Table 2 Summary of aerobic exercise groups in this paper

Reference	*Subjects*				*Aerobic exercise*	
	Gender	*Age (yr)*	*BMI (kg/m^2)*	*% fat (%)*	*Session time and intensity*	*Mode or used exercise instrument*
Despres *et al.*[34]	F	38.8	34.5	47.0	90 min, 55%HRmax	Walking
Donnelly *et al.*[15]	M	22	29.7	28.3	45 min, 70%VO2max	Treadmill
Green *et al.*[17]	F	56.4	29.3	40.8	75%VO2max	Ergometer
Halverstadt *et al.*[18]	M+F	57.9	—	36.0	70%VO2max	—
Irwin *et al.*[19]	F	61	30.5	47.6	Mean 81%HRmax	Treadmill walking and stationary bicycling in Lab, and aerobic exercise (e.g. walking, aerobics, bicycling) at home
Miyatake *et al.*[20]	M	32–59	28.6	29.3	7012→8839 steps/day (plus 1827 steps/days)	Normal walking
Park *et al.*[21]	F	42.2	25.3	42.2	60–70%HRmax	Fast walking
Ross *et al.*[22]	F	43.2	32.8	—	Mean 80%HRmax	Brisk walking or light jogging on treadmill
	F	41.3	32.9	—	Mean 82%HRmax	Brisk walking or light jogging on treadmill
Ross *et al.*[29]	M	45	32.3	—	Mean 77%HRmax	Brisk walking or light jogging on treadmill
	M	44.7	31.3	—	Mean 77%HRmax	Brisk walking or light jogging on treadmill
Schwartz *et al.*[27]	M	67.5	26.2	24.7	45 min, 85%HRreserve	Walking/jogging
Short *et al.*[23]	M+F	40.5	26.6	31.4	80%HRmax	Stationary bicycling
Wilund *et al.*[25]	M+F	56	—	38.0	40 min, 70%VO2max	—
	M+F	56	—	34.0	40 min, 70%VO2max	—
Boudou *et al.*[33]	M	42.9	28.3	—	1) 2 times/week, 45 mi n, 75%VO2peak, 2) 1 time/week, 10 min, 85%VO2peak, and 12 min, 50%VO2peak	Ergometer
Giannopoulou *et al.*[16]	F	55.5	35.9	—	60 min, 65–70%VO2max, energy expenditure: 250.95–298.75 kcal/session	Walking
Mourier *et al.*[9]	M+F	45	30.4	24.4	1) 2 times/week, 45 min, 75%Vo2peak, 2) 1 time/week, 10 min, 75%VO2peak, and 12 min, 50%VO2peak	Ergometer
Slentz *et al.*[24]	M+F	54	29.8	—	40–55%VO2max, 14 kcal/kg/wk (12 miles/week)	Treadmill walking
	M+F	53	29.7	—	65–80%VO2max, 14 kcal/kg/wk (12 miles/week)	Treadmill jogging
	M+F	51.5	29.1	—	65–80%VO2max, 23 kcal/kg/wk (20 miles/week)	Treadmill jogging

Table 2 (Continued)

	Aerobic exercise				Weight						Visceral fat							
VO2max (baseline)	*Frequency (times/ week)*	*Time (min/ session)*	*Energy expenditure (kcal/week)*	*METs· h/w*	*Before (kg)*	*After (kg)*	*Δ (kg)*	*%Δ (%)*	*%Δ (%/ week)*	*Sig*[1]	*Before*	*After*	*Δ*	*Unit*	*%Δ (%)*	*%Δ (%/ week)*	*Sig*[2]	*Method*
	4–5	90	1913	20.2	90.0	86.3	−3.7	−4.11	−0.069	*	124.7	121.3	−3.4	cm²	−2.73	−0.045	NS	CT
	5	45	3300	33.4	94.0	85.2	−8.8	−9.36	−0.136	*	97.9	75.5	−22.4	cm²	−22.88	−0.334	*	
21.3 ± 4.0	3	50	920	11.4	76.8	76.9	0.1	0.13	0.007	NS	121.6	117.8	−3.8	cm²	−3.13	−0.156	NS	CT
25.2 ± 0.5	3	40	853	10.1	80.6	79.5	−1.1	−1.36	−0.057	*	127.8	113.4	−14.4	cm²	−11.27	−0.469	*	CT
20.1 (19.3–20.9)	3.5	176/week	1051	12.3	81.6	—	−1.3	−1.59	−0.031	*	147.6	—	−8.5	cm²	−5.76	−0.113	*	CT
	7	18.27	507	5.9	82.0	79.0	−3.0	−3.66	−0.091	*	108.7	87.0	−21.7	cm²	−19.96	−0.499	*	CT
34.2 ± 3.2	6	60	1908	28.5	63.7	59.0	−4.7	−7.38	−0.307	*	195.0	112.4	−82.6	cm²	−42.36	−1.765	*	CT
	7	64	3668 (524 ± 52/session)	40.2	86.9	80.9	−6.0	−6.90	−0.493	*	2.3	1.6	−0.7	kg	−30.43	−2.174	*	MRI
	7	63	3619 (517 ± 58/session)	39.1	88.1	87.6	−0.5	−0.57	−0.041	NS	2.2	1.8	−0.4	kg	−18.18	−1.299	*	
	7	60.4	4886 (698/session)	45.8	101.5	94.0	−7.5	−7.39	−0.616	*	186.0	134.0	−52.0	cm²	−27.96	−2.330	*	MRI
	7	63.3	4844 (692/session)	47.1	97.9	97.4	−0.5	−0.51	−0.043	NS	191.0	159.0	−32.0	cm²	−16.75	−1.396	*	
29.1 ± 4.4	4.44 ± 0.43	45	2009	24.0	79.6	77.1	−2.5	−3.14	−0.131	*	144.5	109.0	−35.5	cm²	−24.57	−1.024	*	
25.6 (40.5 ± 1.1/ FFM)	4	40	1166	14.0	79.2	78.7	−0.5	−0.63	−0.039	*	133.0	124.0	−9.0	cm²	−6.77	−0.423	*	CT
25 ± 1	3	40	882	10.0	84.0	83.2	−0.8	−0.95	−0.079	NS	146.0	130.0	−16.0	cm²	−10.96	−0.913	*	CT
26 ± 1	3	40	863	10.4	79.0	77.8	−1.2	−1.52	−0.127	*	128.0	109.0	−19.0	cm²	−14.84	−1.237	*	
23.45 ± 3.60	3	1) 45, 2) 22	836	9.2	86.9	85.0	−1.9	−2.19	−0.273	NS	153.3	84.2	−69.1	cm²	−45.06	−5.632	*	MRI
	3–4	60	962	9.9	92.9	91.2	−1.7	−1.83	−0.131	NS	5204.0	4675.0	−529.0	cm³	−10.17	−0.726	*	MRI
23.0 ± 1.2	3	1) 45, 2) 22	795	8.9	85.3	83.8	−1.5	−1.76	−0.220	NS	156.1	80.4	−75.7	cm²	−48.49	−6.062	*	MRI
	3.5	178	1232	6.9	88.0	—	—	−0.70	−0.022	*	173	—	—	—	1.70	0.053	NS	CT
	3.1	120	1190	13.3	85.0	—	—	−0.80	−0.025	*	154	—	—	—	2.50	0.078	NS	
	3.6	173	1971	21.9	85.7	—	—	− 2.60	−0.081	*	168	—	—	—	−6.90	−0.216	*	

Abbreviations: CT; computed tomography; F, female subjects; M, male subjects; METs·h/w, ∑(metabolic equivalents × hour) per week; MRI, magnetic resonance imaging; Sig[1], a significant weight change was observed during the intervention ($P<0.05$); Sig[2], a significant visceral fat change was observed during the intervention ($P<0.05$); Δ, change. Results expressed by mean (range) or mean ± s.d.

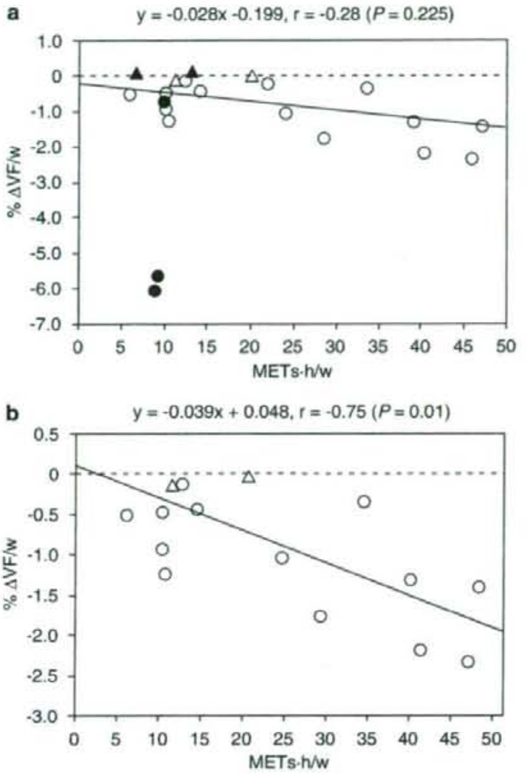

Figure 1 Relations between METs · h/w and %ΔVF/w during interventions in the all selected groups (**a**) and the groups without metabolic-related disorder subjects (**b**). Abbreviations: METs · h/w, ∑(metabolic equivalents × hour) per week; %ΔVF/w, percentage of visceral fat change per week; *r*, Pearson's correlation coefficient weighted for the number of subjects in each group; ○, the no metabolic-related disorder group with a significant visceral fat reduction ($P<0.05$); △, the no metabolic-related disorder group without a significant visceral fat reduction ($P<0.05$); ●, the metabolic-related disorder group with a significant visceral fat reduction ($P<0.05$); ▲, the metabolic-related disorder group without a significant visceral fat reduction ($P<0.05$).

