Assessing Maximal Exercise Capacity: Peak Work or Peak Oxygen Consumption?

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BACKGROUND: Exercise capacity assessed by cardiopulmonary exercise testing is usually measured by peak oxygen consumption ($\dot{V}_{O_2}$). However, not uncommonly, patients achieve a relatively higher work load (peak work) compared to their peak $\dot{V}_{O_2}$. In these situations it is difficult to know which parameter to use in assessing exercise capacity. The purpose of this study was to determine whether there are distinguishing physiological characteristics of patients with discordance between percent-of-predicted peak work versus peak $\dot{V}_{O_2}$, in order to understand how to use these measurements in interpreting exercise capacity. METHODS: We conducted a retrospective study of 172 cardiopulmonary exercise tests performed at our institution between 2003 and 2010. RESULTS: The subjects in the higher peak work group demonstrated higher ventilatory efficiency (lower slope of minute ventilation to carbon dioxide production) and lung function (FEV_1 and FVC), a greater breathing reserve (higher breathing reserve, lower $\dot{V}_E$/maximal voluntary ventilation), and achieved a higher maximal heart rate. Subjects in the higher maximum $\dot{V}_{O_2}$ group were heavier, had lower ventilatory efficiency, and had a reduced breathing reserve. Multivariate logistic regression analysis showed that the predominant independent factors associated with group assignment were body mass index, breathing reserve, and peak heart rate. The subjects with higher percent-of-predicted peak work than peak $\dot{V}_{O_2}$ had a lower body mass index, a greater breathing reserve, and a higher peak heart rate. CONCLUSIONS: The observation that there are distinguishing physiological features between those who have a higher peak work and those who have higher peak $\dot{V}_{O_2}$ provides insight into the underlying processes determining maximal exercise capacity. *Key words: cardiopulmonary exercise test; maximal oxygen consumption; anaerobic threshold; work capacity.* [Respir Care 2014;59(1):90–96. © 2014 Daedalus Enterprises]

Introduction

Cardiopulmonary exercise testing is a comprehensive approach to assess exercise capacity and limitations to exercise. Exercise capacity is usually interpreted in terms of peak oxygen consumption ($\dot{V}_{O_2}$).[1-7] Indeed, peak $\dot{V}_{O_2}$ is a robust predictor of outcomes in many cardiopulmonary diseases such as COPD, congestive heart failure, cystic fibrosis, and pulmonary hypertension.[1-3,8,9] However, we have observed that there are some patients who achieve higher percent-of-predicted peak work than percent-of-predicted peak $\dot{V}_{O_2}$, and vice versa. In these cases it is unclear whether to use peak work or peak $\dot{V}_{O_2}$ as the parameter by which to judge the patient's exercise capacity. As we pointed out in an editorial,[10] this fundamental question was not addressed by a 2003 statement on car-

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diopulmonary exercise testing published by the American Thoracic Society/American College of Chest Physicians.[2] In the majority of exercising subjects this distinction is unimportant, because the relationship between work and $\dot{V}_{O_2}$ is linear; thus, the percentage of the predicted value achieved for either parameter is similar.[7,11,12] However, as described by Wasserman and colleagues,[13] a difference in $\dot{V}_{O_2}$ may be observed between expected and observed values when calculating the expected $\dot{V}_{O_2}$ based on the maximum work rate achieved. The general goal of the current study was to evaluate the exercise characteristics that distinguish patients with discordant values of peak work and peak $\dot{V}_{O_2}$, to better understand the underlying processes that determine maximal exercise capacity. We specifically expected that patients achieving higher work relative to $\dot{V}_{O_2}$ would demonstrate better cardiopulmonary fitness and/or ability to tolerate the discomfort of a high level of exercise.

QUICK LOOK

Current knowledge

Cardiopulmonary exercise testing is a comprehensive approach to assess exercise capacity and limitation. Exercise capacity is commonly assessed as peak oxygen consumption.

What this paper contributes to our knowledge

In patients with a lower body mass index, higher breathing reserve, and greater peak heart rate, peak work may be greater than peak oxygen consumption. Including both peak oxygen consumption and peak work in the interpretation of the exercise test can detect underlying physiological characteristics that reflect important aspects of exercise.

