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Original article

Modeling the dose–response rate/associations between VO_{2max} and self-reported Physical Activity Questionnaire in children and adolescents

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Abstract

Background: This study sought to explore the dose–response rate/association between aerobic fitness (VO_{2max}) and self-reported physical activity (PA) and to assess whether this association varies by sex, age, and weight status.

Methods: VO_{2max} was assessed using the 20-m shuttle-run test. PA was assessed using the Physical Activity Questionnaire (PAQ) for Adolescents (aged >11 years, PAQ-A) or for Children (aged ≤11 years, PAQ-C). The associations between VO_{2max} and PAQ were analyzed using analysis of covariance (ANCOVA), adopting PAQ and PAQ² as covariates but allowing the intercepts and slope parameters of PAQ and PAQ² to vary with the categorical variables sex, age group, and weight status.

Results: ANCOVA identified a curvilinear association between VO_{2max} and PAQ, with positive linear PAQ terms that varied for both sex and weight status but with a negative PAQ² term of -0.39 (95% confidence interval (CI): -0.57 to -0.21) that was common for all groups in regard to age, sex, and weight status. These curvilinear (inverted U) associations suggest that the benefits of increasing PA (same dose) on VO_{2max} is greater when children report lower levels of PA compared to children who report higher levels of PA. These dose–response rates were also steeper for boys and were steeper for lean children compared to overweight/obese children.

Conclusion: Health practitioners should be aware that encouraging greater PA (same dose) in inactive and underweight children will result in greater gains in VO_{2max} (response) compared with their active and overweight/obese counterparts.

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Keywords: Aerobic fitness; Curvilinear association; Sex; Slope parameters; Weight status

1. Introduction

The importance of aerobic fitness for health has been well- and long-established. Low levels of aerobic fitness are a strong predictor for a variety of diseases and causes of death in adults. Although there is less data focused on pediatric populations, the studies available suggest that low levels of aerobic fitness are associated with risk factors of cardiovascular disease^{1–5} and that aerobic fitness tracks from childhood into adulthood.^{6–9} Importantly, low levels of aerobic fitness in adolescence are also associated with an increased risk of development of risk factors of cardiovascular disease in adulthood.^{8,9} In adults a positive relationship between daily physical activity (PA) and aerobic fitness

has been established,^{3,4} but for children the association is less clear. This may be because, compared to adults, PA patterns in children are more random, sporadic and not undertaken in sustained bouts.^{10,11} Of the data available, a weak to moderate relationship has been identified between PA and aerobic fitness.¹² Relationships/correlations in the range of 0.10–0.45 have been identified in participants ranging from 4 to 19 years of age.^{13–16} Prior studies by Dencker et al.¹⁷ and Gutin et al.¹⁵ reported no difference in the relationship between boys and girls, whereas research by Kollé et al.¹⁸ reported a stronger relationship between PA and aerobic fitness maximum oxygen uptake (VO_{2max}) in girls compared to boys at age 9 years but the reverse at age 15 years. However, these studies did not distinguish between weight status for girls and boys when examining these relationships.

Epidemiologic studies have identified the role of PA and physical fitness in reducing overweight and obesity in children

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and adolescents.^{19,20} Previous reviews have also provided an overview of studies on the relationship in children and adolescents either between PA and overweight or between fitness and overweight.^{21,22} However, although both PA and aerobic fitness appear to similarly influence health outcomes, including overweight, no studies appear to have examined the parameters of PA, aerobic fitness and weight status together despite the fact that they should not be considered independently.²³ Ortega et al.³ reported a higher body mass index (BMI) in adolescents with lower aerobic fitness independent of level of PA, whereas Fogelholm et al.²⁴ reported that PA was more strongly associated with physical fitness than weight status. The associations between overweight and PA were similar across sex groups, and Fogelholm et al.²⁴ concluded that a physically active person who was also overweight was unlikely to achieve high levels for physical fitness because of the negative association between fitness and weight status. In this case, weight status acts as a confounder of the PA-physical fitness relationship. A review of the literature on this topic by Rauner et al.²⁵ summarized the equivocality of studies on this topic, concluding that the small number of the associations between aerobic fitness and PA, while also considering weight status and sex, precludes any robust conclusions about the relationship being made. It is, however, important to examine how children's PA might be related to aerobic fitness as PA is a modifiable lifestyle behavior to better guide preventive strategies for health enhancement both in children and through adulthood. Such information is useful in more effectively guiding public health policy and developing effective interventions to enhance health. Surprisingly, research has yet to establish any such dose-response curve considering PA, aerobic fitness and weight status together. The purpose of this study was to address this issue by identifying the nature of the (dose-response) associations between VO_{2max} and PA, adjusting for the confounding effects of age, sex, and weight status.

