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Total body fat does not influence maximal aerobic capacity

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OBJECTIVE: The objective of this study was to examine the influence of body weight and body composition on aspects of aerobic fitness. Our hypothesis was that increased body weight, specifically increased fat mass (FM), would not limit VO_{2max} relative to fat-free mass (FFM), but would reduce maximal and sub-maximal VO_{2max} relative to body weight.
DESIGN: We used data from two ongoing studies. In Study 1 a cross-sectional analysis of 129 children across a wide spectrum of body composition was performed. In Study 2 we examined data from 31 overweight women before and after weight loss.
METHODS: VO_{2max} was measured using a treadmill test. Sub-maximal aerobic capacity was evaluated with respiratory exchange ratio (RER), heart-rate (HR), and oxygen uptake relative to VO_{2max} at a given workload (%VO_{2max}). Body composition was assessed using dual energy X-ray absorptiometry (DXA) (Study 1) and a four-compartment model (Study 2).
RESULTS: In Study 1, FFM was the strongest determinant of VO_{2max} ($r = 0.87$; $P < 0.0001$). After adjusting for FFM, there was no significant influence of FM on VO_{2max}. After separating children into lean and obese sub-groups, absolute VO_{2max} was significantly higher in the obese (1.24 ± 0.27 *vs* 1.56 ± 0.40) and VO_{2max} relative to body weight was significantly lower (44.2 ± 3.2 *vs* 32.0 ± 4.1 ml/(kg-min)), whereas there was no significant difference when expressed relative to FFM (57.9 ± 5.8 *vs* 59.2 ± 4.9 ml/(kgFFM-min)). Sub-maximal aerobic capacity was significantly lower in the obese children, as indicated by a higher HR and %VO_{2max}; time to exhaustion was significantly lower in the obese children (15.3 ± 2.9 *vs* 11.1 ± 2.1 min). In Study 2, FFM was also the strongest determinant of VO_{2max} before and after weight loss. The relationship between VO_{2max} and FFM was identical before and after weight loss so that VO_{2max} relative to FFM was identical before and after weight loss (43.8 ± 4.9 *vs* 45.5 ± 6.4 ml/(kgFFM-min)). However, sub-maximal aerobic capacity was lower in the obese state, as indicated by a significantly higher RER (0.85 ± 0.06 *vs* 0.79 ± 0.05), HR (124 ± 14 *vs* 102 ± 11 bpm), and %VO_{2max} (44% *vs* 36%).
CONCLUSION: The major influence of body weight on VO_{2max} is explained by FFM; FM does not have any effect on VO_{2max}. Fatness and excess body weight do not necessarily imply a reduced ability to maximally consume oxygen, but excess fatness does have a detrimental effect on submaximal aerobic capacity. Thus, fatness and VO_{2max} should be considered independent entities.
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Keywords: aerobic fitness; body weight; body composition; obesity; physical activity

Introduction

Total body fatness and aerobic fitness are frequently used in association with each other, and it is often implied that these physiological parameters are strongly inter-related. Both body fatness and aerobic fitness have been shown to be risk factors for future health outcome, but it is unclear whether these effects are related to one another or are independent risk factors. Some recent studies have shown that there are separate and independent health effects of aerobic fitness and fatness.[1–6] It has recently been argued that aerobic fitness is the primary factor influencing future health outcome,[1,2,4–7] although the physiological basis of this concept remains unclear.

Confusion exists on the proper expression of VO_{2max} data when comparing obese and normal weight individuals. When comparing the physiological ability of the tissue to maximally consume oxygen, VO_{2max} should be presented relative to fat-free mass, (ml/kg FFM · min). On the other hand, when looking at 'endurance' or 'performance', VO_{2max} relative to body weight (ml/kg · min) should be used.[8]

Based upon recent work concerning fitness *vs* fatness[2–7,9] we felt that it was timely to re-examine the nature of the relationship between aerobic fitness and total body fatness in humans. Previous analyses of this relationship[10–14] have not included data normalization procedures to enable the most appropriate comparison of VO_{2max} data. Toth *et al*[15] have previously demonstrated the importance of using regression analysis

