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Maximal oxygen consumption and oxygen uptake efficiency in adolescent males

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A B S T R A C T

Background/objective: Measures of oxygen uptake efficiency (OUE) have been used to evaluate cardiorespiratory fitness (CRF) in adolescents unable to perform maximal exercise. The oxygen uptake efficiency slope (OUES) and oxygen uptake efficiency plateau (OUEP) have been proposed as surrogates for maximal oxygen consumption (VO_{2max}). We assessed the validity of the OUES and OUEP as predictors of VO_{2max} in healthy male adolescents.
Methods: Sixty-three healthy male adolescents aged 15.40 ± 0.34 years underwent an incremental treadmill test to determine VO_{2max}, OUES and OUEP. OUE throughout the test was assessed by dividing each VO_2 value by the corresponding minute ventilation (V_E) value. OUEP was determined as the 90 s average highest consecutive values for OUE. OUES was determined using data up to the ventilatory threshold (VT) by calculating the slope of the linear relation between VO_2 and the logarithm of V_E.
Results: Limits of agreement for VO_{2max} predicted by OUES (±13.3 mL $kg^{-1} \cdot min^{-1}$) and OUEP (±16.7 mL $kg^{-1} \cdot min^{-1}$) relative to VO_{2max} were wide and a magnitude bias was found for OUES and OUEP as predictors of VO_{2max} ($p < 0.001$).
Conclusion: The OUES and OUEP do not accurately predict VO_{2max} in male adolescents and should not replace VO_{2max} when assessing CRF in this population.

Introduction

Cardiorespiratory fitness (CRF) is a powerful indicator of cardiovascular health in children and adolescents.[1] High CRF during childhood and adolescence is associated with a healthier cardiovascular profile during these years[1] and also later in adulthood.[2] Maximal oxygen consumption (VO_{2max}), measured during a standardized cardiopulmonary exercise test (CPET), is considered the gold standard measure of CRF and is defined as the highest rate of oxygen uptake and utilization by the body during intense, maximal exercise that no further increases in work rate result in additional rises in VO_2.[3] The conventional criterion for the attainment of VO_{2max} during a CPET is a levelling-off or plateau in VO_2, and relies entirely on data from the last segment of a CPET. In such cases where the criteria for VO_{2max} attainment is not met, VO_{2peak} is recorded, which is the highest VO_2 value attained during an incremental or other high intensity exercise test, designed to bring the subject to the limit of tolerance.[4] The ability to attain VO_{2max} during a CPET is strongly effort-dependent and sensitive to many factors including participant motivation.[5]

Oxygen uptake efficiency (OUE) measurement, which is the reciprocal of the ventilatory equivalent for oxygen (VO_2/V_E), provides an estimation of the efficiency of minute ventilation (V_E) with respect to oxygen uptake (VO_2).[6] As the OUE is not linear during the entire exercise period, the oxygen uptake efficiency slope (OUES),

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mathematically derived from the linear relation between VO_2 and the logarithmic transformation of V_E during incremental exercise (VO_2 = a log10 VE + b, where a is the OUES and b is the intercept) has been proposed as an objective and effort-independent submaximal measure of exercise capacity[7] and a potential surrogate for VO_{2max}.[8,9] The logarithmic transformation of V_E reduces the curvature expected with increases in exercise intensity making the OUES resistant to disruption by the early termination of exercise.

Studies have shown that the OUES, calculated using only submaximal exercise data, is identical to the OUES calculated over the entire duration of a CPET.[10,11] Furthermore, both maximal OUES and submaximal OUES are significantly related to VO_{2peak} in both normal weight and obese children and adolescents.[10,12–14] There is evidence however, that OUES at submaximal and maximal exercise intensities exhibits a significant magnitude bias when used to predict VO_{2peak} in healthy adults[15] and adolescents[12] with varying levels of CRF, in that it over predicts VO_{2peak} at low levels of CRF and under predicts VO_{2peak} at high levels of CRF.