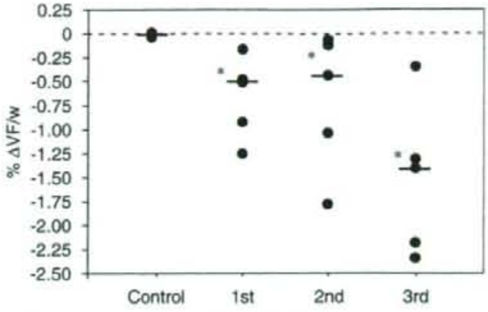

Figure 2 Comparison of mean %ΔVF/w between a control group and exercise groups divided into tertiles by METs · h/w amount in the groups without metabolic-related disorder groups. Ranges of METs · h/w in each categorized group were 5.9–11.4 (1st), 12.3–28.5 (2nd), 33.4–47.1 (3rd). Side bar means median in each group. Statistically significant difference between the groups were observed ($P=0.003$). * A significant difference was found in comparison with the control group using the *post hoc* test ($P<0.05$). Abbreviations: %ΔVF/w, percentage of visceral fat change per week; METs · h/w, ∑(metabolic equivalents × hour) per week.

physical activity and total or regional fat reduction. As a result, even though some literatures were added for the analysis, whether physical activity was associated with reductions in abdominal fat in a dose–response manner was still unclear. Kay and Fiatarone Singh[10] also reviewed the beneficial influence of physical activity on visceral fat reduction, but dose–response data were not examined. These previous reviews did not include studies involving large amounts of exercise. In our analysis, some additional studies, especially three studies with values of 35 METs · h/w or more,[21,22,29] were included in addition to papers used by previously published reviews. Furthermore, the amount of aerobic exercise undertaken during the intervention was expressed as METs · h/w, because METs · h could adjust the EE for each subject's weight. As a result, there was no relationship between METs · h/w and %ΔVF in the 21 groups from 16 studies including the metabolic-related disorder subjects. However, in subjects without metabolic-related disorders, we found a dose–response relationship between aerobic exercise and visceral fat reduction. Indeed, if obese subjects without metabolic-related disorders practiced aerobic exercise, the degree of visceral fat reduction could be directly attributed to the aerobic exercise amount. For example, if an obese person without metabolic-related disorders tries to reduce 10% of his VF amount in 10 weeks, instructors should prescribe about 27 METs · h/w, because 27 METs · h/w corresponds to 1% of ΔVF/w. Thus, our findings could be used to affect decisions on the amount of aerobic exercise recommended for visceral fat reduction in obese people.

In the selected studies, six groups from four studies consisted of metabolic-related disorder subjects. Results from the metabolic-related disorder subjects were contradictory. Two groups with type 2 diabetes[9,38] clearly exhibited a significant visceral fat reduction, although these results may have been exaggerated by the shortest-term intervention (8 weeks) in the selected studies. Two groups with dyslipidemia[24] did not significantly reduce visceral fat, while the group with type 2 diabetes reported by Giannopoulou *et al.*[16] was close to the regression line for identifying a dose–response relationship. Kelly and Simoneau[39] showed that the capacity of fat oxidation during aerobic exercise in individuals with type 2 diabetes was lower than that for healthy individuals. However, several other investigators did not find any significant difference in fat oxidation capacity between subjects with or without type 2 diabetes.[40,41] Furthermore, Raguso *et al.*[42] observed that fat oxidation during aerobic exercise in the group with type 1 diabetes was higher than that of the control group. These studies were conducted

Table 3 Mean METs · h/w and %ΔVF/w, and correlate coefficients between METs · h/w and %ΔVF/w during interventions in the groups categorized by intervention duration or gender

Groups	*Intervention duration*		*Gender*	
	≤16 week	*>16 week*	*Women only*	*Men only*
From all the selected groups				
Number of groups	10	11	7	6
Number of subjects	183	399	168	98
METs · h/w	23.5±17.1	17.1±9.1	23.1±13.0	27.6±17.7
%ΔVF/week	−2.22±2.00	−0.41±0.55	−0.90±0.86	−1.83±1.98
r (*P* value)	−0.06 (0.877)	−0.34 (0.302)	−0.89 (0.007)	−0.05 (0.931)
From the groups without metabolic-related disordered subjects				
Number of groups	7	8	6	5
Number of subjects	154	271	157	90
METs · h/w	29.5±17.2	18.2±9.8	25.3±12.7	31.3±17.1
%ΔVF/w	−1.40±0.67	−0.55±0.58	−0.93±0.94	−1.07±0.73
r (*P* value)	−0.81 (0.027)	−0.36 (0.378)	−0.93 (0.008)	−0.71 (0.184)

Abbreviations: METs · h/w, ∑(metabolic equivalents × hour) per week; *r*, Pearson's correlate coefficient; %ΔVF/w, percentage of visceral fat change per week. *r* values were weighted for the number of subjects in each group.

under conditions where the subjects with or without diabetes had fasted.[39–42] Thus, visceral fat reduction in the metabolic-related disorder subjects could be due to more complex mechanisms. Therefore, formulation of a dose–response relationship between aerobic exercise and visceral fat reduction has to take into account the separation of subjects with and without metabolic-related disorders.

How much exercise is needed for significant visceral fat reduction?

It is important to suggest a lower limit for the quantity of aerobic exercise required for significant visceral fat reduction. In our selected groups, METs · h/w values ranged from 5.9 to 47.1. Except for the lowest METs · h/w obtained from Miyatake *et al.*[20] in which the subjects were instructed to increase the number of steps walked every day for 1 year, significant visceral fat reduction was observed from about 10 METs · h/w.[16,18,25] Thus, at least 10 METs · h/w is required for significant visceral fat reduction by aerobic exercise, such as brisk walking, light jogging or stationary ergometer usage. For the purpose of weight or body fat loss, the American College of Sports Medicine (ACSM) recommends obese individuals to engage in moderately intense physical activity for minimum 150 min/w, and preferably more than 200–300 min/w.[43] The minimum value in this recommendation nearly equals to 10 METs · h/w when performing moderate physical activities such as brisk walking. In the present study, we divided the aerobic exercise groups into tertiles by their METs · h/w amount to determine the boundary of obvious visceral fat reduction. As a result, each exercise group category had a higher visceral fat reduction than the control group. However, there was no significant difference between %ΔVF/w values in the three exercise categories. This result may be due to an insufficient number of groups. The median of %ΔVF/w in the 3rd tertile exercise group was 40.2, which was much higher than that of the 1st and 2nd tertile exercise groups. That is to say, approximately 40 METs · h/w or more may be required to reduce visceral fat solely by aerobic exercise, such as brisk walking, light jogging or stationary ergometer usage. Forty METs · h/w equates to approximately 3780 kcal/w for a person with 90 kg body weight. Although this value is slightly lower than the ACSM's recommendation corresponding to a minimum 4500 kcal/w for combined exercise and diet with intakes of not lower than 1200 kcal/d, this results in an energy deficiency of approximately 500–1000 kcal/d, which could be hard for obese people with low physical fitness to practice continuously. Therefore, for an individual's prescription for visceral fat reduction, recommendations that balance diet and exercise should be examined in another research.

Influences of intervention duration or gender on the dose–response relationship

Ross and Janssen[13] revealed that an increase in physical activity is positively associated with a reduction in total fat in a dose–response manner in short-term interventions (≤16 week), but not in long-term interventions (≤26 week). In the review by Kay and Fiatarone Singh,[10] there was no relation between change in abdominal fat and intervention duration. In the present study, EE by aerobic exercise was positively correlated with visceral fat reduction in the short-term (≤16 wk) studies when the metabolic-related disorder groups were discounted. Ross and Janssen[13] suggested that in long-term exercise studies, it is difficult to complete a weight loss of an expected volume from expended energy consumption, although it is not clear which factors, such as the adherence to interventions, or over-reporting of exercise amount, influenced the results. Our results support this trend with

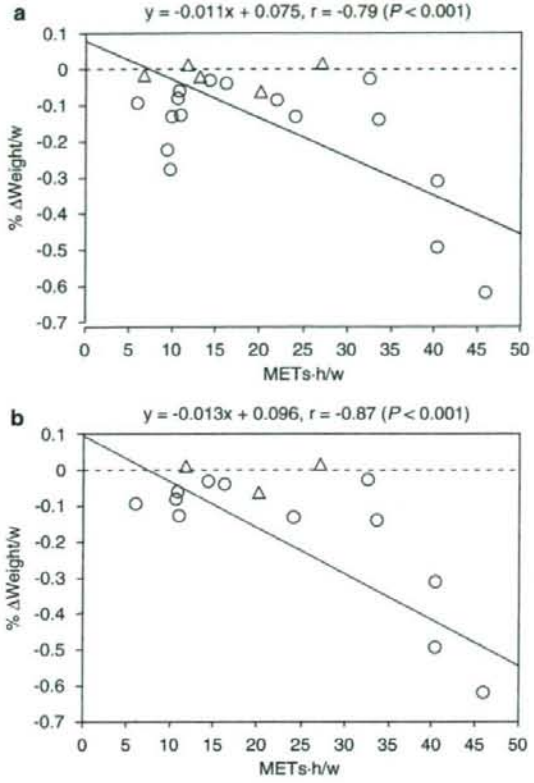

Figure 3 Relations between METs·h/w and %ΔWeight/w during interventions in the all selected groups (**a**) and after excluding the groups with metabolic-related disorder subjects (**b**). Abbreviations: METs·h/w, ∑(metabolic equivalents × hour) per week; %ΔWeight/w, percentage of weight change per week; *r*, Pearson's correlate coefficient; ○, the group with a significant visceral fat reduction ($P<0.05$); △, the group without a significant visceral fat reduction ($P<0.05$). The groups without a weight loss intentionally were excluded for these analysis.

