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Oxygen-Uptake Efficiency Slope as a Determinant of Fitness in Overweight Adolescents

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Abstract

Purpose—Peak oxygen uptake ($\dot{V}O_{2\text{peak}}$) is frequently difficult to assess in overweight individuals; therefore, submaximal measures that predict $\dot{V}O_{2\text{peak}}$ are proposed as substitutes. Oxygen uptake efficiency slope (OUES) has been suggested as a submaximal measurement of cardiorespiratory fitness that is independent of exercise intensity. There are few data examining its value as a predictor of $\dot{V}O_{2\text{peak}}$ in severely overweight adolescents.

Methods—One hundred seven severely overweight (BMI $Z 2.50 \pm 0.34$) and 43 nonoverweight (BMI $Z 0.13 \pm 0.84$) adolescents, performed a maximal cycle ergometer test with respiratory gas-exchange measurements. OUES was calculated through three exercise intensities: lactate inflection point (OUES LI), 150% of lactate inflection point (OUES 150), and $\dot{V}O_{2\text{peak}}$ (OUES PEAK).

Results—When adjusted for lean body mass, $\dot{V}O_{2\text{peak}}$ and OUES at all exercise intensities were lower in overweight subjects ($\dot{V}O_{2\text{peak}}$: 35.3 ± 6.4 vs 46.8 ± 7.9 mL·kg⁻¹ LBM·min⁻¹, $P < 0.001$; OUES LI: 37.9 ± 10.0 vs 43.7 ± 9.2 mL·kg⁻¹ LBM·min⁻¹·logL⁻¹, $P < 0.001$; OUES 150: 41.6 ± 9.0 vs 49.8 ± 11.1 mL·kg⁻¹ LBM·min⁻¹·logL⁻¹, $P < 0.001$; and OUES PEAK: 45.1 ± 8.7 vs 52.8 ± 9.6 mL·kg⁻¹ LBM·min⁻¹·logL⁻¹, $P < 0.001$). There was a significant increase in OUES with increasing exercise intensity in both groups ($P < 0.001$). OUES at all exercise intensities was a significant predictor of $\dot{V}O_{2\text{peak}}$ for both groups ($r^2 = 0.35\text{--}0.83$, $P < 0.0001$). However, limits of agreement for predicted $\dot{V}O_{2\text{peak}}$ relative to actual $\dot{V}O_{2\text{peak}}$ were wide (± 478 to ± 670 mL·min⁻¹).

Conclusions—OUES differs significantly in overweight and nonoverweight adolescents. The wide interindividual variation and the exercise intensity dependence of OUES preclude its use in clinical practice as a predictor of $\dot{V}O_{2\text{peak}}$.

Keywords

OBESITY; EXERCISE TEST; NONOVERWEIGHT; PHYSICAL FITNESS

The gold standard measurement of cardiorespiratory fitness has traditionally been an individual's peak oxygen uptake ($\dot{V}O_{2\text{peak}}$), the point at which no further oxygen is used despite

an increasing work rate. The ability to attain $\dot{V}O_{2peak}$ is dependent on patient effort and can be influenced by pain, shortness of breath, and fatigue. Such issues may be of particular concern when studying overweight individuals (13,17,29,31). A substantial percentage of overweight individuals fail to achieve $\dot{V}O_{2peak}$ during exercise testing (13,23). We recently have reported that 24% of overweight, versus 12% of normal weight, adolescents did not achieve $\dot{V}O_{2peak}$ during exercise testing (26).

Some investigators have proposed that the mathematically derived, oxygen uptake efficiency slope (OUES) can be used as an objective, submaximal measure of cardiorespiratory fitness in the clinical setting that would be independent of exercise intensity (3,18,35). Baba et al. (3) first defined OUES as the slope of the logarithmic relationship between oxygen uptake and minute ventilation (VE) during incremental exercise. The OUES is thought to be determined by 1) plasma pH, 2) the arterial carbon dioxide ($PaCO_2$) set point, and 3) the dead space:tidal volume ratio (V_d/V_t) (1), all of which may be influenced by obesity (33,38).