More recently, Sun et al. (2012) noted that the OUE when plotted against time, reaches its highest and briefly stable values/plateau (OUEP) at a moderate exercise intensity near the ventilator threshold (VT) before declining due to hyperventilation stimulated by the onset of metabolic acidosis.[16] A cross-sectional study involving 214 boys and girls aged between 8 and 19 years found that the OUEP was weak-to-moderately correlated with VO_{2peak} and the OUES was strongly correlated with VO_{2peak}.[6] Similar findings have been observed in healthy adults.[16] The validity of submaximal measures of CRF including the OUES and OUEP to accurately predict VO_{2max} in adolescents is of particular importance for disease risk identification and classification, given that VO_{2max} is not often attained in this cohort. While the validity of the majority of submaximal measures of CRF including OUES and OUEP have been based on their correlations with $VO_{2peak/max}$, a strong correlation between OUES/OUEP and $VO_{2peak/max}$, does not take into account their interchangeability.[15] To date, only one previous study has assessed the interchangeability of OUES with measured VO_{peak} and found that the wide interindividual variation in OUES precluded its use in clinical practice as a predictor of VO_{2peak}.[12] Furthermore, no previous studies have examined the interchangeability of the OUEP with VO_{2max}.

The purpose of this study was to therefore assess the concurrent validity of the OUES and the OUEP as predictors of VO_{2max} in apparently healthy male adolescents by using Bland and Altman method,[17] to compare the VO_{2max} value predicted from OUES and OUEP to the VO_{2max} measured during maximal exercise testing.

Methods

Participants and procedures

Sixty-three apparently healthy male adolescents (mean ± SD; age 15.40 ± 0.34 years) participated in the study. Initially, it was planned that females would participate in the study. However, during the recruitment phase of the study, many females were unwilling to participate and some females reported having an irregular menstrual cycle. Given that we wanted to control for the menstrual cycle in this study and that irregularity in the menstrual cycle would make this difficult, females were not included in the study. Exclusion criteria for male adolescents included current smokers, currently taking vasoactive medications, uncontrolled hypertension (SBP >180 mmHg, diastolic BP > 100 mmHg) or any condition that precluded participants from engaging in moderate to vigorous exercise. Informed parental consent and child assent were obtained prior to participation. The study was approved by Research Ethics Committee at Dublin City University. Participants made a single visit to the research laboratory during which body composition, pubertal status and CRF were assessed. Participants refrained from physical activity for 24 h prior to the visit.

Anthropometry and pubertal assessment

A stadiometer and electronic scale (Seca 797, USA) were used to measure height (cm) and body mass (kg), respectively. Body mass index (BMI) was calculated as body mass in kilograms divided by height in metres-squared ($kg \cdot m^{-2}$). Age- and gender-specific BMI percentiles were calculated and Centers for Disease Control and Prevention (CDC) standards were used to classify participants as normal weight (BMI < 85th percentile), overweight (BMI ≥ 85th and <95th percentile) and obese (BMI ≥ 95th percentile).[18] Participants self-reported their genital and pubic hair development using standardized Tanner drawings representing different stages of sexual maturity.[19] Participants were classified as pre-pubertal (Tanner 1), pubertal (Tanner II-IV) and post-pubertal (Tanner V) as previously described.[20]

Cardiopulmonary exercise testing

CPET was performed on a treadmill (Woodway ELG 55, Waukesha, WI) in a temperature-controlled laboratory environment (temperature 21.1 °C, ambient humidity 60%, atmospheric pressure 750 mm Hg). The test consisted of a continuous incremental protocol designed to ensure that participants reached volitional exhaustion between 8 and 12 min. One month prior to the CPET, participants undertook a school-based 20 m shuttle run test to estimate their level of CRF. Based on the number of shuttle runs completed, participants were classified as low CRF (LCRF) (0–40th percentile), moderate CRF (MCRF) (40–70th percentile), and high CRF (HCRF) (70th-100th percentile), in accordance with European age and gender specific percentiles for aerobic fitness.[21] Three separate protocols were then specifically developed to accommodate LCRF, MCRF and HCRF. Briefly, participants undertook a 2 min warm up on a 0% grade, which consisted of 2 min at 6.0 for $km.hr^{-1}$ for those with LCRF, 7.0 $km\ h^{-1}$ for those with MCRF and 9.0 $km\ h^{-1}$ for those HCRF After the warm-up, the treadmill velocity was increased to 7.0 for LCRF, 8.0 for MCRF and 11.0 $km\ h^{-1}$ for HCRF for 1 min and was then increased to 8.0, 10.0 and 12.0 or 13 $km\ h^{-1}$ in those with LCRF, MCRF and HCRF respectively, after which the speed remained constant and the grade was increased by 0.5% every 30 s until volitional exhaustion. Respiratory metabolic responses were determined using standard open-circuit spirometry techniques (Sensormedics Vmax 229, SensorMedics Corp., CA). Prior to testing, the gas analyzers were calibrated with standard gases of known concentration. A mass flow sensor was used to collect breath-by-breath measurements of ventilation. A 3.0 L volume syringe was used to calibrate the mass flow sensor prior to each test. Heart rate was continuously recorded throughout the test using telemetry (Polar team 2 Pro, Polar Electro Inc., NY, USA) and rating of perceived exertion (RPE) was recorded during the last 15 s of each min using the Borg 16 point category rating scale. Participants were verbally encouraged to give their maximal effort.

