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Peak O_2 Uptake Correlates with Fat Free Mass in Athletes but Not in Sedentary Subjects

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Abstract

Objective: To characterize relationships between peak O_2 uptake (VO_2max) and fat free mass (FFM) in adult sedentary and in young and adult athletes. Methods: Healthy adult male sedentary workers or students reporting no regular physical activity in the last six months (n = 61, 31.0 ± 0.95 years) and young (n = 63, 15.8 ± 0.16 years) or adult (n = 85, 25.9 ± 0.48 years) males athletes were studied. Sports were classified according to their MET intensity. Bruce's treadmill protocol served to measure VO_2max. Weight and seven skin-fold thicknesses were used to estimate body density and FFM. Subjects signed informed-consent forms before the tests. Results: The significant correlations (R^2 = 0.48, $p < 0.01$) between FFM and VO_2max or of log FFM with log VO_2max (R^2 = 0.53, $p < 0.01$) in young athletes were lower in adult athletes (R^2 = 0.34 & 0.30), and not significant (R^2 = 0.19 & 0.17, $p > 0.05$) in sedentary subjects. Stepwise multiple regression analysis (R^2 = 0.65) indicated that VO_2max depended on FFM, heart rates and MET intensity of practiced sport in athletes. In sedentary subjects VO_2max was insignificantly (R^2 = 0.18) related to flexibility. Discussion: Skin-fold based FFM reliably reflects maximally active muscle mass in young athletes, to a lesser extent in adult athletes but not in adult sedentary subjects. In sedentary, VO_2max is often limited by local pain and fatigue and does not reflect the capacity of the oxygen extraction system. In sedentary, varying proportions of surface fat, muscle and bone increase variability in the relationship between skinfolds and FFM.

Keywords

VO_2max, Lean Body Mass, Physical Activity, Age, Regression Analysis

1. Introduction

Maximal oxygen utilization depends on the delivery of oxygen to and on oxygen extraction by active muscles. Maximal oxygen delivery to working muscles depends in turn on heart rate, stroke volume, blood O_2 content and distribution of blood flow to the active sites [1]. Differences in VO_2max among sedentary subjects relate to genetic differences [2] in their blood and stroke volumes [3]. In turn, capillary and mitochondrial densities of active muscles determine their oxygen extraction [4]. Many studies have shown a strong relationship between maximal oxygen consumption and the mass of active muscles [5], with the FFM [6]. Differences in VO_2max between males and females [7] or between young and old subjects [8] or between large and small animals [9] are largely, although not uniquely, related to the different mass of muscles in their organisms. Obese subjects usually have a low aerobic capacity due to the high proportion of fat in their bodies and hence their lower proportions of fat-free and muscle mass [10]. In malnourished subjects maximal oxygen uptake does not increase with nutritional replenishment until proteins required to rebuild muscle mass are restored [11]. On the other hand sedentary subjects in contrast to physically active subjects have a lower maximal oxygen consuming capacity per unit of muscle mass due to their lack of aerobic training. Aerobic exercise training increases oxygen consuming capacity by favoring higher proportion of fibers dependent on mitochondrial aerobic metabolism and in addition increasing muscle tissue mitochondrial and capillary densities [4], blood flow distribution to the active muscles [12], blood and stroke volumes [13] while reducing resting heart rate [4]. In this study we characterize differences in the relationship between peak oxygen consumption and fat free mass (mostly muscle mass) in young and adult male subjects with different degrees of exercise training. Young and adult trained subjects participated regularly in sports while sedentary subjects did not participate regularly in physical activities in the last six months. Surprisingly, we found that the strong relationship between fat free mass and peak oxygen uptake present in physically active subjects was absent in sedentary subjects. This finding indicates that factors other than FFM (and muscle mass) determine the peak oxygen uptake in the sedentary subjects, in spite of similar efforts to reach maximal activity as attested by the similar maximal heart rates and high respiratory exchange ratios reached by both trained and untrained groups.

2. Subjects and Methods

Subjects included were young (n = 63, means ± SE: 15.8 ± 0.16 years, range 13.5 - 17.5 years, 172.1 ± 1.16 cm height) or adult (n = 85, 25.9 ± 0.48 years, range 24 - 28 years, 174.6 ± 0.68 cm height) Kuwaiti students or office workers, males, participating regularly (at least 5 days/week) in vigorous sports (>2400 Met.min/week) for the last six months, or healthy sedentary Kuwaiti urban office workers reporting no regular physical activity (<500 MET.min/week) in the last six months (n = 61, 31.0 ± 0.95 years, range 29-35 years, 170.6 ± 0.86 cm height) (**Table 1**).