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with fat-free mass (FFM) as the co-variate, rather than dividing VO_{2max} by body weight or (FFM). Thus, given that FFM is the single most important co-variate for comparing VO_{2max} data, it is unclear whether fat mass (FM) has any additional independent effects on VO_{2max}. Therefore the purpose of this study was to examine the influence of body weight and body composition (FM *vs* FFM) on aerobic fitness. In particular we were interested in examining whether increased body weight, specifically due to increased fat mass, would limit VO_{2max} and sub-maximal aerobic capacity. This issue was examined in two data sets. The first analysis examined cross-sectional data from 129 children across a wide spectrum of body composition. The second analysis was performed to examine changes in body composition, VO_{2max} and sub-maximal aerobic capacity among 31 overweight women in energy-balance conditions prior to and after a controlled, diet-induced, weight loss intervention study.

Methods

Subjects — Study 1 (children)
The data included observations from 129 pre-pubertal children (including Caucasian and African-American boys and girls). Subjects were screened by a medical history evaluation and were ineligible if they were taking medications known to affect body composition or physical activity (eg prednisone, ritalin, growth hormone) or had been diagnosed with syndromes known to affect body composition and/or fat distribution (eg Cushing's Syndrome, Downs' Syndrome, type I diabetes, hypothyroidism) or any major illness since birth. Data from children beyond Tanner stage I were excluded from this analysis. Tanner stage I was defined based on breast stage and pubic hair development in girls and genitalia development in boys, as assessed by a physical examination by a pediatrician. Since the intent was to recruit a heterogeneous group of children, there were no set criteria for other characteristics such as obesity status. The Institutional Review Board approved this study at the University of Alabama at Birmingham. The parents of all participants provided informed consent before testing commenced.

Subjects — Study 2 (adult weight loss)
Study subjects were 31 (Caucasian and African-American) premenopausal women between the ages of 20 and 46 y who were part of a major study to examine metabolic regulation in the post-obese state. Body mass index (BMI) was 27–30 kg/m^2 at the onset of the study. Subjects were non-smokers and were not taking medications known to affect energy expenditure, fuel utilization, insulin level, heart rate, or thyroid status. This study was also approved by the Institutional Review Board at the University of Alabama at Birmingham.

Protocol — Study 1 (children)
Children were admitted to the General Clinical Research Center (GCRC) at the University of Alabama at Birmingham in the late afternoon for an overnight visit. Upon arrival, anthropometric measurements were obtained and dinner was served at approximately 17:00 h. An evening snack was allowed as long as it was consumed before 20:00 h. After 20:00 h only water and non-caloric, non-caffeine beverages were allowed until after the morning testing. The following morning, resting energy expenditure was measured and blood was collected for hormone and lipid analysis and an oral glucose tolerance test was administered (data not reported in this paper). After the preceding tests were completed, the children were fed breakfast and allowed to leave. Two weeks later, the children arrived at the Energy Metabolism Research Laboratory at 07:00 hours in the fasted state and body composition was determined by dual energy X-ray absorptiometry (DXA) and maximal and sub-maximal aerobic capacity were assessed by a treadmill test to exhaustion.

Protocol — Study 2 (adult weight loss)
All subjects were evaluated in the overweight state and again in the normal-weight state after 4 weeks of weight-stable, diet-controlled conditions through the (GCRC). During each 4 week period, body weight was measured three times weekly at the GCRC for the first 2 weeks and five times weekly during the last 2 weeks, and energy intake was adjusted as necessary to ensure weight stability. After weight stabilization in the overweight and in the normal-weight states, subjects were admitted to the GCRC for a 4 day period of evaluation. Subjects were tested during the follicular phase of their menstrual cycle. Upon discharge, subjects were followed as outpatients of the GCRC, and all meals were prepared and provided by the GCRC Research Kitchen. Subjects were seen twice weekly by the GCRC Research Dietitian to measure body weight, to monitor dietary adherence, and to provide meals until the next visit. The energy content of the meals was 800 kcal/day in all cases (approximately 64%, 14% and 22% of calories as carbohydrate, fat and protein, respectively). No alcohol intake was permitted. All meals were prepared in the GCRC Research Kitchen, and included Stouffer Lean Cuisine® entrees at lunch and dinner kindly provided by Nestle Food Co. (Solon, OH). The 800 kcal diet used in this study was designed to meet all nutrient requirements except for energy. Subjects were maintained on the energy-restricted diet until they lost a minimum of 10 kg and reached a normal body weight, defined as a BMI < 25 kg/m^2. It typically took the women 3–5 months to lose this weight; subjects were not encour-

aged or discouraged to participate in any physical activity program to reduce the time for weight loss.