Criteria for maximal oxygen consumption

Maximal oxygen consumption (VO_{2max}) was determined using the highest consecutive 20 s value. The test was deemed maximal if at least two of the following four criteria were satisfied: (i) a plateau in oxygen consumption (defined as a $\leq 2.0 \cdot mL\ kg^{-1} \cdot min^{-1}$ change in VO_2 during the last min of exercise) (ii) heart rate >200 bpm, (iii) RER >1.0 or (iv) volitional fatigue.[14]

Oxygen uptake efficiency

Oxygen uptake efficiency (OUE) throughout the CPET was assessed by dividing each VO_2 value (ml/min) by the corresponding V_E value (L/min). The OUEP was then determined as the 90 s average highest consecutive values for OUE.[16] OUES was determined on the respiratory data up to the VT by calculating the slope of the linear relation between VO_2 (y-axis) and the logarithm of V_E (x-axis) through single regression analysis.[7] The VO_2 at the VT (VO_2VT) was defined as the level of VO_2 at which the linear relation between VCO_2 and VO_2 disappeared[22] and/or at which an increase in ventilatory equivalent for oxygen occurred (V_EVO_2) without a simultaneous increase in ventilatory equivalent for carbon dioxide (V_EVCO_2). The first minute of exercise was excluded because of the often irregular breathing pattern that is common at the onset of exercise. Relative values for VO_{2max}, VO_2VT, OUES and OUEP were calculated by dividing the absolute values by body mass.

Statistical analysis

Statistical analyses was performed using SPSS for Windows statistical software (V22.0, SPSS Inc, IL). Continuous variables are expressed as mean ± SD. Estimates of VO_{2max} were calculated from the regression equation of the relation between VO_{2max} and OUES and VO_{2max} and OUEP. Bland and Altman[17] analyses was then used to examine the level of agreement between measured and estimated VO_{2max}. Specifically, 2-tailed paired t-tests were conducted at $\alpha = 0.05$, between the measured and estimated VO_2max. To determine if there was measurement bias between objectively measured VO_{2max} and VO_{2max} predicted using OUES and OUEP, the differences between measured VO_{2max} and estimated VO_{2max} measured from OUES and OUEP were regressed against the means of the measured and estimated VO_{2max} from OUES and OUEP. Significance tests on the regression slope were applied to determine if there was measurement bias over the range of VO_{2max} values for OUES and OUEP. Univariate correlation analysis was conducted between VO_{2max}, OUES and OUEP. The significance level was set at $\alpha = 0.05$ using a Bonferroni correction factor of 0.00625 (0.05/8).

Results

Participant characteristics and CPET results

Participant characteristics and CPET results are presented in Table 1. 42 participants (63%) were classified as normal weight, 4 participants were overweight (16%) and 17 participants were obese. 55 participants self-reported that they were in the pubertal stage and 8 participants self-reported that they were in the post-pubertal stage All exercise tests were completed without any contraindications. At least two of the four predetermined criteria used to verify attainment of VO_{2max} were achieved by 94% of the participants. Almost all of the study participants (97%) achieved an RER value > 1.0, 65% had a plateau in oxygen uptake and 41% achieved a HR > 200 bpm. OUEP was obtained in all participants. OUES was obtained in 46 participants as the VT could not be determined in 17 participants. Absolute and relative values for $VO_{2max,}$ OUES and OUEP are summarized in Table 1.

Validity of OUES and OUEP as predictors of VO_{2max}

Measured VO_{2max} ($mL{\cdot}kg^{-1}{\cdot}min^{-1}$) was significantly correlated with OUES ($r = 0.77$, $p < 0.001$) and OUEP ($r = 0.53$, $p < 0.001$). There was no significant difference between measured VO_{2max} and VO_{2max} predicted by OUES (53.5 ± 10.8 vs. 53.5 ± 8.3 $mL\ kg^{-1}{\cdot}min^{-1}$) and OUEP (52.8 ± 10.4 vs. 52.8 ± 5.9 $mL\ kg^{-1}{\cdot}min^{-1}$). The limits of agreement for VO_{2max} predicted by OUES, and OUEP relative to measured VO_{2max} were ±13.3 and ± 16.7 $mL\ kg^{-1}{\cdot}min^{-1}$, respectively.

