競技者の高い安静時エネルギー代謝は器官・組織重量に依存する（英文）

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High REE in heavy-weight athletes attributed to large organ-tissue mass

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Abstract

It is unknown whether increased resting energy expenditure (REE) in athletes is due to changes in organ-tissue mass and/or metabolic rate. The purpose of this study was to investigate the effect of the organ-tissue component of fat-free mass (FFM) on absolute and relative REE (the REE/FFM ratio) for heavy-weight athletes. We examined the relationship between the REE measured by indirect calorimetry and the REE calculated from organ-tissue mass. Ten heavy-weight athletes (Sumo wrestlers) and 11 moderately active male students (controls) were recruited to participate in this study. FFM was measured by two-component densitometry. Contiguous magnetic resonance imaging (MRI) images with a 1cm slice thickness were obtained from the parietal to the ankle joints, and the cross-sectional area and volume were determined for each type of organ-tissue. The volume units were converted into mass by an assumed constant density. The measured-REE was determined by indirect calorimetry. The calculated-REE was estimated as the sum of individual organ-tissue masses multiplied by their metabolic rate constants. The measured-REE for Sumo wrestlers (2286kcal/day) was higher ($P<0.01$) than for controls (1550kcal/day), but the measured-REE/FFM ratio was similar between the two groups (Sumo wrestlers 29.1kcal/kg/day vs. controls 29.3kcal/kg/day). Sumo wrestlers had a greater amount of FFM and FFM components (e.g., skeletal muscle (SM), liver and kidney) except for brain, while the proportion of organ-tissue mass to FFM was not different between the two groups except for liver. The absolute and relative measured-REE values for Sumo wrestlers were not significantly different from the respective calculated-REE values. The REE for heavy-weight athletes can be attributed not to an elevation of the organ-tissue metabolic rate, but to a larger absolute amount of low and high metabolically active tissue including SM, liver and kidney.

Introduction

Since whole body resting energy expenditure (REE) comprises about 60-75% of total daily energy expenditure in modern life, REE is an important component of the energy balance equilibrium (Poehlman, 1989a). The variability of REE is closely associated with that of fat-free mass (FFM) in healthy, normal weight men and women (Wang et al., 2000; Muller et al., 2002). Currently, it is suggested that exercise training to increase FFM may be an effective method of increasing REE. For instance, Dolezal & Potteiger reported a gain of 2.3kg FFM and a gain of 114kcal/day REE following 10 weeks of resistance training in healthy men (Dolezal & Potteiger, 1998), and other studies have found similar results (Byrne & Wilmore, 2001; Lemmer et al., 2001). Therefore, it is likely that the increase in FFM following exercise training is a key factor in increasing REE.

REE is commonly adjusted per unit FFM in order to compare individuals of different body size. According to the regression line between FFM and the ratio of REE to FFM (REE/FFM) for non-athletes reported by Heymsfield and colleagues, the REE/FFM ratio for subjects with a 70kg FFM was approximately 26kcal/kg/day, which was lower than for subjects with a 50kg FFM (about 29kcal/kg/day) (Heymsfield et al., 2002). In other words, the REE/FFM ratio in normal untrained populations is apparently smaller for individuals with a greater FFM. In contrast, it has also been reported that the ratio of sleeping metabolic rate to FFM for body builders with about 70kg FFM was 29kcal/kg/kcal, and no differences in the REE/FFM ratio were found between body builders and non-athletes (60kg FFM) (Bosselaers et al., 1994). Moreover, the REE/FFM ratio measured for various kinds of athletes (e.g., water polo, judo and karate) also averaged 28-29kcal/kg/day for approximately 70kg FFM (De Lorenzo et al., 1999), which was higher compared to non-athletes with the same amount of FFM (i.e. about 26kcal/kg/day). In summary, the REE/FFM ratio appears to decrease with increasing FFM in untrained controls. In contrast, trained athletes with a larger FFM have a higher REE/FFM ratio compared to untrained controls with a similar FFM.

