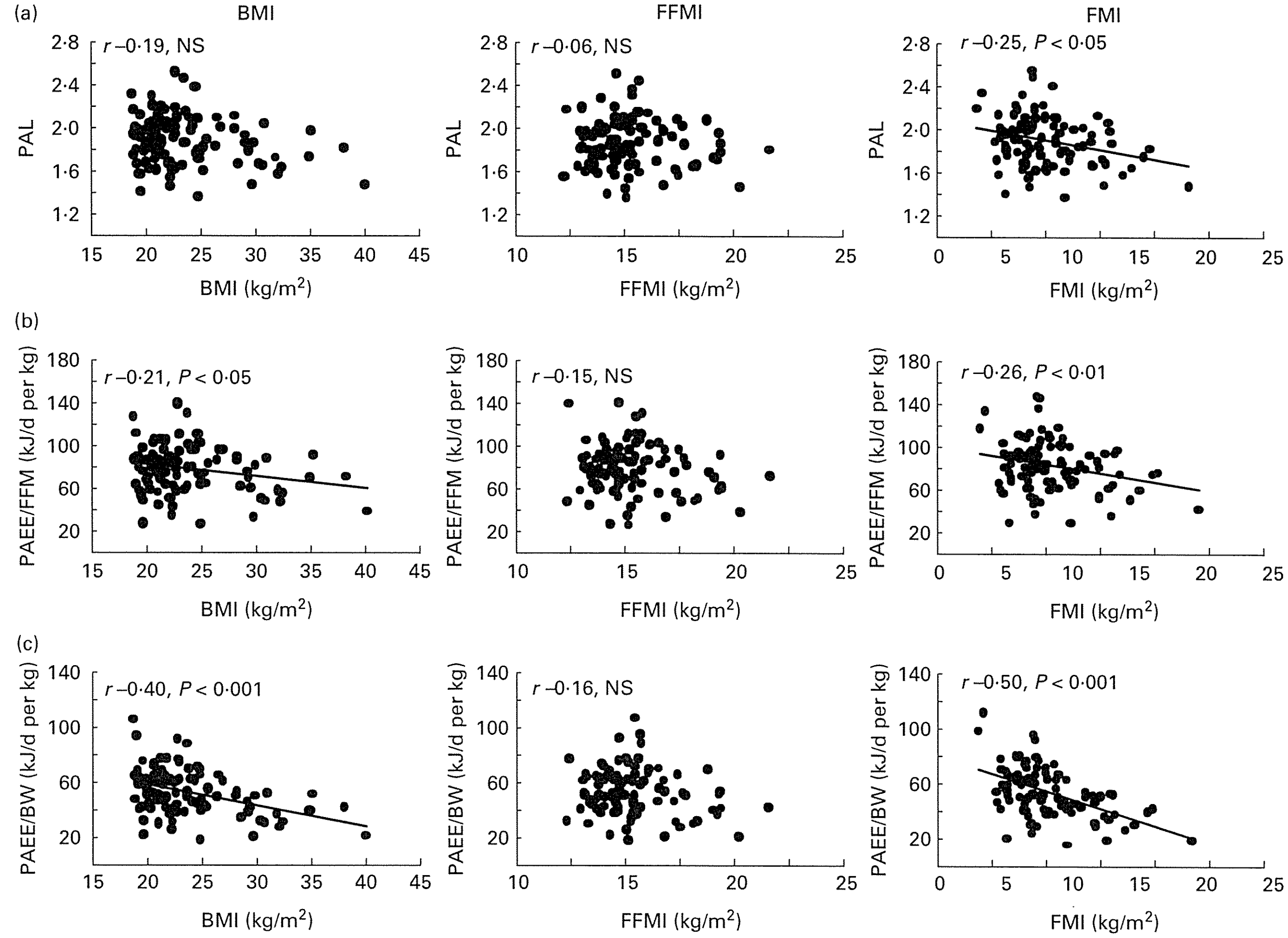

Fig. 2. Relationships between BMI, fat-free mass index (FFMI) or fat mass index (FMI) and physical activity level (PAL) (a), physical activity-related energy expenditure/fat-free mass (PAEE/FFM) (b) or PAEE/body weight (BW) (c). PAL = TEE/BMR, where TEE is total energy expenditure; PAEE = 0·9TEE − BMR; FMI was negatively associated with all physical activity variables obtained by the doubly-labelled water method.

negatively associated with BMI and FMI, but not with FFMI (Fig. 2).

In the accelerometry data, the step counts decreased in the 4th quartile of FMI (Table 3) and %BF (Table 4), whereas there was no difference among quartiles of BMI (Table 1) and FFMI (Table 2). Time spent on moderate- or vigorous-intensity activity decreased in the 4th quartile of FMI, whereas it did not differ among quartiles of BMI, FFMI and %BF. Time spent on light-intensity activity did not differ among quartiles of BMI, FFMI, FMI and %BF.

Discussion

The principal finding in the present study was that only PAEE/FFM and PAEE/BW assessed by the DLW method decreased among women in the highest quartile of BMI. On the other hand, women in the highest quartiles of FMI and %BF obviously had a low level of physical activities assessed by both the DLW method and accelerometer. Particularly, women in the 3rd quartile of FMI or %BF had lower PAEE/BW even though their BMI was below 25 kg/m^2.

The average PAL of 1·88 in the participants of the present study was a little higher than that of 1·75 in the general population of Eastern or Western countries(7,16,23,24). The average BMR in the present data was 88·3 kJ/d per kg BW for normal-weight women (BMI $<$ 25 kg/m^2) and 76·2 kJ/d per kg BW for overweight women (BMI $\geq$ 25 kg/m^2). These values were close to the average BMR of 88·8 kJ/d per kg BW for Japanese normal-weight adult women(25) and 74·9 kJ/d per kg BW in Japanese overweight adult women(19). Moreover, the range of PAL in the present study was 1·36–2·52, which is within the PAL of the general population(26). The average daily steps of about 8500 for participants in the present study were also comparatively higher than the daily steps for Japanese adults women, who generally walk an average of 7215 steps/d(27).

The lack of a significant difference in PAL among BMI quartiles in the present study is consistent with most previous studies(4–6). In contrast, Tooze *et al.*(28) demonstrated that PAL was lower in obese women (BMI $\geq$ 30 kg/m^2) than in normal-weight women (BMI $<$ 25 kg/m^2). However, they used an estimated RMR, but not a measured rate, so some errors in estimating PAL may be induced by the

Table 5. Concordance of classification between BMI and fat mass index (FMI) or percentage body fat (%BF)
(Percentages and number of subjects)

	FMI								%BF							
Quartile*...	1st		2nd		3rd		4th		1st		2nd		3rd		4th	
BMI quartile	%	*n*	%	*n*	%	*n*	%	*n*	%	*n*	%	*n*	%	*n*	%	*n*
1st (lowest)	68	17	32	8	0	0	0	0	60	15	28	7	12	3	0	0
2nd	28	7	44	11	28	7	0	0	36	9	32	8	32	8	0	0
3rd	4	1	24	6	56	14	16	4	4	1	32	8	40	10	24	6
4th (highest)	0	0	0	0	16	4	84	21	0	0	8	2	16	4	76	19

* There are twenty-five subjects in each quartile.

different accuracy of estimated RMR between lean and obese participants(19).

Only PAEE/FFM and PAEE/BW decreased among women in the highest quartiles of BMI, whereas not only PAEE/FFM and PAEE/BW but also PAL apparently decreased in the highest quartile of FMI and %BF. Based on the results of the concordance of classification between BMI and FMI or %BF, most participants with a higher BMI have higher FM as well (Table 5). Thus, women in the highest quartile of BMI might be less active on the basis of PAEE when adjusting for body size. Contrary to the results of the present study, Snodgrass *et al.*(29) reported that PAEE/BW was not different between lean and overweight women. However, lean and normal-weight women in their study had much lower PAL (1·43 (SD 0·21)) and two of the seven women were underweight (BMI < 18·5 kg/m^2).

In contrast to the results of the decrease in PAEE/FFM and PAEE/BW among women in the highest quartile of BMI, there were no differences in PAEE/FFM and PAEE/BW among normal-weight women in the 1st to 3rd quartiles of BMI. Among participants in the 3rd quartile of BMI, the proportion of participants who are included in the 3rd quartile of FMI was only about half and the remaining spread to the other quartiles of FMI (Table 5). This phenomenon was similar to that of participants in the 2nd quartile of BMI. Thus, there appears to be a considerably large interindividual variability, especially for PAEE/FFM in normal-weight women who have a different distribution of FFM and FM at the same BMI.

The present study showed that TEE/BW was correlated with BMI, FMI or % BF. However, the overcorrection of TEE when adjusted by BW should be cautiously interpreted, because BMR accounts for approximately 60 % of TEE in an individual with a PAL of 1·75. On the other hand, in PAEE, which is not influenced by BMR, someone with a larger body mass needs more energy for an activity than someone with a smaller body mass. Thus, PAEE/BW may well reflect lower physical activity among women in the highest quartile of BMI. However, we could not exclude the possibility that PAEE/BW might be also adjusted excessively because there was a great difference in BW and FM between the 3rd and 4th quartile of BMI in the present study. However, among quartiles of FMI and %BF, PAEE/BW was lower in the 3rd quartile than in the 1st or 2nd quartile, although it was not a great difference in BW between the 3rd quartile and the 1st or 2nd quartile. Therefore, lower PAEE/BW could well reflect the status of lower physical activity in women with higher BMI, especially with higher fat deposition, when FMI or %BF was effectively used.

