Relationship between aerobic fitness level and daily energy expenditure in weight-stable humans

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Sharp, Teresa A., George W. Reed, Ming Sun, Naji N. Abumrad, and James O. Hill. Relationship between aerobic fitness level and daily energy expenditure in weight-stable humans. Am. J. Physiol. 263 (Endocrinol. Metab. 26): E121–E128, 1992.—The relationship between exercise and energy expenditure is unclear, with some suggestions that exercise leads to increased energy expenditure over and beyond the increase due to the exercise itself. In this cross-sectional study, we examined the relationships among aerobic fitness level, body composition, and total daily energy expenditure in 78 subjects. Daily energy expenditure (determined in a whole room calorimeter) was significantly correlated with both fat-free mass (FFM) and aerobic fitness (estimated from maximum aerobic capacity or \( V_O_2\) max). However, multiple-regression analysis demonstrated that, after accounting for FFM, \( V_O_2\) max did not explain a significant amount of the remaining variation in energy expenditure. In addition, the relationship between resting metabolic rate and both FFM and \( V_O_2\) max was evaluated using data from 214 weight-stable subjects analyzed retrospectively. The results were identical with the results obtained from the 78 subjects in that \( V_O_2\) max did not have effects independent of FFM on energy expenditure. We conclude that aerobic fitness does not have a direct effect on energy expenditure. However, it may have effects that are mediated through body composition, since in both populations studied here, \( V_O_2\) max was positively correlated with FFM and negatively correlated with adiposity.

The purpose of this cross-sectional study was to use a whole room indirect calorimeter to assess the contribution of fitness level to determining total daily energy expenditure and the individual components of energy expenditure. A second purpose was to assess the contribution of fitness level to daily oxidation rates of protein, carbohydrate, and fat.

**METHODS**

We examined the relationships among \( V_O_2\) max, body composition, and total daily energy expenditure (using a whole room indirect calorimeter) in 78 adult subjects. In addition, we present retrospective data showing the relationship among RMR, body composition, and \( V_O_2\) max in 214 adult subjects. This latter data set was accumulated over a period of 5 yr and consists of data obtained from subjects participating in several other research projects. These data are presented to provide additional support for the conclusions reached with the 78 subjects studied in the whole room calorimeter.

**Subjects.** Thirty-nine men and thirty-nine women participated in this study, which was approved by the Vanderbilt University Committee for the Protection of Human Subjects. Attempts were made to recruit subjects who varied widely in body composition and usual activity levels.

The retrospective data were accumulated from 214 weight-stable subjects. This was a highly heterogeneous group of subjects, chosen from all weight-stable subjects studied (in a variety of different protocols) during the past 5 yr on which measures of body composition, energy expenditure, and \( V_O_2\) max were available. Characteristics of all subjects are shown in Table 1.

**Procedure.** All subjects had the following measures taken: 1) body composition by underwater weighing; 2) measurement of \( V_O_2\) max by treadmill test; 3) measurement of total daily energy expenditure and estimation of each component of energy expenditure using a whole room indirect calorimeter; and 4) measurement of RMR using a ventilated hood system. There was no set order of testing. Measurements of \( V_O_2\) max and energy expenditure were made at least 36 h after the last bout of planned exercise. All subjects were weight stable for at least 6 mo before the study and remained weight stable throughout the study. Data for individuals who did not complete all measurement...
procedures were not included in this analysis. Body weight and height were measured before each assessment.

The measures for the 214 subjects studied retrospectively were made using the same techniques. RMR was measured after a 12-h fast. There was no stipulation in this group about avoiding planned exercise during the 36 h before measurement of RMR.

Measurement of aerobic fitness. We determined aerobic fitness as the V̇O₂ max of the subject, as determined during a treadmill test using the Bruce protocol (3). This protocol increases speed and grade of the treadmill every 3 min until volitional exhaustion. Oxygen consumption and carbon dioxide production were measured continuously using a SensorMedics 2900 oxygen uptake system (Anaheim, CA). V̇O₂ max was defined as the highest rate of oxygen consumption achieved by the subject. To be sure that true V̇O₂ max had been reached, the maximum heart rate had to be near the maximum age-predicted heart rate, and the respiratory quotient (RQ) had to be >1.1. In addition, heart rate and blood pressure were monitored every 1 and 3 min, respectively, before, during, and after the treadmill test. The within-subject coefficient of variation (CV) for V̇O₂ max in our laboratory is 4%.