To explain why the REE/FFM ratio for untrained populations is smaller for those with a greater FFM, it was recently reported that a reduction in the proportion of internal organs-tissue mass to FFM was coupled with an increase in that of skeletal muscle (SM) mass in untrained individuals (Gallagher et al., 1998; Heymsfield et al., 2002). The proportion of low-metabolic active tissue (e.g. SM) and high-metabolic active tissue (e.g. liver and kidney) relative to FFM could account for the REE/FFM ratio for normal untrained populations. At the present time, since there are no published data for athletes' body composition at the organ-tissue level, it is unknown why the REE/FFM ratio for trained athletes with a greater FFM does not decrease as well. Based on the apparent reason for the decline in the REE/FFM ratio for untrained populations, we hypothesized that both SM and internal organ mass increase with FFM accumulation in athletes. Thus, the purpose of the present study was to investigate the effect of the organ-tissue mass component of FFM on the absolute and relative values of the REE/FFM ratio for heavy-weight athletes. To test our hypotheses, we examined the relationship between the measured-REE by indirect calorimetry and the calculated-REE from organ-tissue mass and the assumed metabolic rate constants for non-athletes based on a previously published approach (Gallagher et al., 1998).

Methods

Subjects

Ten male college Sumo wrestlers and 11 male moderately active college students (controls) were recruited for the study. College Sumo wrestlers had participated in regular training (termed "Kei-ko") for an average of 9 years. Kei-ko normally consists of wrestling exercises and additional technical drills (Kondo et al., 1994). Control subjects had played in recreational sports (e.g., swimming, running or athletic training) for at least three years (1-2 times per week). None of the subjects had a history of cardiovascular, endocrine or orthopedic disorders, nor had ever tested positive for anabolic steroids. All subjects received a verbal and written description of the study and gave their informed consent to participate prior to testing. The study was approved by the Tokyo Metropolitan University Ethics Committee for Human Experiments.

Body composition measurements

Body mass and standing height were measured using a digital scale and a wall-mounted stadiometer, respectively, and body mass index (BMI) was calculated. Body density was measured by hydrostatic weighing with simultaneous measurement of residual lung volume by oxygen dilution (Abe et al., 1994). Body fat percentage was calculated from body density using Brozek's equation (Brozek et al., 1963). FFM was estimated as total body mass minus fat mass. We have previously determined that the test-retest reliability of the FFM measurement was 0.7% (390g) (Kojima et al., 2005).

Organ-tissue mass measurements by MRI

The volumes of whole body SM, internal organs (liver and kidney) and brain were measured using a General Electric Signa 1.5 Tesler scanner (Milwaukee, WI, USA). A T1-weighted spin-echo, axial-plane sequence was performed with a 150ms repetition time and a 4.2ms echo time. Subjects rested quietly in the magnet bore in the supine position with their legs and arms extended in the anatomical reference position. Contiguous transverse images with a 1.0cm slice thickness (0cm interslice gap) were obtained from the parietal to the ankle joints for each subject (approximately 160 slices per person). Four sets of acquisitions extended from the parietal to the femoral head during breath-holding (23 seconds). The other three sets of acquisitions were obtained from the femoral head to the ankle joints during normal breathing (Abe et al., 2003).

The volumes of SM, liver, kidney and brain were calculated from the sum of the cross-sectional areas (cm^2) determined by tracing the images and multiplying by the slice thickness (cm). The volumes (cm^3) were converted to masses (kg) by use of the following densities: $1.041 g/cm^3$ for SM (Snyder et al., 1975), $1.060 g/cm^3$ for liver, $1.050 g/cm^3$ for kidney and $1.036 g/cm^3$ for brain (Duck, 1990). The percentage of measurement differences for the same scan on two separate days by the same observer in our laboratory was 1.0% for SM, 1.4% for liver, 2.7% for kidney and 2.5% for brain (n=3).

Since the constantly pulsing heart produced artifacts, heart mass was estimated from body mass using the following formula: $0.006 \times \text{body mass}^{0.98}$ (Calder, 1996). Adipose tissue mass was calculated from fat mass with the assumption that 85% of the adipose tissue was fat and 15% of the adipose tissue consisted of the remaining calculated fat-free component (fat/adipose tissue=0.85) (Garrow, 1978). Total body mass was defined as the sum of the organ masses. Residual mass was calculated as total body mass minus the sum of the SM, adipose tissue, brain, liver, kidney and heart masses. Therefore, residual mass was composed mainly of bone, blood, skin, intestine, connective tissue and lung tissue (Snyder et al., 1975).

