Table 2. **Odds ratios for response to accelerometry, by sociodemographic and lifestyle variables, as compared with questionnaire-only respondents**

	Overall respondents *n* = 1508			Men *n* = 679			Women *n* = 829		
	OR[a,b]	95% CI	*P* value	OR[a,b]	95% CI	*P* value	OR[a,b]	95% CI	*P* value
Sex									
Men	1.16	(0.88, 1.52)	0.287						
Women	1.00								
Age, years									
60–	1.13	(0.72, 1.76)	0.606	0.78	(0.38, 1.63)	0.509	1.32	(0.73, 2.39)	0.353
50–59	1.17	(0.75, 1.81)	0.484	0.72	(0.36, 1.46)	0.368	1.50	(0.84, 2.68)	0.166
40–49	1.79	(1.16, 2.75)	0.008	1.41	(0.71, 2.80)	0.323	1.89	(1.07, 3.34)	0.028
30–39	1.60	(1.04, 2.49)	0.034	0.83	(0.41, 1.70)	0.613	2.31	(1.32, 4.07)	0.004
–29	1.00			1.00			1.00		
City of residence									
Tsukuba	1.08	(0.78, 1.50)	0.648	1.12	(0.69, 1.83)	0.644	1.04	(0.66, 1.64)	0.864
Koganei	1.27	(0.91, 1.77)	0.154	1.06	(0.64, 1.77)	0.815	1.38	(0.88, 2.16)	0.159
Shizuoka	1.00	(0.72, 1.39)	0.992	0.89	(0.55, 1.45)	0.649	1.08	(0.69, 1.69)	0.748
Kagoshima	1.00			1.00			1.00		
Education, years									
>12	1.01	(0.79, 1.30)	0.918	1.41	(0.97, 2.04)	0.069	0.78	(0.55, 1.10)	0.160
≤12	1.00			1.00			1.00		
Employment status									
≥40 h/week	1.00	(0.77, 1.31)	0.990	1.18	(0.77, 1.83)	0.447	0.86	(0.59, 1.24)	0.411
<40 h/week	1.00			1.00			1.00		
Marital status									
Married	1.00	(0.73, 1.37)	0.991	1.27	(0.75, 2.15)	0.382	0.83	(0.54, 1.29)	0.413
Not married	1.00			1.00			1.00		
BMI, kg/m^2									
<25	0.84	(0.63, 1.13)	0.256	0.81	(0.55, 1.19)	0.284	0.92	(0.57, 1.48)	0.724
≥25	1.00			1.00			1.00		
Self-rated health									
Good	0.95	(0.75, 1.20)	0.643	0.92	(0.65, 1.29)	0.612	0.99	(0.71, 1.38)	0.943
Poor	1.00			1.00			1.00		
Smoking									
No	1.35	(1.02, 1.79)	0.038	1.46	(1.02, 2.08)	0.038	1.16	(0.71, 1.90)	0.548
Yes	1.00			1.00			1.00		
Drinking									
Regularly	1.22	(0.95, 1.57)	0.115	1.17	(0.82, 1.67)	0.381	1.25	(0.87, 1.79)	0.229
No/Occasionally	1.00			1.00			1.00		
Walking for leisure									
Yes	1.56	(1.21, 2.01)	0.001	1.64	(1.10, 2.44)	0.015	1.48	(1.05, 2.09)	0.025
No	1.00			1.00			1.00		
Total walking time, min/week									
≥150	1.23	(0.96, 1.58)	0.096	1.42	(0.98, 2.07)	0.065	1.12	(0.80, 1.57)	0.515
<150	1.00			1.00			1.00		

[a] OR: odds ratio.

[b] Odds ratios were adjusted for all other variables shown in the table.

were significantly more likely to participate in the accelerometer portion of the surveillance study. Some sex differences were observed in stratified analyses. As compared with the questionnaire-only subsample, male respondents in the accelerometer subsample were more likely to be nonsmokers and leisure walkers, whereas female respondents were more likely to be older and leisure walkers.