Table 1
Participants characteristics and CPET results.

	Mean (SD)	(Min − Max)
Age (yr.)	15.40 ± 0.34	14.00–16.00
Height (cm)	175.06 ± 6.44	154.40–187.00
Body mass (kg)	70.49 ± 14.88	47.45–116.20
BMI ($kg{\cdot}m^2$)	23.01 ± 4.81	16.33–38.07
VO_{2max} ($L{\cdot}min^{-1}$)	3.66 ± 0.61	2.40–4.93
VO_{2max} ($mL{\cdot}kg^{-1}{\cdot}min^{-1}$)	52.73 ± 10.34	25.40–73.00
VO_2VT ($mL{\cdot}kg^{-1}{\cdot}min^{-1}$)	45.40 ± 10.37	20.90–63.60
VO_2VT (%)	84.50 ± 5.80	70.3–95.80
V_E ($L{\cdot}min^{-1}$)	94.60 ± 17.28	54.80–139.03
OUES	4094.85 ± 937.82	1932.50–6104.00
$OUES{\cdot}kg^{-1}$	60.04 ± 15.86	33.06–102.01
OUEP	47.96 ± 4.85	35.42–61.52
$OUEP{\cdot}kg^{-1}$	0.70 ± 0.14	0.43–1.04
RER	1.11 ± 0.54	0.99–1.29
RPE	18.89 ± 1.43	14.00–20.00

BMI: Body mass index; VO_{2max}: Maximal oxygen consumption; VO_2VT: Oxygen uptake at the ventilatory threshold; V_E: Minute ventilation; OUES: Oxygen Uptake Efficiency Slope; OUEP: Oxygen Uptake Efficiency Plateau; RER: Respiratory Exchange Ratio; RPE: Rating of Perceived Exertion.
Values are mean ± SD.

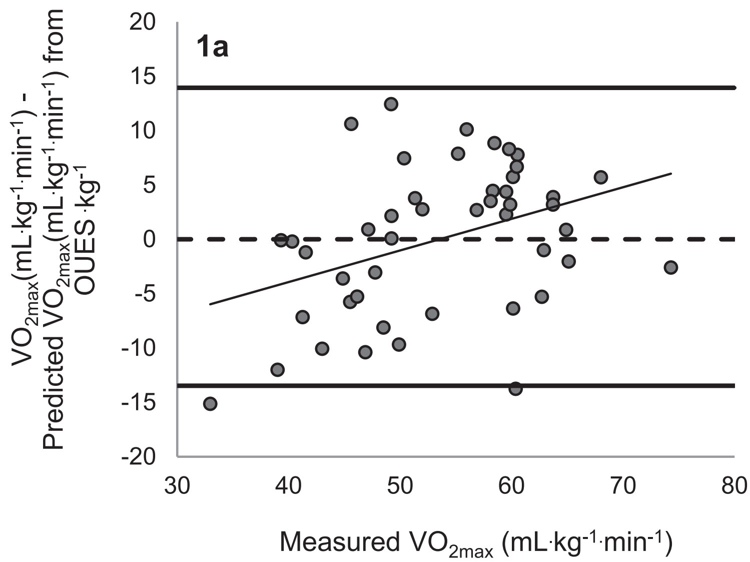
The regression model slopes of the difference between measured VO_{2max} and VO_{2max} predicted by OUES ($b = 0.291$, $t = 2.735$, $p < 0.001$) and OUEP ($b = 0.684$, $t = 5.631$, $p < 0.001$) were significant, indicating a significant magnitude bias when using OUES and OUEP to predict VO_{2max} (Fig. 1). The cutoff points were 53.5 $mL\ kg^{-1}{\cdot}min^{-1}$ and 52.7 $mL\ kg^{-1}{\cdot}min^{-1}$ for under and over estimation for OUES and OUEP respectively. OUES overestimated VO_{2max} at a $VO_2 < 53.5\ mL\ kg^{-1}{\cdot}min^{-1}$ and underestimated VO_{2max} at a $VO_2 > 53.5\ mL\ kg^{-1}{\cdot}min^{-1}$ and OUEP overestimated VO_{2max} at a $VO_2 < 52.7\ mL\ kg^{-1}{\cdot}min^{-1}$ and underestimated VO_{2max} at a $VO_2 > 52.7\ mL\ kg^{-1}{\cdot}min^{-1}$.