Measurement of aerobic fitness

VO_{2max} was measured in both studies using an all-out treadmill test to exhaustion. After becoming familiar with the testing equipment, subjects practiced walking on the motorized treadmill until they were able to walk without holding on to the railings. Subjects followed an all-out, progressive, continuous treadmill protocol appropriate for children, as previously described.[16] Briefly, in Study 1, the children walked for 4 min at 0% grade and 4 km/h, after which the treadmill grade was raised to 10%. Each ensuing work level lasted 2 min, during which the grade was increased by 2.5%. The speed remained constant until a 20% grade was reached, at which time the speed was increased by 0.6 km/h until the subject reached volitional exhaustion. In Study 2, the adults used a modified Bruce graded treadmill protocol as described by Ref. 17. The adults walked for 4 min at 2.5% grade and 4.8 km/h. Each ensuing work level lasted 1 min, while the grade was increased by 2.5%. The speed remained constant until a 15% grade, at which time the speed was increased by 0.8 km/h. The elevation was raised by 2.5% grade until the subject reached volitional exhaustion. Two of the following three criteria were used to determine whether VO_{2max} was achieved: (a) a leveling or plateauing of VO_2 (defined as an increase of oxygen uptake ≤ 2 ml/(kg-min)); (b) a heart rate ≥ 195 for Study Group 1 (children) and for Study Group 2 (adult weight loss) an age-predicted maximal heart rate $\pm$ 10 bpm; and (c) a respiratory exchange ratio (RER) ≥ 1.0.

For both studies, oxygen consumption and CO_2 production were measured continuously via open circuit spirometer, and analyzed using a Sensormedics Metabolic Cart (Model no. 2900, Yorba Linda, CA). Prior to each test session, the gas analyzers were calibrated with certified gases of known standard concentrations. Additionally, heart rate (HR) was measured using a Polar Beat heart rate monitor (Model no. 901201, Woodbury, NY).

Aerobic fitness was measured using VO_{2max} relative to FFM (ml/kg FFM · min) and VO_{2max} relative to body weight (ml/kg · min). This study avoided possible problems with ratio scaling by adjusting VO_{2max} for FFM. Additionally, sub-maximal aerobic capacity was measured using RER, HR, and oxygen uptake as a percentage of VO_{2max} (%VO_{2max}) at 4 min into the exercise protocol.

The overall efficiency of the cardiovascular system during maximal exercise was evaluated using the oxygen pulse (VO_2/HR). The oxygen pulse is a non-invasive index of the efficiency of the ability of the body to transport oxygen to the working tissue, with more fit subjects having a higher oxygen pulse as compared to less fit subjects.[17] It is used as an index of the oxygen utilized per heart rate.[17] The pulmonary efficiency at maximal exercise was evaluated using volume of expired gas (VE) and the ventilatory equivalent for oxygen (VE/VO_2).

Measurement of body composition and anthropometry

Total body composition in Study 1 was measured by DXA using a Lunar DPX-L densitometer. The radiation exposure from this procedure is negligible and is estimated to be 0.06 mR (data from Lunar Corporation). Subjects were scanned in light clothing while lying flat on their backs with arms by the side. DXA scans were performed and analyzed using pediatric software (version 1.5e).

In Study 2, body composition was determined by the four-compartment model, as described by Baumgartner *et al*.[18] The four-compartment model calculates percentage body fat from the independent measures of total body density (by underwater weight), the fraction of body weight that is water (by isotope dilution), and the fraction of body weight that is mineral (DXA). Total body water was determined by the isotope dilution technique using deuterium and oxygen-18 labeled water as previously described.[19] Whole body density was determined by underwater weighing, with residual volume measured simultaneously by the closed-circuit O_2 dilution technique.[20] Bone mineral content was determined by DXA (DPX-L, Lunar Corp., Madison, WI) using adult Software (Version 1.33).