2. Methods

2.1. Participants

This study is based on secondary data analysis of the East of England Healthy Heart Study. Comprehensive details regarding the methods used are presented elsewhere.²⁶ Following the University of Essex Ethical Review Committee's approval of the study, 8002 children (≥ 10 - < 16 years old, 3775 girls) were recruited from a structured convenience sample of 23 state schools. All parents provided written informed consent for their child to participate. All data collection occurred between 2007 and 2009. Only state-run, comprehensive schools were sampled, which ensured that a broad spread of socioeconomic status areas was included in the sample. Letters were sent to schools in the east of England region inviting them to participate in this study. Purposeful sampling was then used to select a representative mix of volunteer schools to take part in the study.

2.2. Outcome variables

2.2.1. Measures of overweight and obesity

Body mass and stature were measured using an SECA Stadiometre and weighing scales (SECA Instruments, Hamburg,

Germany; to the nearest 0.1 kg and 0.1 cm, respectively), with participants dressed in light clothing (T-shirts and shorts) and without shoes. BMI of each participant was calculated in (kg/m^2). We categorized BMI twice to determine the effect of our categorization. In the first analysis, BMI was categorized as underweight, normal weight, overweight, and obese according to the International Obesity Task Force criteria,²⁷ which are less arbitrary criteria than the 85th and 95th cutoffs²⁸ used by the UK's National Obesity Observatory.²⁹

2.2.2. Measures of PA

Each participant completed the Physical Activity Questionnaire (PAQ) for Adolescents (PAQ-A) or Children (PAQ-C). Participants of high school age (> 11 years) completed the PAQ-A, and primary schoolchildren (≤ 11 years) completed the PAQ-C.³⁰ This instrument has been previously validated,³¹ and both the PAQ-A and PAQ-C are compatible, making comparison of data between adolescents and children possible.^{30,32} The PAQ-C is a self-administered, 9-item, 7-day recall of PA designed for adolescents of the ages taking part in the study and shows satisfactory reliability and validity.²³ The PAQ-A is scored on a 5-point Likert scale (1-5), with higher values indicating greater levels of PA. A sample item is: "In the last 7 days, what did you do most of the time at break?" The full questionnaire and scoring method is freely available at www.performwell.org/index.php/find-surveyassessments/outcomes/health-a-safety/good-health-habits/physical-activity-questionnaire-for-children. PAQ-A/C were anglicized (*recess* became *break*; *soccer* became *football*), as described in a previous study.³³

2.2.3. Measurement of aerobic fitness

Fitness was assessed using the 20-m shuttle run test, an incremental running test to maximal exertion.³³ Children ran 20-m shuttles in time to an audible signal at an initial speed of 8.5 km/h, increasing by 0.5 km/h each minute. All testing was carried out by researchers assisted by school physical education staff. Testing was conducted in groups of up to 30 participants, with a ratio of 5 participants to 1 researcher. All participants had undertaken the 20-m shuttle run test previously as part of their school's physical education testing. Recorded instructions on a CD explaining the 20-m shuttle run test instructed participants to "run for as long as possible", and this was reiterated by a researcher at the beginning of each test. Researchers acted as "spotters" during the test and recorded the participant's final shuttle count at either the point of volitional exhaustion or when the participant failed to maintain the given pace for the second time. Running speeds at final completed level were converted to predicted VO_{2max} ($\text{mL}/\text{kg}/\text{min}$), with these values being used as a measure of fitness.³⁴

2.3. Statistical methods

To explore the associations and differences in the PAQ dose-response rate on VO_{2max}, we adopted the following regression model:

$$\text{VO}_{2\text{max}}(\text{mL}/\text{kg}/\text{min}) = a + b \times \text{PAQ} + c \times \text{PAQ}^2 \quad \text{Eq.1}$$

where the parameter “*a*” was allowed to vary by sex, age group, and weight status using analysis of covariance (ANCOVA), adopting the PAQ and PAQ² as covariates. However, the key difference between traditional ANCOVA and the ANCOVA adopted in the current study was that in traditional ANCOVA, the PAQ and PAQ² slope parameters “*b*” and “*c*” remain constant for all categorical variables. The ANCOVA adopted here allowed both the intercepts and slope parameters of PAQ and PAQ² to vary with the categorical variables (sex, age group, and weight status).

