilogram of body mass)$^{2/3}$, which are the two most common approaches to adjust fitness to body size (Rowland, 1996; Welsman & Armstrong, 2000). The exercise test was considered acceptable if it met one of the following criteria; RER ≥ 1.0, max HR >90% of predicted value (≥ 176 beats · min^{-1}) or signs of intense effort (e.g. hyperpnoea, facial flushing or inability to keep adequate revolutions per min (53-64)) (Armstrong & Welshman, 2000). A sample (n=124, boys=70 and girls=54) was used to calculate the various reference equations. The main reference equation was then validated in another sample (n=123, boys=69 and girls=54). The participants that constituted the sample used to calculate reference equations and the participants used to validate the main reference equation were tested during the same days.

Statistical analyses

All analyses were made in Statistica 5.0 (StatSoft Inc, Tulsa, OK, USA). Univariate relationships between VO_{2PEAK} and max W were assessed with Pearson correlation analysis. Group differences between mean values were tested using the unpaired Student´s t-tests. Stepwise multiple regression analysis was used to predict models for absolute values of VO_{2PEAK} or VO_{2PEAK} per kg body mass as the dependent variable and max W, gender, age and body mass as independent variables. Stepwise multiple regression was also used to calculate the standard error of estimate (SEE) for the respective reference equation. Bland-Altman analysis (Bland & Altman, 1986) was used to identify the limit of agreement between direct measurement of VO_{2PEAK} per kg body mass and VO_{2PEAK} calculated from max W determination. Statistical significance was set at a level of $P<0.05$.

Results

One child was excluded due to failure to perform the exercise test. Anthropometric, age and fitness data for the participants providing acceptable measurement (n=247) are displayed in table 1. Five girls were Tanner stage 2 and all remaining 243 children were Tanner stage 1. The final study group consisted of 247 children (boys n=139, girls n=108), where 77% (189/247 all children, 109/139 boys, and 80/108 girls) of the children reached >90% of predicted max HR and 66% (163/247 all children, 94/139 boys, and 69/108 girls) a RER ≥ 1.0. VO_{2PEAK} ($ml \cdot min^{-1} \cdot kg^{-1}$) correlated closely with max W ($W \cdot kg^{-1}$) in the entire sample (n=247), in boys r=0.90, in girls r=0.90, and in both genders r=0.91 ($P<0.001$ for all). Additional analyses were carried out for children who achieved >90% of predicted max HR or RER ≥ 1.0. Values for boys, girls, and all children with max HR >90% were; 0.87, 0.90, and 0.90 ($P<0.001$ for all). Corresponding values for children with RER ≥ 1.0 were; 0.89, 0.88, and 0.89 ($P<0.001$ for all).

Absolute values of VO_{2PEAK} (ml · min^{-1}) correlated closely with max W (W) in boys r=0.89, in girls r=0.88, and in both genders combined r=0.90, (P<0.001 for all). When scaling fitness results to (body mass in kg)$^{2/3}$, similar relationships were observed; r=0.88 for boys, r=0.86 for girls, and r=0.89 for both genders, (P<0.001 for all).

In the group used to calculate the reference equations (n=124), multiple regression analysis indicated that max W was the main predictor (r^2=0.81) for absolute values of VO_{2PEAK}. Including body mass and gender into the model only explained an additional 1% each. This justifies a simple reference equation without separation of gender. However, additional analysis for boys and girls separately indicated that body mass was only a factor in boys and body mass was therefore not included in predicting reference equation for girls.

Linear reference equations for absolute values in boys; VO_{2PEAK} (ml · min^{-1}) =115 + 10.225 · max W (W) + 4.95 · body mass (kg) (SEE=120), girls; VO_{2PEAK} (ml · min^{-1}) =240 + 9.99 · max W (W) (SEE=95), and all children combined; VO_{2PEAK} (ml · min^{-1}) =96 + 10.61 · max W + 3.49 · body mass (kg) (SEE=114).