DISCUSSION

The results of this study indicate that response rates to the accelerometer survey were higher among women than men, and among middle-aged and older adults than younger adults. This suggests that selection bias in surveys that use motion sensors systematically results in underrepresentation of men and younger people. The city of residence was also related to the response rate. We speculate that residents who live near the research center (Koganei is in Tokyo and Kagoshima is the farthest from Tokyo) might be more willing to participate in the study. In multivariate analyses comparing the accelerometer and questionnaire-only subsamples, there was a significantly higher response rate to wearing the accelerometer in adults who were middle-aged vs young, nonsmokers vs smokers, and leisure walkers vs non-leisure walkers after adjustment for other sociodemographic and lifestyle variables. These results must be carefully interpreted, since we were not able to compare the characteristics of the accelerometer subsample with those of the original total sample. However, these findings suggest that survey respondents who agreed to wear an accelerometer tended to be nonsmokers and more active walkers. That is, there may be a selection bias leading to overestimation of physical activity levels of populations assessed by an accelerometer or a pedometer in field studies. Although we began our analysis with this hypothesis, there was very little prior evidence to support this assumption.

Previously, Harris et al[15] conducted a randomized controlled trial of different recruitment strategies to a physical activity study using 560 patients 65 years or older who were registered with a primary care center in the United Kingdom. Participants who responded to the accelerometer assessment portion of that study reported higher physical activity, such as walking, gardening, and heavy housework, and had significantly more health problems, such as chronic pain and chronic diseases, than did nonrespondents. They also reported a faster walking speed and positive attitudes towards activity. Although the setting and age of the target population of this earlier study differ from those of the current analysis, the results were similar: active people were willing to participate in the accelerometer survey. A difference was observed in health status. In our study, health status as measured by self-rated health was not associated with accelerometry response. Because the direction and extent of bias likely differs by target population and study setting, further evidence is needed to understand the impact of selection bias in surveys employing motion sensors, if researchers and practitioners are to effectively implement such strategies and more accurately interpret the results.

Although selection biases are inevitable in field studies, efforts to decrease their impact by increasing the response rate are important. Edwards et al[16] reviewed studies regarding survey methods to obtain better response rates to postal and electronic questionnaire research. They concluded that effective strategies including monetary incentives, recorded delivery, use of a teaser on the envelope (eg, a comment suggesting to participants that they may benefit if they open it), a more interesting questionnaire topic, pre-notification, follow-up contact, shorter questionnaires, providing a second copy of the questionnaire at follow-up, university sponsorship, handwritten addresses, stamped return envelopes, and assurance of confidentiality. These strategies would also likely be effective in terms of increasing response rates to accelerometer and pedometer surveys. Some of these strategies such as monetary incentives, pre-notification, follow-up contact, university sponsorship, stamped return envelopes, and assurance of confidentiality were adopted in this study. The study might have had a higher response rate and been less biased if we had used additional strategies, such as an envelope teaser, a more interesting invitation, reminder calls, providing clear instructions on how to use the device, providing an example of result output, and designing a better survey schedule that made responses easy for subjects. Although feasible strategies differ by study setting, the results of the present study should encourage researchers to adopt these strategies to increase response rate in field studies using these devices.

There are some limitations in this study. Firstly, we compared most of the independent variables of the accelerometer subsample with the questionnaire-only subsample. For the purpose of this study, it would be ideal to compare the accelerometer and nonrespondent subsamples. However, we only had information on age, sex, and city of residence for the nonrespondent subsample. In this study, the response rate to the initial survey was not high. We must consider the possibility that the questionnaire-only subsample itself was biased from the nonrespondent subsample. Second, this study was a mail survey based upon a random sample of community residents. Our results would, of course, be most generalizable to similar study settings. Results may differ depending on the study setting, purpose, and target population. More evidence of biases in physical activity assessment using objective monitoring devices administered in various study settings is needed to clarify these issues. Thirdly, the characteristics of respondents might be different depending on survey schedule. For example, in this study, we divided the survey into 2 parts. However, the results might have differed if we had requested questionnaire and accelerometry data at the same time.

In spite of these limitations, this study provides important initial evidence suggesting selection bias in accelerometer surveys. The results of this study, which show the characteristics of persons who tend to participate in such surveys, have implications for conducting and interpreting the findings of physical activity studies using accelerometers and pedometers.

In conclusion, women and middle-aged and older adults were more likely to join an accelerometer survey delivered by mail. Participants who responded not only to the questionnaire but also to the accelerometer survey tended to report a healthier and more physically active lifestyle than did questionnaire-only participants. This response pattern reveals potential for selection bias in mail-based accelerometry surveillance studies. It is important to develop strategies to increase overall response rates and address this bias.