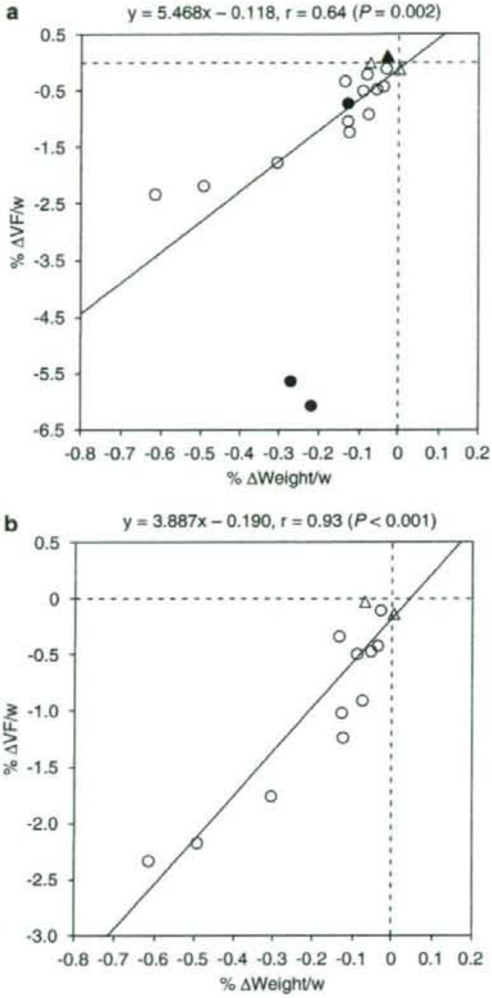

Figure 4 Relations between %ΔVF/w and %ΔWeight/w during interventions in the all selected groups (**a**) and after excluding the groups with metabolic-related disorder subjects (**b**). Abbreviations: %ΔVF/w, percentage of visceral fat change per week; %ΔWeight/w, percentage of weight change per week; *r*, Pearson's correlation coefficient weighted for the number of subjects in each group; ○, the no metabolic-related disorder group with a significant visceral fat reduction ($P<0.05$); △, the no metabolic-related disorder group without a significant visceral fat reduction ($P<0.05$); ●, the metabolic-related disorder group with a significant visceral fat reduction ($P<0.05$); ▲, the metabolic-related disorder group without a significant visceral fat reduction ($P<0.05$).

respect to visceral fat reduction. That is, if subjects can complete the instructed exercise volume, short-term interventions could be more efficient than long-term interventions for weekly visceral fat reduction. Generally, if participants do not quickly observe the benefits of a weight-loss program, their motivation for continuing the regimen is reduced.[44,45] Accordingly, for significant visceral fat reduction, obese people should initially practice a relatively high volume of aerobic exercise, which can then be reduced to a manageable amount that they can practice for the long term.

In the present study, a significant relationship between METs·h/w and %ΔVF was observed in women-only groups, with and without the metabolic-related disorder subjects, while there was no significant relationship in the men-only groups. The limited number of studies was insufficient to determine the influence of gender on the dose–response relationship. However, it is difficult to compare differences of the amount of visceral fat reduction by aerobic exercise between men and women, as women generally store a greater total fat mass relative to body weight than men.[46] Also, body fat distribution is different between men and women as men tend to have more central obesity than women.[47] Initial values of visceral fat could contribute to the amount of visceral fat lost during intervention. If these biases between men and women were excluded, that is, if the absolute amount of total and visceral fat were matched between men and women, then the relative obesity levels for each gender would be much different. It is likely that gender, as well as intervention duration, could be factors in the differences in rate of visceral fat reduction per week.

Relationship between visceral fat reduction and weight reduction

Weight reduction during interventions could be seen solely as the result of fat mass reduction, because fat-free mass reduction accounts for only a small part of weight reduction.[38] Visceral fat volume is about 10–20% of total fat volume[48,49] and reduction of the subcutaneous fat volume largely reflects weight reduction. In a limited number of selected studies, METs · h/w and %ΔWeight/w had a significant correlation in both the groups with and without metabolic-related disorders. Therefore, metabolic-related disorders, especially type 2 diabetes, may have a small impact on a dose-relation between weight loss and aerobic exercise during intervention compared to the amount of visceral fat reduction.

On the other hand, our results indicate a significant relationship between %ΔWeight/w and %ΔVF/w, especially in the subjects without metabolic-related disorders. We can say that %ΔVF/w corresponds to four to five times %ΔWeight/w when obese people practice aerobic exercise. However, previous studies suggest that visceral fat is used more quickly as an energy resource than subcutaneous fat during aerobic exercise-induced weight loss.[50] In our analysis, the intercept of the regression line between %ΔWeight/w and %ΔVF/w in the subjects without metabolic-related disorders was significantly different from zero. Although the trend showed that the more weight was lost, the more visceral fat was reduced, a significant reduction of visceral fat, which occupies less than 5% of body weight,[48,49] may also occur without a significant weight reduction with aerobic exercise. In fact, this phenomenon was reported by studies that examined whether or not visceral fat was reduced by aerobic exercise, if energy intake corresponding to the EE value by prescribed aerobic exercise was added to the baseline. Such an adjustment in the calculation did not lead to a significant weight reduction.[22,29] Generally, it is difficult for obese people to reduce weight largely by practicing exercise alone, compared to diet.[8] Therefore, exercise is inclined to be optional with a diet therapy for weight loss. However, even if insufficient weight loss does occurs, visceral fat could be reduced by doing aerobic exercise, a prescription supported by recent studies.[16,22] These results provide evidence of the usefulness of aerobic exercise for visceral fat reduction.

There are a number of limitations in the present study. The number of selected studies, especially those which measured EE for the prescribed exercises, were still insufficient for defining a clear aerobic exercise amount that resulted in significant visceral fat reduction. Additionally, the influence of several factors, such as metabolic-related disorders, gender and intervention duration, on visceral fat reduction remains unclear. Most of trials in the selected studies had applied brisk walking, light jogging and stationary ergometer, so whether or not other types of activities could lead to a similar result cannot be clarified from this study. Furthermore, while the present study investigated visceral fat reduction, studies with visceral fat gain should also be included in the analyses.

In conclusion, data collected from selected studies suggested that aerobic exercise as a weight loss intervention has a dose–response relationship with visceral fat reduction in obese subjects, excluding groups with metabolic-related disorders. Additionally, visceral fat reduction is significantly related to weight reduction during aerobic exercise intervention, although a significant visceral fat reduction may also occur without significant weight loss. Furthermore, for significant visceral fat reduction, at least 10 METs · h/w of aerobic exercise is required. However, since the number of selected studies was still insufficient, further studies are required.

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Evaluation of Low-Intensity Physical Activity by Triaxial Accelerometry

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Abstract

MIDORIKAWA, TAISHI, SHIGEHO TANAKA, KAYOKO KANEKO, KAYO KOIZUMI, KAZUKO ISHIKAWA-TAKATA, JUN FUTAMI, AND IZUMI TABATA. Evaluation of low-intensity physical activity by triaxial accelerometry. *Obesity*. 2007;15:3031–3038.

Objective: To develop regression-based equations that estimate physical activity ratios [energy expenditure (EE) per minute/sleeping metabolic rate] for low-to-moderate intensity activities using total acceleration obtained by triaxial accelerometry.

Research Methods and Procedures: Twenty-one Japanese adults were fitted with a triaxial accelerometer while also in a whole-body human calorimeter for 22.5 hours. The protocol time was composed of sleep (8 hours), four structured activity periods totaling 4 hours (sitting, standing, housework, and walking on a treadmill at speeds of 71 and 95 m/min, 2 × 30 minutes for each activity), and residual time (10.5 hours). Acceleration data (milligausse) from the different periods and their relationship to physical activity ratio obtained from the human calorimeter allowed for the development of EE equations for each activity. The EE equations were validated on the residual times, and the percentage difference for the prediction errors was calculated as (predicted value − measured value)/measured value × 100.

Results: Using data from triaxial accelerations and the ratio of horizontal to vertical accelerations, there was relatively high accuracy in identifying the four different periods of activity. The predicted EE (882 ± 150 kcal/10.5 hours) was strongly correlated with the actual EE measured by human calorimetry (846 ± 146 kcal/10.5 hours, $r = 0.94$ $p < 0.01$), although the predicted EE was slightly higher than the measured EE.

