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Maximal and submaximal oxygen uptake efficiency slope: influence of cardiorespiratory variables and maximal dynamic strength

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Abstract

Objective: The purpose of this study was to investigate if the OUES is determined by the same factors when calculated with VO_2 and VE values throughout the incremental test ($OUES_{100}$) or using values until 80% of the VO_2 max ($OUES_{80}$).

Methods: 116 healthy male individuals performed a maximal incremental test, two constant-speed tests and a maximal dynamic strength test.

Results: $OUES_{100}$ and $OUES_{80}$ were significantly correlated (r = 0.964; $P < 0.001$). VO_2 max was the main determinant factor for both $OUES_{100}$ and $OUES_{80}$. Additionally, maximal heart rate (HRmax) and maximal dynamic strength (1RM) were the other variables selected for the two models as secondary variables. However, the importances of them were inversed, with the HRmax being the second determinant of the $OUES_{80}$, while 1RM the second determinant for $OUES_{100}$. The running economy, ventilatory threshold and respiratory compensation point were not selected for the models ($P > 0.05$).

Conclusions: Our results suggest that the $OUES_{80}$ might satisfactorily replace maximal variables in aerobic fitness evaluations without maximal effort requirement. VO_2 max seems to be the main factor determining oxygen uptake efficiency slope, regardless the range (maximal or submaximal) used to determine. Otherwise, the muscle strength plays a more important role to the oxygen uptake efficiency considering maximal intensities, while the cardiovascular system seems to more strongly influence the oxygen uptake efficiency only until submaximal intensities.

Introduction

Aerobic fitness has been considered an important marker for both health and athletic performance in different populations [1]. Traditionally, the aerobic fitness has been determined by some cardiorespiratory variables such as the maximal oxygen uptake (VO_2 max) [2]. The VO_2 max represents the highest rate of uptake, transport, and consumption of the atmospheric oxygen during exercise [3]. Despite its large utility, VO_2 max determination demands the attainment of maximal effort, what in turn is not always possible for all individuals [4]. In addition, the maximal effort could trigger uncomfortable effects in some special populations, such as chronic heart failure patients [5]. Hence, several submaximal aerobic fitness markers have been proposed in the literature to overlap this limitation.

Among the main submaximal cardiorespiratory parameters, the Ventilatory Threshold (VT), the Respiratory Compensation Point (RCP) and the Running Economy (RE) are underlined. VT and RCP are related to changes in blood H^+ concentrations and represent physiological transition points demarking different exercise intensity domains [6]. In turn, RE is defined as the oxygen consumption demanded for a given running speed [7]. While these cardiorespiratory parameters are closely associated with aerobic fitness, the detection of the VT and the RCP may be biased by several factors including the different methods of detection and the experience of the evaluators [8-10]. On the other hand, the RE measurement demands at least an additional experimental session, mainly when two or more speeds will be tested or when the individual has a low fitness level. Unfortunately, this time-consuming procedure might discourage exercise physiologists for using RE in their evaluation routines. Therefore, lesser time-demanding methods to assess aerobic fitness would be very appealing from an applied standpoint.

Regarding these concerns, Baba *et al.* [11] proposed the Oxygen Uptake Efficiency Slope (OUES) as a parameter representing the oxygen uptake efficiency. The OUES has been evaluated during incremental exercise tests, which would demand a unique test session. The OUES is determined by the slope of the linear relationship between oxygen consumption (VO_2) and the logarithmic transformation of the Ventilation (VE)values during an incremental exercise test. Its determination can be made using total (*i.e.*, 100%) or partial (*e.g.*, 80%) gas exchange data collected during the incremental test [12,13].

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It is believed that the OUES integrates in a unique physiological index respiratory (*e.g.*, oxygen perfusion in the lungs and pulmonary dead space), cardiovascular (*e.g.*, blood flow distribution to the exercised muscles), and muscular (*e.g.*, oxygen extraction and utilization) functions [14]. In fact, it has been used to evaluate aerobic fitness in a wide number of subjects, including healthy men [12], overweight adolescents [15], and cardiovascular disease patients [12]. It is interesting to note that the OUES determination is not influenced by some intervenient factors, such as the use of experienced and non-experienced evaluators or test protocol [12]. Moreover, the OUES measurement can be performed without necessarily require a maximal effort or additional experimental sessions [16].