Statistics

Bivariate relationships between aerobic fitness and the other physical characteristics were examined using the Pearson correlation coefficient. For Study 1 children were separated into two groups, lean and obese (ie $<20\%$ body fat = lean and $>30\%$ body fat = obese), thus 78 children were used for analysis. Aerobic fitness variables of the subset of lean children were compared with those of the subset of obese children using a paired *t*-test. For Study 2, aerobic fitness variables of the women before and after weight loss were compared using a paired *t*-test. Regression and analysis of covariance were used to compare the relationships between aerobic fitness and body composition before and after weight loss. Statistical analyses were conducted using SPSS version 9.0 with a significance level set at $P < 0.05$ for all analyses.

Results

Study 1 (children)

For the analyses in Study 1, data from 129 children (9.6 ± 1.3 y, 44.1 ± 18.4 kg body weight, 23.5 ± 5.3 kg FFM and 11.8 ± 8.9 kg FM) were examined. As shown in Table 1, maximal oxygen consumption (l/min) was most highly correlated with FFM ($r = 0.87$), body weight ($r = 0.78$), height ($r = 0.75$), sub-maximal oxygen consumption ($r = 0.69$), FM

Table 1 Correlation coefficients for the relationship between maximal oxygen consumption (l/min) and other variables in 129 children in Study 1

Independent variable	*Simple r*	*Partial r (adjusting for FFM, gender and ethnicity)*
Fat-free mass (kg)	0.87 ($P<0.0001$)	—
Weight (kg)	0.78 ($P<0.0001$)	NS
Height (m)	0.75 ($P<0.0001$)	NS
Resting oxygen consumption (l/min)	0.72 ($P<0.0001$)	NS
Sub-maximal oxygen consumption (l/min)	0.69 ($P<0.0001$)	0.29 ($P<0.05$)
Fat mass (kg)	0.66 ($P<0.0001$)	NS
Body mass index (kg/m^2)	0.61 ($P<0.0001$)	NS
Age (y)	0.59 ($P<0.0001$)	NS

NS = not significant.

($r=0.66$), BMI ($r=0.61$) and age ($r=0.59$). However, after adjusting for FFM, gender and ethnicity, only sub-maximal oxygen consumption remained significantly related to maximal oxygen consumption ($r=0.29$; Table 1).

For the regression between maximal oxygen consumption (VO_{2max} l/min) and FFM, the intercept was not significantly different from zero ($VO_{2max}=0.063\times$fat free mass -0.12 l/min), implying that VO_{2max} divided by FFM (ml/(FFM min)) is a valid ratio for comparing VO_{2max} in children of different body size. For the regression between maximal oxygen consumption (VO_{2max} l/min) and body weight, the intercept was significantly different from zero ($VO_{2max}=0.021\times$body weight $+0.56$ l/min), implying that VO_{2max} divided by body weight may not be a valid ratio for comparing VO_{2max} in children of different body size.

The children were separated into lean (< 20% body fat) and obese (> 30% body fat) as shown in Table 2. Absolute VO_{2max} (l/min) was significantly higher in the obese group, VO_{2max} divided by body weight was significantly lower in the obese group, and VO_{2max} divided by FFM was not significantly different between lean and obese children (Figure 1). As shown in Table 2, sub-maximal aerobic capacity was significantly reduced in the obese children as