Discussion: Triaxial accelerometry, when total, vertical, and horizontal accelerations are utilized, can effectively evaluate different types of activities and estimate EE for low-intensity physical activities associated with modern lifestyles.

Key words: accelerometry, energy expenditure, indirect calorimetry, physical activity

Introduction

Activity thermogenesis can be separated into two components: exercise-related activity thermogenesis and non-exercise activity thermogenesis (NEAT)[1] (1). NEAT, composed mainly of the energy expenditure (EE) related to low-to-moderate intensity daily physical activity (PA), is likely to have greater individual variation than exercise-related activity thermogenesis and body size-dependent basal metabolic rate. Levine et al. (2) used inclinometers and triaxial accelerometers to reveal that obese participants were seated for 164 min/d more than and were upright for 152 min/d less than lean participants. Moreover, if the obese subjects had the same posture allocation as the lean subjects, they would have expended an additional 352 kcal/d. Therefore, NEAT has been highlighted recently for helping to prevent weight gain. However, there are currently few effective methods to objectively and noninvasively evaluate the type or quantity of low-intensity PA in free-living conditions.

Triaxial accelerometers that are small in size and minimally intrusive to normal subject movement can be useful

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[1] Nonstandard abbreviations: NEAT, non-exercise activity thermogenesis; EE, energy expenditure; PA, physical activity; IHC, indirect human calorimeter; mG, milligausse; $\dot{V}O_2$, oxygen uptake; $\dot{V}CO_2$, carbon dioxide production; SD, standard deviation; PAR, PA ratio; SEE, standard error of estimation.

devices for predicting PA EE (3). Previous studies demonstrated higher correlation coefficients between counts obtained with triaxial accelerometry and the EE measured by chamber in comparison with counts from uniaxial accelerometry (4–6). However, these previous studies researched moderate-intensity PA such as slow and brisk walking and jogging, not low-intensity lifestyle activities. Moreover, Bassett et al. (7) found that uniaxial waist-mounted accelerometers overestimated the EE of walking and underestimated the EE of all other activities. Thus, we hypothesized that methods for estimating EE would be improved by the development of equations for each daily lifestyle PA.

To accurately predict EE using equations for each activity, it is necessary to classify each daily lifestyle PA using triaxial accelerometry. There are currently no published data concerning the identification of body posture in free-living conditions using triaxial accelerometry, especially light-to-moderate intensity PA with upper body movement such as sweeping, mopping, and window washing, which is a relatively high-energy cost during daily living (4,7). However, a previous study that evaluated standing balance using a triaxial accelerometer found that the accelerometer measurements, especially horizontal acceleration, were able to distinguish between the different test conditions and simultaneous force platform measurements (8). Concomitantly, it is speculated that household activities with upper body movement (e.g., cleaning and sweeping) may have larger horizontal acceleration than sitting and standing. We hypothesized that low-intensity PA in free-living conditions can be identified by using horizontal acceleration obtained from triaxial accelerometry.

Thus, the purpose of the present study was to develop regression-based equations that estimate EE from total acceleration, which was based on the defined thresholds of accelerations that can be used to delineate low-to-moderate intensity PA. Furthermore, we compared the ability to identify the type and quantity of the low-intensity PA and predicted EE using either triaxial acceleration or only vertical acceleration from a triaxial accelerometer.

Research Methods and Procedures

Subjects

Twenty-one Japanese adults (8 men and 13 women) living in the Tokyo metropolitan area were recruited for the study (Table 1). All subjects were adults (≥20 years) and were without any chronic diseases that could affect EE or daily PA. All subjects received a verbal and written description of the study and gave their informed consent to participate before testing. The study protocol was approved by the Ethical Committee of the National Institute of Health and Nutrition.

Table 1. Subject characteristics

	Men (n = **8**)	**Women** (n = **13**)
Age (yrs)	33 ± 15	31 ± 10
Standing height (cm)	171.2 ± 4.7	161.0 ± 5.3
Body weight (kg)	65.3 ± 4.1	55.8 ± 9.8
BMI (kg/m^2)	22.3 ± 2.0	21.5 ± 3.5
Fat (%)	13.2 ± 3.7	23.3 ± 8.4
Fat-free mass (kg)	52.0 ± 5.8	32.6 ± 5.4

Anthropometry

Body weight was measured on a digital balance to the nearest 0.1 kg, and height was measured on a stadiometer to the nearest 0.1 cm. BMI was calculated as the body weight in kilograms divided by the height in meters squared. Body composition was evaluated by the skinfold method at two skinfolds (triceps and subscapular) to the nearest 0.1 mm. The measurements were repeated until the difference between the two readings reached within 1 mm, and the mean value was used. Body density was assessed using the equations for Japanese (9), and the percentage of body fat was estimated using the equation of Brozek et al. (10). Body fat mass and the fat-free mass were calculated from body weight and percent of body fat.

Study Protocol

Subjects were fitted at the left hip with a triaxial accelerometer (AC-301, 51 × 77 × 15 mm, 87 grams; or AC-210, 48 × 67 × 16 mm, 57 grams; GMS, Tokyo, Japan) while also in the indirect human calorimeter (IHC) for 22.5 hours (from 6 PM to 4:30 PM the next day). The triaxial accelerometer obtained three-dimensional accelerations every 40 ms with a sensitivity of 2 milligausse (mG) and a band-pass filter of 0.3 to 100 Hz. The acceleration count was calculated as the average of the absolute values for acceleration in each direction for a given interval (1 minute). The subjects ate breakfast, lunch, and dinner at 8:15 AM, 12:30 PM, and 6:30 PM, respectively. They went to bed at 11 PM and were gently awakened at 7 AM. They were permitted to go to the toilet and were asked to return to bed immediately. The schedule included 8 sessions of standardized activities: 2 × 30 minutes sessions each of walking on a treadmill (95 m/min in the morning and 71 m/min in the afternoon), sitting, standing, and housework representative of typical activities in free-living conditions. Subjects were permitted to spend time freely in a sitting or standing position as long as posture was maintained and to rest periodically during the housework period. During the remaining time periods, subjects were only permitted to do light activities such as reading, writing, viewing television, dressing, and undressing. They were asked to refrain from sleeping and planned strenuous exercise except during the walking periods. Meals were given three times a day to provide the predicted basal metabolic rate (11) multiplied by the estimated PA level (1.5).

IHC

An open-circuit IHC was used to evaluate the EE of the four standardized activities totaling 4 hours, the sleeping time for 8 hours, and the residual time for 10.5 hours. Details of IHC have been reported previously (12,13). Briefly, the respiratory chamber was an air-tight room (20,000 liters), equipped with a bed, desk, chair, television with video deck, compact disc player, telephone, toilet, sink, and treadmill. The temperature and relative humidity in the room were controlled at 25 °C and 55%, respectively. The O_2 and CO_2 concentrations of the air supply and exhaust were measured by mass spectrometry. For each experiment, the gas analyzer (ARCO-1000A-CH; Arco System, Inc., Kashiwa, Japan) was initially calibrated using a certified gas mixture and atmospheric air. The flow rate exhausted from the chamber was measured by pneumotachograph (FLB1; Arco System, Inc.). The flow meter was calibrated before each measurement, and the flow rate was maintained at ~60 L/min. Oxygen uptake (Vo_2) and carbon dioxide production (Vco_2) were determined by the flow rate of exhaust from the chamber and the concentrations of the inlet and outlet air of the chamber, respectively (12). Values of Vo_2 and Vco_2 were expressed under the conditions of standard temperature and pressure and under dry conditions. EE was estimated from Vo_2 and Vco_2 using Weir's equation (14). The accuracy and precision of our IHC for measuring EE as determined by the alcohol combustion test was 99.8 ± 0.5% [mean ± standard deviation (SD)] in 6 hours and 99.4 ± 3.1% in 30 minutes. Sleeping metabolic rate was defined as the average EE over 8 hours of sleep. The PA ratio (PAR) was calculated as the EE during sitting, standing, housework, or walking periods divided by the sleeping metabolic rate.

Identification of the Types for PA

Minute-to-minute anterior-posterior (x-axis), mediolateral (y-axis), vertical (z-axis), and total (synthesized triaxes) accelerations were obtained from a triaxial accelerometer during four standardized periods (sitting, standing, housework, and walking on a treadmill, 2 × 30 minutes each activity). Twenty-eight of the 30 minutes of each structured period, which excluded the first and last minute of each session, were used for the analysis (i.e., 28 data points × two replicate sessions × 21 subjects = 1176 data points for four types of activity). One of the acceleration data for walking on a treadmill at 71 m/min was excluded for the analysis because the subject walked at a different speed. In addition, because the hip-fitted triaxial accelerometer could shift horizontally while the subject was in the IHC, anterior-posterior (x-axis) and mediolateral (y-axis) were synthesized as horizontal acceleration for the analysis. Optimal thresholds for classifying total acceleration and the ratio of vertical to horizontal acceleration into sitting, standing, housework, and walking were determined by receiver operating characteristic analysis, which is the standard approach to evaluate the sensitivity and specificity of test results. We adopted the acceleration for the highest product of sensitivity and specificity as optimal thresholds for each binary classification. Furthermore, the threshold of each activity was defined using only vertical acceleration.