In the validation group (n=123), correlation coefficients for directly measured VO_{2PEAK} (ml · min^{-1} · kg^{-1}) vs. VO_{2PEAK} (ml · min^{-1} · kg^{-1}) calculated from max W (with the use of the reference equation; VO_{2PEAK} (ml · min^{-1}) =96 + 10.61 · max W + 3.49 · body mass) were for boys r=0.91, girls r=0.90, and r=0.91 for both genders (P<0.001 for all). Corresponding values for children with max HR >90% were; 0.88, 0.87, and 0.89 (P<0.001 for all). Corresponding values for children with RER ≥ 1.0 were; 0.90, 0.90, and 0.91 (P<0.001 for all). Bland-Altman analysis concluded an average limit of agreement of 0.2±2.9 (ml · min^{-1} · kg^{-1}) (1 SD), between directly measured VO_{2PEAK} (ml · min^{-1} · kg^{-1}) vs. VO_{2PEAK} (ml · min^{-1} · kg^{-1}) calculated from max W.

Discussion

This report evaluates the relationship between VO_{2PEAK} and max W in a large population-based cohort of young Swedish children. A strong association was established between VO_{2PEAK} and max W, regardless of which scaling method was applied to adjust fitness results to differences in body composition. Our findings therefore suggest that max W serves as a simple and adequate surrogate measure for VO_{2PEAK}, providing a simple protocol for determining aerobic fitness in epidemiological studies that requires less special equipment and training.

An acceptance rate for the cohort in our study of 52% was somewhat low. However, the anthropometrics did not differ when comparing children that took part in the study and those who did not (Dencker *et al.*, 2006a). This suggests that no fundamental selection bias occurred, and that a fairly representative cross-sectional sample of native urban Swedish children aged 8-11 years was studied.

Direct measurement of VO_{2PEAK}, as used in the present study, is considered the optimal method to assess aerobic fitness (Rowland, 1996). A weakness of this method, however, is the arbitrary criteria used to define a maximum effort. A possible limitation of our study is that only 77% of the total sample reached 90% of predicted max HR and even fewer children an RER $\geq$ 1.0, although they subjectively indicated that they had made a maximum effort. Since it is not ethically acceptable to force children to continue the test when they feel exhausted, some children's VO_{2PEAK} and max W may have been underestimated. One could argue that stricter criteria for an acceptable exercise test should have been used. The VO_{2PEAK} acquired in the present study was, however, a result of a maximal effort according to participating children. Also, no significant differences in the relation between VO_{2PEAK} and max W were observed in those children that attained max HR >90% or ≥ RER 1.0, compared with all children combined. This is encouraging since objective data such as max HR or RER may not be available in a field setting during mass-testing. Furthermore, this suggests that the reference equations reported in this study can be used in such a setting to calculate VO_{2PEAK} from max W, derived from a maximal cycle ergometer test performed to volitional exhaustion. It is also of importance that VO_{2PEAK} is a measurement of the aerobic capacity, whereas max W is a combined measurement of both the aerobic and the anaerobic capacity. One should observe this distinction between the variables and the measurements should not be used interchangeably. These variables are, however, highly correlated especially in younger children since they often do not reach RER >1.0 and therefore do not perform significant anaerobic work. Moreover, our intercept from the main reference equation of 6 ($ml \cdot min^{-1} \cdot kg^{-1}$) at 0 W is a reasonable value for children this age (Åstrand, 1986). Also, boys had a higher intercept than girls, which is in agreement with the fact that boys at this age have higher basal metabolism than girls (Guyton, 1986). The present study only evaluated the effect of maximal cycle ergometer testing with one specific protocol. Maximal treadmill and cycle ergometer testing are known to give different results, where treadmill testing consistently give higher VO_{2PEAK} compared to a cycle ergometer protocol (LeMura *et al.*, 2001).

Several different approaches for surrogate measurements of VO_{2PEAK} have been validated. These include physical work capacity at a heart rate of 170 beats per minute (Petzl *et al.*, 1988; Mahoney, 1992; Rowland *et al.*, 1993), maximal 20 meter shuttle run test (Van

Mechelen *et al*., 1986; Leger *et al*., 1988; Mahoney, 1992; Suminski *et al*., 2004), or endurance time on a treadmill test (Rump *et al*., 2002). All these approaches have been shown to generate weaker correlation coefficients, compared to those in the present study.