Methods

Study Design

We retrospectively analyzed all cardiopulmonary exercise tests performed at the University of Vermont/Fletcher Allen Health Care, a tertiary care academic medical center, from 2003 to 2010. The study was approved by the University of Vermont Committee on Human Research in the Medical Sciences (study 10-232). A total of 172 tests were included.

All studies were performed according to standard guidelines.[2] We conducted exercise testing by using a 1 min step protocol to exhaustion on a bicycle ergometer system (MGC Diagnostics, St Paul, Minnesota), using work increments of 15 watts/min or 30 watts/min, estimated to bring the subject to maximal work load in approximately 10 min, as recommended by the American Thoracic Society/American College of Chest Physicians[2] and Wasserman and colleagues.[13] We measured baseline spirometry and maximal voluntary ventilation before exercise (or, estimated the latter as $FEV_1 \times 40$). We continuously monitored cardiovascular parameters (heart rate, blood pressure, electrocardiogram), ventilatory parameters (breathing frequency, tidal volume, S_{pO_2}), and metabolic parameters (CO_2 production [$\dot{V}_{CO_2}$], $\dot{V}_{O_2}$). Of note, we did not consistently record exercise flow-volume loops during the time frame of this study, so we do not report data on ventilatory limitation or changes in end-expiratory lung volume. We measured dyspnea with the modified Borg scale.[14] The following factors were calculated:

Slope of $\dot{V}_{O_2}$ versus work: (final $\dot{V}_{O_2}$ − initial $\dot{V}_{O_2}$)/final work − initial work

Respiratory exchange ratio: $\dot{V}_{CO_2}/\dot{V}_{O_2}$

Expired minute ventilation ($\dot{V}_E$): breathing frequency × tidal volume

Breathing reserve: maximum $\dot{V}_E$/maximal voluntary ventilation, or maximal voluntary ventilation − maximum $\dot{V}_E$

Ventilatory equivalent for oxygen: $\dot{V}_E/\dot{V}_{O_2}$

Ventilatory equivalent for carbon dioxide: $\dot{V}_E/\dot{V}_{CO_2}$

Slope of $\dot{V}_E$ vs $\dot{V}_{CO_2}$

Oxygen pulse: $\dot{V}_{O_2}$/heart rate

Anaerobic threshold: By inspection of the plot of $\dot{V}_{CO_2}$ versus work and of $\dot{V}_E/\dot{V}_{O_2}$ versus work for their respective inflection points in the slope

We used predicted values for work and $\dot{V}_{O_2}$ based on modified Jones criteria.[12] We defined a discordance between predicted peak work and predicted peak $\dot{V}_{O_2}$ as any absolute difference in the percent-of-predicted between these values of > 15 (eg, peak work = 110% of predicted, peak $\dot{V}_{O_2}$ = 85% of predicted). This cutoff was derived empirically from exploring cutoffs of 10%, 15%, and 20%. A cutoff of 10% was too small and within the range of experimental accuracy for peak $\dot{V}_{O_2}$ and peak work. A cutoff of 20% was overly sensitive and yielded a sample size of 11 in the smallest group, which we felt was too small to allow valid statistical analysis. We also assessed whether the results would appear to be substantially altered by using the normative equations of Wasserman and colleagues for work and $\dot{V}_{O_2}$, after adjusting for body weight.[13] We noted that the Wasserman criteria resulted in a more unbalanced distribution of subjects in the predicted work versus predicted $\dot{V}_{O_2}$ categories, which did not seem consistent with our clinical impression of the prevalence of this discrepancy. Accordingly, we used the Jones predicted equations,[12] with a discordance difference of > 15%.

Based on this difference, we divided the subjects into 3 groups: those with percent-of-predicted peak $\dot{V}_{O_2}$ greater than percent-of-predicted peak work (peak $\dot{V}_{O_2}$ > peak work), those with percent-of-predicted peak work greater than percent-of-predicted peak $\dot{V}_{O_2}$ (peak work > peak $\dot{V}_{O_2}$), and those with equivalent percent-of-predicted peak $\dot{V}_{O_2}$ and percent-of-predicted peak work (peak $\dot{V}_{O_2}$ = peak work).