There is not agreement about the best way to express V̇O₂ max One's V̇O₂ max is clearly influenced by one's body size, so that V̇O₂ max is usually expressed as milliliters per kilogram per minute when comparing different subjects. We have used this method of expressing V̇O₂ max in the figures in this report. However, in the statistical analyses, we began with V̇O₂ max, in milliliters per minute and used partial correlation analysis to control for the fact that body composition influences both energy expenditure and V̇O₂ max.

Body composition. Body composition was determined from measurements of body density estimated by underwater weighing (9). Body weights in air and underwater were measured to the nearest 25 g using Heath platform and Chatillon spring scales, respectively. Residual lung volume was determined (simultaneously with underwater weighing) using a closed-circuit nitrogen-dilution method (9). Nitrogen concentration during rebreathing was measured with a Met-Science 505-1 Nitalizer. Percent body fat was estimated from body density using the revised equation of Lohman et al. (20). Reproducibility tests in our laboratory show an average difference of 2-4% between trials of the same subjects.

RMR. RMR was measured using a ventilated hood system (Sensormedics 2900 Oxygen Uptake System). Subjects reported to our laboratory after an overnight fast. Subjects rested quietly for 45-60 min, and then RMR was measured continuously for 30 min. In our laboratory, reproducibility tests show an average variation of 5-8% between trials of the same subjects.

Daily energy expenditure and components of energy expenditure. Total 24-h energy expenditure was measured using a whole room indirect calorimeter, which has been described previously (11). While in the calorimeter, the subjects were free to move around but were not provided with exercise equipment or given specific instructions to exercise. The amount and composition of food eaten in the calorimeter was chosen by the subject but was quantified by the Clinical Research Center (CRC) dietitians. The calorimeter is located within the CRC and is connected via an intercom to the nursing station. Oxygen consumption and carbon dioxide production are determined from the flow rate and the differences in gas concentrations between entering and exiting air. Values are corrected for temperature, barometric pressure, and humidity. The operation of the calorimeter is controlled by a personal computer using a software program written in Turbo C. The calculation of energy expenditure from oxygen consumption and carbon dioxide production is based on equations described by Jequier et al. (15, 16). Values for all parameters were averaged over 1-min intervals and recorded in a raw data file. Computed values were determined over intervals of 30 min.

In addition to total 24-h energy expenditure, the individual components of energy expenditure were estimated during the 24-h stay in the whole room calorimeter. Energy expenditure due to activity or movement (EEACT) was estimated with the assistance of a radar system (29) installed in the whole room calorimeter. The instrument records relative activity, which is significantly correlated with energy expenditure. Using linear regression, one can plot (after elimination of the sleeping period) the relationship between activity (in %time) and energy expenditure for each subject. The slope of the regression line is an estimate of the cost of activity for that subject. Further, an estimate of total EEACT can be obtained for each subject by multiplying the cost of activity by the average percent of time movement. The energy expenditure at zero activity would represent RMR and the thermic effect of food (TEF). TEF was determined by subtracting RMR (measured as described above) from this value.

We also determined sleeping metabolic rate (SMR), which was defined as the average measured metabolic rate during sleep. Periods during which sleep occurred were determined from an activity diary maintained by the subject in the whole room calorimeter in conjunction with measures of activity obtained from the radar detector (sleep defined as movement <1% of any
RESULTS

Figure 1 shows that both FFM (Fig. 1, top) and \( V_O_2 \)max (Fig. 1, bottom) were significantly correlated with total energy expenditure, although the correlation was much stronger for FFM. FFM was significantly correlated with all components of energy expenditure (Fig. 2), whereas \( V_O_2 \)max was significantly correlated with all components except EE\(_{ACT}\) (Fig. 3). FFM was most highly correlated with SMR and RMR and less so with TEF and EE\(_{ACT}\). \( V_O_2 \)max showed a similar correlation with SMR, RMR, and TEF. EE\(_{ACT}\) is calculated as the cost of exercise multiplied by the amount of exercise. FFM was significantly correlated with the cost of activity \( (r = 0.35, P < 0.01) \) but not with the amount of activity \( (r = 0.12) \). \( V_O_2 \)max was not significantly correlated with either cost of activity \( [r = 0.17, \text{not significant (NS)}] \) or amount of activity \( (r = 0.02, \text{NS}) \).