Schulz *et al.*(7) reported a high correlation between PAEE/BW and %BF in healthy adult women, thereby providing support for our data that PAEE/BW decreased from the 3rd quartiles of FMI and %BF. Thus, PAEE/BW could be useful to understand daily physical activity, especially in normal-weight women with higher fat deposition.

Step counts and the duration of physical activity of moderate or vigorous intensity assessed by accelerometry apparently decreased in the highest quartile of FMI, but not among quartiles of BMI and FFMI. Contrary to the present results of no difference in step counts and moderate or vigorous intensity among BMI quartiles, Levine *et al.*(30) reported that the allocation of standing and ambulating during the day was lower in obese subjects than in lean subjects when using BMI cut-points. This discrepancy may be due to the different range of PAL among populations. Levine *et al.*(30) recruited both lean and obese individuals from among ‘couch potato’ subjects, all of whom were sedentary. The populations of the present study were free-living Japanese adult women with a wide PAL range from sedentary to active.

In a longitudinal study using the DLW method in adult women, Schoeller *et al.*(31) demonstrated that increases in weight were lower in active women with a PAL above 1·75. The present study did not attempt to determine a threshold of daily physical activity that is required to have a normal FMI, %BF or BMI due to the limited number of study subjects and the proportion of obese individuals in the present dataset. Another reason was that there were no definite cut-offs for FMI and %BF. Because the present study apparently showed a good relationship between FM (FMI or %BF) and various physical activities, further study is warranted to examine the threshold of daily physical activity that is required to suppress fat accumulation.

The BMI cut-off point is used as the standard for a classification of obesity. On the other hand, Bigaard *et al.* suggested that FMI was also an independent predictor of all-cause mortality in their epidemiological study(32). They revealed that an excess of approximately 10 kg/m^2 of FMI value was associated with considerably increased mortality. The present study showed that Japanese adult women with an average FMI of 12·6 kg/m^2 were less active than those with a below-average FMI of 8·6 kg/m^2. Therefore, we consider that an increase in

PAL may decrease FMI, leading to a decrease in risk of all-cause mortality.

The present study has the following limitations: first, the FFM hydration was assumed as 0·732 for all participants equally(14), so some errors in estimating FFM may be induced by the different levels of obesity. Second, the present results were drawn from a cross-sectional design. Therefore, we were not able to infer a cause–effect relationship between an inactive lifestyle and obesity. Observational or intervention studies with longitudinal design are needed to evaluate the effect of inactivity on the development of obesity for adult women. However, the main purpose of the present study was to investigate the relationship between daily physical activity and body size or body composition. Moreover, the present study provided the results only for Japanese adult women, but not for men or children.

In conclusion, Japanese adult women with larger BMI had lower PAEE adjusted by FFM or BW. Especially, Japanese adult women with higher fat deposition were apparently less active, on the basis of not only PAEE but also the physical activity of moderate or vigorous intensity. The present data suggest that the relationship between obesity and daily physical activities should be discussed using not only BMI but also FMI or %BF.

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SHORT COMMUNICATION

Relation between cigarette smoking and ventilatory threshold in the Japanese

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Abstract The link between cigarette smoking and ventilatory threshold (VT) was investigated. We used data for 407 men and 418 women not taking medication. Habits of cigarette smoking were obtained through interviews by well-trained staff. The influence of cigarette smoking on oxygen uptake, work rate, and heart rate at VT was evaluated. Oxygen uptake at VT in women and work rate at VT in men with cigarette smoking were significantly lower than in subjects without cigarette smoking after adjusting for age. The differences of parameters at VT did not reach significant levels after adjusting for age and exercise habits in both sexes. However, in women without exercise habits, there was significant difference of oxygen uptake at VT between women with and without cigarette smoking after adjusting for age [cigarette smoking (+): 11.5 ± 1.8 ml/kg/min, cigarette smoking (−): 12.4 ± 2.1 ml/kg/min, $p = 0.0006$]. The number of cigarettes smoked per day and the Brinkman Index were not clearly correlated with oxygen uptake at VT. A combination of promoting exercise habits and prohibiting cigarette smoking might be recommended for improving the aerobic exercise level, especially in women.

Keywords Cigarette smoking · Ventilatory threshold · Oxygen uptake · Exercise habits

Introduction

Cigarette smoking has become an important public health challenge, and it has been reported that 39.4% of men and 11.0% of women are current smokers in Japan [1]. Cigarette smoking is also a strong risk factor for atherosclerosis and cardiovascular disease in a dose-dependent manner [2].

Exercise is considered as a useful method for preventing and improving atherosclerosis and cardiovascular disease. The ventilatory threshold (VT) is defined as the upper limit of aerobic exercise and is thought to serve as an accurate and reliable standard for exercise prescription [3]. Since the exercise intensity at VT is not harmful to cardiovascular function, it can be safely applied to patients with myocardial infarction as an exercise prescription [4]. We have previously reported that aerobic exercise level was significantly lower in subjects with metabolic syndrome than that in subjects without the syndrome [5], and the prevalence of metabolic syndrome was significantly higher in subjects with cigarette smoking than that in subjects without cigarette smoking [6]. However, the relationship between cigarette smoking and aerobic exercise level defined by VT is not fully discussed.

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The aim of this study is to explore the link between cigarette smoking and VT in the Japanese population.

Subjects and methods

Subjects

We used data for 407 Japanese men (aged 42.1 ± 11.4 years) and 418 women (aged 44.8 ± 12.0 years) (5.8%), retrospectively from a database of 14,345 subjects who met the following criteria: they had (1) wanted to change their lifestyle, i.e., diet and exercise habits, and had received an annual health checkup from June 1997 to May 2007 at Okayama Southern Institute of Health, (2) they had received anthropometric and oxygen uptake at VT measurements and evaluation of cigarette smoking as part of the annual health checkup, (3) received no medications for diabetes, hypertension, and/or dyslipidemia, and (4) provided written informed consent (Table 1).

Ethical approval for the study was obtained from the Ethical Committee of Okayama Health Foundation.

Anthropometric measurements

Anthropometric and body compositions were evaluated based on the following parameters: height, body weight, abdominal circumference, and hip circumference. Abdominal circumference was measured at the umbilical level, and the hip was measured at the widest circumference over the trochanter in standing subjects after normal exhalation [7].

Cigarette smoking

The data on cigarette smoking were obtained at interviews by well-trained staff in a structured way. The subjects were asked if they currently smoked cigarettes. When the answer was "yes," they were classified as current smokers and further questions were asked regarding the average number of cigarettes smoked per day and their age at starting smoking. When the answer was "no," they were classified as nonsmokers.

Based on answers to those questions, the cumulative amount of cigarette consumption expressed as the Brinkman Index (BI: number of cigarettes consumed per day multiplied by years of smoking) [8].

Table 1 Clinical profiles of enrolled subjects

	Mean ± SD	
	Men	Women
Number of subjects	407	418
Age (years)	42.1 ± 11.4	44.8 ± 12.0
Height (cm)	169.9 ± 5.8	156.0 ± 5.5
Body weight (kg)	79.1 ± 13.3	65.0 ± 12.9
Abdominal circumference (cm)	91.1 ± 10.9	81.4 ± 11.2
Hip circumference (cm)	98.6 ± 6.8	96.7 ± 8.5
Oxygen uptake at ventilatory threshold (ml/kg/min)	14.9 ± 3.9	12.6 ± 2.5
Work rate at ventilatory threshold (W)	82.9 ± 24.4	51.3 ± 14.6
Heart rate at ventilatory threshold (beats/min)	106.0 ± 11.9	107.0 ± 11.8

Exercise testing

A graded ergometer exercise protocol [9] was performed. Two hours after breakfast, a resting electrocardiogram (ECG) was recorded and blood pressure was measured. Then, all participants were given graded exercise after 3 min of pedaling on a bicycle ergometer at zero load (Excalibur V2.0; Lode BV, Groningen, The Netherlands). The profile of incremental workloads was automatically defined using the methods of Jones et al. [9], in which the workloads reach the predicted $\dot{V}O_{2\,\max}$ in 10 min. A pedaling cycle rate of 60 rpm was maintained. Loading was terminated when the appearance of symptoms forced the subject to stop. During the test, ECG was monitored continuously together with recording of heart rate (HR). Exhaled gas was collected, and rates of oxygen consumption $\dot{V}O_2$ and carbon dioxide production ($\dot{V}CO_2$) were measured breath by breath using a cardiopulmonary gas exchange system (Oxycon Alpha; Mijnhrdt b.v., The Netherlands). VT was determined by the standard of Wasserman et al. [3], Davis et al. [10], and the V-slope method of Beaver [11] from $\dot{V}O_2$, $\dot{V}CO_2$, and minute ventilation ($\dot{V}E$). At VT, $\dot{V}CO_2$ (ml/kg/min), work rate (W), and heart rate (beats/min) were measured and recorded.

Exercise habits

The data on exercise habits were obtained through interviews by well-trained staff in a structured way according to the National Nutrition Survey in Japan [12]. The subjects were asked if they currently exercise (over the level of 30 min per session, two times per week, and prolonged duration for 3 months). When the answer was "yes," they were classified as subjects with exercise habits. When the answer was "no," they were classified as subjects without exercise habits.