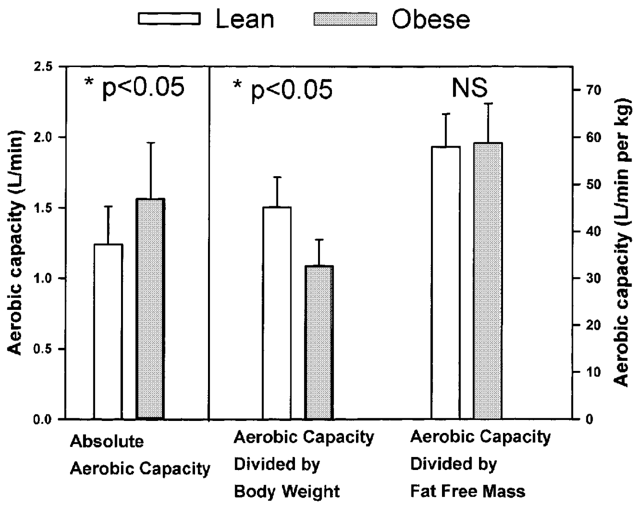

Figure 1 Comparison of maximal oxygen consumption in lean (< 20% fat; unfilled bars) and obese (> 30% fat; shaded bars) children. The physical characteristics of the children are shown in Table 3. Data for absolute maximal oxygen consumption are expressed in l/min using the left-hand *y*-axis, and data for maximal oxygen consumption divided by body weight (ml/(kg-min)) and maximal oxygen consumption divided by fat-free mass (ml/(FFM min)) are expressed in m l/min per kg using the scale on the right hand *y*-axis.

indicated by a significantly higher heart rate (126 ± 13 *vs* 114 ± 15 bpm), and a significantly higher %VO_{2max} (44% *vs* 37%). The overall efficiency of the cardio respiratory system as determined by the oxygen pulse was not significantly different between the obese and lean children (7.8 ± 1.5 *vs* 6.3 ± 1.8), but time to exhaustion for the obese children (11.1 ± 2.1 min) was 27% lower ($P<0.05$) than the lean children (15.3 ± 2.9 min).

Study 2 (adult weight loss)

The physical characteristics of the 31 women before and after weight loss are shown in Table 3. The women lost an average of 13.0 ± 3.6 kg of body weight (equivalent to a 16% reduction), which consisted of a significant 7% reduction in FFM

Table 2 Characteristics of lean (< 20% body fat) and obese (> 30% body fat) children in Study 1

	Lean (n = 39)	*Obese (n = 39)*
Age (y)	8.6 ± 1.6	8.9 ± 1.2
Weight (kg)	28.1 ± 8.7	48.6 ± 13.0*
Percentage fat	14.0 ± 4.0	39.7 ± 5.6*
Fat-free mass (kg)	21.4 ± 3.9	26.4 ± 5.3*
$VO_{2sub\text{-}max}$ (l/min)	0.46 ± 0.15	0.69 ± 0.22*
Sub-max heart rate (bpm)	114 ± 15	126 ± 13*
VO_{2max} (l/min)	1.24 ± 0.27	1.56 ± 0.40*
VO_{2max} (ml/kg · min)	44.2 ± 3.2	32.0 ± 4.1*
VO_{2max} (ml/kg FFM · min)	57.9 ± 5.8	59.2 ± 4.9
Max heart rate (bpm)	198 ± 10	198 ± 7
Max RER	1.02 ± 0.07	1.03 ± 0.05
Max oxygen pulse (VO_2/h × 10^3)	6.3 ± 1.5	7.8 ± 1.6
Time to exhaustion (min)	15.3 ± 2.9	11.1 ± 2.1*

*$P<0.05$ for lean *vs* obese.
Sub-max = sub-maximal work level; max = maximal work level.

Table 3 Physical characteristics of 31 women before and after weight loss in Study 2

	Before weight loss	*After weight loss*
Age	37.3 ± 6.4	
Body weight (kg)	78.8 ± 6.2	65.9 ± 5.2*
Fat-free mass (kg)	49.4 ± 4.7	45.8 ± 4.1*
Fat mass (kg)	29.3 ± 4.9	20.1 ± 4.2*
$VO_{2sub\text{-}max}$ (l/min)	0.95 ± 0.18	0.75 ± 0.14*
Sub-max heart rate (bpm)	124 ± 14	102 ± 11*
Sub-max RER	0.85 ± 0.06	0.79 ± 0.05*
VO_{2max} (l/min)	2.16 ± 0.27	2.08 ± 0.33*
VO_{2max} (ml/kg · min)	27.5 ± 2.9	31.6 ± 4.6*
VO_{2max} (ml/kg FFM · min)	43.8 ± 4.9	45.5 ± 6.4
Max heart rate (bpm)	183 ± 9	178 ± 10*
Max VE	84.5 ± 12.3	79.5 ± 14.5*
Max oxygen pulse (VO_2/h × 10^3)	12.0 ± 1.5	11.9 ± 1.8
Max VE/VO_2	39.5 ± 5.9	38.4 ± 5.3
Max RER	1.27 ± 0.12	1.22 ± 0.07*

All changes after weight loss were significant by paired *t*-test.
*$P<0.05$ for before weight loss *vs* after weight loss.
Sub-max = sub-maximal work level; max = maximal work level.