Figure 4 shows that there was also a significant positive correlation between \( V_O_2 \)max and FFM and a significant negative relationship between \( V_O_2 \)max and percent body fat. Therefore, each measure of energy expenditure was then regressed, using multiple regression, on FFM and 1) \( V_O_2 \)max (expressed both absolutely and per kg body weight), 2) age, 3) percent body fat, and 4) gender. Table 2 shows the results of this analysis. The first column shows the \( R^2 \) and \( P \) values from the regression analysis, using FFM alone. FFM explained a significant proportion of variation for total energy expenditure and each component of energy expenditure. Next, each variable mentioned above was entered into the regression equation with FFM since FFM was the highest univariate correlate for each of the components of energy expenditure. The data are shown in columns 2–6 of Table 2. The \( R^2 \) values for these columns are the total \( R^2 \) for both variables together, and the \( P \) value gives the significance for the variable which was added to FFM. \( V_O_2 \)max, regardless of how expressed, did not add significantly to the explained variation in total or any component of energy expenditure. Additionally, partial correlation analysis was used, adjusting each component of energy expenditure and \( V_O_2 \)max (in ml/min) for FFM. This analysis is shown in Table 3. None of the correlations was significant. Further analysis consisted of adjusting each component of energy expenditure for FFM and plotting the residuals against \( V_O_2 \)max. The points were randomly distributed above and below the regression line. This indicated a good fit in the regression for energy expenditure and FFM and no relationship of any form for energy expenditure with \( V_O_2 \)max (regardless of how expressed).

Table 2 also shows that, although the largest amount of variation in energy expenditure was explained by FFM, age and percent body fat explained a significant portion of the unexplained variation in RMR. The relationships between age and RMR were negative, whereas the relationship between percent body fat and RMR was positive. Upon further analysis, there appeared to be a gender difference in the relationship between age and RMR. Figure 5 shows the residuals (after accounting for FFM) in RMR plotted against age in male and female subjects. There was no significant relationship in females but a significant negative relationship in males.

Total food eaten during the day in the room calorimeter was significantly correlated both with FFM and \( V_O_2 \)max (Fig. 6), although the correlation was stronger with FFM. There was no correlation between \( V_O_2 \)max or FFM and daily balance of protein, carbohydrate, or fat (data not shown). On average, subjects maintained near-zero balances in all nutrients with no systematic variation due to FFM.

Retrospective study of 214 subjects. Figure 7 presents...
the relationship between RMR and FFM (Fig. 7, top) and between RMR and V\textsubscript{O\textsubscript{2}}\textsubscript{max} (Fig. 7, bottom). RMR was significantly correlated with both. However, V\textsubscript{O\textsubscript{2}}\textsubscript{max} was also positively correlated with FFM and negatively correlated with percent body fat (Fig. 8). Using a multiple-regression analysis, we found that V\textsubscript{O\textsubscript{2}}\textsubscript{max} did not account for a significant amount of total variation once FFM was entered into the regression analysis. In addition, partial correlation analysis of RMR and V\textsubscript{O\textsubscript{2}}\textsubscript{max} (in ml/min), adjusting for FFM, showed no significant correlation (r = 0.01, P = 0.81). Also in agreement with the results obtained using the whole room calorimeter, we found that both age and percent body fat explained a significant amount of the variation in RMR, which was not explained by FFM. The regression equation for predicting RMR from FFM was not significantly different (using a liberal test of just slopes) for the 214 subjects (RMR = 23.8 FFM + 372) vs. the 78 subjects (RMR = 21.8 FFM + 497).

DISCUSSION

The major conclusion of this study is that, in weight-stable humans, V\textsubscript{O\textsubscript{2}}\textsubscript{max} is not significantly related, independently of FFM, to daily energy expenditure, SMR, RMR, the TEF, or the energy expended in physical activity. Rather, the effects of aerobic fitness on energy expenditure are mediated through effects of fitness on body composition.

Our results provide strong evidence that energy expenditure varies directly with FFM. The strong correlation found between FFM and energy expenditure is in agreement with other reports (27). Although FFM was significantly correlated with all components of energy expenditure, the strongest correlations were with SMR and RMR and the weakest with TEF and EE\textsubscript{ACT}. Although FFM explained 80% of the variation in either SMR or RMR, it only explained ~15% of the total variation in TEF and EE\textsubscript{ACT}. Age and percent body fat contributed significantly (and independently of FFM) to predicting RMR, although these effects were small in comparison to those of FFM. This emphasizes the importance of obtaining accurate measurements of body composition and taking FFM into consideration when making within- or between-subject comparisons in RMR. However, FFM does not explain all of the variation in any component of energy expenditure, and understanding reasons for the remaining variation may be important in our understanding of body weight regulation.