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Relation of body composition to daily physical activity in free-living Japanese adult women

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Abstract

The objective of the present study was to investigate the relationship between the indices of body size such as BMI, fat-free mass index (FFMI, FFM/height^2), fat mass index (FMI, FM/height^2), and body fat percentage (%BF), and physical activities assessed by the doubly-labelled water (DLW) method and an accelerometer in free-living Japanese adult women. We conducted a cross-sectional study in 100 female subjects ranging in age from 31 to 69 years. Subjects were classified in quartiles of BMI, FFMI, FMI and %BF. Daily walking steps and the duration of light to vigorous physical activity were simultaneously assessed by an accelerometer for the same period as the DLW experiment. Only physical activity-related energy expenditure (PAEE)/FFM and PAEE/body weight (BW) decreased in the highest quartile of BMI. Physical activity level, PAEE/FFM and PAEE/BW decreased in the highest quartile of FMI and %BF, whereas they were not different among quartiles of FFMI. Daily walking steps and the duration of moderate- and vigorous-intensity physical activities decreased or tended to decrease in the highest quartile of FMI and %BF, but did not differ among quartiles of FFMI and BMI. These results clearly showed that Japanese adult women with higher fat deposition obviously had a low level of physical activities assessed by both the DLW method and accelerometry, but those with larger BMI had lower PAEE/FFM and PAEE/BW only. Our data suggest that the relationship between obesity and daily physical activities should be discussed using not only BMI but also FMI or %BF.

Key words: **Body composition: Physical activity: Doubly-labelled water: Accelerometry: Japanese adult women**

Obesity is caused by an imbalance between energy intake and energy expenditure. Obese individuals are often considered to be physically less active than normal-weight individuals. However, most cross-sectional studies using the doubly-labelled water (DLW) method, which is known to be the most accurate method of measuring energy expenditure in free-living conditions(1,2), have reported that physical activity level (PAL; the ratio of total energy expenditure(TEE):BMR) did not differ among BMI categories(3–6). The reason for the lack of this association may be partly explained by differences in the distribution of fat-free mass (FFM) and fat mass (FM). PAL appears to be negatively associated with FM(7,8), but not correlated with FFM(5). However, these studies have only reported information on the association between PAL and either FM or FFM, which are not adjusted for body size, such as body height. To our knowledge, no information is available from thoroughly examining the relationship between BMI or body composition, i.e. FFM index (FFMI, FFM divided by height squared), FM index (FMI, FM divided by height squared) or body fat percentage (%BF) and physical activity in adult women, particularly in Asian populations.

Recently, many cross-sectional studies on adult women in Western countries and Japan reported that BMI and %BF were inversely associated with daily walking steps(9,10). Furthermore, %BF was negatively associated with the duration of vigorous-intensity physical activity assessed by accelerometry(11). Therefore, not only physical activity-related energy expenditure (PAEE) but also the intensity of the physical activity or walking steps should be lower among adult women with higher body mass or fat deposition.

In the present study, we investigated the relationship between various indices of body size such as BMI, FFMI,

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Abbreviations: %BF, body fat percentage; BW, body weight; DHQ, diet history questionnaire; DMW, doubly-labelled water; FFM, fat-free mass; FFMI, fat-free mass index; FM, fat mass; FMI, fat mass index; METs, metabolic equivalents; PAEE, physical activity-related energy expenditure; PAL, physical activity level; SCOP, Saku Control Obesity Program; TEE, total energy expenditure.

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FMI and %BF, and daily physical activities assessed by the DLW method and accelerometry in free-living Japanese adult women.

Methods

Subjects

Study participants were recruited through healthcare centres or at workplaces from various prefectures of the Kanto area (central Japan) and the Kyushu area (Western Japan), and from the Saku Control Obesity Program (SCOP). The details of SCOP are described elsewhere(12). In each location, subjects were included according to the following criteria: (a) in good health; (b) not pregnant or breast-feeding; (c) BMI higher than 18·5 kg/m^2; (d) living in their home prefecture 2 weeks before and during the study; (e) not on a weight-loss or treatment diet; and (f) alcohol consumption less than 40 g/d. As a result, 100 female subjects aged 31 to 69 years participated in the present study. Daily physical activity was estimated over the 14 d study period in free-living conditions using the DLW method and accelerometry. Over the entire assessment period, subjects were carefully instructed to maintain their normal daily activities and eating patterns and to make no conscious effort to lose or gain weight.