Prediction and Validation of EE

The total accelerations from the different periods and the data's relationship to PAR obtained from the IHC allowed for the development of EE equations for four types of activity (sitting, standing, housework, and walking). The averaged value of minute-to-minute total acceleration for each activity was used for the analysis (i.e., one data point × 21 subjects = 21 data points for four types of activity), which corresponded to the 30-minute averaged PAR data obtained by IHC. The validation of the EE equations was tested on the residual time (10.5 hours). Initially, the minute-to-minute total acceleration for the residual time was classified into four types of activity using thresholds we developed. Subsequently, the PAR for each minute was predicted using a selected equation among four types of regression-based equations and/or constant value. The estimated EE for 1 minute was calculated as follows: the predicted PAR × the measured sleeping metabolic rate, which is a highly stable value in IHC. The estimated EE per 1 minute for the residual time (i.e., 630 minutes = 10.5 hours) was totaled. We investigated the validity of the equations by comparing the EE measured by IHC with the EE estimated using the developed equations. Similarly, in cases that only utilized vertical acceleration, the development and validation of equations were conducted.

Supplementary Experiment

To supplement the data of housework and walking, additional protocols that tested these activities were conducted using the same triaxial accelerometer and a portable gas analyzer (Metamax3B; CORTEX, Leipzig, Germany). Japanese adults (5 men and 7 women) 21 to 38 years old were recruited for the study. The measurement time was 4 minutes for housework (pull up weeds and sweep up) and 5 minutes for walking (walk in place and walk slowly). The relationship between the acceleration data (mG) from the different periods and PAR was tested.

Statistics

Statistical analyses were performed using SPSS for Windows (version 10.0; SPSS, Inc., Chicago, IL). All results are

Table 2. Minute-to-minute acceleration data for each activity

Activity	Acceleration (mG)			Vertical/ Horizontal
	Total	Horizontal	Vertical	
Sit	6.1 ± 8.5	3.5 ± 6.7	0.7 ± 2.3	0.05 ± 0.17
Stand	19.0 ± 20.8	13.0 ± 16.2	4.4 ± 7.3	0.18 ± 0.21
Housework	52.8 ± 31.6	37.5 ± 23.6	18.7 ± 14.0	0.44 ± 0.22
Walk	436.3 ± 107.7	261.2 ± 62.7	281.1 ± 87.3	1.08 ± 0.27

mG, milligausse.

presented as the mean ± SD. The relationship between two variables was evaluated by Pearson's and Spearman's correlation. The percentage difference was calculated as follows: [(predicted value − measured value)/measured value] × 100. Agreement of EE between the predicted and measured values was further examined by plotting the difference in predicted values against the mean with limits of agreement (mean difference ± 2 SD of the differences, which gives an indication of the precision of the method), as suggested by Bland and Altman (15). Differences were regarded as significant when the probabilities were <0.05.

Results

The physical characteristics of the subjects are shown in Table 1. In general, the mean values were comparable with those obtained in the National Nutrition Survey, although a slightly larger variation was observed for body weight among women. Means and SD of total, horizontal, and vertical acceleration and the ratio of vertical-to-horizontal acceleration for structured activities are listed in Table 2. Only the vertical-to-horizontal acceleration ratio for walking exceeded 1.00. The resulting receiver operating characteristic curve characterized the performance of a binary classification by describing the trade-off between sensitivity and specificity over an entire range of possible thresholds (Table 3). The thresholds for sitting vs. standing and standing vs. housework were classified by total acceleration. Because it is possible to combine the total acceleration between housework and walking activities, the threshold for housework vs. walking was determined by the vertical-to-horizontal acceleration ratio and 30 mG or more of total acceleration. Sensitivities and specificities were >75% for each combination of two activities, except for specificity of sitting vs. standing. Moreover, when classifying PA by the

Table 3. Threshold, sensitivity, and specificity (%) for each activity

Activity	Acceleration (mG)		Sensitivity (%)	Specificity (%)	
	Total	Vertical/ horizontal			
When using tri-axes acceleration:					
Sit	<7	<0.750	75.3	64.6	Sit vs. stand
Stand	8 to 29	<0.750	78.9	76.3	Stand vs. housework
Housework	>30	<0.750	95.9	94.5	Housework vs. walk
Walk	>30	>0.751			
When using vertical acceleration:					
Sit	<7				Sit vs. stand
Stand	<7		82.4	73.5	Stand vs. housework
Housework	8 to 99		99.8	99.5	Housework vs. walk
Walk	>100				

mG, milligausse.

Table 4. Prediction equation for each activity

Activity	PAR		
	Model	R^2	SEE
When using tri-axes acceleration:			
Sit	1.3786		
Stand	0.0093AC (mG) + 1.3566	0.66	0.05
Housework	0.0123AC (mG) + 1.7208	0.45	0.18
Walk	0.0081AC (mG) + 0.9234	0.72	0.32
When using vertical acceleration			
Sit	0.0329AC (mG) + 1.3846	0.51	0.02
Stand			
Housework	0.0333AC (mG) + 1.7316	0.60	0.13
Walk	0.0092AC (mG) + 1.8443	0.64	0.29

PAR, physical activity ratio; SEE, standard error of the estimate; AC, acceleration count; mG, milligausse.

threshold in the present study, the percentage of each classified PA was calculated during standardized periods of sitting (sitting, 75.3%; standing, 22.2%; housework, 2.5%; and walking, 0%), standing (sitting, 35.4%; standing, 43.5%; housework, 20.6%; and walking, 0.5%), housework (sitting, 8.2%; standing, 15.5%; housework, 72.4%; and walking, 3.8%), and walking (sitting, 0%; standing, 0.4%; housework, 5.1%; and walking, 94.4%). The same thresholds were also obtained by discriminant analysis. In contrast, when using vertical acceleration only, standing, housework, and walking activities were identified as accurately as total acceleration (sensitivity and specificity: standing vs. housework, 82% and 74%; housework vs. walking, 99% and 99%); however, it was not possible to distinguish between sitting and standing positions.

The averaged values of PAR were 1.38 ± 0.07 for sitting, 1.54 ± 0.18 for standing, 2.39 ± 0.27 for housework, and 4.34 ± 0.84 for walking, which corresponded to total acceleration values of 7.0 ± 2.9, 19.5 ± 14.7, 54.2 ± 14.6, and 426.0 ± 95.3 mG, respectively. Significant simple correlations were observed between PAR obtained by IHC and total acceleration obtained by triaxial accelerometry for standing, housework, and walking [$R^2 = 0.45$ to 0.72, $p < 0.01$, standard error of estimation (SEE) = 0.05 to 0.32] (Table 4, Figure 1A). Because PAR for sitting was not associated with total acceleration, the averaged value of PAR (i.e., 1.3786) was used for predicting EE. Thresholds between the activities and three equations, or a constant value, for each kind of activity to predict EE were applied to the residual time for validation. There was a strong correlation between the measured and predicted EE ($r = 0.94$, $p < 0.01$) (Figure 2), although the predicted EE (882 ± 150 kcal/10.5 hours) was slightly higher than the EE measured by IHC (846 ± 146 kcal/10.5 hours; 4.4 ± 6.2% difference) (Figure 3). The same analyses were also performed using only vertical acceleration. Three EE equations (1, sitting and standing; 2, housework; 3, walking) were developed using only vertical acceleration ($R^2 = 0.51$ to 0.64, $p < 0.01$, SEE = 0.02 to 0.29) (Table 4) but overestimated EE ($p < 0.01$) (981 ± 181 kcal/10.5 hours, 16.0 ± 10.0% difference).

In the supplemental experiment, the average values of PAR and total acceleration were, respectively, 3.22 and 91.8 mG in men ($n = 5$), and 3.12 and 85.3 mG in women ($n = 7$) for pulling up weeds and 3.12 and 106.4 mG in men and 3.16 and 117.6 mG in women for sweeping up, which were categorized as housework in our study (Figure 1B, open triangle). Similarly, the PAR and total acceleration were, respectively, 2.90 and 170.2 mG in men, and 2.84 and 188.2 mG in women for walking in place and 3.21 and 202.1 mG in men and 2.84 and 218.1 mG in women for walking slowly, which were categorized as walking (Figure 1B, closed rhombus).

Discussion

The major finding of this study is that we can accurately identify four different periods of activity (i.e., sitting, standing, housework, and walking) using total acceleration and the vertical-to-horizontal acceleration ratio obtained from a triaxial accelerometer under close-to-normal living conditions. When we used vertical accelerations only, it was not possible to distinguish between sitting and standing positions. In addition, the sensitivity and specificity between housework and walking using the vertical-to-horizontal acceleration ratio, which was our original method, was over 90%. A recent study found that the time allocated to sitting and standing was closely related to weight gain (2). Moreover, PA with upper body movement such as housework has a relatively high energy cost during daily living (4,7).