Data Analysis

We analyzed all data for distribution, and expressed the data as mean ± SD. We assessed differences across the 3 groups by analysis of variance, with differences between any 2 groups analyzed with the Tukey honest significant difference test. In addition we performed a backwards, stepwise multivariate logistic regression analysis to determine which exercise parameters identified as significant between the peak work > peak $\dot{V}_{O_2}$ and peak $\dot{V}_{O_2}$ > peak work groups were independently associated with group assignment. Two-tailed *P* values < .05 were taken as indicating statistical significance. All data were analyzed using statistics software (JMP 9.0, SAS Institute, Cary, North Carolina).

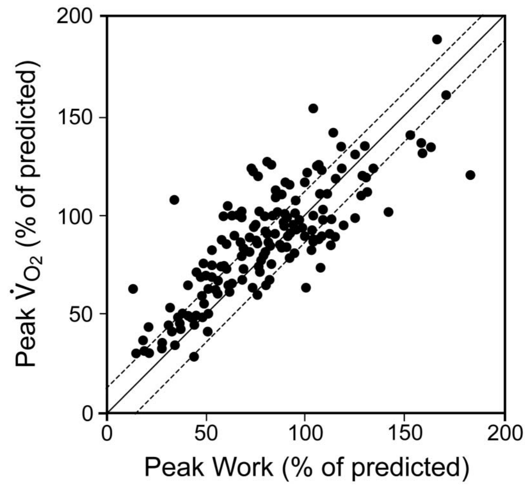

Figure. Percent-of-predicted peak oxygen consumption ($\dot{V}_{O_2}$) versus percent-of-predicted peak work. The solid line is the line of identity, and the 2 dashed lines represent the 15% differences above and below the line of identity, thus defining 2 groups: peak $\dot{V}_{O_2}$ > peak work (above the upper dashed line), and peak work > peak $\dot{V}_{O_2}$ (below the lower dashed line).

Results

A total of 172 tests were included for analysis. Patients were referred for testing for a variety of reasons, the most common of which were unexplained dyspnea (n = 90, 52%) and COPD, the latter mostly for evaluation prior to pulmonary resection for lung cancer (n = 28, 16%) or pulmonary rehabilitation (n = 25, 14%). There were 2 cases of cardiac disease (cardiomyopathy and diastolic dysfunction). Other diagnoses included cough, chest pain, interstitial lung disease, sarcoidosis, scoliosis, tracheobronchomalacia, and vocal cord dysfunction. All subjects were instructed to exercise to exhaustion. The most common reasons for stopping exercise were leg fatigue (42%), shortness of breath (28%), and a combination of equal leg fatigue and shortness of breath (21%). None of the subjects had any particular experience with bicycle ergometry, which might have given them an unseen advantage in terms of motor efficiency.

The Figure displays the distribution of groups based on the 15% cutoff between percent-of-predicted peak $\dot{V}_{O_2}$ versus peak work. The majority of subjects (n = 92) were in the peak work = peak $\dot{V}_{O_2}$ group. As seen in Table 1, there were distinct differences in the groups' demographics. Subjects who achieved higher percent-of-predicted peak work than percent-of-predicted maximum $\dot{V}_{O_2}$ were younger, had a lower body mass index (BMI), and had a more even distribution of males versus females than those who achieved a higher percent-of-predicted peak $\dot{V}_{O_2}$ than percent-of-predicted peak work. There were no overall differences in diagnostic category distribution between the 3 groups (P = .57). Both the cardiac subjects fell within the peak $\dot{V}_{O_2}$ = peak work group, as did the majority (62%) of the COPD subjects and half (49%) of the unexplained dyspnea subjects. The remaining COPD and unexplained dyspnea subjects were mainly in the peak $\dot{V}_{O_2}$ > peak work group rather than the peak work > peak $\dot{V}_{O_2}$ group (32 vs 6%, and 34 vs 17%, respectively).