Discussion

The present study assessed the concurrent validity of the OUES and the OUEP as predictors of VO_{2max} in an adolescent population. The findings indicate that the large inter-individual variation and significant magnitude bias in both OUES and OUEP may impede their use as a predictor of VO_{2max} in healthy normal weight and overweight adolescents with varying levels of CRF.

VO_{2max} is considered to be the gold standard measurement for assessing cardiorespiratory fitness. The determination of VO_{2max} is based on the attainment of predetermined criteria which children and individuals with poor motivation and chronic disease are often unable to meet due to its effort dependency.[23] Similar to VO_{2max}, both the OUES and OUEP provide an objective measure of cardiorespiratory function, reflecting the efficiency of ventilation with regard to oxygen uptake during exercise, but do not require maximal effort.[16,24] Higher OUES and OUEP values indicate a more efficient VO_2 while lower values represent a lower VO_2 for any given V_E. The OUEP represents the maximal and most efficient OUE which occurs at submaximal exercise intensities around the VT.[16] The OUES describes the slope of the linear relation between VO_2 and the log transformation of V_E. Theoretically, OUES should be robust to the early termination of exercise allowing it to be used as an objective, effort independent measure of cardiorespiratory fitness.[7,25]

Studies in adults have found the OUES to be a reliable index of cardiorespiratory functional reserve.[5,19] Using correlation analysis,



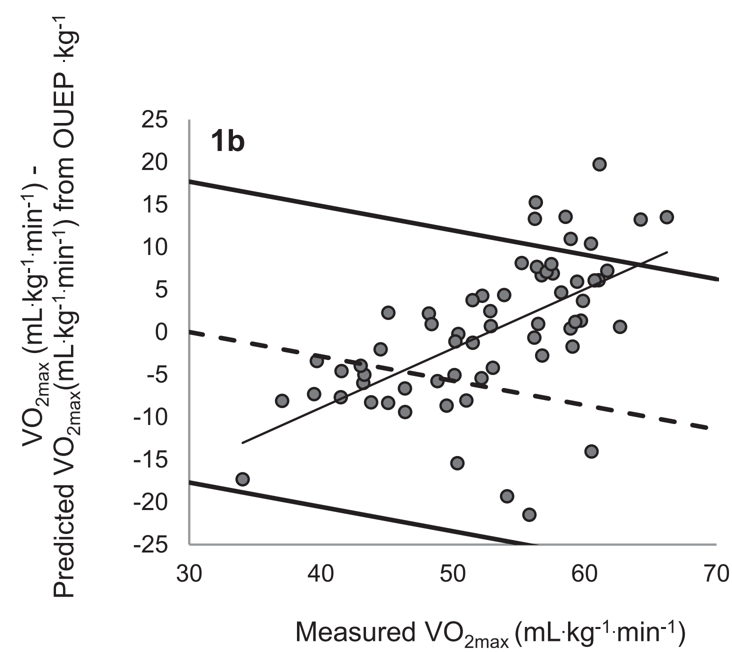


Fig. 1. Difference between measured VO_{2max}. (mL·kg^{-1}·min^{-1}) and (a) predicted VO_{2max} using OUES.kg^{-1} and (b) predicted VO_{2max} using OUEP.kg^{-1}.

OUES was found to be an accurate replacement for VO_{2max} in healthy individuals and heart disease patients.[4,18] OUES and OUEP were both significantly correlated with VO_{2max} in the present study. The present findings are similar to previous studies involving healthy children and adolescents that reported a significant relation between both OUES and OUEP and VO_{2max} or VO_{2peak}.[7,10,11,13,14] However, a strong correlation between OUES and OUEP with VO_{2max} or VO_{2peak} does not take into account their interchangeability.[15] The current study is the first study to assess the interchangeability of both the OUES and OUEP with measured VO_{2max} in an adolescent population. Although there were no significant differences between measured VO_{2max} and predicted VO_{2max} using OUES and OUEP, the limits of agreement varied greatly, indicating a significant magnitude bias. OUES and OUEP over predicted VO_{2max} at lower levels of CRF and under predicted VO_{2max} at higher levels of CRF. The heterogeneity in fitness levels in our study population, may have contributed to the variability in VO_{2max} values predicted from OUES and OUEP. Drinkard et al. (2007) also found a significant magnitude bias when OUES at the lactate inflection point, OUES at 150% of lactate infection and OUES at VO_{2peak} was used to predict VO_{2max} in both normal weight and overweight adolescents varying in levels of CRF.[12] The fact that both the OUES and OUEP over predicted VO_{2max} at lower levels of VO_2 in the present study, suggests that they should not be used as a replacements for VO_{2max} to assess CRF in clinical practice, particularly in adolescents with low CRF who are a target for primary prevention of CVD.