Measured-REE

REE was measured using open-circuit indirect calorimetry using the Douglas bag technique (Douglas, 1911). The subjects did not eat or consume any liquids, except water, for 12h prior to testing. None of the subjects performed any exercise 36h prior to testing. Subjects were asked to minimize any walking while en route from their home to the laboratory before REE determination. All REE measurements were performed between 0730 h and 1000 h. After entering the laboratory, subjects rested in the supine position for 30 min, and a face mask (Vise Medical, Japan) was attached. Expired air was collected for 10 min × 2 times, and the mean value was used for analysis. During the test, the room was maintained at a stable temperature (20-25C°) and noise was kept to a minimum. The subjects were instructed to remain awake, quiet and motionless before and throughout the measuring periods. An oxygen and carbon dioxide analyzer (MG-360, Minato, Japan) was used to analyze the rates of oxygen consumption and carbon dioxide production. The volume of expired air was determined using a dry gas volume meter (DC-5, Shinagawa, Japan) and converted to standard temperature, standard pressure and dry gas (STPD). Gas exchange results were converted to REE (kcal/day) using Weir's equation (Weir, 1949). The average between-measurement difference for REE on two separate days within 1 week was 4.2% (n=5).

Calculated-REE

Calculation of REE was based on the sum of 7 body compartments (SM, adipose tissue, brain, liver, kidney, heart and residual mass) times the corresponding tissue-respiration rate, on the basis of specific tissue-metabolic rates (Elia, 1991; Elia, 1992). The calculated-REE was computed using the following equation (Gallagher et al., 1998):

$$\text{Calculated-REE (kcal/day)} = (13\times\text{SM mass}) + (4.5\times\text{adipose tissue mass}) + (240\times\text{brain mass}) + (200\times\text{liver mass}) + (440\times\text{kidney mass}) + (440\times\text{heart mass}) + (12\times\text{residual mass})$$

Statistical analysis

Descriptive data are presented as means ± standard deviation (SD). The differences between college Sumo wrestlers and control subjects were tested for significance by unpaired t-test. The difference between the measured-REE and the calculated-REE was examined using a paired t-test. Pearson's product-moment analysis was used to determine all correlations. All statistical analyses were done using SPSS 10.0 software. Statistical significance was set at the $P<0.05$ level.

Results

Body composition and measured-REE

Mean body mass was higher in Sumo wrestlers compared with controls. Sumo wresters had a higher ($P<0.01$) body fat percentage and mass than controls. FFM was 47% greater ($P<0.01$) in Sumo wrestlers than controls (78.6 vs. 53.3kg) (Table 1). The measured-REE was also 47% higher ($P<0.01$) in Sumo wrestlers compared with controls (2286 vs. 1550kcal/day) (Table 3). The ratio of measured-REE to FFM was similar between the two groups (Sumo wrestlers 29.1 vs. controls 29.3kcal/kg/day). A significant negative correlation ($r=-0.80$, $P<0.01$) was observed between FFM and the measured-REE/FFM ratio in control subjects, but not in Sumo wrestlers ($r=-0.18$, n.s.; Figure 1).

Organ-tissue mass and calculated-REE

Sumo wrestlers had greater ($P<0.01$) SM, liver and kidney masses, but not brain, compared with controls (Table 2). The ratios of SM mass to FFM (46.9 vs. 45.9%) and kidney mass to FFM (0.6 vs. 0.6%) were similar between Sumo wrestlers and controls. However, the ratio of liver mass to FFM was higher ($P<0.05$) in Sumo wrestlers than controls (3.1 vs. 2.6%) (Table 2). The calculated-REE was 47% higher ($P<0.01$) in Sumo wrestlers compared with controls (2324 vs. 1575kcal/day). There was no difference between measured-REE and calculated-REE in both Sumo wrestlers and controls (Table 3). A significant relationship between measured-REE and calculated-REE was also observed in the two groups (Sumo wrestlers: r=0.93, P<0.01; controls: r=0.69, P<0.05) (Figure 2). A Bland-Altman plot showed no significant trend in either group (Sumo wrestlers: r=0.60, P=0.05; controls: r=-0.27, P=0.43).