As shown in Table 1, there were also differences in exercise variables between the groups. All subjects had similar baseline $\dot{V}_{O_2}$ at rest. Subjects who achieved a higher percent-of-predicted peak $\dot{V}_{O_2}$ than percent-of-predicted peak work had a higher $\dot{V}_{O_2}$/work slope, as at least partly expected, due to their having a lower work rate increment during exercise.[15] Subjects with peak $\dot{V}_{O_2}$ > peak work were more likely female, heavier, had lower ventilatory efficiency (higher $\dot{V}_E/\dot{V}_{CO_2}$ slope), and a reduced breathing reserve. The subjects in the peak work > peak $\dot{V}_{O_2}$ group demonstrated higher ventilatory efficiency, lung function (FEV_1 and FVC), and breathing reserve (higher breathing reserve, lower $\dot{V}_E$/maximal voluntary ventilation). The subjects in this group also achieved a higher peak respiratory exchange ratio and heart rate. Multivariate logistic regression analysis showed that the independent factors associated with having a higher percent-of-predicted peak work than peak $\dot{V}_{O_2}$ were lower BMI, higher breathing reserve, and greater peak heart rate (Table 2).

Discussion

In the current study we sought to determine which physiological characteristics distinguish patients who have discordance between peak work and peak $\dot{V}_{O_2}$. We found that

Table 1. Subject Demographics and Physiological Characteristics

	Peak $\dot{V}_{O_2}$ > Peak Work $n = 57$	Peak $\dot{V}_{O_2}$ = Peak Work $n = 92$	Peak Work > Peak $\dot{V}_{O_2}$ $n = 23$	P*
Age, y	63 ± 13†	59 ± 15	51 ± 10‡	.001
Male/female, %	26/74†‡	49/51	52/48	.04
Body mass index, kg/m^2	30 ± 7†‡	27 ± 5	26 ± 4	< .001
FVC, % predicted	78 ± 17†‡	86 ± 18	95 ± 15	< .001
FEV_1, % predicted	66 ± 23†	74 ± 25	93 ± 20‡	< .001
FEV_1/FVC	0.85 ± 0.23†	0.84 ± 0.21	0.97 ± 0.14‡	.03
Work increment (15/30 watts/min), %	91/9	66/34	9/91	< .001
Total exercise time, min	4.7 ± 1.7	5.4 ± 1.9	6.8 ± 2.5‡§	< .001
Peak $\dot{V}_{O_2}$, % predicted	97 ± 28‡	80 ± 26	94 ± 25	< .001
Peak work, % predicted	70 ± 28	78 ± 30	119 ± 29‡§	< .001
$\dot{V}_{O_2}$/work slope, mL/min/watt	13 ± 3†‡	10 ± 2	8 ± 1‡	< .001
$\dot{V}_{O_2}$/work slope above anaerobic threshold, mL/min/watt	10.6 ± 7.0	11.4 ± 4.8	9.5 ± 2.8	.32
Rest $\dot{V}_{O_2}$, mL/min/kg	4.3 ± 1.2	4.1 ± 1.1	4.1 ± 1.3	.37
Peak $\dot{V}_{O_2}$, mL/min/kg	17 ± 7†	19 ± 10	26 ± 10‡	< .001
$\dot{V}_E/\dot{V}_{O_2}$ at anaerobic threshold, L/mL	31 ± 8	32 ± 8	26 ± 3‡§	.003
$\dot{V}_E/\dot{V}_{CO_2}$ slope, L/mL	32 ± 6	34 ± 8	29 ± 6‡	.01
Peak $\dot{V}_{CO_2}/\dot{V}_{O_2}$	1.04 ± 0.12†‡	1.10 ± 0.12	1.21 ± 0.09‡§	< .001
$\dot{V}_E$/maximal voluntary ventilation, %	73 ± 20†	67 ± 17	57 ± 16‡	.002
Breathing reserve, L	23 ± 22†	32 ± 25	54 ± 27‡	< .001
Peak heart rate, % predicted	81 ± 13†	79 ± 14	89 ± 10‡	.004
Peak $\dot{V}_{O_2}$/heart rate, % predicted	102 ± 32	93 ± 28	105 ± 26	.09
Change in O_2 saturation, %	0.16 ± 0.20	0.67 ± 0.16	−0.66 ± 0.32‡	< .001
Change in Borg dyspnea score/change in work, units/watt	0.07 ± 0.08	0.05 ± 0.03	0.02 ± 0.01	.004‡
Time to anaerobic threshold, % of total time	50 ± 24	56 ± 19	59 ± 14	.14
Time above anaerobic threshold, % of total time	50 ± 24	44 ± 19	41 ± 14	.14
Anaerobic threshold, % of peak predicted $\dot{V}_{O_2}$	63 ± 19‡	51 ± 18	60 ± 20	< .001