All sedentary subjects were volunteers for a study of the effects of the Ramadan monthly fast on fitness or served as healthy controls in other studies in our laboratory. The athletes were members of several junior or senior amateur or national sports teams evaluated for aerobic fitness in our laboratory. All were Kuwaiti nationals, tested at the Exercise Laboratory, Department of Physiology, Faculty of Medicine, at Kuwait University. Criteria for exclusion were any physical or mental disability and any acute or chronic illness [14] [15]. None of the subjects were dieting or considered themselves overweight. None were taking medications and none were diabetic or suffered acute or chronic cardiovascular, respiratory, neuromuscular, or muscular-skeletal diseases

The type of sport engaged in, weekly, during at least the last 6 months by the athletes was classified in a scale according to their relative MET intensity (MET/10), as follows [16]: long distance swimming or running (1), water-polo (0.9), tennis (0.8), soccer referee (0.6), soccer (0.7), handball (1.2), basketball ([0.6), fencing (0.6]) karate (1), or weight training (0.3).

After a thorough explanation of the procedures and risks involved, all participants (or their parents when minors) signed an informed consent form, previously approved by the Ethics Committee for Human Research, Faculty of Medicine, at Kuwait University.

3. Procedures

Each participant performed a maximal, graded, treadmill exercise test. Bruce's protocol was used to measure the VO_2max [17]. Oxygen uptake (VO_2) and carbon dioxide production (VCO_2) were measured using appropriately calibrated Quinton (Seattle, WA) expired gas flow meters, O_2 and CO_2 gas analyzers [15]. VO_2max was defined as the highest VO_2 observed during any 1 minute of the exercise test. Criteria for attainment of VO_2max were a plateau or a decrease in VO_2 with increasing work rate, a respiratory exchange ratio > 1.05, and a maximum heart rate within five beats of the age- and sex-predicted maximum. Mid trunk flexibility was measured using a sit and reach measurement instrument (Lafayette Instruments, Lafayette, IN). Strength was measured using a Harpenden handgrip dynamometer (British Indicators, UK). Height, weight (Balance, Detecto, Webb City, MO), and skinfold thickness (John Bull caliper, British Indicators, UK) were measured in all participants by a single experienced investigator (JR). Seven skinfolds (chest, midaxillary, triceps, subscapular, abdomen, suprailiac, and thigh) were used to estimate body density [18] and the percent body fat [19].

One-way ANOVA was used to test for differences between groups. This was followed by unpaired two-tailed t-tests between group means. Differences were considered significant at $p < 0.05$. Data are shown as means plus or minus one SEM. Regression analysis was done using the SPSS statistical package.

4. Results

1) Adult sedentary (S) compared to athletic (A) group

The S subjects were older compared to A (31 vs. 25 years). Height was shorter in S than in A (170 vs. 176 cm) but body weight did not differ between the two groups (78 vs. 77 Kg). Consequently body mass index (BMI) was significantly higher in the sedentary than in the athletic group. Athletes had however a higher mean fat-free mass (FFM) than the sedentary subjects (**Table 1**). Mean body fat (**Table 1**) or percent fat by contrast, were higher in S than in A. Athletes were more flexible but grip strength did not differ between adult athletes and sedentary subjects (**Table 1**).

The average resting hear rate was higher in the sedentary than in the athletic subjects (76 vs. 69 bpm) as expected from their different training status; the average resting systolic (124 vs. 119 mmHg) and diastolic (83 vs. 81 mmHg) blood pressures were also higher in the S than in the A group. At maximal exercise the average heart rate reached was higher in the S than in the A group (186 vs. 182 bpm) but the respiratory exchange ratio was similar in the two groups (1.10 vs. 1.12) indicating, on the average, similar maximal efforts. Mean maximal exercise oxygen consumption (VO_2max, 3.2 vs. 4.1 L/min, **Table 1**) and aerobic power (40.7 vs. 53.7 ml O_2/min Kg BW, **Table 1**) were significantly lower in S than in A.