Having fitted the saturated model, that is, when all available categorical and covariates together with their interactions are entered into the model, an appropriate parsimonious solution can be obtained using backward elimination, in which the least important (nonsignificant) variable or interaction is eliminated sequentially from the model. A parsimonious model is a model that achieves a desired level of explanation or prediction with as few predictor variables as possible. The Statistical Package for Social Sciences Version 24.0 (SPSS, IBM Corp., Armonk, NY, USA) was used for all analysis.

3. Results

Table 1 presents demographic information regarding the number of participants in the current study by age, sex, and weight status. The parsimonious ANCOVA identified a significant quadratic polynomial association between VO_{2max} and PAQ (entered as both a linear PAQ and PAQ² terms), where the linear PAQ term varied by weight status and sex but the quadratic PAQ² term was common for all groups (Table 2). The PAQ values at which VO_{2max} reaches a peak can be estimated using differential calculus; the results are given in Table 3. As an example, Fig. 1 illustrates the nature of the curvilinear association between VO_{2max} and PAQ for normal-weight boys and overweight girls. Note that the quadratic regression model for normal weight boys’ is given by $VO_{2max} = 32.8 + 5.34 \times PAQ - 0.39 \times PAQ^2$ and the quadratic regression model for overweight girls’ is given by

Table 1
Number of children with complete data by sex, age group, and weight status.

Age group (year)	Underweight	Normal	Overweight	Obese	Total
Girls					
10	9	121	39	11	180
11	65	593	217	49	924
12	65	674	223	47	1009
13	54	546	142	44	786
14	31	424	99	30	584
15	27	214	43	8	292
Boys					
10	11	120	38	12	181
11	49	617	204	68	938
12	57	650	221	63	991
13	47	614	183	47	891
14	38	544	119	37	738
15	24	343	89	32	488
	477	5460	1617	448	8002

Table 2

The curvilinear (quadratic polynomial) association between VO_{2max} and PAQ by sex and weight status, parameters “*b*” and “*c*” as described in Eq. 1.

Linear terms <i>b</i>	Δb	<i>b</i>	95%CI of Δb	
			Lower bound	Upper bound
PAQ				
Underweight	1.81	5.80	0.84	2.78
Normal	1.35	5.34	0.59	2.11
Overweight	0.85	4.84	0.02	1.67
Obese ^a	–	3.99	2.73	5.25
Girls	–0.87	3.12	–1.20	–0.53
Quadratic term “<i>c</i>”				
PAQ ²	–	–0.39	–0.57	–0.21

Notes: ^aReference category: obese boys. PAQ scale 1–5; VO_{2max} (mL/min/kg). Abbreviations: CI = confidence interval; PAQ = Physical Activity Questionnaire; VO_{2max} = maximum oxygen uptake.

$VO_{2max} = 23.58 + 3.97 \times PAQ - 0.39 \times PAQ^2$ (all regression parameters derived for Table 2)

The parsimonious ANCOVA also identified significant differences in the intercept “*a*” of Eq. 1 on VO_{2max} due to age group and weight status together with sex-by-age group and sex-by-weight status interactions having controlled for differences in PAQ and PAQ² (Fig. 2). The parsimonious ANCOVA explained $R^2 = 36.4\%$ (adjusted $R^2 = 36.1\%$) of the variance in VO_{2max} with a residual error of 4.88 mL/kg/min.

4. Discussion

The current study sought to examine the dose–response relationship between PA and aerobic fitness, while also considering gender and weight status, in a sample of British children. The current study is the first to demonstrate that the dose–response relationship between PA and aerobic fitness in children aged ≥ 10 – < 16 years is curvilinear in nature and is influenced by sex and weight status. It is well-known that aerobic fitness (VO_{2max}) increases with greater PA. However, as far as we are aware and for the first time, we have identified that this association is curvilinear, with greater initial benefits (gains in fitness) with sedentary children (those who report low levels of PA) while also considering confounding factors of weight status, age, and sex. This message should be welcomed by those health practitioners who are trying to encourage sedentary children to get more active. Previous work on

Table 3

Estimated PAQ values at which VO_{2max} reaches a peak, estimated using differential calculus.

	Boys’ peak (PAQ units)	Girls’ peak (PAQ units)
Underweight	7.50	6.37
Normal weight	6.91	5.78
Overweight	6.25	5.13
Obese	5.16	4.03

Abbreviations: PAQ = Physical Activity Questionnaire; VO_{2max} = maximum oxygen uptake.