Discussion

It was previously found that the REE/FFM ratio for those with a large FFM was lower than for those with a small FFM in untrained populations (Heymsfield et al., 2002). In contrast, the REE/FFM ratio for heavy-weight athletes was not lower despite a large FFM (Bosselaers et al., 1994; De Lorenzo et al., 1999). The reasons for this discrepancy had not been clarified. Our data demonstrated that, although Sumo wrestlers had a greater FFM by 25kg compared with controls, the measured-REE/FFM ratio was similar between the two groups (Sumo wrestlers 29.1 vs. controls 29.3kcal/kg/day; Table 3, Figure 1), in contrast to what is seen with untrained populations (Heymsfield et al., 2002). As predicted from the regression line between FFM and the REE/FFM ratio for the normal population reported by Heymsfield and colleagues (Heymsfield et al., 2002), the REE/FFM ratio for non-athletes with an 80kg FFM (which was approximately the same as the FFM of the Sumo wresters in the present study) was only about 25kcal/kg/day. This value was lower by 4kcal/kg/day than the value for Sumo wrestlers in the present study. Moreover, the present study found that the estimated-REE/FFM ratio [29.5kcal/day = (2322kcal/day) / (78.6kg)] for Sumo wrestlers using an approach previously validated in non-athletes (Gallagher et al., 1998; Illner et al., 2000) was very similar to the measured-REE/FFM ratio [29.1kcal/day = (2286kcal/day) / (78.6kg)] (Table 3). This supports our hypothesis that the REE/FFM ratio for heavy-weight athletes can be attributed to increases in both SM and internal organ mass with FFM accumulation. In addition, these results also suggest that the metabolic coefficients per unit organ-tissue mass remain almost constant between heavy-weight athletes and non-athletes.

Several previous studies observed that aerobically trained athletes with a small FFM had a higher REE/FFM ratio than non-athletes. Poehlman and colleagues found a 10% higher REE/FFM ratio for highly trained male athletes (VO_{2max} about 70ml/kg/min) than for non-athletes (VO_{2max} about 50ml/kg/min) (Poehlman et al., 1988; Poehlman et al., 1992). They speculated that an increase in the rate of norepinephrine production mediating the sympathetic nervous system may partially account for this phenomenon (Poehlman et al., 1988). In addition, there may also be an elevation of protein synthesis and energy costs of muscle cell damage and repair secondary to intense exercise (Poehlman et al., 1992). However, an increase in organ-tissue metabolic rate for highly trained aerobic athletes is not clearly indicated by previous published data. In addition, Poehlman and other investigators found that moderately trained aerobic athletes (VO_{2max} about 60ml/kg/min) did not have a significantly higher REE/FFM ratio than non-athletes (Poehlman et al., 1989b; Smith et al., 1997). Based on the results of the present study and previous studies, the possibility that highly trained aerobic athletes (VO_{2max} >70ml/kg/min) may have an increased organ-tissue metabolic rate cannot be ruled out. However, since the large majority of aerobic and resistance trained athletes do not have a high maximal aerobic power, the metabolic rate of organ-tissue, especially SM, is not usually enhanced in these athletes. Moreover, it may be possible that the proportion of internal organ-tissue mass (especially liver and kidney) and a large heart mass (metabolic rate of 200-440kcal/kg/day) also contributes to this phenomenon.

According to longitudinal training experiments, the exercise training-induced change in FFM elicits the change in REE (Ryan et al., 1995; Dolezal et al., 1998; Byrne & Willmore, 2001). However, it is equivocal whether the REE/FFM ratio, which is an indicator of variation in the organ-tissue metabolic rate, is simultaneously increased following exercise training. The disparate results can be attributed to a long-term EPOC (excess post-exercise O_2 consumption) (Speakman & Selman, 2003). Moreover, it has been reported that acute and sustained energy restriction induces low concentrations of thyroid hormones and decreased protein synthesis, which are related to REE variability (Speakman & Selman, 2003). Byrne & Willmore performed training experiments designed to exclude these confounding effects (Byrne & Willmore, 2001). According to this excellent study, on a 20-week whole body resistance training program, the subjects gained 1.9kg of FFM and 44kcal/day of REE, but did not increase their REE/FFM ratio. Based on the results of that study and the present cross-sectional study, the increase in REE following exercise training can be attributed to the change in mass of organ-tissue, not to a change in the metabolic rate of organ-tissue. Additionally, Byrne & Willmore observed that the exercise training REE change per kg FFM was about 25kcal/kg FFM/day [(REE 44kcal/day) / (FFM 1.9kg)] (Byrne & Willmore, 2001), and the REE/FFM ratio for Sumo wrestlers in the present study was about 30kcal/kg/day (Table 3). Therefore, it is likely that REE increases by around 30kcal/day for each increase of 1kg FFM following exercise training. Future studies should take into consideration the relationship between changes in REE and organ-tissue level body composition following exercise training.