The VO_2max /Kg FFM was also lower in S than in A probably reflecting a lower oxygen consuming capacity of their muscles. Regression analysis of log VO_2max vs. log FFM (**Figure 1** middle Panels #2 A and S) revealed a striking difference between the groups. In athletes, a significant correlation (R = 0.56) was found between these two variables with a determination coefficient (R^2) of 0.30 and a regression coefficient of 0.78 close to the allometric coefficient described for the log of basal oxygen consumption and the log of body mass, within and between species [20]. By contrast the relationship between log VO_2max and log FFM was not statistically significant (R^2 = 0.17) in the S group (**Figure 1**, Panel 2 S), indicating that factors other than FFM were involved in the variance of VO_2max found in the sedentary subjects.

Table 1. Characteristics of sedentary and athletic groups.

Variable	Athletes young (Y) group N = 63	Athletes adult (A) group N = 85	Sedentary adult (S) group N = 61
Age (year)	15.8 ± 0.16**	25.9 ± 0.48*	31.0 ± 0.95
Height (cm)	172.1 ± 1.16	174.6 ± 0.68*	170.6 ± 0.82
Fat weight (Kg)	4.5 ± 0.39**	10.5 ± 0.95*	16.2 ± 1.07
Fat free mass (Kg)	58.9 ± 1.0**	67.0 ± 0.94*	61.8 ± 0.91
Flexibility (cm)	22.0 ± 1.40**	26.2 ± 1.16*	19.6 ± 1.64
Rest heart rate (bpm)	76.5 ± 1.40**	68.8 ± 1.18*	75.7 ± 1.34
Max heart rate (bpm)	190.5 ± 1.3**	181.2 ± 1.11*	185.9 ± 1.56
Rest systolic es (bpm)	118.0 ± 0.89	119.2 ± 0.87*	123.6 ± 1.16
VO_2max L/min	3.44 ± 0.07**	4.02 ± 0.07	3.19 ± 0.08

The results are mean ± SE, * = significant at $p < 0.05$ vs. sedentary or ** vs. adult athletes.