Although it has been well accepted that aerobic fitness is highly dependent on cardiorespiratory system [17], several studies have also found a strong association between muscle strength and aerobic fitness [18,19]. Individuals with greater muscle strength could generate lower relative force at the same absolute running intensity. This lower relative force might result in an increased local blood flow, augmenting the oxygen extraction and utilization [20]. As a result, this increased oxygen availability to the working muscles could improve muscular metabolism and control acidosis in the muscle fibers [18]. In fact, a 12% improvement in healthy men $\dot{V}O_2max$ was found after a 12-week strength-training [21]. On this basis, the muscle strength seems to influence important processes and may be important to OUES determination. However, to the best of our knowledge, the possible relationship between maximal dynamic muscle strength and OUES during running was not still analyzed.

Therefore, the objective of the current study was to investigate the main determinants of OUES calculated with maximal (*i.e.*, 100%) and submaximal (*i.e.*, 80%) intensities during running in healthy individuals. It was hypothesized that OUES would be associated with VO_2 max, ventilatory thresholds, RE, and maximum dynamic strength. In case of confirming this association, it could be argued that OUES might be used as a general aerobic fitness marker summarizing different physiological and muscular parameters.

Methods

116 healthy male individuals participated in this study after the assignment of a written informed consent. All experimental procedures were previously approved by the Ethics Committee for Humans Studies from the School of Physical Education and Sport of University of São Paulo (2010/44). Participants were asked to refrain from any exhaustive or unaccustomed exercise in the 48H preceding each test session, and from taking nutritional supplements throughout the experimental period.

A maximal incremental test was performed to determine the VO_2 max, maximal heart rate (HRmax), VT and RCP. Specific details of the maximal incremental test, as well as the physiological variables determination, have been described elsewhere [22].

The two constant-speed tests were performed to determine the running economy at 10 km.h^{-1} (RE_{10}) and 12 km.h^{-1} (RE_{12}). Specific details of the constant speed tests and RE determination have been described elsewhere[22].

Participants were familiarized with all procedures, leg press machine equipment, and proper exercise technique prior to maximal dynamic strength test. After a brief warm up of five minutes run at 8 kmh^{-1}, participants performed two sets, being five repetitions at 50% of 1RM determined in the familiarization session for the first set, and three repetitions at 70% for the second set. After that, participants rested for three minutes. Then, they had up to five trials to achieve the 1RM load (maximum weight lifted once with the proper technique), with a 3-minute interval between attempts.

The relationship between VO_2 and VE during the incremental test is best described by a single exponential function. Thus, the OUES was determined from VO_2 and VE data during the incremental running test using the equation 1, as suggested by Baba et al.[11]:

$$\dot{V}O_2\,(L.min^{-1}) = a\,.log_{10}\dot{V}E\,(L.min^{-1}) + b \quad (1)$$

Excluding the warm-up period, VO_2 (mL.min^{-1}) during the incremental test was plotted on the *y* axis and the VE (L.min^{-1}) on the *x* axis after a semilog transformation. The slope of this relation, determined by the angular coefficient "a", represents the OUES. The constant "b" is the linear coefficient of the relation. The OUES was calculated using 100% of the data ($OUES_{100}$) and with the data contained until 80% of the VO_2 max ($OUES_{80}$).

Data normality in all the variables was confirmed through Kolmogorov-Smirnov test. Data are expressed by means ± standard deviations, and 95% confidence intervals (CI). Pearson product-moment coefficient was used to test the correlation between $OUES_{100}$ and $OUES_{80}$. Two stepwise multiple linear regression models were used to identify which variable(s) explained the $OUES_{100}$ and the $OUES_{80}$ variance. The parameters $\dot{V}O_2max$, HRmax, VT, RCP, RE10, RE12 and 1RM were considered as independent variables, whereas $OUES_{100}$ and $OUES_{80}$ were considered as dependent variables in each model. All the statistical analyses were conducted using the SPSS statistical package (version 16.0, Chicago, USA). The significance level was set at α = 0.05 for all statistical analysis.