Values are mean ± SD unless otherwise indicated.
* P via analysis of variance across groups.
† $P < .05$ in comparison to Work > $\dot{V}_{O_2}$ group.
‡ $P < .05$ in comparison to $\dot{V}_{O_2}$ = Work group.
§ $P < .05$ in comparison to $\dot{V}_{O_2}$ > Work group.
$\dot{V}_E$ = minute ventilation
$\dot{V}_{CO_2}$ = carbon dioxide production

Table 2. Factors Associated With Being in the Peak $\dot{V}_{O_2}$ > Peak Work Group Rather Than the Peak Work > Peak $\dot{V}_{O_2}$ Group, Via Multivariate Logistic Regression Analysis*

	Odds Ratio	95% CI	P
Body mass index	1.18	1.03–1.38	.03
Breathing reserve	0.94	0.90–0.96	< .001
Peak heart rate	0.94	0.88–0.99	.03

* R^2 for model = 0.42.

those who can perform relatively higher work relative to their maximal $\dot{V}_{O_2}$ were less heavy, had a greater breathing reserve and a higher peak heart rate. Meanwhile, those who consumed more oxygen relative to their work achieved were heavier, with less breathing reserve and a lower peak heart rate. Our data support the concept that lower weight (ie, mean BMI 26 vs 30 kg/m^2), better ventilatory function, and ability to exercise to a higher heart rate are associated with the ability to perform higher work loads for a given $\dot{V}_{O_2}$.

Most clinicians and researchers alike classify exercise tolerance on the basis of maximal $\dot{V}_{O_2}$ achieved (eg,[7,16-18]). Ideally, one would want to demonstrate maximal exercise capacity on the basis of achieving a plateau in maximum $\dot{V}_{O_2}$, suggesting that the limit of aerobic energy production has been reached.[19-21] However, the visualization of such a plateau is highly variable among patients and typically not seen in most clinical cardiopulmonary exercise tests[22] (only 22% of subjects in the current study achieved such a visual plateau); for this reason, we used the term "peak" $\dot{V}_{O_2}$, which is more accurate and tends to confer the same information.[20] Classifying maximal exercise capacity on the basis of peak $\dot{V}_{O_2}$ makes sense, as the majority of work performed during physical activity utilizes energy from aerobic metabolism.[5,7] In fact, the terms "work capacity" and "maximal $\dot{V}_{O_2}$" are often used interchangeably (eg, in Oren et al[7]). Indeed, maximum $\dot{V}_{O_2}$ or peak $\dot{V}_{O_2}$ is a robust measure of outcomes and influence of interventions in a wide variety of cardiopulmonary diseases.[1,3,8] Yet the functional aerobic capacity reflected in the peak $\dot{V}_{O_2}$ does not necessarily reflect the total work performed. This so-called "$\dot{V}_{O_2}$ difference," as coined by Wasserman,[13] may be due to many factors, such as failure to reach steady state, obesity, cardiovascular disease, or improper ergometer calibration.[13] While some authors use power output or work capacity as a reflection of exercise tolerance (eg, Jones and Killian[5]; Katz et al[23]), most studies continue to use peak $\dot{V}_{O_2}$ as the primary measure of exercise capacity.