(3.6 ± 3.4 kg) and a significant 31% reduction in fat mass (9.2 ± 3.3 kg).

Absolute VO_{2max} expressed as l/min, decreased significantly by 3.7% after weight loss. VO_{2max} divided by body weight increased significantly by 15% after weight loss from 27.5 ± 2.9 to 31.6 ± 4.6 ml/kg min and VO_{2max} adjusted for FFM (ml/kg FFM · min) was unchanged after weight loss (Figure 2). As shown in Figure 3, the relationship between VO_{2max} (21 l/min) and FFM was identical before and after weight loss.

For the regression between VO_{2max} (l/min) and FFM, the intercept was not significantly different from zero either in the obese state ($VO_{2max} = 0.053 \times FFM - 0.38$ l/min) nor in the normal weight state ($VO_{2max} = 0.052 \times FFM - 0.29$ l/min), and the slopes were not significantly different before or after weight loss (Figure 3). This would imply that VO_{2max} divided by FFM (ml/kg FFM · min) is a valid ratio for comparing VO_{2max} in adults of different body size and body fat composition. For the regression between VO_{2max} (l/min) and body weight, the intercepts were also not significantly different from zero either in the obese state ($VO_{2max} = 0.025 \times$ body weight $+ 0.24$ l/min) nor in the normal weight state ($VO_{2max} = 0.04 \times$ body weight $- 0.19$ l/min); however, the regression slopes were significantly different before and after weight loss. Due to the different regression slopes before and after weight loss, the VO_{2max} to body weight ratio is not a good tool for data comparison.

VO_{2max} (ml/kg FFM · min) was not significantly different when the women were in the overweight state *vs* after weight loss (43.8 ± 4.9 *vs* 45.5 ± 6.4 ml/kg FFM · min) (Table 3). However, VO_{2max} divided by body weight was significantly lower (13%) in the obese state (27.5 ± 2.9 *vs* 31.6 ± 4.6 ml/kg · min) (Table 3). Sub-maximal aerobic capacity was significantly reduced in the obese state, as indicated by a higher heart rate (124 ± 4 *vs* 102 ± 11 bpm), RER (0.85 ± 0.06 *vs* 0.79 ± 0.05), and %VO_{2max} (44% *vs* 36%) as compared with the normal weight state (Table 3).

No difference between the obese and normal weight states was seen in cardio-respiratory function ie. oxygen pulse (11.8 ± 1.5 *vs* 11.7 ± 1.8) or in pulmonary efficiency (VE/VO_2; 39.5 ± 5.9 *vs* 38.4 ± 5.3, Table 3). However, when in the obese state, subjects' max VE was significantly greater (84.5 ± 12.3 *vs* (79.5 ± 14.5).