Results

Table 1 shows the main characteristics of the participants. The mean (± SD), and 95% CI $OUES_{100}$, $OUES_{80}$, cardiorespiratory parameters, and muscle strength are presented in table 2 (Table 1 and Table 2).

$OUES_{100}$ and $OUES_{80}$ were significantly correlated (r = 0.964; $P < 0.001$) (Figure 1). The stepwise multiple regression with the $OUES_{100}$ as the depen $\dot{V}O_2max$ ble resulted in a final model with (in order of importance) $\dot{V}O_2max$, 1RM, and HRmax as predictors of $OUES_{100}$. Otherwise, VT ($P = 0.620$), RCP ($P = 0.553$), RE10 ($P = 0.112$), and RE12 ($P = 0.134$) were not included in the model. The stepwise multiple regression with the $OUES_{80}$ as the dependent variable resulted in a final model with (in order of importance) VO_2 max, HRmax, and 1RM as predictors of $OUES_{80}$ (Table 3). Otherwise, VT ($P = 0.921$), RCP ($P = 0.562$), RE10 ($P = 0.074$), and RE12 ($P = 0.085$) were not included in the model.

Discussion

The present study was conducted aiming to verify if submaximal OUES might represent maximal values as well as to identify the main

Table 1. Age and anthropometric characteristics of the participants (n = 116).

Characteristics of the participants	Mean ± SD	95% Confidence interval
Age (years)	25.9 ± 3.9	24.8 - 26.6
Body mass (kg)	78.9 ± 14.1	74.8 - 79.4
Height (cm)	176 ± 13	176 - 178
Body fat (%)	13.5 ± 4.1	12.8 - 14.8
BMI (kg.m^{-2})	25.2 ± 4.8	24.3 - 26.2

BMI: Body Mass Index

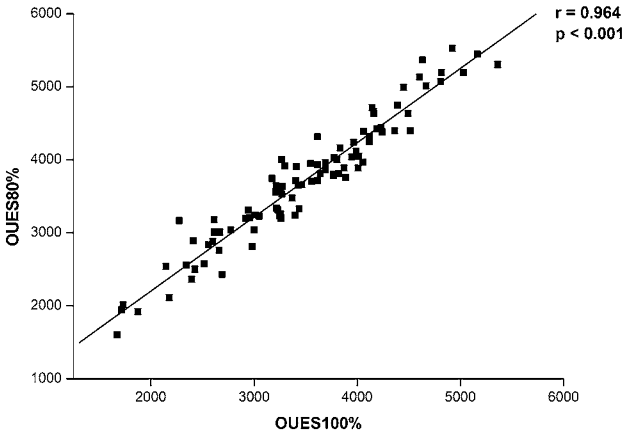

Figure 1. Correlation between oxygen uptake efficiency slope calculated using 80% ($OUES_{80}$) and 100% ($OUES_{100}$) of the gas exchange data collected during a maximal incremental test (n = 116).

Table 2. Oxygen uptake efficiency slope, cardiorespiratory parameters and muscle strength (n = 116)

	Mean ± SD	**95% Confidence interval**
$OUES_{100}$	3442 ± 611	3291 - 3564
$OUES_{80}$	3738 ± 885	3555 - 3920
VO_2max (mL.kg^{-1}.min^{-1})	48.7 ± 6.0	46.3 - 49.2
HRmax (bpm)	189 ± 9	187 - 192
VT (km.h^{-1})	10.5 ± 1.0	10.3 - 10.8
RCP (km.h^{-1})	13.5 ±1.5	13.2 - 13.9
RE10 (mL.kg^{-1}.min^{-1})	36.6 ± 3.2	36.0 - 37.4
RE12 (mL.kg^{-1}.min^{-1})	41.9 ± 3.6	41.4 - 43.0
1RM (kg)	305 ± 73	285 - 319

$\dot{V}O_2max$: Maximal oxygen uptake; HRmax: Maximal heart rate; VT: Ventilatory threshold; RCP: Respiratory Compensation Point; $OUES_{100}$: Oxygen Uptake Efficiency slope measured with 100% of the incremental test data; $OUES_{80}$: Oxygen Uptake Efficiency slope measured with data until 80% of the incremental test; RE10: Running Economy measured at 10 km.h^{-1}; RE12: Running Economy measured at 12 km.h^{-1}; 1RM: one Repetition Maximum in the leg press exercise.