One limitation of room calorimeters is in determining the amount of energy spent in physical activity. The reason for this is that confinement to the small room likely limits the amount of movement of the subject. Estimation of EE\textsubscript{ACT} in the calorimeter is thus likely to be substantially below EE\textsubscript{ACT} during a day outside the calorimeter. Therefore, although we can conclude that EE\textsubscript{ACT} was significantly related to FFM and not to V\textsubscript{O\textsubscript{2}}\textsubscript{max}, this result only applies to the day inside the calorimeter and cannot necessarily be generalized to a day of usual physical activity. Because there is no reason to think that the energy cost of physical activity would be different outside vs. inside the room calorimeter, differences in energy expended in physical activity inside vs.
outside of the calorimeter are more likely to be due to differences in the amount of voluntary physical activity. Further, because FFM was not significantly correlated with the amount of physical activity inside the room, it may be unrelated to the amount of physical activity performed in usual daily life as well. Therefore, FFM may be less strongly related to total energy expenditure during a day of usual physical activity than during a day inside the room calorimeter. In support of this notion is our finding that, although FFM explained ~80% of the variation in total energy expenditure during the day in the calorimeter, it explained only ~40% of the variation in total food eaten. This may be important if ad libitum food intake inside the calorimeter more accurately reflects usual food intake than physical activity in the calorimeter reflects usual physical activity.

These results are directly relevant to the question of whether trained athletes have a higher daily energy expenditure than nontrained subjects and whether any differences are explained entirely by differences in body composition. Schulz et al. (28) reported no difference in daily energy expenditure between trained and untrained subjects when differences in FFM between groups were taken into consideration. Additionally, Ravussin and Bogardus (26) reported that VO\textsubscript{2max} did not explain a significant amount of variation in RMR (after taking FFM into account). In contrast, Poehlman and colleagues (23, 24, 31) have consistently found a higher RMR in trained as compared with untrained subjects when differences in FFM between groups were taken into consideration. Additionally, Ravussin and Bogardus (26) reported that VO\textsubscript{2max} did not explain a significant amount of variation in RMR (after taking FFM into account). In contrast, Poehlman and colleagues (23, 24, 31) have consistently found a higher RMR in trained as compared with untrained subjects, but it is not always clear whether there was a direct relationship between RMR and VO\textsubscript{2max}. In some cases the positive linear relationship between VO\textsubscript{2max} and RMR may have been due to very high RMR in subjects with extremely high VO\textsubscript{2max} (25). Tremblay et al. (31) reported that a program of exercise training (without planned food restriction) increased RMR with no effect on FFM. Many other investigators have found that any difference in RMR between trained and untrained subjects was due to
Table 2. Multiple-regression analysis with various components of total energy expenditure as dependent variables

<table>
<thead>
<tr>
<th>Dependent Variable</th>
<th>FFM, kg</th>
<th>FFM + VO(<em>2)(</em>\text{max}), ml/min</th>
<th>FFM + VO(<em>2)(</em>\text{max}), ml·kg(^{-1})·min(^{-1})</th>
<th>FFM + Age, yr</th>
<th>FFM + %Fat</th>
<th>FFM + Gender</th>
</tr>
</thead>
<tbody>
<tr>
<td>24-h EE</td>
<td>0.813</td>
<td>0.820</td>
<td>0.817</td>
<td>0.815</td>
<td>0.813</td>
<td>0.821</td>
</tr>
<tr>
<td></td>
<td>(0.001)</td>
<td>(0.06)</td>
<td>(0.21)</td>
<td>(0.40)</td>
<td>(0.78)</td>
<td>(0.08)</td>
</tr>
<tr>
<td>SMR</td>
<td>0.830</td>
<td>0.832</td>
<td>0.821</td>
<td>0.832</td>
<td>0.837</td>
<td>0.834</td>
</tr>
<tr>
<td></td>
<td>(0.01)</td>
<td>(0.76)</td>
<td>(0.78)</td>
<td>(0.12)</td>
<td>(0.26)</td>
<td></td>
</tr>
<tr>
<td>RMR</td>
<td>0.813</td>
<td>0.813</td>
<td>0.814</td>
<td>0.823</td>
<td>0.823</td>
<td>0.818</td>
</tr>
<tr>
<td></td>
<td>(0.001)</td>
<td>(0.80)</td>
<td>(0.47)</td>
<td>(0.45)</td>
<td>(0.49)</td>
<td>(0.15)</td>
</tr>
<tr>
<td>TEF</td>
<td>0.152</td>
<td>0.176</td>
<td>0.161</td>
<td>0.155</td>
<td>0.152</td>
<td>0.158</td>
</tr>
<tr>
<td></td>
<td>(0.001)</td>
<td>(0.15)</td>
<td>(0.38)</td>
<td>(0.62)</td>
<td>(0.93)</td>
<td>(0.64)</td>
</tr>
<tr>
<td>EE(_\text{ACT})</td>
<td>0.120</td>
<td>0.120</td>
<td>0.122</td>
<td>0.120</td>
<td>0.123</td>
<td>0.120</td>
</tr>
<tr>
<td></td>
<td>(0.005)</td>
<td>(0.85)</td>
<td>(0.64)</td>
<td>(0.75)</td>
<td>(0.61)</td>
<td>(0.35)</td>
</tr>
</tbody>
</table>