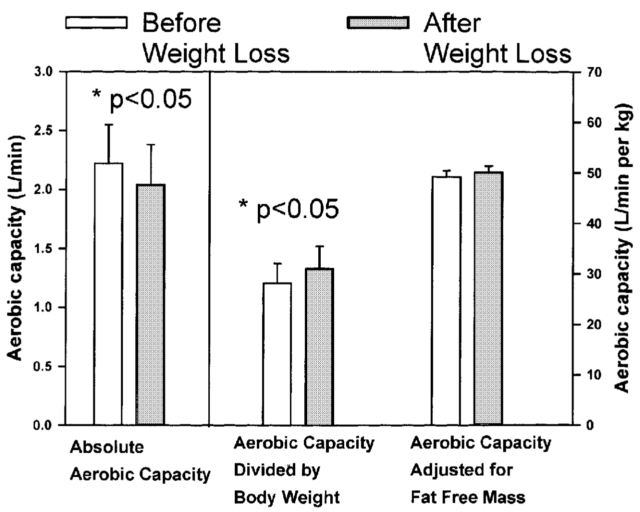

Figure 2 Comparison of maximal oxygen consumption before (unfilled bars) and after (shaded bars) weight loss in women. The physical characteristics of the women before and after weight loss are shown in Table 3. Data for absolute maximal oxygen consumption are expressed in l/min using the left-hand *y*-axis, data for maximal oxygen consumption divided by body weight (ml/(kg-min)) are expressed in ml/min per kg using the scale on the right-hand *y*-axis, and data for maximal oxygen consumption adjusted for fat-free mass using analysis of covariance are expressed as the least square means in ml/min using the scale on the right hand *y*-axis.

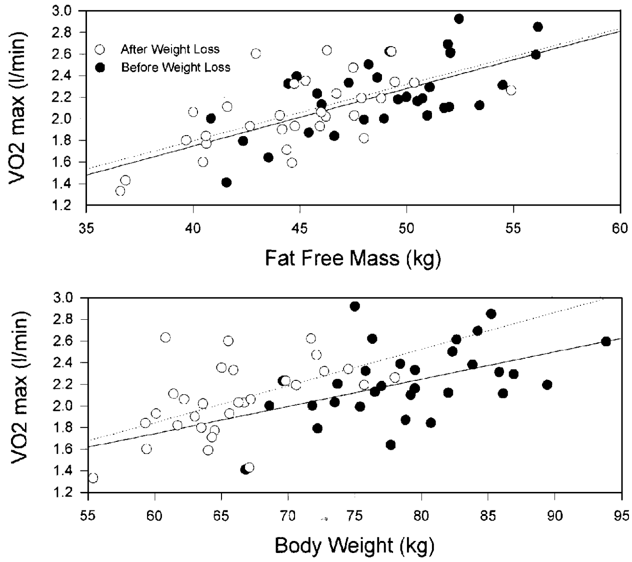

Figure 3 Relationship between maximal oxygen consumption and fat-free mass (top panel) and maximal oxygen consumption and body weight (lower panel) before weight loss (solid circles, solid regression lines) and after weight loss (open circles, dashed regression lines). The physical characteristics of the women before and after weight loss are shown in Table 4. Regression slopes and intercepts are not significantly different for the relationship between maximal oxygen consumption and fat-free mass (see text for details).

Discussion

The major finding from this study indicates that overweight and obese individuals do not have an impaired VO_{2max}, but have a reduced sub-maximal aerobic capacity. VO_{2max} relative to FFM examines the 'physiological' status of the cardio-respiratory system to meet the oxidative demands of the body and does not seem to be influenced by excess body fat mass. However, obese individuals had a reduced VO_{2max} relative to body weight. This is explained by the fact that VO_{2max} relative to body weight evaluates the ability of an individual to perform exhaustive work, ie their aerobic 'performance'.[21]

Comparisons of VO_{2max}

In the literature comparing VO_{2max} relative to FFM during running or cycling in obese and normal weight individuals, the data are equivocal, with eight studies showing no limitations in VO_{2max}[21–28] and two studies finding obese individuals having significantly reduced VO_{2max}.[29,30] The results from our studies showed no difference in VO_{2max} either in children or in adults varying greatly in body composition.

Differences in VO_{2max} relative to body weight appear to be clearer, with 11 studies reporting a significantly reduced VO_{2max}[10,11,14,21,24–27,29–31] and one study reporting no difference.[23] The difference in VO_{2max} between obese and normal weight subjects in our studies was due to higher FFM or body weight while in the obese state. This seems reasonable because the 'excess' fat is not contributing to the work being performed, thus increasing the challenge by the obese individual.

Cardio-respiratory function and pulmonary efficiency were not significantly different between obese and normal weight individuals in our studies. However, others have shown the cardio-respiratory function (oxygen pulse) to be higher in the obese state,[10,11,27,30] while no such difference is seen in pulmonary efficiency.[10,27] It is possible that weight loss in our subjects led to an effective de-training because the effect of carrying excess fat was removed, and the increased load on the myocardium was removed. Thus, the effective change in cardio-respiratory function and pulmonary efficiency may be a function of the degree of weight loss.