Previous studies also found that a reduction in the proportion of internal organs-tissue mass to FFM was coupled with an increase in that of SM mass in untrained individuals, which was assumed to contribute to the fact that the REE/FFM ratio for normal populations decreases with increasing FFM (Gallagher et al., 1998; Heymsfield et al., 2002). However, the Sumo wrestlers in the present study had greater absolute liver and kidney masses (2.40kg and 0.49kg), respectively, in comparison with untrained controls (1.40 and 0.33kg). Additionally, the present study found that the relative liver and kidney masses expressed as a percentage of the FFM for Sumo wrestlers was not lower than that for controls. These cross-sectional data suggest, but do not prove, that the liver and kidney masses increase with long-term high-intensity training-induced FFM accumulation.

However, the cause of the proportionally larger internal organs of athletes has not yet been clarified. It is reasonable to speculate that the liver and kidney masses increased in order to attenuate the extra burden that these tissues might experience from high-intensity exercise training. For instance, the lactate formed in SM following anaerobic exercise training can be converted back to glucose via gluconeogenesis in the liver, thus burdening the liver. Also, when muscle protein is broken down by exercise training, the ammonia generated from amino acids is converted into urea by the liver and is then excreted as urine through the kidneys, thus burdening both the liver and kidneys (Fouillet et al., 2002). In addition, the number of hepatocytes and nephrons, which are important determinants of metabolite elimination, are related to the volume of liver and renal tissue, respectively (Nawaratne et al., 1998). Zoli and colleagues have reported that in humans following hepatic resection, both liver volume and liver function progressively return to states compatible with the subject's physique (Zoli et al., 1986). Moreover, a previous study with rats found that the tissue oxygen consumption of liver slices in 60g rats did not differ from that of 350g rats (Holliday et al., 1967). Similarly, the glomerular filtration rate (GFR), which is a direct function of oxygen consumption, increased with changes in kidney mass, while the GFR per unit kidney mass was stable from 100g to 400g rats (Holliday et al., 1967). Thus, it is expected that greater liver and kidney masses in heavy-weight athletes would be one of the adaptations in body composition that allows an enhanced ability to eliminate metabolites from high-intensity exercise training.

A possible limitation of this study is that we assumed that the constants for organ-tissue energy expenditure were static. However, it is known that some of these constants may change, for instance, in the case of obesity (Ravussin et al., 1988). Since Sumo wrestlers can be considered obese by some measures, we cannot exclude the possibility that the organ-tissue energy expenditure constants were different in our subjects. On the other hand, Sumo wrestlers are athletes who participate in vigorous activity on a daily basis. In any event, further research is needed to clarify whether organ-tissue energy expenditure constants are altered in Sumo wrestlers.

Conclusion

In this study, there was a very strong agreement between the measured-REE and the calculated-REE in Sumo wrestlers. Thus, both the absolute and relative REE (the REE/FFM ratio) for heavy-weight athletes can be attributed not to an elevation of the organ-tissue metabolic rate, but instead to a larger absolute amount of low and high metabolically active tissue including SM, liver and kidney.

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3.8. Tables and figures

Table 1. Subject characteristics

	Sumo wrestlers n = 10	Controls n = 11
Age (year)	19.4 ± 1.5 *	21.7 ± 2.7
Standing height (cm)	172.9 ± 8.4	170.6 ± 5.4
Body mass (kg)	109.1 ± 14.7 **	62.0 ± 6.1
BMI (kg/m ^{2})	36.5 ± 4.3 **	21.3 ± 1.8
Fat (%)	27.7 ± 4.5 **	14.0 ± 4.2
Fat mass (kg)	30.5 ± 7.6 **	8.7 ± 3.0
Fat-free mass (kg)	78.6 ± 9.7 **	53.3 ± 5.4

Sumo wrestlers vs. Controls: * $P < 0.05$, ** $P < 0.01$.

Table 2. Organ-tissue level body composition

	Sumo wrestlers n = 10	Controls n = 11
Organ-tissue mass (kg)		
Skeletal muscle	36.9 ± 5.9 **	24.5 ± 3.4
Adipose tissue 1)	35.9 ± 8.9 **	10.2 ± 3.5
Liver	2.40 ± 0.52 **	1.40 ± 0.20
Brain	1.44 ± 0.07	1.46 ± 0.10
Heart 2)	0.60 ± 0.08 **	0.34 ± 0.03
Kidney	0.49 ± 0.08 **	0.33 ± 0.04
Residual 3)	31.4 ± 5.1**	23.7 ± 2.6
Organ-tissue mass/FFM (%)		
Skeletal muscle	46.9 ± 3.9	45.9 ± 3.0
Liver	3.1 ± 0.6 *	2.6 ± 0.3
Kidney	0.6 ± 0.1	0.6 ± 0.1

1) Assumed that 85% of adipose tissue is fat and 15% of adipose tissue is the remaining calculated fat-free component (Garrow, 1978).