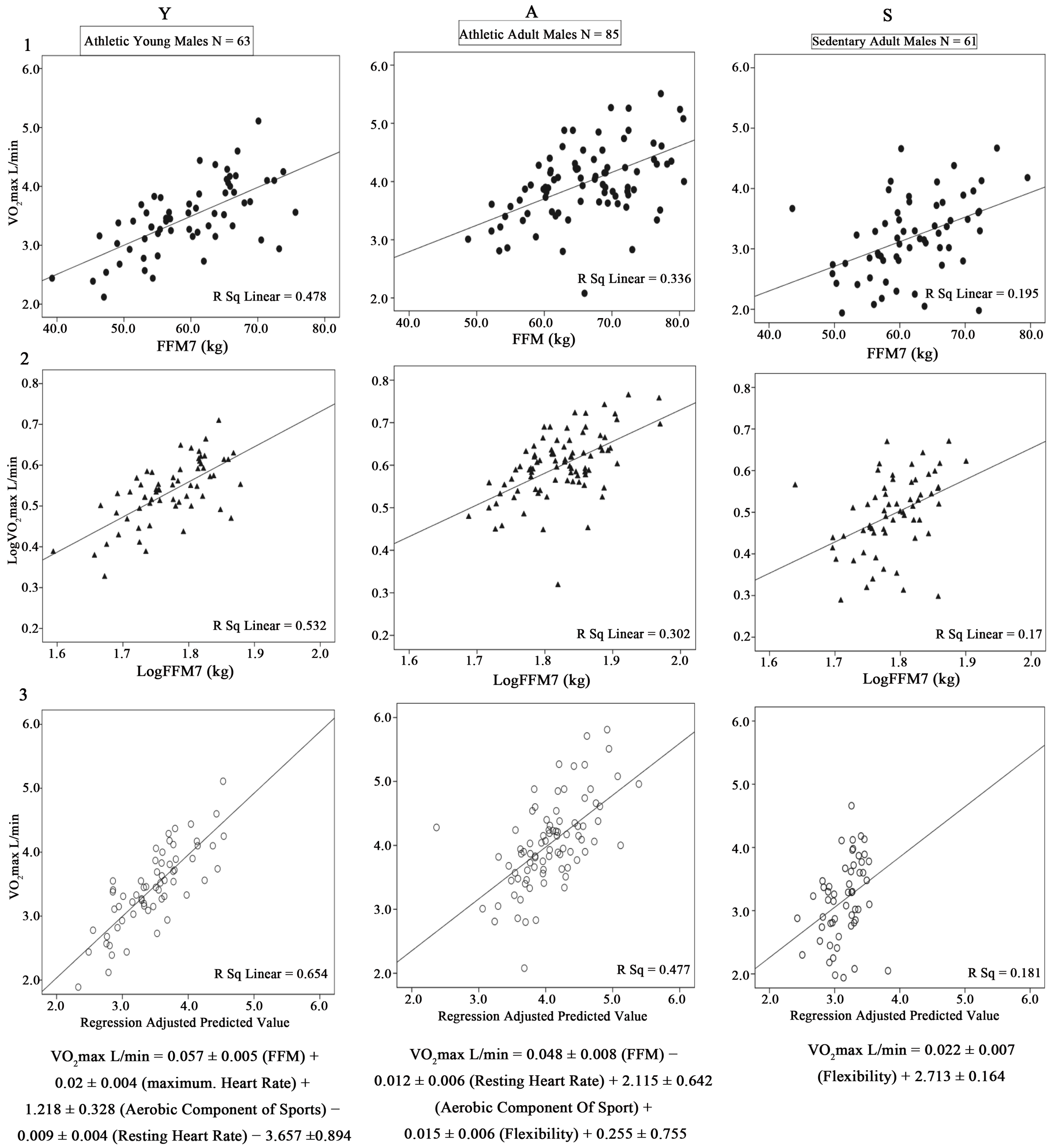

Figure 1. Correlations between peak O_2 uptake (VO_2max) (first 3 horizontal Panels #1) and fat free mass (FFM), between log VO_2max and log FFM (mid horizontal Panels #2) and between measured and predicted VO_2max (last 3 horizontal Panels #3) in young athletes (first 3 vertical Panels, Y), adult athletes (mid vertical Panels, A) and adult sedentary (last 3 vertical Panels, S) subjects. R^2 = determination coefficient. The equations at the bottom are the result of step-wise linear regression analysis of VO_2max with the variables indicated in the text.

Stepwise linear multiple regression analysis of VO_2max (F < 0.05 to enter, F > 0.1 to exclude) against all variables measured in group A (age, anthropometry, resting and maximal heart rates, resting and maximal blood pressures, flexibility, grip strength and type of sport in which they participate), confirmed that FFM contributes importantly (standardized beta Sβ = 0.63) to the variance in Vo2max and that together with the value of the aerobic component of the sport in which they participate (Sβ = 0.35), their flexibility (Sβ = 0.24), their resting (Sβ = −0.22) and maximal exercise heart rates (Sβ = 0.17), they accounted for 48% of the variance in VO_2max (R2 = 0.48, R = 0.69) in this group of adult athletes (see **Figure 1**, Panel A3). A similar step wise multiple regression analysis of VO_2max in the sedentary group revealed that flexibility was weakly and not significantly correlated with VO_2max (R^2 = 0.23, **Figure 1** Panel S3). Neither FFM, nor resting or maximal heart rates were related to the variation in VO_2max values found in these sedentary subjects.

2) Young compared to adult athletes

Young athletes (group Y) had less fat (4.5 vs. 10.5 Kg), less lean (58.9 vs. 67 Kg FFM), were less flexible (22 vs. 26.2 cm reach) but had higher resting (76.5 vs. 68.8 bpm) and maximal (190.5 vs. 181.2 bpm) heart rates than the adult athletes (group A).

Linear regression analysis in young (Y) athletes showed stronger correlation of log VO_2max with log FFM (R^2 = 0.53, vs. 0.30) and higher regression coefficient (0.9 vs. 0.78) than in group A.

In addition, stepwise multiple linear regression analysis of VO_2max in this group of young athletes showed significant contributions of FFM (Sβ = 0.75), the MET intensity of the sport they participate in (Sβ = 0.26), their resting (Sβ = −0.23) and maximal (Sβ = 0.18) heart rates to the variance of VO_2max. Together these variables accounted for 65% (R2 = 0.65, R = 0.8) of the VO_2max variance in young athletes. Flexibility did not correlate with VO_2max in these young athletes compared to its small contribution to the correlation in older athletes (group A).