Normalization issues

A secondary objective of this study was to examine data normalization procedures for examining VO_{2max} in lean and obese individuals. Several previous papers have examined data normalization procedures for VO_{2max}.[15,32–40] Historically, VO_{2max} has been adjusted using ratio scaling that makes the assumption that, once VO_{2max} has been divided by body weight, any difference in VO_2 due to body weight is removed.[36] Much dialogue has occurred with the expression of VO_2 as a ratio of body weight.[33,34,36,39,41] In part this is due to the negative correlation between body weight and VO_2 per unit of body weight.[35,36] This relationship gives the misleading impression that heavier persons have a relatively lower oxygen uptake and hence, low aerobic capacity.[35–37] In fact, Heil[39] reported that lighter subjects were more likely to be placed in a low VO_{2max} category. If two individuals had the same FFM and VO_2 (l/min), the subject with the lesser amount of FM would appear to have a higher VO_{2max} and aerobic fitness. The apparent lower VO_{2max} in the person with the higher FM is due to inherent limitations of VO_2 being scaled with body weight by the power factor ratio of 1.[35] The power function ratio of 1 implies that the relationship between VO_2 and body weight would have a linear relationship with a *y*-intercept equal to zero and be proportional; however a zero *y*-intercept is rarely seen in biological systems.[33,41,42]

Recently it has been suggested that VO_2 should be normalized by FFM,[15,35,38] since FFM is more metabolically active than FM. Vanderburgh and Katch[35] reported a near zero relationship between VO_2 and FFM, which suggests that the ratio imposes no bias across the range of FFM. When used in concert with regression modeling, FFM can be used to express VO_2 per unit of FFM, as long as the *y*-intercept is not statistically different form zero.[15,40] Thus, the stronger bivariate correlation with FFM compared with body weight, and the lack of a significant partial correlation with FM, suggest that body fat does not contribute to individual variation in VO_2. Thus, FFM and not body weight is the preferred co-variate for comparing children and adults of different body size and body composition.

Practical applications

After normalizing for differences in body size, obese individuals appear to have a similar VO_{2max} to normal weight individuals. This suggests that the limiting factor in aerobic-type activities for the obese individual is not the cardio-respiratory system, but rather a limitation in their sub-maximal aerobic capacity as indicated by a higher sub-maximal HR, RER, % VO_{2max}, and shorter time to exhaustion. The implication is that it is physiologically more difficult for the obese individual to do the same amount of work as a normal weight person, at least in weight-bearing activities. This may explain why obese individuals perceive walking to be difficult, even at low intensities.[13] Mattson *et al*[13] reported that obese patients used 57% of VO_{2max} during normal walking, whereas their normal weight counterparts used only 36% of VO_{2max}. We also found that heavier subjects required a greater VO_{2max} to complete the same exercise task: (obese 44% *vs* lean 37%, respectively, in the children) and (obese 44% *vs* lean 36%, respectively, in the adults). This could have implications for exercise prescription in the obese individual. Low intensity non-weight-bearing activities like bike riding and swimming may result in greater ease of performing the physical tasks, resulting in greater energy expenditure and weight loss.

We note that our findings are specific to pre-pubescent boys and girls (Study 1) and pre-menopausal women (Study 2) and can therefore not necessarily be generalized to the population as a whole. In addition, our findings are specific to weight-bearing activities (specifically running on a treadmill), and may not be applicable for non-weight-bearing activities.

Conclusion

The results of this study indicate that the maximal oxygen consumption of fat-free tissue is independent of body fat mass. Further, the findings suggest that obese individuals do not have lower maximal aerobic capacity of their FFM compared with lean individuals or impaired cardio-respiratory and pulmonary responses to exercise. By contrast, since aerobic capacity is body weight dependent, the overweight and obese individuals require a greater proportion of their aerobic capacity to conduct weight-bearing physical activities. Thus, individuals with obesity are more likely to find it physiologically difficult to participate in physical activities, that require movement of their increased body mass.

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