Statistical analysis

All data are expressed as mean ± standard deviation (SD). Statistical analysis was performed using an unpaired *t* test, χ^2 test, logistic regression analysis, covariance analysis, one-way analysis of variance (ANOVA), and Scheffe's F test, where $p < 0.05$ was considered to be statistically significant. We used the unpaired t test to compare parameters between subjects with and without cigarette smoking; the χ^2 test was used to evaluate the relationship between cigarette smoking and exercise habits. Logistic regression analysis and covariance analysis were also used to adjust for parameters. ANOVA and Scheffe's F test were used to compare among subjects with and without cigarette smoking and exercise habits. Pearson's correlation coefficients were calculated and used to test the significance of the linear relationship between oxygen uptake at VT and the number of cigarette smoked per day, the BI.

Results

The results of age and parameters at VT in subjects with and without cigarette smoking are presented in Table 2. A total of 166 men (40.8%) and 46 women (11.0%) were current smokers. In men, there was no significant difference of age between subjects with and without cigarette smoking. Oxygen uptake and work rate at VT in subjects with cigarette smoking were significantly lower than those in subjects without cigarette smoking. However, in women, age in subjects with cigarette smoking was significantly lower than that in subjects without cigarette smoking. Therefore, to avoid the influence of age on parameters at VT, we used age as a covariate and compared parameters at VT using covariance analysis. Oxygen uptake in women and work rate at VT in men with cigarette smoking were significantly lower than in subjects without cigarette smoking even after adjusting for age (Table 2).

It is well known that aerobic exercise level is closely linked to exercise habits [5]. We evaluated the relationship between cigarette smoking and exercise habits (Table 3). A total of 164 men (40.3%) and 105 women (25.1%) were defined as having exercise habits. In men, the prevalence of subjects with cigarette smoking was significantly lower in subjects with exercise habits than that in subjects without exercise habits (Table 3). However, no significant difference in the prevalence of cigarette smoking in subjects with and without exercise habits was noted in women.

To avoid the influence of age and exercise habits on cigarette smoking, we used age, exercise habits, and parameters of VT as explanatory variables, and cigarette smoking as a response variable. No significant differences of parameters at VT in subjects with and without cigarette

Table 2 Comparison of parameters at ventilatory threshold between subjects with and without cigarette smoking

	Mean ± SD		p	p (after adjusting for age)	p (after adjusting for age and exercise habits)
	Cigarette smoking (+)	Cigarette smoking (−)			
Men					
Number of subjects	166	241			
Age (years)	41.8 ± 11.0	42.4 ± 11.7	0.5803		
Oxygen uptake at ventilatory threshold (ml/kg/min)	14.3 ± 3.1	15.3 ± 4.4	**0.0193**	0.0595	0.1156
Work rate at ventilatory threshold (W)	79.8 ± 20.7	85.0 ± 26.5	**0.0333**	**0.0377**	0.0764
Heart rate at ventilatory threshold (beats/min)	105.5 ± 11.0	106.3 ± 12.5	0.4683	0.9970	0.1839
Women					
Number of subjects	46	372			
Age (years)	39.6 ± 12.9	45.4 ± 11.8	**0.0019**		
Oxygen uptake at ventilatory threshold (ml/kg/min)	12.0 ± 2.8	12.7 ± 2.4	0.1011	**0.0120**	0.0514
Work rate at ventilatory threshold (W)	52.9 ± 18.1	51.1 ± 14.1	0.4092	0.6883	0.6414
Heart rate at ventilatory threshold (beats/min)	106.2 ± 11.4	107.1 ± 11.9	0.6136	0.2680	0.0881

Table 3 Relationship between cigarette smoking and exercise habits

	Exercise habits (+)	Exercise habits (−)	p	p (after adjusting for age)
Men				
Cigarette smoking (+)	52	114	**0.0022**	**0.0024**
Cigarette smoking (−)	112	129		
Women				
Cigarette smoking (+)	8	38	0.2002	0.5304
Cigarette smoking (−)	97	275		

smoking were noted after adjusting for age and exercise habits in both sexes (Table 2). We separately compared oxygen uptake at VT in subjects without exercise habits. After adjusting for age, no significant difference of oxygen uptake at VT was noted between men with and without cigarette smoking [cigarette smoking (+): 13.8 ± 2.6 ml/kg/min, cigarette smoking (−): 13.8 ± 2.5 ml/kg/min, $p = 0.4089$]. However, there was significant difference of oxygen uptake at VT between women with and without cigarette smoking [cigarette smoking (+): 11.5 ± 1.8 ml/kg/min, cigarette smoking (−): 12.4 ± 2.1 ml/kg/min, $p = 0.0006$].

In addition, we compared the parameters of VT among subjects with and without cigarette smoking and exercise habits [A: cigarette smoking (+) exercise habits (+), B: cigarette smoking (−) exercise habits (+), C: cigarette smoking (+) exercise habits (−), D: cigarette smoking (−) exercise habits (−)] (Table 4). In men, oxygen uptake at VT in group C and D was significantly lower than that in group A and B. Work rate at VT in group C and D was significantly lower than that in group B. No significant differences of heart rate were not noted among the four groups. In women, oxygen uptake at VT in group C was significantly lower than that in group A and B. Work rate at VT in group A was significantly higher than that in group B, C, and D. Heart rate at VT in group D was significantly higher than that in group B. Oxygen uptake at VT in group A and B (with exercise habits) was higher than that in group C and D (without exercise habits) in both sexes, as in our previous report [5].

Finally, we evaluated the relationship between the number of cigarettes smoked per day and oxygen uptake at VT, and also between the BI and oxygen uptake at VT (Fig. 1). The number of cigarettes smoked per day was not correlated with oxygen uptake at VT in either sex (men $r = -0.172$, $p = 0.0265$; women $r = -0.294$, $p = 0.0470$). BI was also not clearly correlated with oxygen uptake at VT (men $r = -0.192$, $p = 0.0132$; women $r = -0.214$, $p = 0.1535$). In subjects without exercise habits, the number of cigarettes smoked per day was not correlated with oxygen uptake at VT in either sex (men $r = -0.072, p = 0.4487$; women $r = -0.180, p = 0.2791$). BI was also not clearly correlated with oxygen uptake at VT (men $r = -0.135$, $p = 0.1515$; women $r = -0.088$, $p = 0.5976$).

Discussion

Impairment of pulmonary oxygen exchange [13, 14], downregulation of adrenergic receptors [15], and long-term cardiac damage caused by stimulation of catecholamine by smoking [16] may also in part explain lower oxygen uptake at VT in subjects with cigarette smoking. Some cross-sectional studies show that cigarette smoking is correlated with cardiovascular fitness [17–19]. Hirsch et al. [17] evaluated the immediate effects of cigarette smoking on aerobic exercise capacity, and cigarette smoking resulted in a significantly lower $\dot{V}O_{2\max}$ and higher heart rate after 3 cigarettes/h for 5 h. Marti et al. [18] reported that, among army conscripts, the distance covered in a 12-min endurance run was inversely related to daily cigarette consumption and years of smoking. Rotstein et al. [19] also reported that smoking retards physiological responses to submaximal exercise immediately after smoking three cigarettes. In a longitudinal analysis, Sandvik et al. [20] showed that decline in physical fitness and lung function was greater among smokers than that among nonsmokers

Table 4 Comparison of parameters at ventilatory threshold among subjects with and without cigarette smoking and exercise habits

	A Cigarette smoking (+) Exercise habits (+)	B Cigarette smoking (−) Exercise habits (+)	C Cigarette smoking (+) Exercise habits (−)	D Cigarette smoking (−) Exercise habits (−)
Men				
Number of subjects	52	112	114	129
Oxygen uptake at ventilatory threshold (ml/kg/min)	15.6 ± 3.7	16.9 ± 5.4	13.8 ± 2.6^{ab}	13.8 ± 2.5^{ab}
Work rate at ventilatory threshold (W)	84.8 ± 25.2	92.5 ± 31.8	77.5 ± 18.0^{b}	78.6 ± 18.8^{b}
Heart rate at ventilatory threshold (beats/min)	103.8 ± 12.2	104.7 ± 13.3	106.2 ± 10.3	107.7 ± 11.6
Women				
Number of subjects	8	97	38	275
Oxygen uptake at ventilatory threshold (ml/kg/min)	14.4 ± 5.0	13.2 ± 3.3	11.5 ± 1.8^{ab}	12.4 ± 2.1
Work rate at ventilatory threshold (W)	70.0 ± 27.0	53.2 ± 17.3^{a}	49.3±13.5^{a}	50.3 ± 12.8^{a}
Heart rate at ventilatory threshold (beats/min)	105.6 ± 13.3	104.1 ± 12.0	106.3±11.2	108.2 ± 11.7^{b}

Mean ± SD

[a] $p < 0.05$ versus cigarette smoking (+), exercise habits (+)

[b] $p < 0.05$ versus cigarette smoking (−), exercise habits (+)