Values in first column represent \(R^2\) (with associated \(P\) value in parenthesis) for regression with fat-free mass (FFM) alone. Remaining columns show total \(R^2\) associated with FFM and added variable. \(P\) value is for added variable (added to FFM) alone. EE, energy expenditure; SMR, sleeping metabolic rate; RMR, resting metabolic rate; TEF, thermal effect of food; EE\(_\text{ACT}\), energy expenditure due to activity or movement.

Table 3. Partial correlations of \(VO_2\)\(_\text{max}\) with components of total energy expenditure after adjusting for FFM

<table>
<thead>
<tr>
<th></th>
<th>(r)</th>
<th>(p)</th>
</tr>
</thead>
<tbody>
<tr>
<td>24-h EE</td>
<td>0.21</td>
<td>0.07*</td>
</tr>
<tr>
<td>RMR</td>
<td>0.03</td>
<td>0.80</td>
</tr>
<tr>
<td>SMR</td>
<td>0.07</td>
<td>0.50</td>
</tr>
<tr>
<td>TEF</td>
<td>0.02</td>
<td>0.85</td>
</tr>
<tr>
<td>EE(_\text{ACT})</td>
<td>0.02</td>
<td>0.85</td>
</tr>
</tbody>
</table>

\(VO_2\)\(_\text{max}\) is measured in ml/min. * Further analysis indicated 2 highly influential points. With omission of these 2 points, \(r = 0.13\), \(P = 0.27\).

Fig. 5. Residuals (after regressing FFM on RMR) plotted against age for males and females. Relationship was not significant for females (dashed regression line) but was significant for males (solid regression line).

Fig. 6. Correlation between total energy consumed during day in room calorimeter and FFM and \(VO_2\)\(_\text{max}\) for 78 subjects. Although we used \(VO_2\)\(_\text{max}\) as a measure of aerobic physical fitness, we realize that there are limitations with this measure. Future studies may benefit by using additional measures such as anaerobic threshold in assessing the degree of physical fitness. In addition, exercise fitness may be better measured in subjects who train through primarily anaerobic means (e.g., resistance training) by using variables such as peak power and fatigue index.
though the amount of body fat was positively associated with RMR, as reported by others (1), RMR and percent body fat were negatively associated after accounting for FFM. Although this provides some support for high-energy efficiency in the obese, it should be noted that the relationship between percent body fat and RMR was much weaker than that between FFM and RMR. Results of the retrospective study of 214 subjects added further support to the conclusions reached with the 78 subjects studied in the whole room calorimeter regarding the relationship of age and body composition to RMR. It should, however, be emphasized that FFM had a much stronger relationship with RMR than did either age or percent body fat. Finally, neither age nor percent body fat explained a significant amount of the variation not explained by FFM in total daily energy expenditure.

Our conclusion that the effects of physical fitness on energy expenditure are exerted through effects on body composition may at first glance appear to suggest exercise is not of major importance in body weight regulation. However, physical fitness is positively correlated with FFM and negatively correlated with percent body fat. Therefore, a higher fitness level is strongly associated with a lower percent body fat. Because all subjects in this study were weight stable, this suggests that a major function of chronic exercise is to allow the steady state of energy balance to be reached at a lower level of body fat than would occur with no exercise.

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