It is intuitive that the OUES above and below the lactate inflection point (LI) would be different because of differences in ventilatory drive that accompany metabolic acidosis. However Marinov et al. (21) report no difference in OUES above and below LI and no difference in OUES between moderately overweight and normal-weight children, suggesting that OUES is exercise intensity independent.

The OUES has been found to be reproducible (2) and related to $\dot{V}O_{2max}$ in healthy children (4), moderately overweight children (21), healthy adults, and adults with heart disease (3,5,12,18,35). Others have demonstrated that the OUES is a good predictor of $\dot{V}O_{2max}$ in nonoverweight individuals when data up to 75, 85, or 90% of $\dot{V}O_{2max}$ are included in the analysis (5,18,27). Pichon et al. (27) and Van Laethem et al. (36), using the Bland–Altman method, conclude that interindividual variation in OUES limits its clinical utility. The Bland–Altman method involves plotting the difference between measured and predicted $\dot{V}O_{2peak}$ against the average of measured and predicted $\dot{V}O_{2peak}$, revealing limits of agreement between measures and the presence or absence of magnitude bias, which can significantly increase error of prediction at high and low values of the predicted variable (i.e., $\dot{V}O_{2peak}$). To our knowledge, there has been no investigation of the relationship between OUES and fitness in severely overweight adolescents. Therefore, the purpose of this investigation was to determine whether the OUES is a clinically useful submaximal predictor of fitness in severely overweight adolescents.

METHODS

Subjects

We studied 141 severely overweight African American and Caucasian adolescents ages 12–17 yr recruited for a weight loss study (22), before they underwent weight loss treatment, and 48 healthy, nonoverweight (body mass index, BMI, between 5th and 94.99th percentiles for age and sex) volunteer adolescents ages 12–17 yr, recruited specifically for exercise studies (Table 1). Overweight subjects were in good general health but were required to have a BMI $\geq$ 95th percentile for age, sex, and race (24) and at least one obesity-related comorbid condition (primarily hyperinsulinemia and/or dyslipidemia). For both groups, subjects were excluded if they had used any anorexiant within the past 6 months; were pregnant; had major pulmonary, hepatic, or cardiac disorders; or had lost more than 3% of body weight during the past 2 months. All participants were recruited from the greater Washington, DC metropolitan area by newspaper advertisements, flyers posted in local commercial venues, and through physician referrals. No subject had previously performed a cycle test with measurements of gas exchange, and none were familiar with exercising to maximal capacity. Each subject was admitted to the National Institutes of Health Clinical Research Center for a cycle ergometry test. Before

exercise testing, each subject was evaluated with a medical history, physical examination, and 12-lead electrocardiogram. All subjects were free of musculoskeletal injury as determined by a physician, and American Heart Association guidelines for exercise testing (37) were observed. Subjects' parents signed consent statements (and adolescents gave their written assent) for all studies under a protocol approved by the institutional review board of the National Institute of Child Health and Human Development, National Institutes of Health.