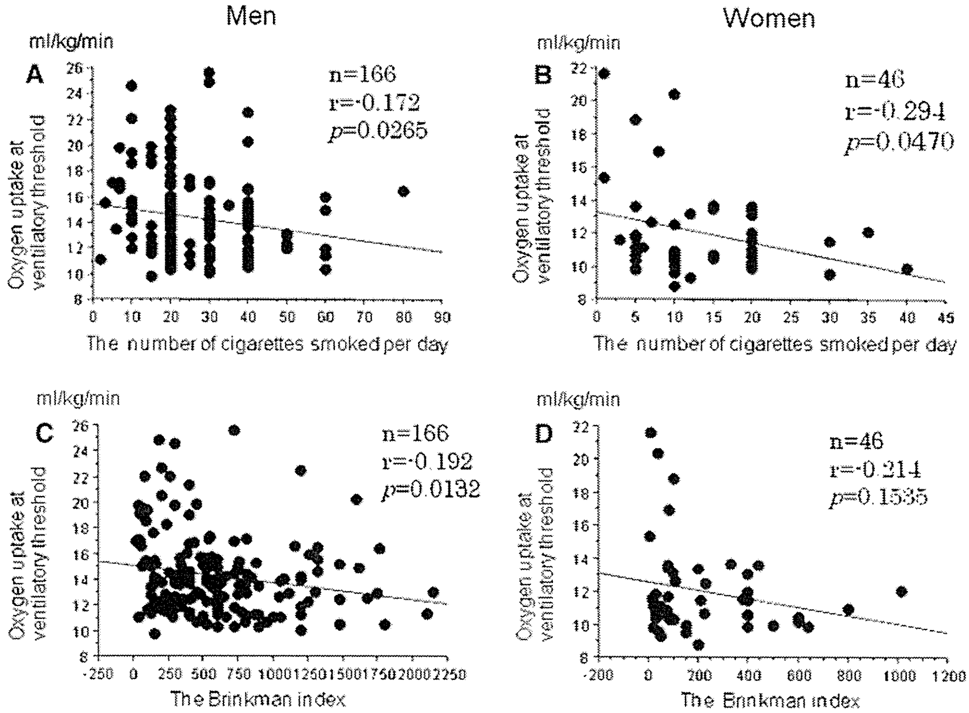

Fig. 1 Simple correlation analysis between the number of cigarettes smoked per day and oxygen uptake at ventilatory threshold (**a** men, **b** women), and between the Brinkman Index and oxygen uptake at ventilatory threshold (**c** men, **d** women)

among 1,393 men over 7 years. In this study, we solely evaluated the relationship between cigarette smoking and aerobic exercise level defined by VT in the Japanese. Exercise habits were closely linked to cigarette smoking in men, and the differences of parameters at VT between subjects with and without cigarette smoking were attenuated after adjusting for age and exercise habits. However, in women without exercise habits, oxygen uptake at VT in women with cigarette smoking was significantly lower than that in women without, after adjusting for age. In addition, we compared oxygen uptake at VT among subjects with and without cigarette smoking and exercise habits, and found that oxygen uptake at VT in group B was highest among four groups in men. Oxygen uptake at VT in group C was lowest among four groups in both sexes. Taken together, a combination of promoting exercise habits and prohibiting cigarette smoking might be considered for improving aerobic exercise level, especially in women.

Potential limitations still remain in this study. First, our study was a cross-sectional and not a longitudinal study. Second, 407 men and 418 women in our study voluntarily underwent measurements; they were therefore more likely to be health conscious compared with the average person. Third, we could not show a clear relation between cigarette smoking and oxygen uptake at VT. Fourth, the relationship between cigarette smoking and exercise habits was not noted in women. The low prevalence of subjects with exercise habits and cigarette smoking might affect the results. However, it seems reasonable to suggest that prohibiting smoking and promoting exercise habits might result in amelioration of aerobic exercise level in some Japanese. Sandvik et al. [21] reported that physical fitness was a graded, independent, long-term predictor of mortality from cardiovascular causes in healthy, middle-aged men. To show this, further prospective studies are needed in the Japanese.

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Real-time estimation of daily physical activity intensity by a triaxial accelerometer and a gravity-removal classification algorithm

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Abstract

We have recently developed a simple algorithm for the classification of household and locomotive activities using the ratio of unfiltered to filtered synthetic acceleration (gravity-removal physical activity classification algorithm, GRPACA) measured by a triaxial accelerometer. The purpose of the present study was to develop a new model for the immediate estimation of daily physical activity intensities using a triaxial accelerometer. A total of sixty-six subjects were randomly assigned into validation (*n* 44) and cross-validation (*n* 22) groups. All subjects performed fourteen activities while wearing a triaxial accelerometer in a controlled laboratory setting. During each activity, energy expenditure was measured by indirect calorimetry, and physical activity intensities were expressed as metabolic equivalents (MET). The validation group displayed strong relationships between measured MET and filtered synthetic accelerations for household (r 0·907, $P<0{\cdot}001$) and locomotive (r 0·961, $P<0{\cdot}001$) activities. In the cross-validation group, two GRPACA-based linear regression models provided highly accurate MET estimation for household and locomotive activities. Results were similar when equations were developed by non-linear regression or sex-specific linear or non-linear regressions. Sedentary activities were also accurately estimated by the specific linear regression classified from other activity counts. Therefore, the use of a triaxial accelerometer in combination with a GRPACA permits more accurate and immediate estimation of daily physical activity intensities, compared with previously reported cut-off classification models. This method may be useful for field investigations as well as for self-monitoring by general users.

Key words: **Non-exercise activity thermogenesis: Accelerometry: Household activity: Locomotive activity: Metabolic equivalents**

Low physical activity (PA) levels in daily life are probably correlated with obesity and other diseases[1]. According to the International Association for the Study of Obesity, prevention of weight regain in formerly obese individuals requires 60–90 min of daily moderate activity or lesser amounts of vigorous activity, with 45–60 min of daily moderate activity required to prevent the transition to overweight or obese[2]. In addition to exercise, non-exercise activity thermogenesis, a much larger part of daily PA, may also contribute to obesity prevention[3,4]. Therefore, assessment of the type, quantity and intensity of PA is important for the development of strategies to prevent obesity and chronic diseases. However, accurate methods for the measurement of energy expenditures (EE) induced by various PA under free-living conditions are still under consideration.

At present, several methods are used for the measurement of EE in a field setting[5,6]. The doubly labelled water method displays high accuracy for the measurement of 24 h EE under free-living conditions. However, this method can only evaluate total EE and cannot provide day-to-day or minute-by-minute variations. Although questionnaires could individually measure PA intensity and EE (as value by intensity × time) in addition to the PA type,

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Abbreviations: ACC_{fil}, filtered synthetic acceleration; ACC_{unfil}, unfiltered synthetic acceleration; EE, energy expenditure; GRPACA, gravity-removal physical activity classification algorithm; MET, metabolic equivalent; PA, physical activity.

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the accuracy of these methods is not sufficient(7). On the other hand, accelerometers are objective, small, non-invasive tools for measuring PA intensity and EE, with the potential to measure locomotive as well as household activities(8–10). Furthermore, activity monitors such as accelerometers or pedometers may serve as useful tools for promoting active life behaviour(11,12).

At the least, uniaxial and triaxial accelerometers can accurately estimate the intensity of ambulatory activities(13–15). However, the intensities of household activities such as vacuuming and sweeping cannot be accurately estimated by accelerometers, possibly leading to underestimation of total EE by algorithms based on locomotive activities(14). Indeed, different relationships between counts per minute and metabolic equivalents (MET) observed for locomotive *v.* household activities led to MET underestimation for household activities(13–15). Time spent in sedentary and light activities is also underestimated by locomotion-based equations(16). Therefore, accurate MET estimation for household and sedentary activities is required in addition to locomotive activity.

Recently, several studies have attempted to discriminate between PA types using accelerometer counts(17–26). Although these algorithms have improved accuracy for estimating the MET of various activities compared with single regression models, some limitations remain: percentage of correct classification was slightly lower in some types of PA(21,22); multiple sensors make it difficult to continuously wear the device on the body(26); estimation is a complex procedure requiring large amounts of data, a barrier for applied researchers as well as for the general public. An accelerometer-based algorithm that accurately and immediately estimates PA intensity would be a useful tool for assessing PA in free-living conditions, as well as for promoting active life behaviour in general users. We have recently developed a simple but accurate algorithm for the classification of locomotive and household activities, using the ratio of unfiltered to filtered synthetic acceleration (ACC_{unfil}/ACC_{fil}) combined with a gravity-removal PA classification algorithm (GRPACA)(27). A correct classification percentage of almost 100 % was achieved during our selected activities. Furthermore, we have confirmed the separation of sedentary activities from both locomotive and household activities by accelerometer counts. Therefore, the purpose of the present study was to develop a new model for instantly estimating the intensity of daily PA using a triaxial accelerometer.

Subjects and methods

Subjects

A total of sixty-six subjects (thirty-one males and thirty-five females) volunteered to participate in the present study. The present study was conducted according to the guidelines laid down in the Declaration of Helsinki, and all procedures involving human subjects were approved by the Ethical Committee of the National Institute of Health and Nutrition in Tokyo, Japan. Subjects were excluded from the study if they had any contraindications to exercise, or if they were physically unable to complete the activities. Descriptive characteristics of the study subjects are presented in Table 1. Subjects were randomly assigned into validation (*n* 44) and cross-validation (*n* 22) groups. Before measurement, the purpose and procedure of the study were explained in detail. Informed consent was signed by all subjects.

Anthropometric measurements

Before performing PA, body weight was measured by a digital scale to the nearest 0·1 kg, with the subjects dressed in light clothing. Barefoot standing height was measured to the nearest 0·1 cm using a wall-mounted stadiometer (YL-65S; Yagami, Nagoya, Japan). BMI was calculated as body weight (kg) divided by height squared (m^2).