Procedures

The experimental design is shown in Fig. 1. Participants completed two visits to study sites on day 0 and day 15. On the day before the start of measuring physical activity (day 0), urine samples were collected early in the morning, 12 h or longer after the last meal (baseline urine sample), and body weight (BW) and height were measured. BMR was measured in the supine position and then the participants received a dose of DLW. On the day after the physical activity measurement (day 15), BW was measured and we then received back the urine samples, accelerometer and a self-administered diet history questionnaire (DHQ). 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 Japan. All subjects gave their written informed consent before the commencement of the investigations.

Anthropometric measures

Anthropometric measures were obtained in the fasting state on the day before (day 0) and after the 14 d study period (day 15). BW was measured to the nearest 0·1 kg and height to the nearest 0·1 cm, in individuals wearing the lightest clothing, with underwear and no shoes. BMI was calculated as BW (kg) divided by the square of body height (m^2).

Diet history questionnaire

The DHQ is a validated sixteen-page structured questionnaire that assesses dietary habits in the preceding 1-month period(13). Well-trained dietitians checked the DHQ to find omissions or errors and corrected them by asking questions of each participant. Details of the DHQ, methods of calculating nutrients and validity are given elsewhere(13). We calculated the food quotient using the data from the DHQ to evaluate TEE.

Doubly-labelled water

After providing a baseline urine sample, a single dose of approximately 0·06 g $^{2}H_2O$/kg BW (99·8 atom%; Cambridge Isotope Laboratories, Andover, MA, USA) and 1·4 g $H_2{}^{18}O$/kg BW (10·0 atom%; Taiyo Nippon Sanso, Tokyo, Japan) was given orally to each subject on day 0. After dose administration, participants were asked to collect urine samples on day 1 (the day after the DLW dose) and on eight additional times during the study period at the same time of the day (Fig. 1). All urine samples except for the baseline one were collected by the participant either at home or their place of work, and the time of sampling was recorded. All samples were first stored by freezing at −30°C in airtight parafilm-wrapped containers, and then analysed in our laboratory.

Gas analysis

Gas samples for the isotope ratio mass spectrometer were prepared by equilibration of urine samples with a gas. The gas for equilibration of ^{18}O was CO_2 and that for ^{2}H was H_2. Pt catalyst was used for equilibration of ^{2}H. The urine was analysed by a DELTA Plus isotope ratio mass spectrometer (Thermo Electron Corporation, Bremen, Germany). Each sample and the corresponding reference were analysed in duplicate.

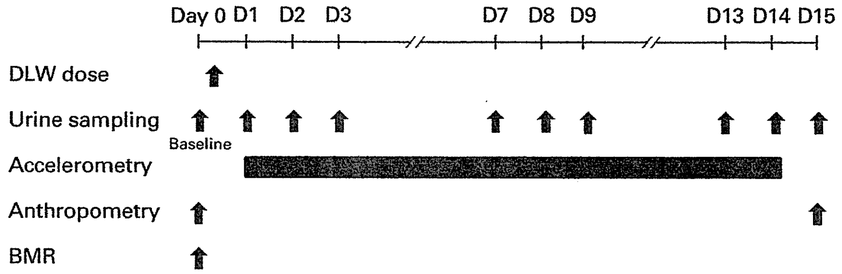

Fig. 1. Schematic representation of the experimental design. On day 0, the $^{2}H_2{}^{18}O$ (doubly-labelled water; DLW) dose was given orally to each subject after collecting a baseline urine sample and performing the BMR and anthropometric measurements.

The average standard deviations through the analyses were 0·5‰ for ^{2}H and 0·03‰ for ^{18}O.