Table 3. Predictors of the oxygen uptake efficiency slope at 100% and 80%. (n = 116)

Dependent variable	Independent Variables	Standardized coefficient	Partial r	p value	Adjusted r^2
$OUES_{100}$	VO_2max	0.621	0.614	0.001	0.405
	1RM	0.296	0.349	0.001	
	HRmax	-0.192	-0.239	0.031	
$OUES_{80}$	VO_2max	0.605	0.602	0.001	0.379
	HRmax	-0.303	-0.362	0.001	
	1RM	0.193	0.235	0.04	

$OUES_{100}$: oxygen uptake efficiency slope measured with 100% of the incremental test data; $OUES_{80}$: oxygen uptake efficiency slope measured with data until 80% of the incremental test; $\dot{V}O_2max$ = maximal oxygen uptake; 1RM = repetition maximum in leg press exercise; HR: maximal heart rate.

factors determining OUES calculated from maximal and submaximal gas exchange data range. For this purpose, we used a stepwise multiple regression model to evaluate the contribution of cardiorespiratory and muscular parameters for $OUES_{100}$ and $OUES_{80}$ determination during running in healthy individuals. Our main results were that maximal and submaximal OUES were significantly correlated and both were mainly determined by the $\dot{V}O_2max$. Additionally, HRmax and 1RM were the other selected variables in the two models, but in an inverse order.

Our data demonstrated that $OUES_{100}$ and $OUES_{80}$ were positively correlated. Similarly, previous studies demonstrated that maximal and submaximal OUES were positively correlated. Van Laethem et al. [23] observed a significant correlation between OUES measured until 90% of the incremental test and OUES with maximal data (r = 0.973; p < 0.0001) in 35 male and female patients with chronic heart failure. Williamson et al. [24] also observed that full test OUES was significantly correlated with OUES until RER 1.0 was reached (r = 0.90) and with OUES until RER 0.9 was reached (r = 0.79) (*p* < 0.05) in 100 healthy men. These results support a linear relationship between maximal and submaximal OUES and suggest that the submaximal OUES might be an interesting parameter to replace maximal OUES in individuals whom are unable to reach maximal effort.

Interestingly, data from the multiple regression models selected only variables measured during maximal effort to explain the variation of both $OUES_{100}$ and $OUES_{80}$ (*i.e.*, VO_2 max HRmax, and 1RM). This is in line with previous findings [12], reinforcing the capacity of the OUES measured at submaximal intensities to reflect maximal parameters. Furthermore, VO_2 max was the main determinant explaining ~ 60% of the $OUES_{100}$ and $OUES_{80}$ variance. The positive relationship between VO_2 max and OUES found in this study has been found in other studies. Moll[illegible]5] observed a high correlation of $OUES_{80}$ and $OUES_{100}$ with $\dot{V}O_2max$ in 24 healthy men (r = 0.85 and r = 0.89, respectively). In addition, Baba et al. [26] observed a significant correlation (r = 0.78) between OUES and VO_2 peak. Considering that VO_2 max is influenced by both maximal cardiac output and a-v O_2 difference, it could be proposed that the OUES is linked to these cardiorespiratory factors and would represent a parameter of aerobic fitness, but with the advantage to be determined using submaximal intensities. It seems especially important, particularly in special populations such as cardiovascular disease patients, which might be unable to complete a test until to exhaustion [12].