Experimental protocol

Fasting subjects visited the laboratory in the morning of the experimental day. After anthropometric measurements, they performed fourteen activities with a facemask and Douglas bag while wearing a triaxial accelerometer on the left side of the waist. The selected activities were as follows: (1) sedentary activity – resting in the supine position as BMR, resting in the sitting position as RMR and personal computer work; (2) household activity – laundry, dishwashing, moving a small load (5 kg) and vacuuming; (3) locomotive activity – slow walking (3·3 km/h), normal walking (4·2 km/h), brisk walking (6·0 km/h), normal walking while carrying a bag (3 kg) in the hand, jogging (8·4 km/h) on a track, and ascending and descending stairs at personal normal speeds without using handrails. These activities were chosen as representative activities of daily life, based on our observations in a preliminary study using the activity records of other subjects. The subjects were permitted to consume only drinking-water during the experiment. They were instructed to lie down quietly for 30 min, and then BMR was measured for two periods of 10 min, followed by RMR measurement for 10 min. Subsequently, the other activities were performed for 3–7 min. The entire experimental protocol took each subject about 4·5 h to complete, and there was enough rest between activities to eliminate any carry-over effect from one activity to another. Each subject performed the experiment following the same schedule. The expired air for the subject in each activity was collected under a steady state. We defined the beginning of the steady state as 2–3 min after starting an activity, depending on the activity intensity(28). This experimental protocol has previously been described in detail(27).

Table 1. Physical characteristics of the subjects in each group

(Mean values and standard deviations)

	Validation group*						Cross-validation group*						Total					
	Men (*n* 21)		Women (*n* 23)		All (*n* 44)		Men (*n* 10)		Women (*n* 12)		All (*n* 22)		Men (*n* 31)		Women (*n* 35)		All (*n* 66)	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Age (years)	42·2	14·4	43·0	13·1	42·6	13·7	41·9	14·3	42·0	11·4	42·0	12·8	42·1	14·6	42·6	12·7	42·4	13·5
Height (cm)	170·2	5·8	159·3	5·4	164·5	7·8	170·2	7·5	156·9	5·2	162·9	9·2	170·2	6·5	158·5	5·5	164·0	8·4
Weight (kg)	68·3	15·1	55·6	9·8	61·6	14·1	68·2	11·9	54·9	7·6	61·0	11·8	68·3	14·3	55·3	9·2	61·4	13·4
BMI (kg/m^2)	23·4	4·2	21·9	3·7	22·6	4·0	23·4	3·2	22·3	2·9	22·8	3·1	23·4	4·0	22·0	3·5	22·7	3·7

* Subjects were randomly assigned into validation (67 %) and cross-validation (33 %) groups matched for age, height and weight.

Indirect calorimetry

During each activity, the subject's expired air was collected in a Douglas bag. Expired O_2 and CO_2 gas concentrations were measured by MS (ARCO-1000; Arco System, Kashiwa, Japan), and gas volume was determined using a certified dry gas meter (DC-5; Shinagawa, Tokyo, Japan). For each measurement, the gas analyser was initially calibrated using a certified gas mixture and atmospheric air. EE was estimated from VO_2 and VCO_2 using Weir's equation(29). MET values as reference were calculated as EE during the activities divided by the measured RMR.

Triaxial accelerometer

We used a triaxial accelerometer with 4 GB of memory consisting of Micro Electro Mechanical Systems-based accelerometers (LIS3LV02DQ; ST-Microelectronics, Geneva, Switzerland), which respond to both acceleration due to movement and gravitational acceleration. The sensor was built into a plastic case without a liquid crystal display and was designed to be clipped to a waist belt (size: 80 × 50 × 20 mm; weight: approximately 60 g including batteries). Anteroposterior (*x*-axis), mediolateral (*y*-axis) and vertical (*z*-axis) acceleration measurements were obtained during each activity at a rate of 32 Hz to 12 bit accuracy. The range of the acceleration data of each axis is ± 6 G, resulting in a resolution of 3 mG. The acceleration data were uploaded to a personal computer.

The signals obtained from the triaxial accelerometer were processed in the following way. Each of the three signals from the triaxial accelerometer was passed through a high-pass filter with a cut-off frequency of 0·7 Hz, in order to remove the gravitational acceleration component from the signal. We calculated the synthetic acceleration of all three axes (vector magnitude $\sqrt{x^2+y^2+z^2}$) using signals before and after high-pass filtering. Then, the ratio of ACC_{unfil} to ACC_{fil} was calculated. The acceleration signals, calculated as the average of the absolute value of the accelerometer output of each axis from 10 s epochs at the middle of each activity, were processed to various acceleration output variables. In our previous study, we reported the algorithm for the classification of household and locomotive activities by the ACC_{unfil}:ACC_{fil} ratio which resulted in almost 100 % correct demarcation for our eleven selected activities(27).

A commercial product (Activity Style Pro HJA-350IT; Omron Healthcare, Kyoto, Japan) has been developed from the prototype accelerometer that we made in the present study. This commercial device measures 74 × 46 × 34 mm and weighs 60 g, including batteries. The liquid crystal display in this device has several modes that provide different types of information: (1) a research mode that provides no information; (2) a mode that displays step counts; (3) a mode that displays real-time MET intensity. Both devices are shown in Fig. 1.

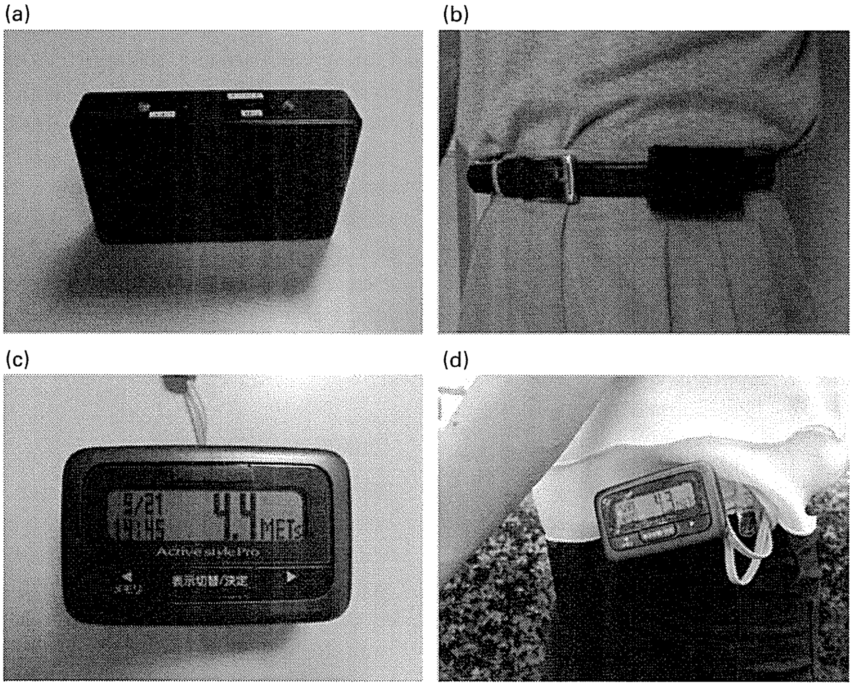

Fig. 1. Prototype accelerometer used in the present study and a commercial accelerometer based on the algorithm developed in the present study. (a) Prototype accelerometer that was used to perform all measurements; (b) subjects wore the prototype accelerometer on the waist with a clip during the entire protocol; (c) commercial accelerometer based on the algorithm that was developed in the present study; (d) real-time metabolic equivalents (MET) are shown on the liquid crystal display (LCD) of the commercial accelerometer (the LCD can also show step counts).

Table 2. Energy expenditure, metabolic equivalents (MET), accelerations and acceleration ratios for each activity in the validation group

(Mean values and standard deviations, *n* 44)

	Energy expenditure (kJ/min)		MET*		MET†		Unfiltered synthetic acceleration (mG)		Filtered synthetic acceleration (mG)		Ratio of unfiltered synthetic acceleration to filtered synthetic acceleration	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Light activity												
Resting in the sitting position (*n* 44)	4·142	0·79	–		–		5·6	1·8	2·6	0·6	2·15	0·63
Resting in the supine position (*n* 44)	3·765	0·79	0·91	0·05	0·89	0·10	4·6	2·4	2·1	0·7	2·14	0·88
Personal computer work (*n* 42)	4·602	1·00	1·12	0·08	1·08	0·12	10·2	3·7	5·7	1·7	1·80	0·37
Household activity												
Laundry (*n* 44)	9·706	2·59	2·34	0·37	2·26	0·31	154·1	38·4	50·2	11·5	3·11	0·57
Dishwashing (*n* 43)	7·614	2·01	1·84	0·34	1·77	0·30	56·8	17·9	26·3	6·7	2·20	0·64
Moving a small load (*n* 44)	18·32	4·98	4·40	0·68	4·27	0·63	360·5	51·9	157·1	21·5	2·32	0·35
Vacuuming (*n* 42)	12·34	3·01	2·97	0·52	2·88	0·53	153·2	34·3	82·8	24·9	1·92	0·39
Locomotive activity												
Slow walking (*n* 44)	13·01	3·39	3·12	0·45	3·03	0·42	245·5	47·4	240·1	48·1	1·02	0·02
Normal walking (*n* 44)	15·22	3·81	3·67	0·55	3·56	0·49	320·8	48·7	313·8	48·7	1·02	0·02
Brisk walking (*n* 44)	19·53	5·10	4·70	0·76	4·56	0·75	428·4	69·6	426·8	72·2	1·01	0·02
Walking while carrying a bag (*n* 44)	17·90	4·14	4·33	0·60	4·20	0·59	361·5	51·8	355·7	51·9	1·02	0·02
Jogging (*n* 44)	39·24	9·37	9·42	0·98	9·16	1·18	974·2	118·6	954·0	116·7	1·02	0·02
Ascending stairs (*n* 39)	31·54	6·86	7·64	0·75	7·32	0·61	232·4	29·5	220·1	29·1	1·06	0·04
Descending stairs (*n* 41)	13·38	3·31	3·20	0·44	3·09	0·42	287·9	50·6	277·2	49·4	1·04	0·02

* MET were calculated as energy expenditure for each activity divided by energy expenditure for resting in the sitting position.