Calculations of total energy expenditure and body composition

The ^{2}H and ^{18}O zero-time intercepts and elimination rates (k_H and k_O) were calculated by using a least-squares linear regression on the natural logarithm of the isotope concentration as a function of the elapsed time from dose administration. The zero-time intercepts were used to determine the isotope pool sizes. Total body water (TBW) was calculated from the mean value of the isotope pool size of ^{2}H divided by 1·041 and that of ^{18}O divided by 1·007. FFM was calculated assuming a FFM hydration of 0·732[14]. FM was calculated as BW minus FFM and %BF was then computed from BW and FFM. The TEE (kJ/d) calculation was performed using a modification of Weir's formula[15] based on the CO_2 production rate (rCO_2) and respiratory quotient. rCO_2 was calculated as follows: $rCO_2 = 0{\cdot}4554 \times TBW \times (1{\cdot}007k_O - 1{\cdot}041k_H)$. The food quotient calculated from DHQ was used instead of the respiratory quotient. This assumes that under conditions of perfect nutrient balance the food quotient must equal the respiratory quotient[16,17]. PAL was estimated by dividing TEE by BMR. PAEE was calculated as 0·9 × TEE − BMR, assuming the thermic effect of food was 10 % of TEE[18].

BMR

BMR was measured in the supine position in the early morning 12 h or longer after the last meal, as described previously[19]. The measurement was performed using a Douglas bag for 10 min × 2 with 1 min of intermission. After the expired air was sampled, the O_2 and CO_2 concentrations were measured using a gas analyser (Arco System, AR-1, Kashiwa, Japan for the participants from the SCOP study, or Arco System, ARCO-1000, Kashiwa, Japan, for the rest of the participants) and the volume of expired air was measured with a certified dry gas meter (DC-5; Shinagawa, Tokyo, Japan). BMR was estimated from O_2 consumption and CO_2 production using Weir's equation[15].

Accelerometry

The Lifecorder EX (Suzuken Co., Ltd, Nagoya, Japan) is a uniaxial accelerometer widely used in many countries due to its reasonable cost and reliable validity for measuring metabolic equivalents (METs) and step counts[20–22]. In the present study, the Lifecorder EX was attached on the left side of the waist at the midline of the left thigh. The movement data are categorised into eleven activity levels (0, 0·5, and 1 to 9). We applied METs for each activity level according to the study of Kumahara *et al.*, and the intensity of activity was divided into light (<3 METs), moderate (≥3 and < 6 METs) and vigorous (≥6 METs)[20].

Statistics

All values are presented as mean values and standard deviations. BMI was calculated as BW (measured before DLW dose) divided by height squared. FFMI and FMI were calculated as FFM and FM divided by height squared, respectively. Subjects were classified by quartiles of BMI, FFMI, FMI and %BF. Homoscedasticity or homogeneity of variances was examined using Levene's test. Because some variables in physical characteristics did not follow a normal distribution, the non-parametric test of Kruskal–Wallis analysis was used to compare the variables in physical characteristics among quartiles, and the Mann–Whitney *U* test was used for multiple comparisons. In variables that were normally distributed, one-way ANOVA was used to compare the variables among quartiles and Fisher's least square difference was used as a *post hoc* test for multiple comparisons. The associations between physical activities and body size or composition were examined by linear regression analysis. In one-way ANOVA, *post hoc* tests and Kruskal–Wallis tests, differences were considered to be statistically significant if the *P* value was less than 0·05; using the Mann–Whitney *U* test, differences were deemed significant at $P<0{\cdot}0125$ (modification using Bonferroni's inequality). All statistical treatments were done using SPSS for Windows (version 16.0J; SPSS Inc., Chicago, IL, USA).

Results

Of the total 100 women studied, the proportion of normal-weight (BMI ≥ 18·5 to < 25 kg/m^2) and overweight participants (BMI ≥ 25 kg/m^2) was 76 and 24 %, respectively. The mean age of the subjects was 51·8 (SD 11·2; range 31–69) years. The mean BW and BMI were 57·4 (SD 12·2; range 41·7–109·7) kg and 23·5 (SD 4·4; range 18·8–40·0) kg/m^2, respectively. BW did not change during the study (change of BW 0·02 (SD 0·7) kg; P=0·987). The range of PAL was 1·36–2·52, with a mean value of 1·88.

Physical characteristics and physical activity variables among quartiles of BMI, FFMI, FMI and %BF are shown in Tables 1–4, respectively. Among the physical characteristics, age and height were not significantly different among quartiles. BMI increased linearly with FMI (*r* 0·943) and %BF (*r* 0·749), whereas FFM increased in the 4th quartiles of FMI and %BF (Tables 3 and 4).