It is interesting to observe that the both 1RM and HRmax were selected by multiple regression models to explain the partial variances of the $OUES_{100}$ and $OUES_{80}$ (Tables 3 and 4), but in a different order of importance. While 1RM was the second more important parameter for the $OUES_{100}$, HRmax was selected as the second more important factor explaining the partial variances for the $OUES_{80}$. This suggests that, although muscle tissue and cardiovascular system were relevant to both $OUES_{100}$ and $OUES_{80}$, maximal dynamic strength might be more important to $OUES_{100}$, while cardiovascular function might be more important to $OUES_{80}$. It is plausible to assume that the muscle strength is critical to the oxygen uptake efficiency in the last stages of the incremental test because there is a higher demand of force production at higher running intensities [27]. On the other hand, the cardiac work might be determinant to the oxygen uptake efficiency at submaximal speeds, since heart rate is an index of the rate-pressure product, a marker of cardiac work [28]. As suggested by our results, $OUES_{80}$ is negatively related to HRmax, what suggests that the submaximal oxygen uptake efficiency increases as the cardiac work decreases at submaximal intensities. Therefore, these findings suggest that the oxygen uptake efficiency could be differently determined accordingly to the intensity of measurement. From the practical standpoint, it seems especially important that exercise physiologists consider that, depending on the intensity of the OUES determination, it might be more dependent on cardiovascular or muscular functions, what should be fit with the evaluated subject or population.

As aforementioned, the stepwise regression models selected the HRmax as a determinant of both $OUES_{100}$ and $OUES_{80}$. It is known that the aerobic fitness level is associated with low values of HRmax in healthy individuals, what has been related to high values of maximal cardiac output [29], high stroke volume and hypertrophy of the left ventricle [30]. This is in agreement with the findings of Fu et al. [31], whom observed higher values of cardiac output after 12 weeks of aerobic training accompanied by an improvement in the OUES. Thereby, it is tempter to suggest that the oxygen uptake efficiency may be increased by similar mechanisms responsible to decrease HRmax such as cardiac output enhancement [29] and parasympathetic nervous system activity [32]. Thus, future studies should investigate the relationship between the parameters able to regulate HRmax (*e.g.*, maximal cardiac output, autonomic nervous system, and stroke volume) and OUES.

Our multiple regression models also selected 1RM as a determinant of the $OUES_{100}$ and the $OUES_{80}$. Once the muscle strength is highly determined by muscle mass, this result confirms the previous suggestion of Baba et al. [11] and Akkerman et al. [33] that the OUES depends, among other factors, on the muscle mass able to extract oxygen from the blood and utilize it in bioenergetic processes. Furthermore, during running, a higher muscle strength in the lower limbs is able to provide a lower time of occlusion and a higher blood flow to the exercised muscles [18,20]. For instance, Storen et al. [18] observed that the improvements in 1RM after 8 weeks of strength training were accompanied by a significant increase in time to exhaustion at maximal aerobic speed. In this sense, OUES may be related to muscle strength through the improvement of blood flow to the exercise muscles during running. This increased blood flow could positively influence the oxygen uptake by augmenting the oxygen transit in muscle capillaries per time unit during exercise in stronger individuals. This increased oxygen transit would be important for oxygen and substrates offer to the working muscles, and to metabolites clearance, both of which would improve bioenergetic processes and the control of the acidosis in the muscle fibers [18].

The present study has some limitations. Mainly, we used only healthy subjects, in spite of the highlighted advantage of the OUES to special populations [26]. However, our results might be used as standard parameters of a normal population of healthy young men, similarly with the results of Buiys et al. [34], in order to compare with participants with other characteristics, such as cardiovascular disease patients. Moreover, once we used treadmill running and the type of exercise influences physiological variables and their associations with OUES [35], the data should be seen with caution and interpreted in an ergometer-manner dependent way.

Conclusion

In conclusion, the results of the present study demonstrate that both maximal and submaximal OUES are determined by the maximal oxygen uptake, muscle strength and maximal heart rate (*i.e.*, $\dot{V}O_2max$, 1RM, and HRmax, respectively). While the VO_2 max was the main determinant of the OUES regardless the intensity range used, 1RM and HRmax were more important for $OUES_{100}$ and $OUES_{80}$, respectively. Thus, it seems that at maximal intensities the muscle strength plays a more important role to the oxygen uptake efficiency. Otherwise, at submaximal intensities, the cardiovascular system seems to exert a strongly influence on the oxygen uptake efficiency. Despite the submaximal OUES is able to reflect maximal values, it is important to consider the determinant factors of oxygen uptake efficiency in different intensity ranges.

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