Cycle ergometry testing procedure

Before the test, each subject was familiarized with the cycle ergometer (Ergoline 800, SensorMedics; Yorba Linda, CA) and instructed to maintain pedaling cadence at 60 rpm. Exercise began with a 4-min warm-up with no additional resistance applied to the pedals (unloaded exercise), followed by continuously increasing workloads of 15–20 W·min⁻¹, until the subject could no longer continue to maintain the prescribed pedaling cadence. Subjects were encouraged to exercise to the limit of their tolerance. Workloads were selected to result in total test time of 8–12 min. Expired gas exchange was measured breath by breath during exercise using a metabolic cart (Sensormedics Vmax, Yorba Linda, CA). Before each exercise test, the gas analyzers and flow meter were calibrated using gas mixtures of known concentrations and a 3-L syringe. The gas-transit time delay and analyzer response times, measured during calibration, were used by the metabolic cart software (Sensormedics Vmax, Yorba Linda, CA) to align ventilation and fractional gas-concentration signals. LI was determined using the V-slope method (6). Peak oxygen uptake and respiratory exchange ratio (RER) were defined as the highest 20-s average value achieved during the last minute of exercise. Continuous heart rate was measured by 12-lead electrocardiogram (Cardiosoft, Sensormedics Vmax, Yorba Linda, CA) during exercise, and the highest heart rate achieved during the last minute of exercise was defined as the peak heart rate. Peak exercise rating of perceived exertion (RPE) was measured within the first minute of exercise recovery using the Borg 6–20 rating of perceived exertion scale (8,10). Subjects who met at least two out of the four following criteria during cycle ergometry were considered to have achieved their $\dot{V}O_{2\text{peak}}$: 1) maximal heart rate ≥ 185 bpm; 2) RER ≥ 1.10 ; 3) RPE = 18–20; and 4) achievement of an oxygen plateau (13,15). Attainment of an oxygen plateau was defined as a change ≤ 2.0 mL O₂·kg⁻¹·min⁻¹ in oxygen uptake during the last minute of exercise. We use the term $\dot{V}O_{2\text{peak}}$ rather than $\dot{V}O_{2\text{max}}$, even though we applied criteria similar to those used to define $\dot{V}O_{2\text{max}}$, because for most non-cycle-trained subjects, a cycle ergometer test will yield lower values than would be obtained with treadmill testing (28).

Body composition

Height was recorded as the average of three measurements using a stadiometer (Holtain Ltd., Crymmyck, Wales) calibrated before each height to the nearest 1 mm. Weight was obtained using a calibrated digital scale (Scale-Tronix, Wheaton, IL) to the nearest 0.1 kg. Body composition was assessed after an overnight fast by air-displacement plethysmography (Life Measurement Instruments, Concord, CA) as previously described (25). Subjects wore minimal clothing (either tight-fitting underwear or a tight-fitting bathing suit) and a swim cap during measurements. Thoracic gas volume was measured during tidal breathing and during exhalation against a mechanical obstruction. Percent body fat was determined from body density using the standard two-compartment model calculated from the Siri equation (34).

Data analysis

Data were analyzed using StatView 4.5 software (Abacus Concepts, Inc., Berkeley, CA). The OUES was determined using simple regression of $\dot{V}O_2$ plotted against the semilogarithmic transformation of minute ventilation (3). The OUES slope was determined using data starting 1 min after exercise began and including all data through three defined end points: at LI (OUES

LI), at 150% of LI (OUES 150), and at $\dot{V}O_{2peak}$ (OUES PEAK), for those subjects who achieved $\dot{V}O_{2peak}$.

Using a two-tailed design, and P of 0.05, unpaired t -tests were used to test for significant differences in $\dot{V}O_{2peak}$, LI, and OUES (expressed relative to lean body mass) between the overweight and nonoverweight groups. Regression analysis was used to determine the relationships between three independent variables: OUES LI, OUES 150, OUES PEAK and one dependent variable: $\dot{V}O_{2peak}$. The regression equations were then used to predict $\dot{V}O_{2peak}$ from each subject's OUES values. Predicted $\dot{V}O_{2peak}$ for each subject was calculated from the regression equation of measured $\dot{V}O_{2peak}$ against OUES LI ($y = 1098.6 + 0.417x$), OUES 150 ($y = 749.5 + 0.528x$), and OUES PEAK ($y = 472.6 + 0.6x$). The Bland–Altman procedure (7,19) was used to evaluate the agreement between measured $\dot{V}O_{2peak}$ and $\dot{V}O_{2peak}$ predicted from OUES LI, OUES 150, and OUES PEAK. *A priori* acceptable limits of agreement for predicted $\dot{V}O_{2peak}$ were set at $\pm 15\%$ of measured $\dot{V}O_{2peak}$, which equates to clinically significant changes reported to occur with aerobic training and deconditioning (9). To identify whether OUES was exercise intensity dependent, repeated-measures ANOVA with t -test *post hoc* analysis was used to test for differences between OUES LI, OUES 150, and OUES PEAK.