Of energy expenditure components, TEE/BW decreased linearly with BMI, FMI and %BF. On the other hand, TEE/BW decreased only in the 4th quartile of FFMI (Table 2). PAEE/FFM and PAEE/BW decreased in the 4th quartile of BMI, but PAL did not differ among quartiles (Table 1). Among FFMI quartiles, there were no significant differences among PAL, PAEE/FFM and PAEE/BW. However, among FMI quartiles, all PAL, PAEE/FFM and PAEE/BW decreased in the 4th quartile. Among %BF quartiles, PAL and PAEE/FFM were significantly lower in the 3rd and 4th quartiles than in the 2nd quartile, whereas PAEE/BW decreased from the 3rd quartile. Fig. 2 shows that PAL was negatively associated with FMI, but not with BMI and FFMI (Fig. 2). PAEE/FFM and PAEE/BW were

Table 1. Participant characteristics, energy expenditure components and physical activity variables by BMI grouping
(Mean values and standard deviations)

BMI (kg/m^2) quartiles‖. . .	1st (18·6–20·4)		2nd (20·5–22·1)		3rd (22·3–24·7)		4th (24·7–40·0)			
	Mean	SD	Mean	SD	Mean	SD	Mean	SD	*P* (ANOVA)	*r*
Physical characteristics										
Age (years)	49·7	11·9	51·4	11·8	53·9	11·9	52·4	9·4	0·630	0·038
Height (m)	1·55	0·04	1·56	0·06	1·56	0·04	1·56	0·06	0·890	0·133
Weight (kg)¶	47·1	3·1	52·1††	4·2	57·2††‡‡	3·3	73·0††‡‡§§	13·4	<0·001	0·948***
BMI (kg/m^2)¶	19·5	0·6	21·3††	0·5	23·5††‡‡	0·9	29·8††‡‡§§	3·9	<0·001	1
%BF¶	28·9	5·1	32·3	4·3	36·0††‡‡	5·0	42·0††‡‡§§	4·6	<0·001	0·747***
FFM (kg)¶	33·5	2·5	35·7	3·6	36·3††	3·8	42·2††‡‡§§	6·7	<0·001	0·743***
FM (kg)¶	13·7	2·8	16·9††	2·7	20·6††‡‡	3·3	30·5††‡‡§§	7·7	<0·001	0·930***
Energy expenditure										
TEE (kJ/d)	8441	1149	8534	883	9333†‡	1244	9939††‡‡	1523	<0·001	0·527***
TEE/BW (kJ/d per kg)	179·8	27·1	164·7†	21·2	163·5†	23·0	138·1††‡§§	20·4	<0·001	−0·588***
BMR (kJ/d)	4492	351	4604	462	4777	588	5558††‡‡§§	892	<0·001	0·725***
PAL	1·88	0·23	1·85	0·22	1·97	0·27	1·80	0·18	0·065	−0·187
PAEE (kJ/d)	3105	913	3077	747	3623	1069	3387	886	0·099	0·120
PAEE/FFM (kJ/d per kg)	92·4	24·8	86·8	21·8	100·7‡	30·6	81·3§	20·3	0·040	−0·207*
PAEE/BW (kJ/d per kg)	66·2	20·6	59·7	16·0	63·8	19·7	47·5††‡§§	13·1	0·001	−0·403***
Accelerometer										
Step counts (per d)	8994	2151	8872	2619	8624	2729	7808	3402	0·427	−0·286**
Light (<3 METs) (min/d)	57·0	15·8	58·4	23·0	62·0	24·8	55·0	20·3	0·691	−0·107
Moderate (≥ 3 and < 6 METs) (min/d)	28·8	12·0	27·1	13·8	23·3	10·2	21·0	13·8	0·122	−0·316**
Vigorous (≥ 6 METs) (min/d)	3·7	3·4	3·0	2·9	2·7	2·7	2·0	2·7	0·246	−0·239*

%BF, body fat percentage; FFM, fat-free mass; FM, fat mass; TEE, total energy expenditure; BW, body weight; PAL, physical activity level (= TEE/BMR); PAEE, physical activity energy expenditure (= 0·9TEE − BMR); METs, metabolic equivalents.

* Significant correlation with BMI: * $P<0·05$, ** $P<0·01$, *** $P<0·001$.

Mean value was significantly different from that for the 1st quartile: † $P<0·05$, †† $P<0·01$.

Mean value was significantly different from that for the 2nd quartile: ‡ $P<0·05$, ‡‡ $P<0·01$.

