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Original research

Ventilatory efficiency in juvenile elite cyclists

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ABSTRACT

Objectives: Ventilation (V'_E) as a function of CO_2 output, and oxygen uptake (V'_{O_2}) as a function of $\log_{10} V'_E$, define cardio-respiratory efficiency, although few data compare efficiency with maximum oxygen uptake ($V'_{O_2\,max}$), or consider reproducibility. Currently there are no data for trained juveniles.
Design: Twenty-five trained juvenile cyclists (mean age 14.7 years), performed maximal exercise testing on two occasions, separated by 16 weeks.
Methods: V'_E vs. V'_{CO_2} slope, oxygen uptake efficiency slope, and $V'_{O_2\,max}$ were measured during cycle ergometer exercise to volitional exhaustion on two occasions, 16 weeks apart.
Results: Mean (SD) V'_E vs. V'_{CO_2} slope, oxygen uptake efficiency slope, and $V'_{O_2\,max}$ were 28.14 (3.89), 4.16 (0.73), and 75.4 (8.9) ml kg^{-1} min^{-1} on visit 1, and 27.92 (4.63), 4.22 (0.76), and 73.6 (9.3) ml kg^{-1} min^{-1} on visit 2. Good reproducibility (differences ≤2.4%), but poor correlations ($r \leq 0.29$) between efficiency and $V'_{O_2\,max}$ were recorded.
Conclusions: Reproducibility of efficiency measures was comparable to $V'_{O_2\,max}$, however, poor associations between efficiency and $V'_{O_2\,max}$ suggested independence. Efficient ventilation may be of limited importance in determining the $V'_{O_2\,max}$ in a trained juvenile cyclist.

1. Introduction

Increased minute ventilation (V'_E) and the removal of CO_2 during physical exercise are essential for homeostatic control of whole body pH. During incremental exercise, the slope of the linear relation between V'_E and carbon dioxide output (V'_{CO_2}) has been used as a measure of ventilatory efficiency. Values for healthy adults range from 19 to 30,[1–3] and values >34 are indicative of the inefficient ventilation often associated with cardiovascular and respiratory diseases.[4–6] An alternative linear model ($V'_{O_2} = a \log_{10} V'_E + b$) also describes ventilatory efficiency, where the coefficient is the oxygen uptake efficiency slope (OUES).[7,8] Typical values range from 3 to 5[9] where higher values (e.g. ≥5) indicate efficiency typical of a trained athlete. Peak oxygen uptake ($V'_{O_2\,PEAK}$) showed a weak association with ventilatory efficiency,[10] and OUES may increase with both physical training[11–13] and respiratory muscle training.[14,15] Correlations of 0.68, 0.78 and >0.94 for the association between OUES and peak V'_{O_2} have been reported,[8–10] and in trained ($V'_{O_2\,max}$ 65 ml kg^{-1} min^{-1}) and untrained ($V'_{O_2\,max}$ 44 ml kg^{-1} min^{-1}) adults, OUES and $V'_{O_2\,PEAK}$ were positively correlated (>0.8).[16] However, others[1] reported a correlation of −0.27 between OUES and $V'_{O_2\,max}$ in trained cyclists.

The increasing role of sport science in the training and testing of elite juvenile athletes requires that measures purporting to identify efficiency are scrutinised for both relevance and reliability. Despite the ubiquity of efficiency measures in patients,[17] the utility of ventilatory efficiency measures have not been fully investigated in athletes. Any potential contribution which ventilatory efficiency has regarding athletic performance is unknown. There are limited data suggesting the plasticity of ventilatory efficiency with appropriate training,[11–15] only limited data on the reliability of the OUES,[18] and equivocal data showing associations between ventilatory efficiency and V'_{O_2}. No data are currently available for trained juveniles. Therefore, the current study aims to:

1. Quantify the relation between the V'_E vs. V'_{CO_2} slope and the OUES in trained juveniles;
2. Quantify the test–re-test reliability of both the V'_E vs. V'_{CO_2} slope and the OUES in trained juveniles;

2. Methods

All procedures were approved by the Massey University Human Ethics Committee (Southern) and parental/guardian consent was obtained for all subjects. An initial group of 30 subjects were tes-

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Table 1
Mean (SD) power outputs, $V'_{O_2\,max}$, V'_E vs. V'_{CO_2} slope, and OUES for a group of 25 trained juvenile cyclists (mean age 14.7 years). An incremental exercise test to volitional exhaustion was carried out on two visits, and visit 1 preceded visit 2 by 16 weeks. $V'_{O_2\,max}$: maximum oxygen uptake; V'_E: minute ventilation; V'_{CO_2}: carbon dioxide output; OUES: oxygen uptake efficiency slope; ICC: Intra-class correlation coefficient.

	Power at the estimated ventilatory threshold, W	Power at $V'_{O_2\,max}$, W	$V'_{O_2\,max}$, ml kg^{-1} min^{-1}	V'_E vs. V'_{CO_2} slope	OUES
Visit 1	318 (40)	429 (45)	75.4 (8.9)	28.14 (3.89)	4.16 (0.73)
Visit 2	323 (55)	402 (63)	73.6 (9.3)	27.92 (4.63)	4.22 (0.76)
Mean difference	4.8 (6.4)	25 (28)	1.8 (4.4)	0.23 (2.32)	0.06 (0.51)
Relative difference (%)	1.5	6	2.4	0.82	1.43
ICC	0.87	0.91	0.88	0.87	0.76

ted for visit 1, however, 5 were unavailable for visit 2 – therefore, data presented are only for 25 subjects (6 female). Subject characteristics were: mean (SD) age 14.7 (1.3) years; mass 61.95 (10.68) kg; height 170.5 (8.3) cm. For each test, all subjects arrived at the laboratory following a 4–6 h fast, and all testing took place in a built-for-purpose Human Performance Lab with appropriate temperature and ventilation control. Before and after exercise, heart rate and blood pressure were checked for normality, and subjects were excluded if these were outside normal ranges.