RESULTS

Group comparisons

The overweight and non-overweight adolescents who achieved $\dot{V}O_{2peak}$ were of similar height and age but differed significantly in race, total weight, BMI, lean body mass, body fat mass, percent body fat, and BMI Z score (Table 1). Exercise data for the adolescents who reached $\dot{V}O_{2peak}$ are presented in Table 2 and Figure 1. Absolute $\dot{V}O_{2peak}$ ($P = 0.33$), LI ($P = 0.87$), and OUES 150 ($P = 0.11$) were not different between overweight and nonoverweight groups. However, OUES PEAK and OUES LI were both significantly greater in overweight subjects ($P \leq 0.05$). When expressed relative to lean body mass (LBM) $\dot{V}O_{2peak}$, LI, OUES LI, OUES 150, and OUES PEAK were significantly lower in the overweight versus the nonoverweight group ($P < 0.001$). Maximal heart rate and power at the lactate inflection point were significantly lower in the overweight group ($P \leq 0.05$). There was no significant difference in maximal respiratory exchange ratio for the overweight and nonoverweight groups ($P = 0.5$).

Five of 48 (10%) nonoverweight and 34 of 141 (24%) overweight subjects did not achieve $\dot{V}O_{2peak}$ and were not included in the analysis of OUES. In the normal-weight group, those who did not achieve $\dot{V}O_{2peak}$ did not significantly differ in BMI or lean body mass. However, among the overweight group that did not achieve $\dot{V}O_{2peak}$, there was a higher percentage of African Americans, and both BMI ($P = 0.02$) and BMI Z score were significantly greater ($P = 0.03$).

Relationship between OUES and fitness and exercise intensity

OUES at all exercise intensities for both groups was significantly related to $\dot{V}O_{2peak}$ ($r^2 = 0.35$ – 0.83 $P < 0.0001$; overweight data shown in Figs. 2A, 2C, and 2E). LI was significantly related to $\dot{V}O_{2peak}$ in nonoverweight adolescents ($r^2 = 0.84$, $P < 0.0001$) and overweight adolescents ($r^2 = 0.69$, $P < 0.0001$). Bland–Altman plots comparing measured $\dot{V}O_{2peak}$ with $\dot{V}O_{2peak}$ predicted from OUES in the overweight and nonoverweight groups showed large limits of agreement (± 478 to ± 670 mL·min⁻¹) for all exercise intensities (overweight data shown in Figs. 2B, 2D, and 2F). These limits of agreement were as high as 30% of average $\dot{V}O_{2peak}$ in the nonoverweight group and 34% of average $\dot{V}O_{2peak}$ in the overweight group. Significant magnitude bias was found for OUES as a predictor of $\dot{V}O_{2peak}$ for all exercise intensities in the overweight group ($P < 0.0001$), with OUES overpredicting $\dot{V}O_{2peak}$ at low fitness levels

and under-predicting $\dot{V}O_{2peak}$ at high fitness levels (Figs. 2B, 2D, and 2F). Similar results were found for the nonoverweight group, with significant magnitude bias for OUES LI and OUES 150 ($P \leq 0.05$). There was a significant increase in OUES with increasing exercise intensity in both overweight and nonoverweight groups (Fig. 1, $P < 0.001$).

DISCUSSION

The purpose of this investigation was to determine whether OUES was a useful submaximal estimate of fitness that might substitute for the actual determination of $\dot{V}O_{2peak}$. The fact that almost one quarter of the present investigation's overweight subjects did not achieve $\dot{V}O_{2peak}$ underscores the need for a suitable submaximal measurement of fitness in such individuals. Our results suggest that, although OUES is related to $\dot{V}O_{2peak}$, it shows large interindividual variation, magnitude bias, and dependence on exercise intensity.