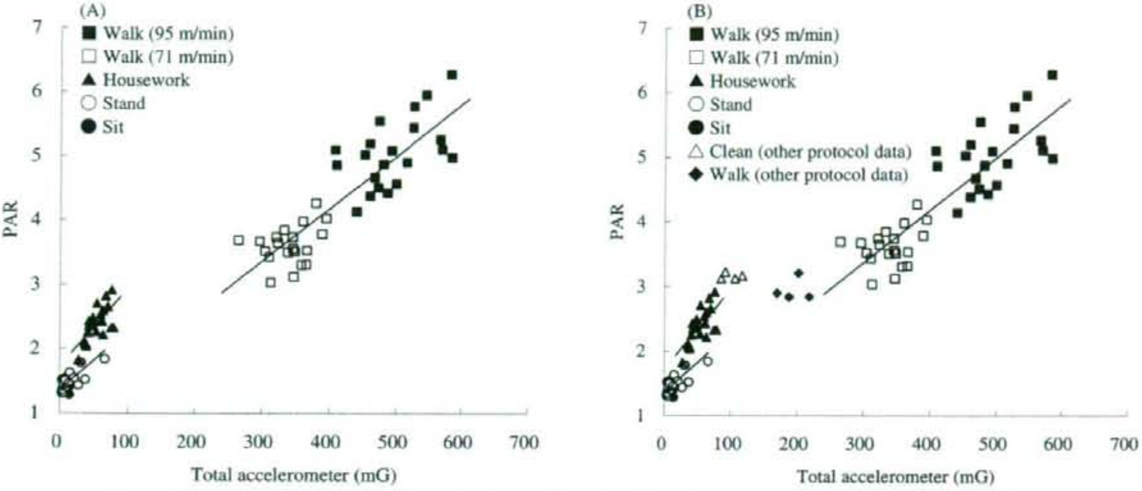

Figure 1: Relationship between total acceleration and PAR. Original data (A) with additional protocol data (B).

Therefore, the classification of daily lifestyle PA in our study could be a significant contribution to weight management, especially in the area of clinical practice.

Additionally, we found a high validation of predicting EE in low-intensity PA. Our results indicate that EE measured by chamber was closely correlated with EE estimated using the three equations and one constant value (percentage difference, 4.4%; correlation coefficient, 0.94; SEE, 61 kcal/10.5 hours). Although a previous study that estimated daily EE using triaxial accelerometry was limited, the percentage difference between EE measured by chamber and EE estimated by the developed non-linear model using Tritrac (triaxial accelerometer) was small (16). Moreover, Plasqui et al. (17) observed the relationship between total EE measured by the doubly labeled water technique for 15

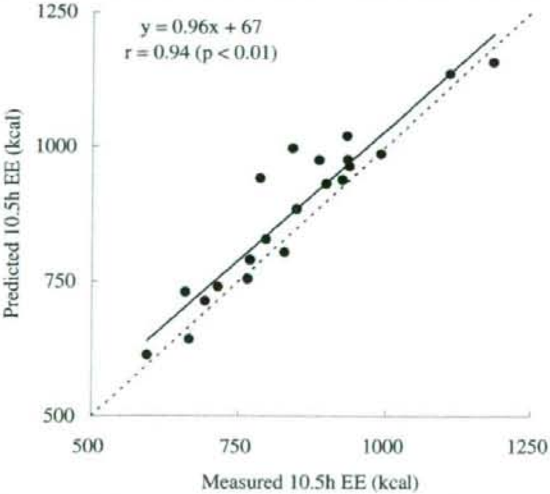

Figure 2: Relationship between measured and predicted 10.5-hour EE.

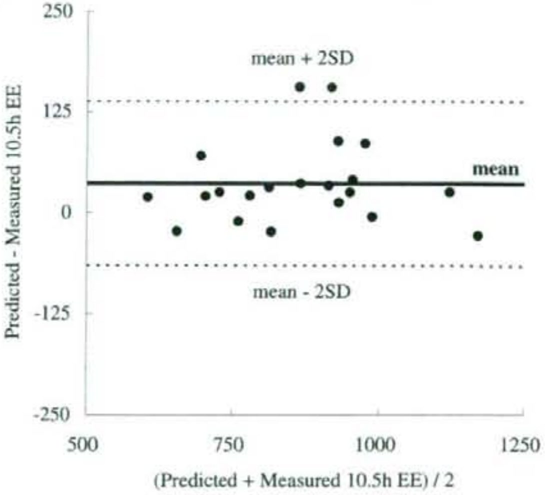

Figure 3: Bland and Altman analysis. The differences between measured and predicted 10.5-hour EE are plotted against the measured and predicted mean 10.5-hour EE.

consecutive days and the predicted EE using the equation of counts for Tracmor (triaxial accelerometer), age, weight, and height as parameters. These authors indicated that the correlation coefficient was 0.90, and SEE was 167 kcal/d between measured and predicted EE. Our study presents a novel method to objectively evaluate EE of low-intensity PA under close-to-normal living conditions using triaxial accelerometry that compares favorably with the previous study.

We believe that our highly accurate prediction of EE for low-intensity PA is due to the method used to develop each equation for standing, housework, and walking. A previous study reported that an equation based on the acceleration of walking underestimated EE of moderate-intensity lifestyle activities (7). Recently, Crouter et al. (18) found that the estimation of EE both in walking and lifestyle activity could be improved by the two regression lines. In the present study, if only one equation was developed from the relationship between total acceleration and PAR of all plots, including sitting, standing, housework, and walking [EE kcal = 0.0068 × acceleration count (mG) + 1.5509], the predicted EE of residual time (10.5 hours) would be overestimated (931 ± 155 kcal/10.5 hours, $p < 0.01$, 10.3 ± 5.2% difference). One possible explanation for this overestimation is that EE of static body posture such as sitting and standing may be overestimated by all plots included in the equation. Thus, the developed equations for each daily lifestyle PA are a novel method for predicting EE.

A previous study compared the ability to predict EE using uniaxial and triaxial accelerometry (7,19). The results indicated that triaxial accelerometry had higher accuracy of estimating EE than uniaxial accelerometry. However, as Plasqui et al. (17) pointed out, because two devices from different manufacturers were used, no conclusions can be drawn regarding the possible benefits of triaxial vs. uniaxial accelerometry. When Plasqui et al. (17) initially observed the contributions of vertical and horizontal acceleration to total EE per day adjusted for weight, height, and age, vertical acceleration explained an additional 16% of the variation in total EE. Furthermore, because horizontal acceleration contributed another 5%, it was concluded that triaxial accelerometers are more suitable than uniaxial accelerometers for estimating daily life activities. Similarly, the present study also compared the ability to quantitate low-intensity PA using either triaxial acceleration or only vertical acceleration from a triaxial accelerometer. Our results demonstrate that EE equations developed using only vertical acceleration overestimated EE by 135 kcal/10.5 hours. Further analysis of our data shows that there is no difference in EE for sitting and standing between equations using triaxial acceleration and only vertical acceleration (triaxial, 681 kcal/10.5 hours vs. uniaxial, 672 kcal/10.5 hours, $p = 0.06$), whereas the equation using only vertical acceleration overestimated the EE of housework periods by 109 kcal/10.5 hours (triaxial, 195 kcal/10.5 hours vs. uniaxial, 304 kcal/10.5 hours, $p < 0.01$). Therefore, we conclude that a triaxial accelerometer has a higher ability to predict EE of low-intensity PA, especially when the activity includes a large variation in horizontal acceleration, such as housework. Additionally, the technique of using not only total acceleration but also the vertical-to-horizontal acceleration ratio can be emphasized as a merit of the three-dimensional accelerometer.

There are some limitations of this study. The first limitation concerns the validity of the equations developed by comparing the EE measured by IHC with the EE estimated using developed equations for the residual time (i.e., 630 minutes = 10.5 hours). It is noted that this approach tends to overestimate the validity of the methods developed. We need to test the prediction equations of the present study in free-living conditions using the doubly labeled water method. The second limitation was that total acceleration data from 100 to 250 mG were blank during the chamber stay, although the relationship between PAR and total acceleration allowed for the development of EE equations for each activity. However, the plots describing the relationship between PAR and total acceleration for housework and walking in the supplemental experiment were likely to be an extension of the regression line, explaining this relationship in both activities in the present study. The results indicate that either of the equations for housework and walking can be applied to the range of 100 to 250 mG for total acceleration. Another limitation is that we did not develop an equation for cycling, which is a very popular lifestyle PA. Future studies should apply to all types of lifestyle activities. Lastly, the reason for the slight overestimation of the EE/10.5 hours in the present study should be clarified.

In conclusion, we identified low-intensity PA with high accuracy using total acceleration and the vertical-to-horizontal acceleration ratio obtained from a triaxial accelerometer. Notably, the use of the vertical-to-horizontal acceleration ratio is a novel method. Due to the classification of low-intensity PA, it is possible to accurately predict EE using equations for each activity. We demonstrated that triaxial accelerometry, when the total, vertical, and horizontal accelerations are utilized, can effectively evaluate different types of activities and estimate EE for low-intensity physical activities associated with modern lifestyles. In combination with measured or a highly accurately predicted sleeping metabolic rate (20), EE in sedentary lifestyle can be obtained.

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Twenty-four–hour analysis of elevated energy expenditure after physical activity in a metabolic chamber: models of daily total energy expenditure[1–3]

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ABSTRACT

Background: The Institute of Medicine proposed that 15% of energy expenditure (EE) as excess post-exercise oxygen consumption should be added to additional physical activity energy expenditure (ΔPAEE) to estimate total EE. However, the magnitude of elevated post–physical activity energy expenditure (EPEE) under normal daily living conditions has not been examined.

Objective: We examined the effects of EPEE on 24-h EE by modeling standard living conditions in a metabolic chamber.