The hypothesis that maximum power output serves as a good surrogate measurement for VO_{2PEAK} is not new and this hypothesis has been evaluated in adolescents and adults (McArdle & Magel, 1970; Pedersen & Nielsen, 1984; Kuipers *et al.,* 1985; Andersen *et al.,* 1987; Andersen, 1995), also in children (Woynarowska, 1980; Binkhorst *et al.,* 1985; Hansen *et al.,* 1989). Woynarowska (1980) and Hansen *et al*. (1989) have validated various ergometer cycle protocols. Woynarowska (1980) evaluated 80 boys and 43 girls aged 11-12 years and found significant gender differences in the correlation between directly measured VO_{2PEAK} and VO_{2PEAK} estimated from the Åstrand Ryhming nomogram (Åstrand, 1986) (r=0.82 for girls and r=0.52 for boys). The reference equation derived from this study was for boys; VO_{2PEAK} (ml · min^{-1}) =1.444 · VO_{2PEAK} estimated from the Åstrand Ryhming nomogram, and for girls; VO_{2PEAK} (ml · min^{-1}) =1.2999 · VO_{2PEAK} estimated from the Åstrand Ryhming nomogram. Hansen *et al*. (1989) investigated a small sample of 18 boys and girls aged 10-11 years and found a close correlation between directly measured VO_{2PEAK} and VO_{2PEAK} calculated from max W (r=0.79 for boys and 0.68 for girls). These results are reasonably in line with ours, regardless of whether only those children who attained max HR >90% or ≥ RER 1.0 are analysed, or whether all children are included. Our linear reference equation VO_{2PEAK} (ml · min^{-1}) =96 + 10.6 · max W + 3.5 · body mass (kg), is slightly different to the one published by Hansen *et al*. (1989); VO_{2PEAK} (ml · min^{-1}) =12 · max W + 5 · body mass (kg). The "Hansen equation" has recently been used in several publications (Ruiz *et al*., 2006; Rizzo *et al*., 2007; Ruiz *et al*., 2007a,b,c). For the average child with a body mass of 35 kg and a max W of 105 W, as in our study, the difference between the two reference equations would be 8% (38 vs. 41 (ml · min^{-1} · kg^{-1})) which may be explained partly by differences in test protocols and partly by true differences. These findings indicate that a reference equation derived from one paediatric population can not indiscriminately be used in another population although of similar age. The slope of the linear regression equation in the present study was 10.6 (ml · min^{-1} · W^{-1}), which is very close to 10 (ml · min^{-1} · W^{-1}), which has been suggested for adults (Wasserman, 1994). The slope of 12 (ml · min^{-1} · W^{-1}) in the "Hansen equation" might be attributed to sample size and selection. More importantly, it may be the result of differences in exercise protocols. The present study used a steep ramp with an initial workload of 30 W and an increase of 15 W · min^{-1} (1 W · 4 sec^{-1}), whereas Hansen et al. (1989) had a much flatter ramp with an initial workload of 20 W and an increase of 6.67 W · min^{-1}. If using the reference equation in the present study it is also advisable to similar exercise protocol. One advantage with the present protocol is that it is short and therefore suitable in a mass-testing situation where numerous subjects are to be tested, usually in a short period of time. Binkhorst *et al. (*1985) evaluated a population of Dutch children and adolescents with a mixed age span from 6 to 18 years. This study consisted of 279 children, all children performed a maximal treadmill test and children aged 12 to 18 years (n=154) also performed a maximal cycle ergometer test. They found a close correlation ($r=0.95$, $P<0.05$) between directly measured VO_{2PEAK} and VO_{2PEAK} calculated from max W. The standard deviation of 2.9 (ml · min^{-1} · kg^{-1}) in the present study corresponds to 7-8%, whereas Binkhorst *et al*. (1985) reported values of 10-13% for their group of 12-year-old boys and girls (boys n=13 and girls n=21). Whether this represents a sufficiently precise measurement depend on how the values are being used. It may be inadequate to assess or follow VO_{2PEAK} in each and every individual, whereas it might be adequate to assess VO_{2PEAK} in larger groups of children.

In conclusion, the data from this population-based study suggests that maximum power output serves as a god surrogate measurement for VO_{2PEAK} in population studies and thereby opens the possibilities for a substantially simpler testing protocol for epidemiological studies in paediatric populations.

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Figure legend;

Figure 1: Bland-Altman plot of the limit of agreement between aerobic fitness (VO_{2PEAK}) estimated from maximal power output (max W) and direct measurement of VO_{2PEAK}, both per body mass, in the subset of children used to validate the reference equation (n=123).