† MET were calculated as energy expenditure for each activity divided by 4·184 kJ/kg per h.

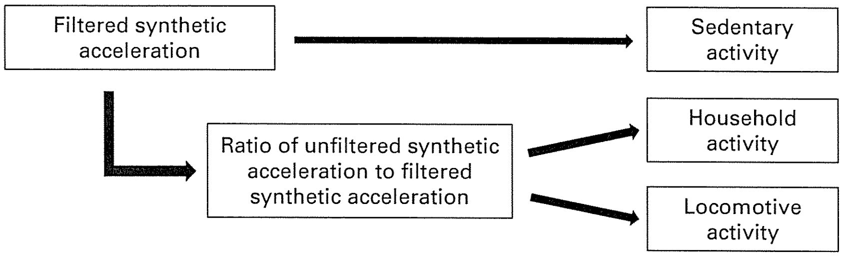

Fig. 2. Algorithm for the classification of three different activity types, using a triaxial accelerometer.

Statistical analysis

All values are presented as means and standard deviations. Differences are considered to be statistically significant if the *P* value is less than 0·05. The relationship between measured MET and the ACC_{fil} count in the validation group was evaluated by Pearson's correlation coefficient (*r*) and the standard error of the estimate. Linear and non-linear regression models were used in the validation group to develop equations to predict MET based on the intensity of PA, as measured by the ACC_{fil} count. Differences between measured and estimated MET in the cross-validation group were assessed by one-way ANOVA followed by Dunnett's *post hoc* test or a paired *t* test. Bland–Altman plots were used to graphically show the variability in individual error scores in the cross-validation group(30). All statistical analyses were performed using SPSS version 15.0J for Windows (SPSS, Inc., Chicago, IL, USA).

Results

Data collected during the present study were analysed if both MET and ACC could be correctly measured during each activity. Mean EE, MET, ACC_{unfil}, ACC_{fil} and the ACC_{unfil}:ACC_{fil} ratio for each activity are shown in Table 2. As suggested previously(16), the one-regression models overestimate MET for light activity; we observed

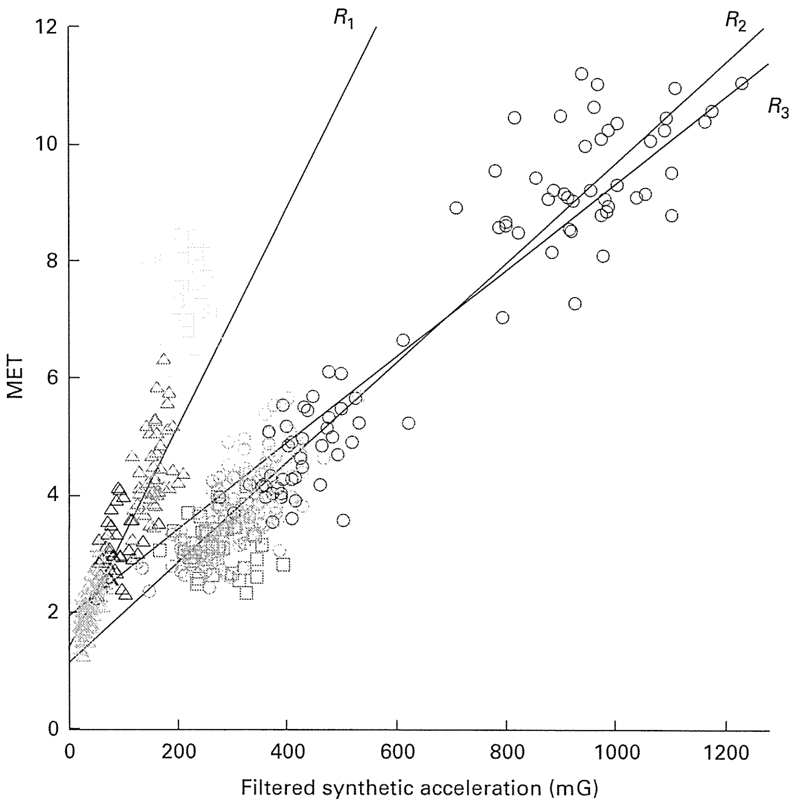

Fig. 3. Relationships between measured metabolic equivalents (MET) and filtered synthetic accelerations during locomotive and household activities in the validation group (*n* 44). R_1 (*r* 0·907, $P<0·001$), regression line for household activities only; R_2 (*r* 0·930, $P<0·001$), regression line for combined household and locomotive activities; R_3 (*r* 0·961, $P<0·001$), regression line for locomotive activity only. Ascending and descending stairs were removed from the regression analyses for R_1, R_2 and R_3. △, Laundry; △, dishwashing; △, moving a small load; △, vacuuming; ○, slow walking; ○, normal walking; ○, brisk walking; ○, walking while carrying a bag; ○, jogging; , ascending stairs; □, descending stairs.

Table 3. Equations for estimating metabolic equivalents (MET) in locomotive and household activities by using filtered synthetic acceleration (ACC_{fil}, mG) in the validation group (*n* 44)

(*r* Values and standard errors of the estimate (SEE))

	Equation	*r*	SEE (MET)
Linear regression model			
Model 1			
Locomotive plus household activities	$\text{MET} = 1{\cdot}9494 + 0{\cdot}0074 \times \text{ACC}_{\text{fil}}$	0·930*	0·804
Model 2			
Locomotive activity only	$\text{MET} = 1{\cdot}1372 + 0{\cdot}0085 \times \text{ACC}_{\text{fil}}$	0·961*	0·658
Household activity only	$\text{MET} = 1{\cdot}4023 + 0{\cdot}0188 \times \text{ACC}_{\text{fil}}$	0·907*	0·460
Non-linear regression model			
Model 3			
Locomotive activity only	$\text{MET} = 0{\cdot}8944 + 0{\cdot}0126 \times \text{ACC}_{\text{fil}}^{0{\cdot}947}$	0·961*	0·657
Household activity only	$\text{MET} = 0{\cdot}8149 + 0{\cdot}1014 \times \text{ACC}_{\text{fil}}^{0{\cdot}701}$	0·910*	0·453
Sex-specific linear regression model			
Model 4			
Locomotive activity only (male)	$\text{MET} = 0{\cdot}8766 + 0{\cdot}0088 \times \text{ACC}_{\text{fil}}$	0·968*	0·634
Locomotive activity only (female)	$\text{MET} = 1{\cdot}3488 + 0{\cdot}0083 \times \text{ACC}_{\text{fil}}$	0·955*	0·658
Household activity only (male)	$\text{MET} = 1{\cdot}4022 + 0{\cdot}0181 \times \text{ACC}_{\text{fil}}$	0·911*	0·446
Household activity only (female)	$\text{MET} = 1{\cdot}3951 + 0{\cdot}0195 \times \text{ACC}_{\text{fil}}$	0·907*	0·470
Sex-specific non-linear regression model			
Model 5			
Locomotive activity only (male)	$\text{MET} = 0{\cdot}6714 + 0{\cdot}0120 \times \text{ACC}_{\text{fil}}^{0{\cdot}959}$	0·968*	0·633
Locomotive activity only (female)	$\text{MET} = 0{\cdot}5367 + 0{\cdot}0284 \times \text{ACC}_{\text{fil}}^{0{\cdot}834}$	0·956*	0·654
Household activity only (male)	$\text{MET} = 1{\cdot}3172 + 0{\cdot}0254 \times \text{ACC}_{\text{fil}}^{0{\cdot}939}$	0·911*	0·445
Household activity only (female)	$\text{MET} = 0{\cdot}2828 + 0{\cdot}2393 \times \text{ACC}_{\text{fil}}^{0{\cdot}563}$	0·915*	0·451

* $P<0{\cdot}001$.

a similar result (data not shown). Therefore, we modelled the classification of our selected activities into three types of activities: sedentary, household and locomotive (Fig. 2). Sedentary activities are discriminated from household and locomotive activities, because ACC_{fil} for sedentary activities was lower than for other activities. Household and locomotive activities are classified by the $\text{ACC}_{\text{unfil}}$:$\text{ACC}_{\text{fil}}$ ratio according to our previous study (1·16)(27).

Fig. 3 depicts the relationship between measured MET and ACC_{fil} during household and locomotive activities performed by the validation group. The correlation coefficients for locomotive (*r* 0·961, $P<0{\cdot}001$), household (*r* 0·907, $P<0{\cdot}001$) and combined household and locomotive activities (*r* 0·930, $P<0{\cdot}001$) were high. We developed linear and non-linear regressions for estimating the intensities of household and locomotive activities; ascending and descending stairs were excluded from developing regressions, because the relationships between MET and ACC_{fil} for ascending and descending stairs differed from the relationship for the other locomotive activities (Table 3). As a result, the linear regression calculated with combined data of household and locomotive activities had a lower *r* value compared with all other regressions for locomotive activities only. Regressions for only household activities had slightly lower *r* values than those for all activities, but the regression standard errors of estimate were improved. Table 4 shows the cross-validation for all regressions. Significant differences were observed between measured values and values estimated from model 1 for most activities. However, models 2–5 accurately estimated the intensity of most household and locomotive activities, with the exceptions of ascending and descending stairs from models 2–5 and normal walking from models 2, 4 and 5, although the differences for normal walking were relatively small. In the cross-validation group, household and locomotive activities were correctly classified 100 % of the time by the $\text{ACC}_{\text{unfil}}$:$\text{ACC}_{\text{fil}}$ threshold reported previously(27). Bland–Altman plots showed that there was improved accuracy of individual activities with models 2–5 compared with model 1 (Fig. 4). Although all models tended to underestimate higher vigorous intensity activity with significant r^2 values ($P<0{\cdot}05$), household activities were clearly well estimated by models 2–5. The results of the present study remained consistent, whether estimated from linear or non-linear regressions or from sex-specific regressions.