5. Discussion

In sedentary (S) subjects VO_2max does not depend on the fat free (and muscle) mass, but was found to vary weakly (likely a non-causal correlation) with mid trunk flexibility, since both are known to be affected by the level of daily physical activity. However, residual variance is high and prediction unreliable. Skin-fold based FFM does not relate to the maximally metabolically active cell mass in these sedentary subjects. Variability in the relationship of skinfold thickness to body density [21] due to differences in internal and surface fat, differences in bone density and in muscle proportion in the FFM can contribute to the high variance in the VO_2max vs. FFM relationship estimated from skinfolds in sedentary subjects. Heterogeneity in the proportion of active muscle within the FFM [5], muscle heterogeneity in fiber type, mitochondrial and capillary densities [4] [9] may also preclude any proportionality between FFM and maximally active muscle mass in sedentary subjects. Furthermore, peak VO_2 in sedentary subjects may be determined by factors other than maximal oxygen extraction capacity of muscles such as those influencing maximal oxygen deliveries (stroke volume, heart rate, flow distribution, blood oxygen capacity). In addition, pain or local fatigue may often determine the end of the test and the peak VO_2 reached in this group. The mass of muscles involved, local muscle mechanics, fatigue or pain, are known to influence VO_2max in various types of exercise tests [22] (such as arms or legs, running or cycling, etc.) and these may contribute to the large unaccounted variability of peak VO_2 values in this sedentary group when tested using the treadmill walking Bruce protocol [17]. Neural sympathetic regulation limits blood flow distribution to active muscles resulting in VO_2max during two legs biking lower than 2 times the VO_2max during one leg biking ([23]. Variability in vascular sympathetic tone of active muscles may similarly induce large variability in peak O_2 uptake found in sedentary subjects. Because of these reasons, it is unlikely that in these sedentary subjects, peak oxygen uptake reflects the full capacity of oxygen extraction by muscles. In addition, oxygen delivery and extraction systems may not be adequately matched in untrained sedentary as they are in active subjects [6].

In athletic young (Y) subjects, FFM, heart rate reserve (maximal – rest) and type of training are found to be the major determinants of VO_2max and account together for about 2/3 of the variance in VO_2max. In young athletes, log VO_2max varies in almost direct proportion (0.9:1.0) to log FFM. The nearly proportional scaling of VO_2max with FFM in young active subjects suggests that in the growing young subjects differences in muscle cell size, cell number, capillary and mitochondrial density are in proportion to differences in FFM (mostly muscle) resulting in a maximal oxygen consumption capacity per unit of FFM (VO_2max /FFM) nearly independent of the absolute value of the FFM [20].

In adult (A) athletes VO_2max variability is highly dependent on fat free mass (mostly muscle), their type of training as reflected by the relative MET intensity of the sport they participate in, their extent of aerobic training as reflected by their low resting heart rates, the relative effort during the test, as revealed by the maximal heart rates reached and also correlated with mid trunk flexibility (likely a correlative non causal relationship due to their mutual dependence on daily physical activity levels). The unaccounted VO_2max variance is higher and prediction is less reliable than in young (Y) active subjects. In this group A, VO_2max variability was thus found to depend mostly on characteristics of the oxygen delivery and extraction systems and to a lesser extent on a non-causally related factors such as mid trunk flexibility. In these active mature adults (A), differences in log VO_2max scale as a fraction (0.78) of differences in log FFM. This could indicate that although differences in muscle cell size and number may be proportional to those in FFM, the average maximal cell metabolic rate (VO_2max /FFM) is not independent of FFM but rather decreases at the larger FFM probably due to reduced maximal muscle capillary and mitochondrial densities in the larger subjects [9], which may limit their fractal surface exchanges. This age related difference suggests that muscle adaptive responses to training may not be identical in mature and in growing subjects.

6. Conclusion

In summary, in young athletes and to a lesser extent in adult athletes, peak VO_2 relates well to FFM indicating that FFM reflects well the mass of maximally active muscles. By contrast in sedentary adults, peak VO_2 is unrelated to FFM, probably because oxygen delivery and local factors (neural pain and local fatigue) rather than oxygen extraction determine the mass of muscles activated in sedentary subjects. In addition, skinfold estimates of FFM in sedentary subjects are more variable as they are influenced by fat distribution and changes in bone density and in the proportion of muscle in the FFM.

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Conflict of Interests

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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