Subjects performed two tests, 16 weeks apart, and throughout this period, subjects maintained their normal training/competition schedules. The 16 week gap was due to limited availability of all subjects during the school term, and it was necessary to make current tests coincident with the routine testing of elite National representatives. All exercise was undertaken on an electronically braked Lode Excalibur Cycle Ergometer (Groningen, The Netherlands) set in pedal rate-independent mode. The ergometer was set up to replicate each subject's normal cycling position. Throughout each test, expired gases were analysed using a commercially available cardio-pulmonary exercise testing system (Turbofit, Vacumed, CA, USA). Standard algorithms were used to determine $V'_{E\,BTPS}$, $V'_{O_2\,STPD}$, and $V'_{CO_2\,STPD}$. Heart rate (not ECG) was continuously monitored throughout the tests using standard telemetry methods (Polar Vantage XL, New Zealand). Gas analysers were calibrated according to manufactures' instructions before all testing using gas mixtures of known O_2, CO_2, an N_2 content. Also, calibration of the gas volume measures were in accordance with the manufacturer's instructions, and used a Hans Rudolph 3 litre syringe evacuated over set time periods. For consistency, all testing was carried out by the same experimenters, each of which were fully trained and proficient in the required testing procedures.

Each subject performed a 10 min warm-up on the ergometer at 60 W for females, and at 100 W for males – these exercise intensities are well tolerated in young, elite cyclists. All subjects performed a continuous ramp protocol at 20 W per minute until volitional fatigue, with a starting power output equivalent to that of the warm-up. The test was terminated at a point where the subject could no longer perform exercise at the required power output (or at the request of the subject), and when oxygen uptake showed no further increases with increasing power output – this plateau in V'_{O_2} was determined to be $V'_{O_2\,max}$. At this point, all subjects were within 10% of their age-predicted maximum heart rate and achieved a respiratory exchange ratio >1.1. Throughout the test, verbal encouragement was given. Following the test, each subject performed a 5 min 'recovery' ride on the ergometer at 50 W.

Statistical procedures. Measures of cardio-respiratory system efficiency were determined by linear regression (Microsoft Excel), using all data from the start of the exercise test up to $V'_{O_2\,max}$. Efficiency was quantified as:

1. The slope of the linear relation between $V'_{E\,BTPS}$ and $V'_{CO_2\,STPD}$.
2. The slope of the linear relation between $\log_{10} V'_{E\,BTPS}$ and $V'_{O_2\,STPD}$.

In each case, the strength of the association was checked using the coefficient of determination. Also, the association between:

1. The two measures of cardio-respiratory system efficiency.
2. The measures of efficiency and $V'_{O_2\,max}$.

were each quantified using correlation (Microsoft Excel). Intra-class correlations (ICC) were determined for $V'_{O_2\,max}$, OUES, and V'_E vs. V'_{CO_2} slope. For each test the ventilatory threshold was estimated using either the *V*-slope method where possible, or identifying the point at which the ventilatory equivalent for O_2 increased without an increase in the ventilatory equivalent for CO_2.

3. Results

Summary data for all subjects' exercise performance, $V'_{O_2\,max}$ and efficiency measures are shown in Table 1. A representative example of how the ventilatory equivalents for oxygen and carbon dioxide change during exercise, and the relation between V'_E and V'_{CO_2}, and the relation between V'_{O_2} and $\log_{10} V'_E$, is shown in Fig. 1. In this example, the V'_E vs. V'_{CO_2} slope was 25.7, OUES was 5.01 and the $V'_{O_2\,max}$ was 77 ml kg^{-1} min^{-1}. For all subjects on both visits, the coefficient of determination for the V'_E vs. V'_{CO_2} slope was always ≥0.93, and was always ≥0.81 for the OUES. Intra-class correlation coefficients for $V'_{O_2\,max}$, V'_E vs. V'_{CO_2} slope, and OUES were 0.88, 0.87, and 0.76 respectively.

Test–re-test reliability for V'_E vs. V'_{CO_2} slope, OUES, and $V'_{O_2\,max}$ are described in Fig. 2. In this Bland–Altman plot, the difference between the measurement made on visit one and that made on visit 2 (ordinate) is plotted against the mean value of the variable when measured on the two visits (abscissa).

The relations between V'_E vs. V'_{CO_2} slope and OUES for both visits were weak, where coefficients of determination (R^2) were 0.2097 and 0.146 for visits 1 and 2, respectively. Also, the measures of efficiency showed very weak association with $V'_{O_2\,max}$ with correlation coefficients ranging from 0.09 to 0.29 (all non-significant).

4. Discussion

The unique findings of the current study were firstly, good reproducibility of measures of cardio-respiratory system efficiency, and secondly, no association between measures of efficiency and maximal oxygen uptake. This study also uniquely reports weak but significant associations between the V'_E vs. V'_{CO_2} slope and the OUES in trained juveniles.

The two linear models used to define cardio-respiratory system efficiency consistently yielded high correlation coefficients, suggesting the close association between V'_{CO_2} and V'_E, and between $\log_{10} V'_E$ and V'_{O_2}. In the current study, the slope of each relation was determined using all data collected throughout the tests, up to $V'_{O_2\,max}$. Although it has been suggested that the OUES may become more reliable when calculated from data obtained from higher