2) 0.006 _ body mass $^{0.98}$ (Calder, 1996).

3) Residual mass was calculated as body mass minus sum of other measured mass components.

FFM: fat-free mass.

Sumo wrestlers vs. Controls: * $P < 0.05$, ** $P < 0.01$.

Table 3. Measured- and calculated-resting energy expenditure

Resting enegy expenditure (kcal/day)	Sumo wrestlers n = 10	Controls n = 11
Measured-REE (kcal/day)	2286 ± 350 **	1550 ± 108
Measured-REE/FFM (kcal/kg/day)	29.1 ± 3.0	29.3 ± 2.4
Calculated-REE	2324 ± 264 **	1575 ± 133
Difference (Measured - Calculated)	-38 ± 144	-25 ± 98
Measured-REE vs. Calculated-REE	n.s.	n.s.

REE: resting energy expenditure, FFM: fat-free mass.

Sumo wrestlers vs. Controls: ** $P < 0.01$.

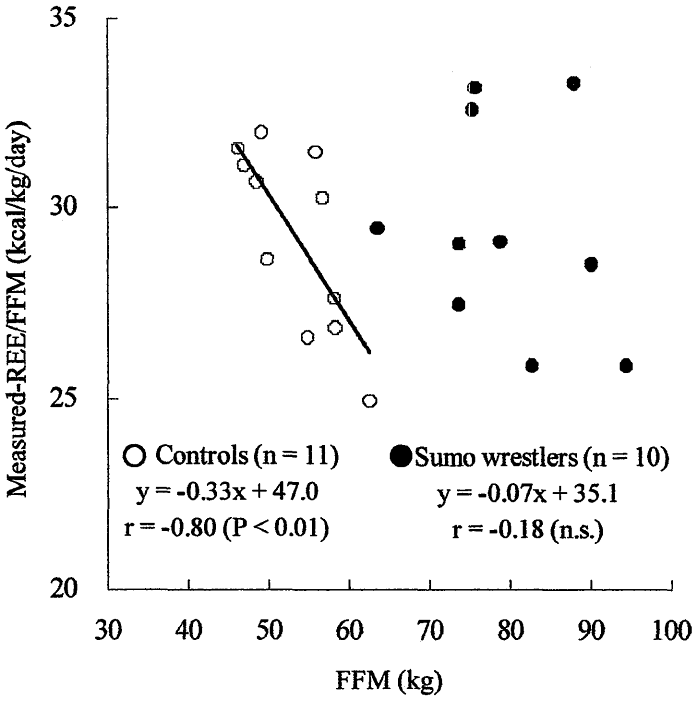

Figure 1. Relationship between FFM and the ratio of REE to FFM.

REE: resting energy expenditure, FFM: fat-free mass.

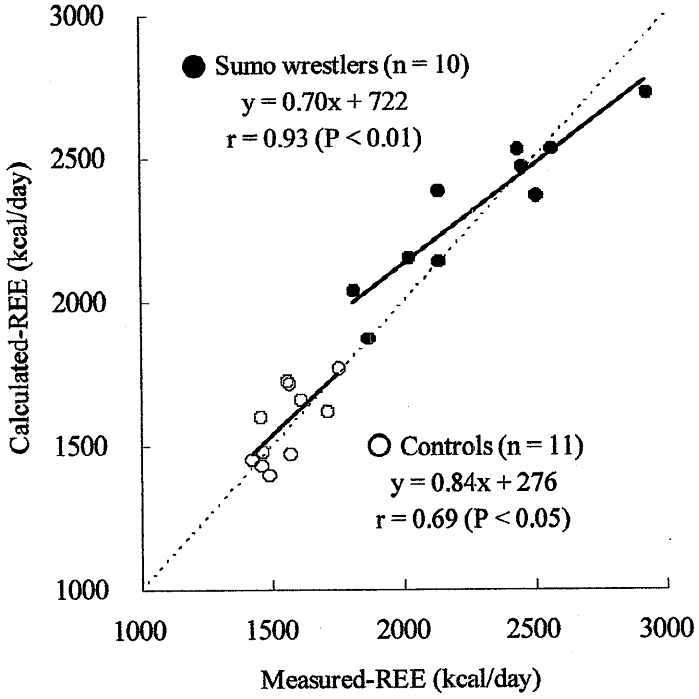

Figure 2. Relationship between the measured-REE and the calculated-REE.

REE: resting energy expenditure.