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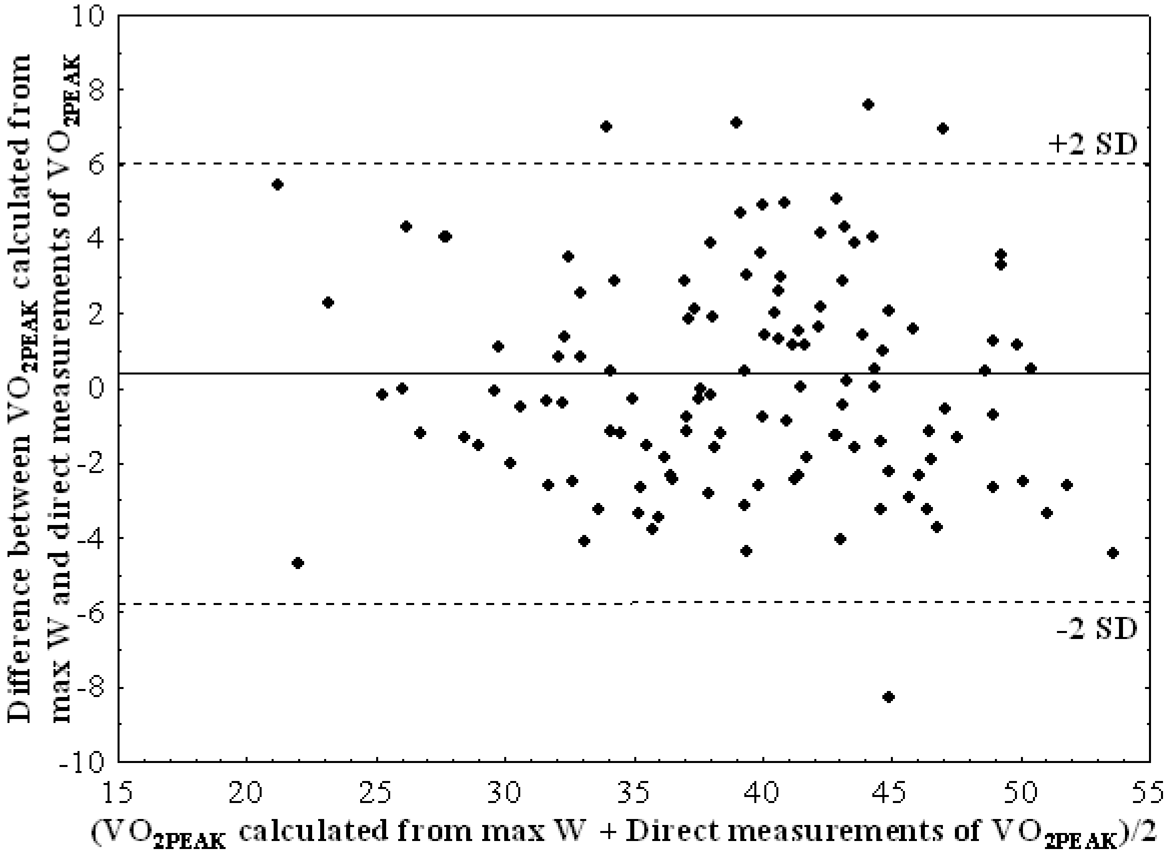
Table 1. Age, anthropometric data and fitness results in children with valid measurements.

Values are presented as mean ± SD.

	Boys (n=139)	Girls (n=108)	P-value
Anthropometrics and age			
Age (y)	9.9±0.6	9.7±0.6	0.07 ns
Height (cm)	141±6.8	140±7.8	0.40 ns
Body mass (kg)	35.0±7.7	34.6±7.7	0.64 ns
BMI ($kg \cdot m^{-2}$)	17.4±2.8	17.4±2.9	0.95 ns
Fitness			
VO_{2PEAK} ($ml \cdot min^{-1}$)	1422±258	1207±203	<0.001
VO_{2PEAK} ($ml \cdot min^{-1} \cdot kg^{-1}$)	42±7.2	36±6.4	<0.001
max W (W)	111±21	97±17	<0.001
max W ($W \cdot kg^{-1}$)	3.3±0.6	2.9±0.5	<0.001
max HR ($beats \cdot min^{-1}$)	188±16.2	185±15.5	0.18 ns
max RER	1.0±0.1	1.0±0.1	0.85 ns

Figure 1



Difference between VO2PEAK calculated from max W and direct measurements of VO2PEAK
(VO2PEAK calculated from max W + Direct measurements of VO2PEAK)/2
+2 SD
-2 SD
10
8
6
4
2
0
-2
-4
-6
-8
-10
15
20
25
30
35
40
45
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