We view the cause of this discrepancy between peak $\dot{V}_{O_2}$ and peak work to fall into the following categories. First, some work is achieved on the basis of anaerobic energy production (ie, that above the anaerobic threshold), and use of peak $\dot{V}_{O_2}$ only will underestimate the total work or energy expenditure achieved.[24] Second, total work, at least in endurance athletes, is linked to other variables besides peak $\dot{V}_{O_2}$, such as fractional utilization of peak $\dot{V}_{O_2}$ (ie, the percent of peak $\dot{V}_{O_2}$ that can be sustained during exercise) and mechanical exercise efficiency.[19]

Indeed, mechanical efficiency is a critical factor to consider. For example, subjects with obesity are reported to have a higher $\dot{V}_{O_2}$ at rest, but a lower work capacity for a given $\dot{V}_{O_2}$, reflecting their lower gross mechanical efficiency.[25] Indeed, the obese subjects in our study had a higher $\dot{V}_{O_2}$ at rest (350 ± 104 mL/min vs 298 ± 91 mL/min, $P = .002$). In addition, the obese subjects had a higher $\dot{V}_{O_2}$/work slope, even when isolated to the subgroup of subjects with peak $\dot{V}_{O_2}$ > peak work (obese 13.7 ± 3.7 mL/min/watt, non-obese 12.2 ± 2.5 mL/min/watt, $P = .08$). One may consider that the subjects in this study with peak work > peak $\dot{V}_{O_2}$ were more familiar with bicycle exercise than the subjects in the peak $\dot{V}_{O_2}$ > peak work group, thus allowing them a potential biomechanical advantage by more efficient pedaling to generate work.[26] However, we do not think this factor was relevant, because there was no overall difference in the use of or experience with bicycle ergometry in any of the 3 groups.

There are also other factors to consider. Muscle fiber type, specifically the relative amount of type I (slow twitch) and type II (fast twitch) fibers, might be associated with greater $\dot{V}_{O_2}$/work slope, as seen in the peak $\dot{V}_{O_2}$ > peak work group in our study, but data are conflicting,[27,28] and we have no direct information on muscle fiber type in this study. Biochemical inefficiency may also result in peak $\dot{V}_{O_2}$ > peak work, such as in McArdle disease, where there is a higher $\dot{V}_{O_2}$ for a given amount of work, due to altered substrate utilization and a greater cardiovascular response to exercise.[29] Both mechanical and biochemical factors may explain why different levels of work are achieved for the same peak $\dot{V}_{O_2}$ depending on the exercise protocol. For example, total work achieved is higher with a greater work increment protocol, as seen here.[15] In addition, the work involved in an incremental exercise test is 30% greater than that achieved for a constant load test for the same level of $\dot{V}_{O_2}$.[30] Meanwhile, an important factor that may result in peak work > peak $\dot{V}_{O_2}$ is circulatory impairment. For example, in congestive heart failure, $\dot{V}_{O_2}$ is limited for a given work load, due to the inability of cardiac output to fully compensate for increased oxygen extraction by the tissues, yielding a lower $\dot{V}_{O_2}$ versus work relationship.[31] We believe that circulatory impairment was an unlikely contributing factor in this study, because there was no clear discordance of cardiovascular disease in any of the subject groups. Finally, psychological factors, such as anxiety, fear, motivation, and perception of breathlessness or fatigue, clearly play a role in limiting exercise capacity.[5,32,33]

Since the amount of work for any given $\dot{V}_{O_2}$ can vary due to all the reasons discussed above, we suggest that *overall exercise tolerance* be judged on the basis of the peak work achieved. This is in accordance with the general concept of rating impairment versus disability,[34] wherein the former reflects physiological function, while the latter reflects the ability to perform work in the context of personal and environmental factors: a more global measure. It is important to emphasize, however, that peak $\dot{V}_{O_2}$ remains an important measure of cardiovascular conditioning,[35] preoperative risk in lung resection surgery,[36] and a predictor of future cardiopulmonary outcomes,[1-3,8,9] and such relationships have not been found for direct measures of work.

Our findings suggest that a lower BMI, greater breathing reserve, and higher peak heart rate are important independent factors associated with the ability to achieve relatively higher peak work than peak $\dot{V}_{O_2}$. A lower BMI would allow a greater amount of work to be done for a given level of $\dot{V}_{O_2}$, because of the improved mechanical efficiency of exercise.[25] A greater breathing reserve would be consistent with the ability to handle the metabolic acidosis associated with exercise above the anaerobic threshold.[13] The greater heart rate seen in subjects achieving higher peak work than peak $\dot{V}_{O_2}$ most likely reflects these subjects' ability, effort, and motivation to exercise to physiological cardiovascular limitation.[37] The higher respiratory exchange ratio in this group is consistent with this as well.