Design: Eleven Japanese men completed three 24-h metabolic chamber measurements: a control day (C-day), a day with high-frequency moderate-intensity physical activity (M-day), and a day with high-frequency vigorous-intensity physical activity (V-day).

Results: Mean (± SD) 24-h EE for the C-day, the M-day, and the V-day was 2228 ± 143 kcal, 2816 ± 197 kcal, and 2813 ± 163 kcal, respectively. No significant difference was observed in 24-h EE between an M-day and a V-day. Mean EPEEs on the M-day and the V-day did not significantly contribute to increasing 24-h EE. Relative EPEEs to ΔPAEEs were 6.2 ± 13.9% (M-day) and 5.1 ± 9.2% (V-day). However, EPEE/24-h EE was negatively correlated with maximal oxygen uptake on the V-day ($r = -0.68$, $P = 0.02$), although no significant correlation between these variables was observed on the M-day ($r = -0.41$, $P = 0.21$).

Conclusions: These results suggest that EPEE has a small effect on 24-h EE in the course of normal daily activities, findings that do not support the proposition by the Institute of Medicine for estimating TEE. However, persons with low physical fitness levels could enhance EE as EPEE by increasing vigorous-intensity daily physical activity. *Am J Clin Nutr* 2008;87:1268–76.

INTRODUCTION

The prevalence of obesity has been increasing over the past few decades (1). The increase in weight or body fat is explained by a chronic imbalance between energy expenditure (EE) and energy intake. It is reported that regular exercise could play a major role in the control of body weight (2). Exercise (or physical activity) contributes to weight maintenance or weight reduction in several ways. First, thermogenesis is retained by maintaining fat-free mass. Second, EE is increased through exercise itself corresponding to work. Finally, increased EE may be induced by excess post-exercise oxygen consumption (EPOC) (3, 4).

EPOC is due to elevated oxygen consumption during the post-exercise period and consists of a rapid component and a prolonged component (5). The rapid component decays within approximately 1 h, followed by the prolonged component, which lasts for several hours. Many laboratories have examined the relation between exercise duration or intensity and the magnitude of EPOC (4, 6). According to Bahr and Sejersted (7), exercise intensity is curvilinearly related to EPOC. They suggested that exercise intensity must exceed 40% to 50% of maximal oxygen uptake ($\dot{V}O_{2max}$) to produce the prolonged component of EPOC, whereas 30% of $\dot{V}O_{2max}$ produces the rapid component of EPOC (7). Furthermore, it has been suggested that exercise duration has a linear relation to the magnitude of EPOC (8).

Physical activity thermogenesis can be divided into volitional exercise thermogenesis (sports and fitness-related activities) and nonexercise activity thermogenesis (9). It is generally accepted that obesity could be reduced through exercise or physical activity. That is, persons should increase total energy expenditure (TEE) by a range of physical activities including daily activities such as cleaning and gardening (10, 11). Levine et al (12) suggested that increasing nonexercise activity thermogenesis could be a strong contributor to preventing obesity. To support this proposition, it is important to verify the effects of additional EE after physical activity (elevated post–physical activity energy expenditure, or EPEE). There are no data on the effect of EPEE on 24-h EE under normal living conditions. Nevertheless, the Institute of Medicine proposed that 15% of EE as EPOC should be added to the additional physical activity energy expenditure (ΔPAEE) from sedentary conditions to estimate TEE, because adjustment for EPOC and dietary induced thermogenesis is expected to improve the underestimation of TEE by the factorial method compared with TEE measured by doubly labeled water (13, 14). Although it has been reported that these adjustments improved estimates of TEE (15, 16), they could be inappropriate

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for other studies in which TEE was not underestimated (17, 18). The purpose of this study was to examine the effects of EPEE on 24-h EE by modeling normal living conditions in a metabolic chamber.

SUBJECTS AND METHODS

Subjects

Eleven Japanese men participated in this study. All subjects were adults (≥20 y) and lacked chronic diseases that could affect metabolism or daily physical activity. They had not participated in regular intensive sports or physical activity for the past year but were able to complete a jogging regimen (8.0 km/h). The descriptive characteristics of the study subjects are presented in **Table 1**. Informed consent was signed by all subjects. The study protocol was approved by the Ethical Committee of the National Institute of Health and Nutrition.

Experimental design

Weight, height, and body composition were measured while the men were in a fasting state. Each subject completed a 24-h metabolic chamber measurement under 3 different protocols so that we could examine the effects of physical activity intensity: a control day (C-day); a day with high-frequency, moderate-intensity physical activity (M-day); and a day with high-frequency, vigorous-intensity physical activity (V-day). A test for peak oxygen uptake and metabolic chamber measurements were done at intervals of 2 to 3 d, but within 14 d to avoid metabolic influences from other protocols. We instructed the subjects to live under normal daily conditions during the measurement period (within 14 d) to maintain the same conditions, weight, and body composition for each measurement day. The order of the 3-d metabolic chamber measurements was randomly assigned to each subject.

Anthropometry and body composition

A digital scale was used to measure body weight to the nearest 0.1 kg while the subjects were dressed in light clothing. Barefoot standing height was measured to the nearest 0.1 cm by using a wall-mounted stadiometer. Body mass index was calculated as body weight (kg) divided by height squared (m^2).

Lean soft tissue mass, fat mass, and bone mineral content were measured by dual-energy X-ray absorptiometry (QDR-4500A scanner; Hologic, Waltham, MA). The subjects were positioned for whole-body scans according to the manufacturer's protocol. They lay in a supine position on the scanner table with their limbs close to their bodies. Fat-free mass was defined as the sum of lean soft tissue mass and bone mineral content.

TABLE 1

Physical characteristics of the subjects[1]

	$\bar{x}$ ± SD (range)
Age (y)	24.7 ± 5.8 (20–40)
Height (cm)	168.1 ± 3.9 (163.5–174.1)
Weight (kg)	64.5 ± 7.9 (50.6–74.0)
BMI (kg/m^2)	22.8 ± 2.8 (18.7–27.2)
Body fat (%)	16.4 ± 4.6 (10.3–22.8)
$\dot{V}O_{2peak}$ (L/min)	3.03 ± 0.57 (1.99–3.98)
$\dot{V}O_{2peak}$ (mL · min^{-1} · kg^{-1})	47.3 ± 8.3 (29.2–59.1)

[1] n = 11. $\dot{V}O_{2peak}$, peak oxygen uptake.

Peak oxygen uptake

Peak oxygen uptake ($\dot{V}O_{2peak}$) was measured by use of an incremental running test on a treadmill (TREAD-MILL; Nishikawa Iron Works, Kyoto, Japan). The subjects warmed up at 160, 180, or 200 m/min at a fixed 0° grade for 5 min. The treadmill speed increased at a rate of 10 m/min for each successive minute of running until fatigue, defined as the speed at which the subject could no longer continue to keep up with the treadmill. Heart rate and rating of perceived exertion were monitored continuously. The rating of perceived exertion was obtained by using the modified Borg scale (19). Oxygen uptake was measured over 30-s intervals after the rating of perceived exertion reached 15. Subjects breathed through a low-resistance 2-way valve, and the expired air was collected in Douglas bags. Expired oxygen and carbon dioxide gas concentrations were measured by mass spectrometry (ARCO-1000A; Arco System, Kashiwa, Japan), and gas volume was determined by using a certified dry gas meter (DC-5; Shinagawa, Tokyo, Japan). For each measurement, the gas analyzer was initially calibrated by using a certified gas mixture and atmospheric air. The highest value of $\dot{V}O_2$ during the exercise test was designated as $\dot{V}O_{2peak}$.

Metabolic chamber

An open-circuit indirect metabolic chamber was used to evaluate 24-h EE, basal metabolic rate (BMR), and sleeping metabolic rate (SMR) (20, 21). Briefly, the respiratory chamber was an airtight room (20 000 L) equipped with a bed, desk, chair, TV with video deck, CD player, telephone, toilet, sink, and treadmill. The temperature and relative humidity in the room were controlled at 25 °C and 55%, respectively. The oxygen and carbon dioxide concentrations of the air supply and exhaust were measured by mass spectrometry. For each experiment, the gas analyzer (ARCO-1000A-CH; Arco System, Kashiwa, Japan) was initially calibrated by using a certified gas mixture and atmospheric air. The flow rate exhausted from the chamber was measured by pneumotachography (FLB1; Arco System). The flow meter was calibrated before each measurement, and the flow rate was maintained at ≈90 L/min (ATP). $\dot{V}O_2$ and carbon dioxide production ($\dot{V}CO_2$) were determined by the flow rate of exhaust from the chamber, and the concentrations of the inlet and outlet air of the chamber, respectively (20). EE was estimated from $\dot{V}O_2$ and $\dot{V}CO_2$ by using Weir's equation (22). The accuracy and precision of our metabolic chamber for measuring EE as determined by the alcohol combustion test was 99.8 ± 0.5% (mean ± SD) over 6 h and 99.4 ± 3.1% over 30 min.

Spontaneous physical activity was evaluated by using a motion-detecting system. The chamber had 2 independent sensors of passive infrared type (Matsushita Automation Controls Co, Ltd, AMP2009B01, Tokyo, Japan) that detected movement at speeds >7 cm/s. When at least 1 sensor detected movement, the movement was regarded as positive. The system provided percentage of time when movement was observed in each minute, and averaged spontaneous physical activity over each 15-min interval was used for analyses.