$\dot{V}O_{2peak}$ and LI were significantly lower in the overweight group when expressed relative to lean body mass (Table 2). In contrast, others have found no differences in $\dot{V}O_{2peak}$ values between nonoverweight and moderately overweight adolescents and children when scaled to lean body mass (16,20). Rowland et al. (28) suggest that moderately obese children have normal cardiorespiratory function, although a significant decline in physical performance may exist because of differences in body composition. Indeed, several investigations have found that body composition is a major determinant of performance (11,14,26). In the present study of severely overweight individuals, we found that once $\dot{V}O_{2peak}$ and LI were adjusted for LBM, these measures were lower in the overweight group, suggesting that some degree of cardiorespiratory impairment or deconditioning exists. This was also further substantiated by the significant differences in the lactate inflection point expressed in watts per minute. Mean $\dot{V}O_{2peak}$ (scaled to LBM) was 25% less in the overweight group compared with the nonoverweight group. This degree of decline in $\dot{V}O_{2peak}$ has been reported with bed rest-related deconditioning (9). It is possible that overweight subjects similarly spend more time in a physically inactive state, contributing to deconditioning. However, we cannot rule out that other factors unique to obesity may have contributed to the decrease in $\dot{V}O_{2peak}$ observed in this study. Absolute values for OUES PEAK and OUES LI were actually greater in the overweight group, which might suggest that overweight adolescents were aerobically fitter. However, when scaled to lean body mass, OUES at all exercise intensities was significantly lower in the overweight group.

Similar to results of previous studies (3–5,12,18,21,27,35), we found that OUES at all intensities for both groups was significantly related to $\dot{V}O_{2peak}$. However, there was large interindividual variation in $\dot{V}O_{2peak}$ predicted by OUES, with limits of agreement as high as 30% of average $\dot{V}O_{2peak}$ in the nonoverweight group and 34% of average $\dot{V}O_{2peak}$ in the overweight group. Meaningful clinical changes in $\dot{V}O_{2peak}$ can be much smaller than the interindividual variation in $\dot{V}O_{2peak}$ predicted by OUES in our study. Typical changes in $\dot{V}O_{2max}$ with training or deconditioning are on the order of 10–15% (30,32). In addition, a significant magnitude bias in OUES was identified for the overweight group, indicating that OUES may increasingly underpredict $\dot{V}O_{2peak}$ at higher fitness levels and overpredict $\dot{V}O_{2peak}$ at lower fitness levels. It is likely that the large variability in OUES predictions of $\dot{V}O_{2peak}$ and the magnitude biases make it of limited value for predicting fitness for individuals.

In contrast to some previous studies (5,18,35) Pichon et al. (27) found a significant difference in OUES at different exercise intensities in nonoverweight and overweight adolescents. Similarly, we found a significant increase in OUES with increasing exercise intensity in nonoverweight and overweight adolescents. These differences were not confined to slopes below the LI; they included differences in OUES above the LI as well. This indicates that the $\dot{V}O_2$ (y-axis variable in the OUES slope calculation) increased in a disproportionate manner,

relative to VE, with increasing exercise intensity. Typically, at exercise intensities above LI, there is hyperventilation with respect to $\dot{V}O_2$. When plotting OUES, VE is logarithmically transformed to produce a linear slope. Because $\dot{V}O_2$ continues to rise with increasing exercise intensity, and the change in VE is mathematically altered, the OUES seems to increase with increasing exercise intensity. However, because a primary requisite for a submaximal determinant of fitness would be exercise intensity independence, this finding again suggests that the OUES may not be a valid submaximal predictor of $\dot{V}O_{2peak}$.

In conclusion, OUES adjusted for lean body mass was shown to be lower in overweight adolescents. In addition, the wide interindividual variation, the magnitude bias, and the intensity dependence of the OUES impede its clinical utility for assessing the fitness level of severely overweight adolescents.