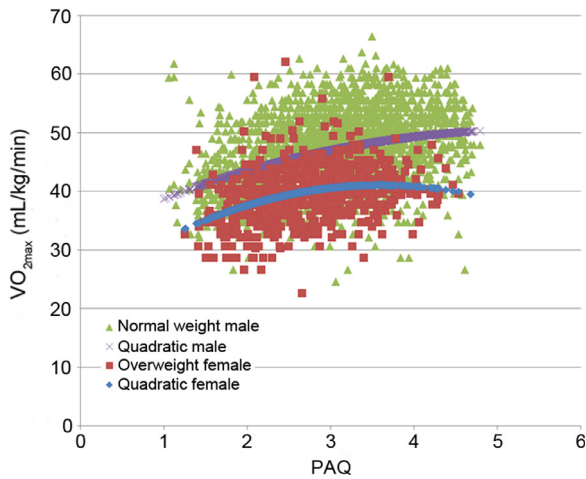


Fig. 1. The curvilinear associations between VO_{2max} and PAQ for normal weight boys and overweight girls. The quadratic regression model for normal weight boys' is given by $VO_{2max} = 32.8 + 5.34 \times PAQ - 0.39 \times PAQ^2$. The quadratic regression model for overweight girls' is given by $VO_{2max} = 23.58 + 3.97 \times PAQ - 0.39 \times PAQ^2$. PAQ = Physical Activity Questionnaire; VO_{2max} = maximum oxygen uptake.

this topic has largely assumed that any dose–response is linear in nature, while our study demonstrates this is not the case. Importantly, the dose–response rate slopes were steeper where PAQ scores were lower. This curvilinear association suggests that the benefits of increasing PA on VO_{2max} is greater (i.e., having a steeper slope) when children are reporting low levels of PA (PAQ scores from 1 to 2) compared to when children are reporting higher levels of PA (PAQ scores from 4 to 5), when the slope parameters would be less steep (Fig. 1).

The dose–response rates in the present study were steeper for boys compared to girls and are steeper in the leaner weight status groups (i.e., underweight and normal weight) compared with the overweight and obese weight status groups (Table 2). This information highlights that the curvilinear association between PA and aerobic fitness needs to be considered in the context of sex and weight status rather than as a simple one-size-fits-all linear association. As a consequence, this information adds to the knowledge base on this issue, since failing to account for the curvilinear association and failing to differentiate between sex and weight status groups may lead to erroneous conclusions about the relationship between increasing PA and increased aerobic fitness. In particular, where girls reported the same amount of PA as boys, PA was associated with lower a VO_{2max}. The pattern was similar for weight status groups where, for the same level of reported PA, the association with VO_{2max} was steeper in the leaner weight status groups.

PA accounted for 36% of the variance in aerobic fitness in the current study. It is important to note that other factors will account for the other 64%. This might include genetics³⁵ or the fact that the PAQ examines short-term (7-day) PA recall and does not provide any assessment of long-term PA patterns. Despite the fact that the PAQ is one of the more valid and reliable self-report measures for use with children,³⁶ the use of self-report questionnaires to assess PA in children is also open to bias in reporting (e.g., overestimating the amount of activity undertaken or seeking social desirability).³⁶ Likewise, the use of a 7-day recall period may preclude situations where an active child has undertaken less activity than is habitually the case (or *vice versa*) in the 7 days prior to the administration of the self-report. All of this may have influenced the estimates of the association between PA and VO_{2max} in the present study.

The findings in the current study may have several explanations. The steeper dose–response slopes observed for boys may be because they can attain a greater ‘potential’ range of performance scores than girls can attain.³⁷ In adults, the difference in aerobic fitness between an untrained man and a trained man is greater than the difference between trained and untrained women.³⁸ The youngest age group in the current study comprised boys, whereas in the oldest age group it is likely there is a mix of boys and men in terms of maturation status. Likewise, for girls, the youngest age group in the present study comprises girls, but the oldest, a mix of girls and women. We therefore see different slopes for boys because the range of scores for aerobic fitness are greater after puberty, compared to before puberty, due to increased body size and