The VO_2 or workrate corresponding to the nonlinear increase in V_E during exercise demarcates the ventilatory anaerobic threshold (VT). Like OUES and OUEP, the VO_2VT does not require a physiologically maximal exercise effort, and is considered to be more consistent with an individual's ability perform activities of daily living.[26] A major shortcoming of the VT measurement, is the fact that often it is not identifiable, and its measurement is subject to substantial intra-and inter-observer variability.[27,28] Measurement of OUEP is an appealing alternative to VO_2VT as it does not rely on VT determination. Furthermore, while data up to the VT was used to calculate OUES in the present study, OUES does not necessarily need to rely on VT determination and can be calculated using a certain percentage of the max/peak exercise data i.e., 50%. A recent study calculated OUES using data up to 3, 4, 5 and 6 min of the exercise test and found that OUES determined from 5 min of exercise data was strongly related to VO_{2max} in obese children and adolescents.[29] However, while the OUES and OUEP are both objective and effort-independent submaximal measures of exercise capacity and are related to VO_{2max}, their potential application for assessing CRF in a group or population setting for surveillance purposes is limited as they rely on the administration of a CPET in a laboratory setting which is expensive and not very feasible.

Key strengths of the present study is that it is the first study to concurrently assess the interchangeability of both the OUEP and OUES in an adolescent population. Our findings revealed that the OUEP and the OUES do not accurately predict VO_{2max} in a normal and overweight adolescents varying in CRF and should not be used as a replacement for VO_{2max} when assessing adolescents CRF. Accurate and routine monitoring of CRF in adolescents is of paramount importance given that it has been recently shown that low CRF in adolescence is independently associated with risk of heart failure in adulthood.[30] The present study included both normal weight and overweight obese adolescents. Body mass has been shown to influence OUES, with a larger body mass resulting in increased absolute OUES values.[13] To account for the influence of body mass, VO_{2max}, OUES and OUEP values were normalized relative to body mass. Moreover, our findings are similar to that of a previous study that found a significant bias in OUES expressed relative to lean body mass when used predict VO_{2max} in normal and overweight adolescents with varying levels of CRF.[12]

A limitation of this study is use of the VT to calculate the OUES as 17 participants could not be included in the analysis. Future studies should employ a certain percentage of exercise data or duration of the exercise test to calculate OUES rather than relying on VT determination and should assess the validity of these measures of OUE as predictors of VO_{2max} Secondly, another limitation of the present study is that participants self-reported their pubertal status. The OUES has been shown to be influenced by maturation with an inverse relation observed between OUES and puberty stage.[31] While the majority of participants (87%) in the preset study self-reported that they were in the pubertal stage, 8% reported that they were post-pubertal. The disadvantage of using self-reported measures to assess pubertal status in adolescents is that there may be bias. While we adjusted for body mass in the current study, a previous study showed that adjusting for body mass did not eliminate differences across maturational groups suggesting that qualitative factors such as oxidative metabolism may be responsible for the inverse relation observed between pubertal stage and the OUES. Thirdly, while we expressed VO_{2max}, OUES and OUEP values relative to body mass, expressing these values relative to lean body mass would have allowed for better control of the influence of adiposity. Finally, this study was conducted in male adolescents only and therefore the findings cannot be generalized and extrapolated to female adolescents.

Conclusion

The OUES and OUEP do not reliably predict VO_{2max} and therefore should not be used in as a replacement for VO_{2max} to assess CRF in male adolescents.

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Author statement

Sheridan Sinead: Conceptualization, Methodology, Investigation, Writing - Original draft preparation. McCarren Andrew: Formal analysis, Writing – Review & Editing. Gray Cleona: Writing – Review & Editing. Murphy Ronan.P.: Writing – Review & Editing. Harrison Michael: Writing – Review & Editing. Moyna Niall.M.: Conceptualization, Supervision, Writing – Review & Editing.

Declaration of competing interest

The authors have no conflicts of interest relevant to this article.

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