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FIGURE 1.

OUES (Mean ± SD) at different exercise intensities in nonoverweight and overweight adolescents. OUES was determined using data collected from initiation of exercise through LI (OUES LI), 150% of LI (OUES 150), or $\dot{V}O_{2peak}$ (OUES PEAK). * $P \leq 0.05$, overweight vs nonoverweight group; ** $P < 0.001$, comparisons between groups at different exercise intensities.

FIGURE 2.

OUES and $\dot{V}O_{2peak}$ in overweight adolescents. Association between $\dot{V}O_{2peak}$ and OUES (panels A, C, and E) and Bland–Altman comparisons between predicted $\dot{V}O_{2peak}$ derived from OUES estimates (predicted by OUES) and actual $\dot{V}O_{2peak}$ (panels B, D, and F). OUES was determined using data collected from initiation of exercise through: LI (OUES LI, panels A and B), 150% of LI (OUES 150, panels C and D), or $\dot{V}O_{2peak}$ (OUES PEAK, panels E and F).

TABLE 1Subject demographics (mean $\pm$ SD unless otherwise indicated).

	Overweight, Achieved $\dot{V}O_{2\text{peak}}$ (N = 107)	Nonoverweight, Achieved $\dot{V}O_{2\text{peak}}$ (N = 43)
Age (yr)	14.4 $\pm$ 1.5	14.8 $\pm$ 1.7
Sex (% female)	61%	49%
Race (% African American)	52%*	26%
Weight (kg)	110.3 $\pm$ 25.8*	56.3 $\pm$ 12.8
Height (cm)	165.5 $\pm$ 7.8	164.5 $\pm$ 9.0
Body mass index (kg·m ⁻²)	40.0 $\pm$ 8.0*	20.5 $\pm$ 3.0
Lean body mass (kg)	56.9 $\pm$ 11.8*	44.2 $\pm$ 10
Fat body mass (kg)	53.1 $\pm$ 6.6*	12.2 $\pm$ 7.1
Percent body fat (%)	47.7 $\pm$ 5.6*	21.1 $\pm$ 9.0
BMI Z-score	2.50 $\pm$ 0.34*	0.13 $\pm$ 0.84

* $P \leq 0.05$.

TABLE 2Cycle ergometry test results in adolescents who achieved $\dot{V}O_{2peak}$.

	Overweight (N = 107)	Nonoverweight (N = 43)
LI (mL·min ⁻¹)	1129 ± 267	1120 ± 360
Power at LI (W·min ⁻¹)	69.1 ± 21.0 [*]	92.7 ± 30.7
$\dot{V}O_{2peak}$ (mL·min ⁻¹)	1986 ± 416	2068 ± 574
LI/LBM	20.0 ± 3.9 ^{**}	25.3 ± 5.7
$\dot{V}O_{2peak}$ /LBM (mL·kg ⁻¹ LBM·min ⁻¹)	35.3 ± 6.4 ^{**}	46.8 ± 7.9
OUES LI/LBM (mL·kg ⁻¹ LBM·min ⁻¹ ·logL ⁻¹)	37.9 ± 10.0 ^{**}	43.7 ± 9.2
OUES 150/LBM (mL·kg ⁻¹ LBM·min ⁻¹ ·logL ⁻¹)	41.6 ± 9.0 ^{**}	49.8 ± 11.1
OUES PEAK/LBM (mL·kg ⁻¹ LBM·min ⁻¹ ·logL ⁻¹)	45.1 ± 8.7 ^{**}	52.8 ± 9.6
Maximal heart rate (bpm)	187 ± 11 [*]	198 ± 9
Maximal respiratory exchange ratio	1.16 ± 0.08	1.17 ± 0.08

Values are means ± SD.

^{*}
 $P \leq 0.05$.^{**}
 $P < 0.001$ vs nonoverweight group.