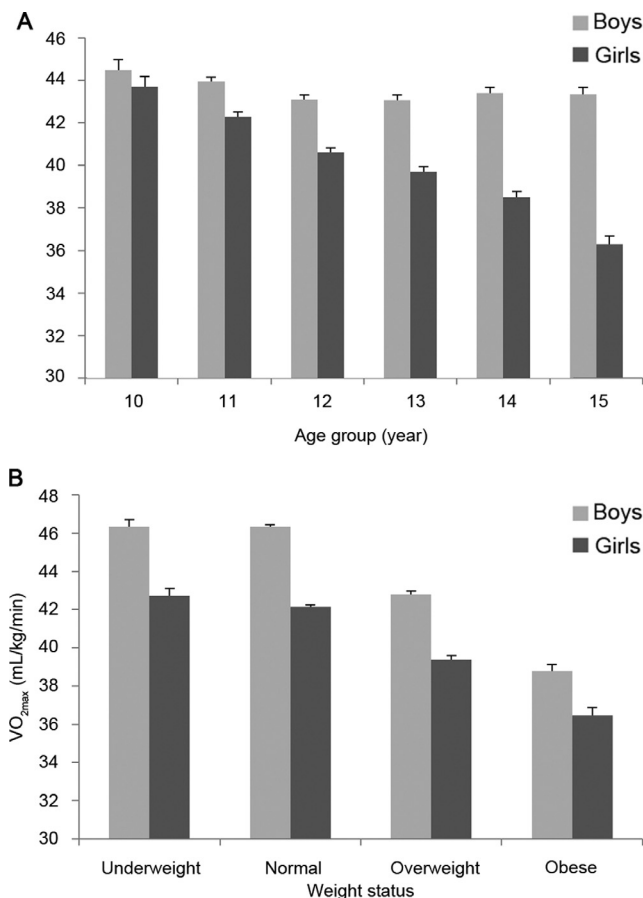


Fig. 2. VO_{2max} (Mean ± SE) by age group and sex (A), weight status and sex (B) having controlled for differences in self-reported PAQ and PAQ² scores. PAQ = Physical Activity Questionnaire; VO_{2max} = maximum oxygen uptake.

lean mass in active males (*vs.* boys) and lower fat mass in active women (*vs.* girls). Importantly, the parsimonious model reported in the current study suggests that although the slope parameters may differ by age, they were not significant when the curvilinear nature of the PAQ–VO_{2max} relationship was considered. Similarly, performance on weight-bearing aerobic performance tests, such as the 20-m shuttle run test, is typically greater in leaner individuals,³⁹ resulting in a greater potential range of scores for leaner individuals.

There are, of course, some limitations of the present study. We acknowledge that the cross-sectional nature of the data precludes any conclusions being made in relation to causality. Even though the 20-m shuttle run test is a widely used and validated tool for estimating VO_{2max}, particularly in pediatric populations, test familiarization and day-to-day performance variation may influence results.⁴⁰ Variations in the motivation to perform and understating of instructions might also have caused the results to differ in relation to age and maturity level.¹² It is not ethically acceptable to force a child to continue a test when the child has reached volitional exhaustion; thus, some children's VO_{2max} scores may be underestimated. Indeed, an alternative explanation for the steeper dose–response curve identified for the relationship between PA and aerobic fitness in overweight and obese children may be because children in these weight status groups overestimate how much PA they actually do, given that many forms of PA feel harder to do when there is greater metabolically inert mass (*i.e.*, fat mass), resulting in inflation of PA scores. Recent systematic review data identified the PAQ, which was used in the present study, as one of the most reliable and valid self-report measures of PA for use with children and adolescents.³⁶ However, the same review also noted that children's self-report of activity does not provide the fidelity of PA measurement that objective methods such as accelerometry may provide.³⁶ Future research should therefore consider assessment of PA via accelerometry either alongside self-report measures or instead of self-report measures. Maturation was not assessed in the present study. Given the age ranges of the participants, it is highly likely that maturation plays a role in the differential dose–response curves we identify. One strength of the present study is the use of a large-scale data set that captures PA and aerobic fitness variables. The limitations noted above are consistent with such large-scale epidemiologic approaches where it is more difficult and labor intensive to assess VO_{2max} directly or use objective measures such as accelerometry to capture PA or where it is deemed too sensitive to assess maturation in the school setting. Consequently, future research that confirms the data presented here and addresses these issues would be welcome.

5. Conclusion

The results of the current study suggest that the dose–response relationship between PA and aerobic fitness in children aged ≥10–<16 years is curvilinear in nature. In the current study the association between PA and VO_{2max} is greater/steeper in magnitude when children are less active, demonstrating that the benefit of increasing PA on aerobic fitness is greater in low active,

compared to high active, children. The practical implications of the findings presented here suggest that health benefits of PA are greater in less active children and health professionals should encourage sedentary and low active children to engage in PA rather than more active children to increase existing levels of PA.

Authors' contributions

AMN conceived the study, performed data analysis, and drafted the manuscript; MJD conceived the study and drafted the manuscript; GS conceived the study, carried out data collection, and drafted the manuscript. All authors have read and approved the final version of the manuscript, and agree with the order of presentation of the authors.

Competing interests

The authors declare they have no competing interests.

Supplementary materials

Supplementary material associated with this article can be found in the online version at doi:10.1016/j.jshs.2019.05.001.

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