Design for timetables in the metabolic chamber

Physical activity level (PAL), which is calculated as TEE divided by BMR, has been categorized by the Institute of Medicine as low active (average: 1.5; range: 1.4–1.59), active (average: 1.75; range: 1.6–1.89), and very active (average: 2.2; range: 1.9–2.49) (14). The 2005 Japanese Dietary Reference Intakes reported similar categorization (23). Therefore, C-day was designed to correspond to a PAL of 1.4–1.59 including reference physical activity. On the basis of the C-day, we modeled M-day and V-day as follows: *1*) comparable PAL between M-day and V-day for comparing with these EPEEs, 2) PALs to include the normal human range, and *3*) actual percentages of low-, moderate-, and vigorous-intensity physical activity encountered in daily living (24, 25).

In the present study, we sought to model normal daily living in the metabolic chamber. Daily living activities consist of various physical activities, such as cleaning, cooking, washing, and gardening. However, it is very difficult to prescribe daily physical activity strictly, as well as to continue them for extended periods of time. Therefore, daily physical activity was substituted as follows: slow walking [3.2 km/h, 2.5 metabolic equivalents (METs)] as low-intensity physical activity, brisk walking (5.6 km/h, 3.8 METs) as moderate-intensity activity, and jogging (8.0 km/h, 8.0 METs) as vigorous-intensity activity (26). Note that physical activities in the course of daily living are carried out at high frequencies, but are relatively short in duration. For that reason, each activity was limited to a period of 15 min, which is the minimum duration required by our instrument to measure EE with high accuracy.

The schedules in the metabolic chamber are shown in **Table 2**. The subjects entered the chamber at 1750 and stayed until 1805 the next day. Sampling data were collected between 1800 and

TABLE 2

Timetables for each modeling day in the metabolic chamber[1]

Time	C-day	M-day	V-day
1750	Entry into a room	Entry into a room	Entry into a room
1800	Sit quietly	Sit quietly	Sit quietly
1815		Walking (5.6 km/h)	Walking (5.6 km/h)
1830		Sit quietly	Sit quietly
1845	Dinner → Sit quietly	Dinner → Sit quietly	Dinner → Sit quietly
1930		Walking (5.6 km/h)	Walking (5.6 km/h)
1945		Sit quietly	Sit quietly
2000		Walking (5.6 km/h)	
2015		Sit quietly	
2100	Walking (3.2 km/h)	Walking (3.2 km/h)	Walking (3.2 km/h)
2130	Sit quietly	Sit quietly	Sit quietly
2215		Walking (5.6 km/h)	
2230		Sit quietly	
2245		Walking (5.6 km/h)	
2300		Sit quietly	
2400	Go to sleep	Go to sleep	Go to sleep
700	Get up → Basal metabolic rate	Get up → Basal metabolic rate	Get up → Basal metabolic rate
800	Sit quietly	Sit quietly	Sit quietly
815	Breakfast → Sit quietly	Breakfast → Sit quietly	Breakfast → Sit quietly
900		Walking (5.6 km/h)	Walking (5.6 km/h)
915		Sit quietly	Sit quietly
925	Stretching	Stretching	Stretching
930	Sit quietly	Walking (5.6 km/h)	Jogging (8.0 km/h)
945		Sit quietly	Sit quietly
1030	Walking (5.6 km/h)	Walking (5.6 km/h)	Walking (5.6 km/h)
1100	Sit quietly	Sit quietly	Sit quietly
1140	Stretching	Stretching	Stretching
1145	Sit quietly	Walking (5.6 km/h)	Jogging (8.0 km/h)
1200		Sit quietly	Sit quietly
1215		Walking (5.6 km/h)	
1230		Sit quietly	
1245	Lunch → Sit quietly	Lunch → Sit quietly	Lunch → Sit quietly
1355	Stretching	Stretching	Stretching
1400	Sit quietly	Walking (5.6 km/h)	Jogging (8.0 km/h)
1415		Sit quietly	Sit quietly
1455	Stretching	Stretching	Stretching
1500	Jogging (8.0 km/h)	Jogging (8.0 km/h)	Jogging (8.0 km/h)
1515	Sit quietly	Sit quietly	Sit quietly
1600		Walking (5.6 km/h)	Walking (5.6 km/h)
1615		Sit quietly	Sit quietly
1805	Exit from a room	Exit from a room	Exit from a room

[1] C-day, a control day; M-day; a day with high-frequency, moderate-intensity physical activity; V-day, a day with high-frequency, vigorous-intensity physical activity.

1800 (24 h). The subjects went to bed at 2400 and were gently awakened at 0700 (7 h). The mean metabolic rate during this period was used as the SMR. After getting up, the subjects were permitted to use the toilet and were required to return to bed immediately. Then, the subjects remained in a supine position without movement until 0800. BMR was determined as the mean metabolic rate between 0715 and 0800. Except for prescribed physical activity and using the toilet, the subjects were only permitted to carry out light activities in a sitting position, such as reading, writing, and viewing television. Sleeping was not permitted. Meals were given 3 times a day to provide the predicted BMR (23) multiplied by the estimated PAL of 1.75, as an intermediate value for C-day and M-day (or V-day) modeling. Ratios of protein to fat to carbohydrate in total energy intake per day were 18:20:62. The same meals were provided on each of the 3 d to unify dietary induced thermogenesis.

Calculation of elevated post–physical activity energy expenditure

We estimated EPEE on the M-day and the V-day as measured 24-h EE minus predicted 24-h EE without EPEE. Predicted 24-h EE without EPEE was obtained from a model based on the C-day with use of the factorial method (**Figure 1**). That is, 24-h EE without EPEE for M-day and V-day was predicted by the 24-h EE for the C-day plus the reference EE for brisk walking and jogging. The reference EEs for brisk walking (5.6 km/h) and jogging in this model were calculated from each activity during C-day. To calculate steady state values for EE for these activities, EE values for the first 3 min and the last 1 min during the 2 reference activities were removed, and mean EE in the remainder was extended to 15 min (27, 28). Furthermore, for comparing with relative EE as EPOC to additional physical activity energy expenditure (ΔPAEE) in the US and Canada DRI equation, ΔPAEE was calculated as the predicted 24-h EE without EPEE on the M-day or V-day minus the 24-h EE for the C-day.

Statistical analysis

We performed a power calculation ($\alpha = 0.05$ and $\beta = 0.80$) to determine whether the EPEE value corresponded to 15% of ΔPAEE, which was ≈100 kcal in our subjects. Data from previous observations showed that the SD for the 24-h EE measurement in our metabolic chamber is ≈75 kcal. From this power

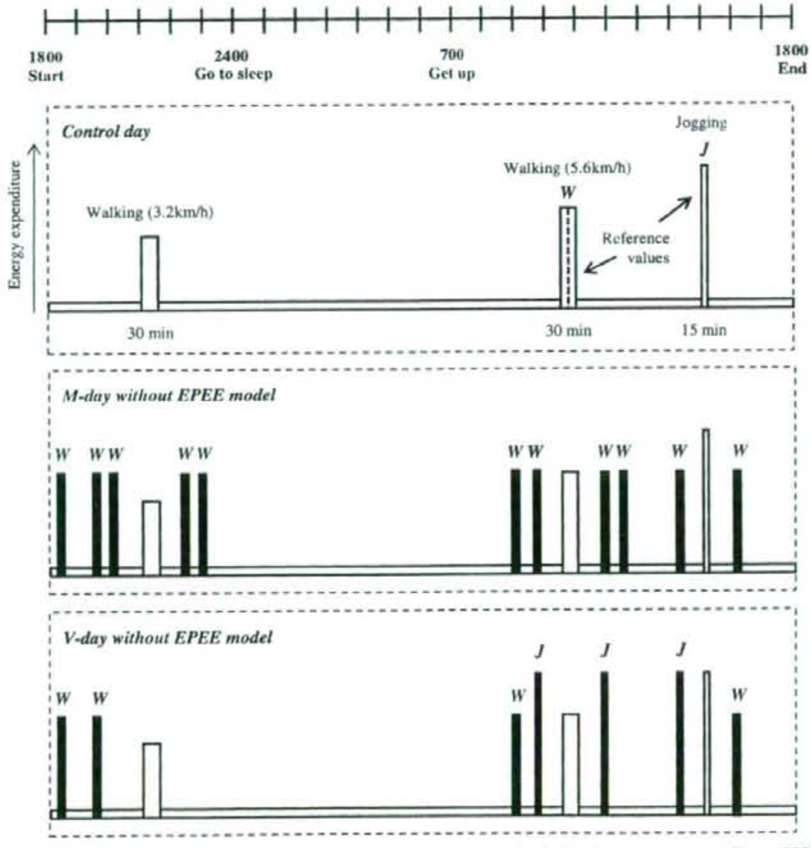

FIGURE 1. Model for predicting 24-h energy expenditure (EE) without elevated post–physical activity energy expenditure (EPEE). M-day, a day with high-frequency, moderate-intensity physical activity; V-day, a day with high-frequency, vigorous-intensity physical activity; W, reference energy expenditure for walking (5.6 km/h); J, reference energy expenditure for jogging; empty bar, actual energy expenditure by the prescribed physical activity for each day; filled bar, reference energy expenditure for brisk walking (5.6 km/h) or jogging.