Fig. 5 depicts the relationship between measured MET and ACC_{fil} during sedentary activities performed by the validation group. We selected three activities to represent sedentary activities. As shown in Fig. 5, we calculated the regression equation for estimating the intensity of sedentary activities by including dishwashing with the lowest MET on average in our selected household and locomotive activities. The threshold for the classification between sedentary activities and other activities was determined by the point of intersection in the linear regressions for sedentary activities and household activities (29·9 mG). With these threshold and regression equations, resting in the supine position (mean difference 0·04 (SD 0·06) MET, $P<0{\cdot}01$), personal computer work (mean difference −0·03 (SD 0·09) MET, NS) and dishwashing (mean difference 0·02 (SD 0·31) MET, NS) were estimated adequately in the cross-validation group.

Table 4. Absolute and percentage of differences between measured and estimated metabolic equivalents (MET) from five equation models for household and locomotive activities in the cross-validation group

(Mean values and standard deviations, *n* 22)

	Model 1†				Model 2‡				Model 3§				Model 4‖				Model 5¶			
	Absolute difference		% Difference		Absolute difference		% Difference		Absolute difference		% Difference		Absolute difference		% Difference		Absolute difference		% Difference	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Laundry (*n* 22)	0·12	0·33	8·3	16·0	0·07	0·30	5·3	14·4	0·09	0·30	6·0	14·4	0·07	0·30	5·4	14·6	0·09	0·31	6·1	15·0
Dishwashing (*n* 21)	0·36	0·27	23·7***	21·3	0·11	0·27	9·0	19·1	0·03	0·29	3·8	19·6	0·11	0·27	8·8	19·0	0·03	0·31	3·9	20·6
Moving a small load (*n* 22)	−1·46	0·72	−30·4***	10·3	−0·22	0·69	−3·0	14·4	−0·25	0·70	−3·5	14·3	−0·22	0·72	−2·7	14·8	−0·23	0·72	−2·9	14·7
Vacuuming (*n* 22)	−0·46	0·73	−10·4**	19·7	−0·05	0·64	3·0	22·2	0·04	0·64	6·2	23·0	−0·05	0·64	3·1	21·9	0·04	0·65	6·0	22·4
Slow walking (*n* 21)	0·63	0·42	21·5***	14·8	0·10	0·45	4·2	14·6	0·07	0·47	3·2	15·0	0·12	0·41	4·8	13·6	0·06	0·44	2·9	14·3
Normal walking (*n* 21)	0·67	0·48	19·8***	15·1	0·23	0·50	7·6*	14·3	0·22	0·50	7·4	14·4	0·22	0·48	7·4*	13·7	0·23	0·48	7·7*	14·0
Brisk walking (*n* 22)	0·34	0·70	9·1	15·7	0·03	0·72	2·4	15·1	0·04	0·72	2·6	15·2	0·04	0·69	2·5	14·7	0·09	0·69	3·6	15·0
Walking while carrying a bag (*n* 22)	0·34	0·59	9·8*	15·3	−0·06	0·61	0·1	14·6	−0·06	0·61	0·1	14·7	−0·06	0·57	0·1	13·8	−0·03	0·58	0·7	14·1
Jogging (*n* 20)	−0·50	1·39	−3·8	13·9	−0·18	1·44	−0·4	14·9	−0·23	1·43	−0·9	14·7	−0·17	1·42	−0·3	14·7	−0·19	1·38	−0·6	14·3
Ascending stairs (*n* 19)	−4·13	0·78	−53·3***	4·9	−4·69	0·78	−60·6***	4·5	−4·73	0·78	−61·2***	4·6	−4·68	0·81	−60·5***	4·8	−4·75	0·80	−61·4***	4·7
Descending stairs (*n* 20)	1·13	0·73	40·7***	30·0	0·68	0·78	25·6**	29·2	0·66	0·79	25·1**	29·5	0·70	0·79	26·2**	28·9	0·69	0·81	26·1**	29·6

Mean values were significantly different compared with measured MET: $^{*}P<0·05$, $^{**}P<0·01$, $^{***}P<0·001$.

† Linear regression model for estimating locomotive and household activities together.

‡ Linear regression model for estimating locomotive and household activities separately.

§ Non-linear regression model for estimating locomotive and household activities separately.

‖ Sex-specific linear regression model for estimating locomotive and household activities separately.

¶ Sex-specific non-linear regression model for estimating locomotive and household activities separately.

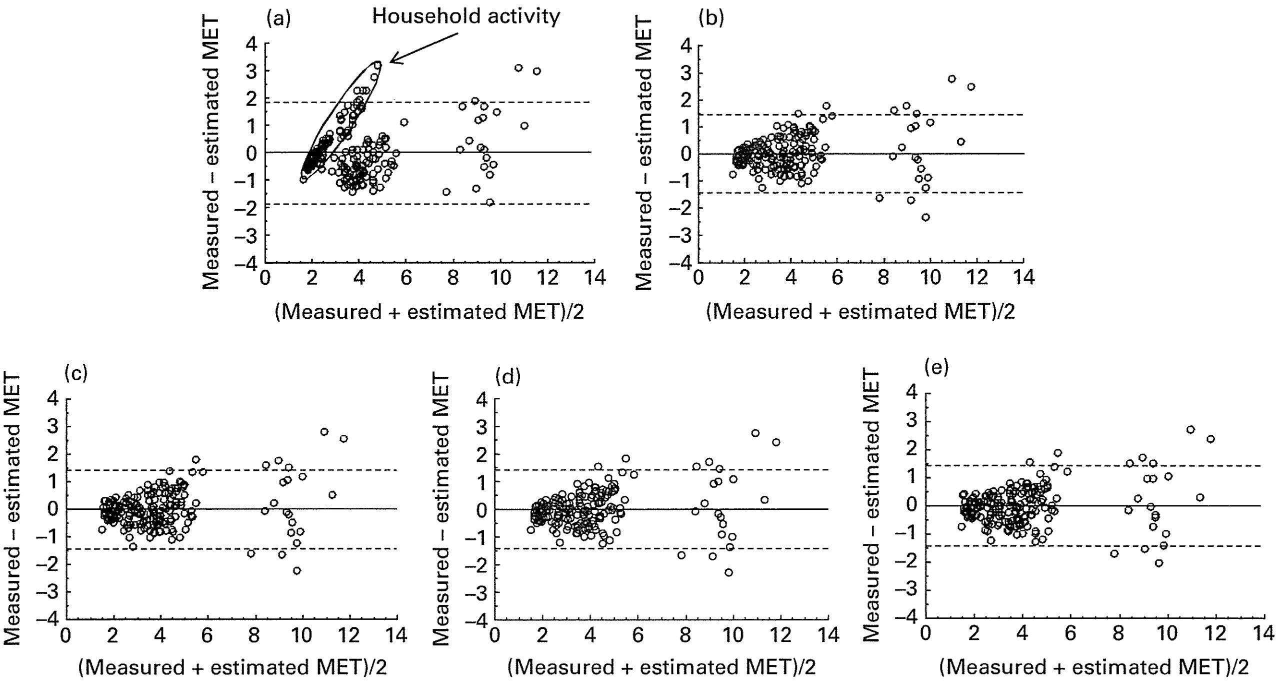

Fig. 4. Bland–Altman analysis. Differences between measured and estimated metabolic equivalents (MET) are plotted against measured and estimated mean MET for household and locomotive activities. (a) Model 1, linear regression model for estimating locomotive and household activities together (*r* 0·237); (b) model 2, linear regression model for estimating locomotive and household activities separately (*r* 0·207); (c) model 3, non-linear regression model for estimating locomotive and household activities separately (*r* 0·219); (d) model 4, sex-specific linear regression model for estimating locomotive and household activities separately (*r* 0·212); (e) model 5, sex-specific non-linear regression model for estimating locomotive and household activities separately (*r* 0·207). —, Mean; - - -, 95 % CI of the observations.

Final model for estimating intensity of physical activity (n 66)

If $29{\cdot}9\,\mathrm{mG} > \mathrm{ACC_{fil}}$,

$$\text{Sedentary activity: MET} = 0{\cdot}8823 + 0{\cdot}0351 \times \mathrm{ACC_{fil}}.$$

If $29{\cdot}9\,\mathrm{mG} \le \mathrm{ACC_{fil}}$,

Then if $1{\cdot}16 \le \mathrm{ACC_{unfil}}:\mathrm{ACC_{fil}}$ ratio.

$$\text{Household activity: MET} = 1{\cdot}3435 + 0{\cdot}0196 \times \mathrm{ACC_{fil}}.$$

Else if $1{\cdot}16 > \mathrm{ACC_{unfil}}:\mathrm{ACC_{fil}}$ ratio.

$$\text{Locomotive activity: MET} = 1{\cdot}1128 + 0{\cdot}0086 \times \mathrm{ACC_{fil}}.$$

Discussion

We have developed a new model to estimate the intensity of daily PA, using a triaxial accelerometer in combination with a novel PA classification algorithm. We classified PA into locomotive, household and sedentary activities with thresholds determined by the $\mathrm{ACC_{unfil}}$:$\mathrm{ACC_{fil}}$ ratio (GRPACA) or accelerometer counts(27). The rate of correct classification was excellent: 100 % of the activities performed by our subjects were correctly classified as locomotive or household. With our new classification algorithm, the regressions clearly improved the accuracy of estimating the intensity of various PA, compared with a non-classification model. This novel method is capable of estimating the intensity of PA accurately and immediately, serving as a practical field tool for researchers as well as for general users.