Limitations

This was a single center, retrospective review using bicycle ergometry and a step exercise protocol. How our results would compare to a different population using different equipment or protocols is unclear; however, since our hospital is a large, tertiary care facility that cares for a wide variety of patients, we believe our results would be broadly applicable. Importantly, even though the majority of subjects with COPD were within the peak $\dot{V}_{O_2}$ = peak work group, there were more subjects with COPD in the peak $\dot{V}_{O_2}$ > peak work group, which might have been the cause of the lower breathing reserve associated with this group and thus confounded our findings. Our definition of equivalence of peak work and peak $\dot{V}_{O_2}$ was arbitrary, but seemed to best reflect our clinical impression of prevalence and importance.

We were unable to assess the contribution of psychological factors involved in exercise, such as motivation, anxiety, or thresholds for pain, although we did find no significant differences in the change in Borg dyspnea scores. Interestingly, this lack of differences may reflect reduced sensitivity to dyspnea among the subjects achieving high work loads.[38] This reduced sensation of dyspnea is supported by the lower change in Borg dyspnea score adjusted for the amount of work performed among subjects in the peak work > peak $\dot{V}_{O_2}$ group. In addition, although we suggest that peak work better reflects global exercise capacity than does peak $\dot{V}_{O_2}$, we have not validated this concept by correlating this finding with any clinically meaningful outcomes, such as response to therapy or relationship to job or athletic performance. However, total work load is thought to be a critical factor in improving cardiopulmonary conditioning.[35]

It is important to note that there was discordance between the exercise protocols used in the peak work > peak $\dot{V}_{O_2}$ group and the peak $\dot{V}_{O_2}$ > peak work group. Namely, the group achieving higher work than $\dot{V}_{O_2}$ exercised in higher work load increments (30 watts/min) than the group achieving higher $\dot{V}_{O_2}$ than work (15 watts/min). These increments were chosen by the exercise technologist on the basis of the subject's self-reported exercise capacity, in order to create a protocol that would allow the subject to reach peak work capacity in approximately 10 min.[13] The difference in these increments may have contributed to why different relationships of peak work versus peak $\dot{V}_{O_2}$ were achieved.[15] However, the altered rate of $\dot{V}_{O_2}$ for different levels of work is usually seen for work rates above the anaerobic threshold,[13,15] and there were no significant differences in slope of $\dot{V}_{O_2}$-work above the anaerobic threshold in any of the 3 groups (see Table 1). In addition, in the study by Hansen and colleagues[15] higher work rate increments resulted in shorter total exercise time among the same healthy subjects who were tested under different work rate protocols. We found just the opposite, which was that subjects who had the higher work rate increment (the majority of the peak work > peak $\dot{V}_{O_2}$ group) had longer total exercise times (see Table 1). This suggests that other factors besides the exercise protocol are important in determining peak work versus peak $\dot{V}_{O_2}$. Nevertheless, given this aspect of our study, and the finding of only modest odds ratios from the multivariate logistic regression analysis, one must interpret the findings with caution and realize that they may be of marginal clinical importance. In addition, the fact that the exercise increments were chosen on the basis of subject self-reported exercise capacity may have resulted in a selection bias that favored the more fit subjects exercising on the higher work increment protocol, thus creating a self-fulfilling situation of achieving higher peak work relative to peak $\dot{V}_{O_2}$.

Conclusions

Subjects who had higher peak work than peak $\dot{V}_{O_2}$ had lower BMI, higher breathing reserve, and higher peak heart rate. While the work protocol might have primarily determined this, the fact that differences in BMI, breathing reserve, and peak heart rate differentiate the peak work and peak $\dot{V}_{O_2}$ groups suggests that underlying physiological characteristics reflect important aspects of exercise capacity that go beyond the peak $\dot{V}_{O_2}$. The clinical corollary of this is that encouraging weight loss, treating any reversible lung disease, and recommending regular, strenuous exercise are appropriate strategies to help these patients improve their exercise capacity. When a cardiopulmonary exercise test is ordered to assess overall exercise tolerance, we suggest measuring both peak work and peak $\dot{V}_{O_2}$, to provide the most comprehensive interpretation of the results.

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