In agreement with previous studies(18–21,31), we observed that the multiple equation model improved the accuracy of estimating household and locomotive activity intensities, compared with the one-equation model; accuracy improvements occurred for household activities in particular. With the exceptions of ascending and descending stairs, average percentage differences were within 10 % in the two-equation model, with more than 10 % differences in several activities in the one-equation model. Furthermore, we attempted to estimate the intensity of PA with non-linear regression and sex-specific regression (or non-regression) models. Prediction errors obtained from the linear and non-linear regression models were comparable in the present study (Table 4). While it is still controversial whether the linear or non-linear regression model is a better predictive model(8), inclusion of the GRPACA did not necessitate non-linear or sex-specific regression equations. To our knowledge, there is no evidence of a quadratic relationship between MET and accelerometer counts in various PA. Therefore, the linear regression model may obtain comparable predictions as the non-linear regression model in the present

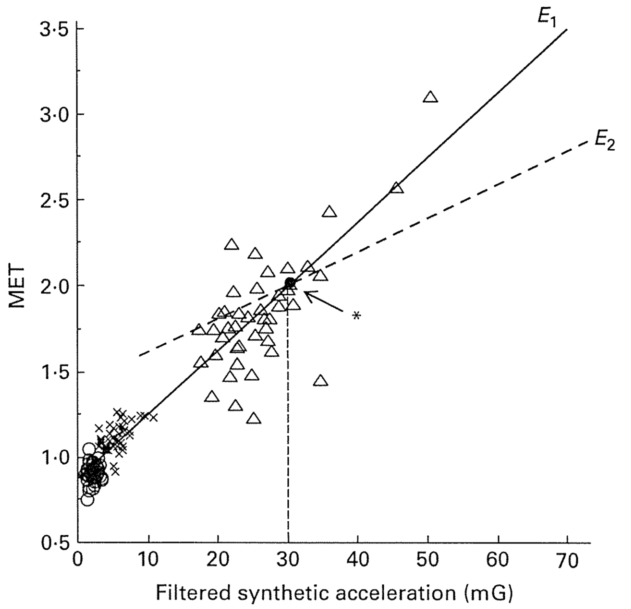

Fig. 5. Relationship between measured metabolic equivalents (MET) and filtered synthetic accelerations during sedentary activities in the validation group (*n* 44). E_1 (*r* 0·942, $P<0·001$, standard error of estimate 0·151 MET), regression line for sedentary activities; E_2, regression line for household activities. *Threshold point for the classification between sedentary and household activities (29·9 mG). Dishwashing was included in both E_1 and E_2. ○, Resting in the supine position; ×, personal computer work; △, dishwashing.

study, under actual free-living conditions. Furthermore, the sex-specific equation model did not provide a more accurate estimation (Table 4), indicating that we have developed new equations by linear regressions without taking sex into account.

Accurate estimation of sedentary activities is important, as many people perform sedentary activities at least several hours/d(32,33). Previously developed accelerometer-based models overestimate the intensity of sedentary activities(16). In the present study, sedentary activities clearly had lower accelerometer counts than other activities. Initially, we hypothesised that the cut-off threshold between intensities of sedentary and other activities should be the midpoint of the highest sedentary accelerometer count and the lowest accelerometer count from the other activities. However, in the present study, we observed a small gap between sedentary and household activities in the relationship between MET and ACC_{fil}. Therefore, we developed the equation for sedentary activities by including dishwashing, which displayed the lowest accelerometer counts of our household or locomotive activity. Using this consideration, activities about 1·5 MET could be estimated accurately. Therefore, we have classified an activity of less than 2 MET as a sedentary activity, using a cut-off threshold determined by accelerometer counts.

Although PA intensity estimates were improved with our model, we could not directly compare the present results with previously reported models designed for data collecting and developing equations. However, our accuracies for some activities, such as personal computer work, vacuuming and dishwashing, are slightly better than the results obtained by Crouter *et al.*(18–21,34), who used two equations with a classification algorithm based on the CV of the acceleration count. Moreover, our model possesses the following advantages over previous models: (1) our classification algorithm is accurate but simple, leading to immediate estimation of PA intensity following a long period of data collection; (2) our measuring device is secured to the waist by a clip only; (3) the Douglas bag method, not a portable analyser, was used as the reference method; (4) MET were calculated with measured RMR (not 3·5 ml/kg per min or 4·2 kJ/kg per h (1 kcal/kg per h)); (5) values from a triaxial accelerometer, not a uniaxial accelerometer, were used for developing equations.

Several algorithms have been developed for PA classification. These algorithms were constructed using the CV of the acceleration count based on the ActiGraph or Actical devices(18–21,34) or using the ratio of vertical acceleration counts to horizontal acceleration counts based on the ActivTracer device(22,25). In these studies, the percentage of correct classifications does not seem to be high, even for the subjects used in the classification development. Our algorithm may classify locomotive and household activities with higher accuracy. On the other hand, other reported classification algorithms(26,35,36) were developed to divide PA into further subtypes. These additional divisions require a large quantity of data, a complex calculation process or the placement of sensors over the whole body; it is difficult to maintain battery power over long periods, to check PA intensities in real time and to wear and remove the device easily. Our device is worn just on the waist, is held by a clip and PA intensities were displayed immediately. This unique device is useful for applied researchers or professional health advisers to investigate PA in the field, and general users can monitor their activity status by themselves, as the commercial product has an liquid crystal display that can indicate real-time MET values or step counts.

We employed the Douglas bag method as a reference for measuring EE, while previous studies used a portable metabolic system such as Aerosport TEEM 100 or COSMED K4b2. For these portable metabolic systems, validation of assessing EE during PA has been reported(37–40). A portable metabolic system also has the advantage of measuring various dynamic activities outdoors. However, portable metabolic systems slightly overestimate or underestimate O_2 uptake during exercise testing, compared with reference methods(40–43). Therefore, the Douglas bag method may be preferable to a portable metabolic system as a reference method for measuring EE during various types of PA.

Whether measured values or a constant value of 3·5 ml/kg should be used for the RMR value of 1 MET is debatable. Typical values for the normal-weight population were 3·5 ml/kg per min and 4·2 kJ/kg per h (1 kcal/kg per h). However, average measured RMR were much lower than 3·5 ml/kg per min or 4·2 kJ/kg per h (1 kcal/kg per h) in 671 subjects, although many were overweight or obese(44). In particular, body composition contributed to the variance in RMR. In the present study, the average RMR value was 4·1 kJ/kg per h (0·99 kcal/kg per h), but the standard deviation was relatively large (0·8 kJ/kg per h (0·19 kcal/kg per h)). To our knowledge, no description exists of whether the RMR value of 3·5 ml/kg per min was previously measured in a fasting state(45), although the present study and Byrne *et al.*(44) measured RMR in the fasting state. Therefore, the use of measured RMR as 1 MET could lead to increased accuracy of estimating the intensity of PA.

A triaxial accelerometer, capable of measuring both vertical and horizontal accelerations, is more informative than a uniaxial accelerometer, possibly permitting more accurate estimates of PA intensities. However, previous studies(16,25,46) have reported that the accuracy of estimating PA intensities did not differ between triaxial and uniaxial accelerometers if these values were estimated by a one-equation model. Although our classification algorithm can calculate the cut-off threshold even using a uniaxial accelerometer count, we confirmed that the classification developed with a synthetic accelerometer count is more accurate than that based only on a vertical (uniaxial) accelerometer count. Therefore, our estimation by triaxial accelerometer counts should lead to increased accuracy compared with a uniaxial accelerometer.

The present study had several limitations. We could not accurately estimate the intensity of ascending and descending stairs. Although previous studies(18–21,36) have estimated the intensities of these activities relatively well, validity was assessed by a condition combining ascension and descension of stairs, with only Yamazaki *et al.*(47) performing the individual assessments. Under daily living conditions, ascending and descending stairs are normally performed separately, and thus these activities should be assessed separately. In addition, we did not include stationary ergometer or cycling in the present study. Furthermore, the developed model tended to underestimate higher vigorous intensity activity. Therefore, future studies are needed using the doubly labelled water method or a metabolic chamber to investigate the validity of our model. In addition, studies are needed to compare our accelerometer with other types of accelerometers under free-living conditions. Furthermore, more investigation is needed to determine how well the model developed in the present study applies to other populations such as obese individuals or children.

We have recently reported a simple but accurate classification algorithm to differentiate between locomotive and household activities, with a cut-off determined by the ACC_{unfil}:ACC_{fil} ratio(27). Additionally, sedentary activities could be discriminated from household and locomotive activities with accelerometer counts. With this classification algorithm, our new model exhibited improved accuracy in estimating the intensity of various PA, compared with non-classification models. Furthermore, this new model is capable of estimating PA intensity immediately. Therefore, the method is useful for field investigations by scientists as well as for self-monitoring of activity by the general public.

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