Mean value was significantly different from that for the 3rd quartile: § $P<0·05$, §§ $P<0·01$.

‖ Subjects were categorised by quartile. There are twenty-five subjects in each quartile.

¶ Because some variables in physical characteristics did not follow a normal distribution, Kruskal–Wallis analysis was used to compare the variables among quartiles, and the Mann–Whitney *U* test was used for multiple comparisons.

Table 2. Participant characteristics, energy expenditure components and physical activity variables by fat-free mass index (FFMI) grouping
(Mean values and standard deviations)

FFMI quartiles‖…	1st (12·2–13·8)		2nd (13·8–14·6)		3rd (14·7–15·6)		4th (15·7–21·6)			
	Mean	SD	Mean	SD	Mean	SD	Mean	SD	*P* (ANOVA)	*r*
Physical characteristics										
Age (years)	48·5	12·9	55·6	10·5	54·0	10·9	49·1	9·1	0·054	−0·026
Height (m)	1·56	0·05	1·56	0·05	1·55	0·06	1·57	0·05	0·587	0·093
Weight (kg)¶	50·1	4·4	52·0	4·5	56·2††	7·7	71·1††‡‡§§	15·1	<0·001	0·753***
BMI (kg/m^2)¶	20·6	1·4	21·6	2·1	23·3††	2·6	28·7††‡‡§§	5·2	<0·001	0·794***
%BF¶	34·9	4·0	32·8	6·2	33·9	7·4	37·6	8·3	0·045	0·247*
FFM (kg)¶	32·2	2·0	34·6††	2·2	36·8††‡‡	2·8	44·0††‡‡§§	4·9	<0·001	0·890***
FM (kg)¶	17·6	3·2	17·2	4·5	19·5	6·4	27·3††‡‡§§	10·5	<0·001	0·581***
FFMI (kg/m^2)	13·3	0·4	14·3	0·3	15·2	0·3	17·8	1·5	<0·001	1
Energy expenditure										
TEE (kJ/d)	8017	891	8676	932	9306††	1100	10 248††‡‡§§	1358	<0·001	0·626***
TEE/BW (kJ/d per kg)	160·9	20·2	167·6	20·2	169·3	35·2	148·4‡§	26·8	0·025	−0·262**
BMR (kJ/d)	4391	444	4582	423	4871††‡	533	5587††‡‡§§	826	<0·001	0·708***
PAL	1·83	0·18	1·91	0·24	1·92	0·29	1·85	0·20	0·484	−0·064
PAEE (kJ/d)	2824	659	3226	841	3505†	1090	3636††	890	0·011	0·263**
PAEE/FFM (kJ/d per kg)	88·0	21·9	93·4	24·5	96·3	31·0	83·6	22·6	0·368	−0·151
PAEE/BW (kJ/d per kg)	56·6	13·1	62·4	17·1	64·5	24·7	53·6	17·3	0·182	−0·157
Accelerometer										
Step counts (per d)	8589	2592	8914	2437	8267	2635	8528	3403	0·878	−0·159
Light (<3 METs) (min/d)	53·6	20·4	59·1	17·2	55·7	18·9	64·1	26·5	0·320	0·040
Moderate (≥ 3 and < 6 METs) (min/d)	28·0	15·2	27·3	10·4	23·9	12·0	21·1	12·3	0·187	−0·300**
Vigorous (≥ 6 METs) (min/d)	3·4	3·0	2·6	2·8	3·1	3·6	2·3	2·3	0·513	−0·108

%BF, body fat percentage; FFM, fat-free mass; FM, fat mass; TEE, total energy expenditure; BW, body weight; PAL, physical activity level (= TEE/BMR); PAEE, physical activity energy expenditure (= 0·9TEE − BMR); METs, metabolic equivalents.

* Significant correlation with FFMI: * $P<0·05$, ** $P<0·01$, *** $P<0·001$.

Mean value was significantly different from that for the 1st quartile: † $P<0·05$, †† $P<0·01$.

Mean value was significantly different from that for the 2nd quartile: ‡ $P<0·05$, ‡‡ $P<0·01$.

Mean value was significantly different from that for the 3rd quartile: § $P<0·05$, §§ $P<0·01$.

‖ Subjects were categorised by quartile. There are twenty-five subjects in each quartile.

¶ Because some variables in physical characteristics did not follow a normal distribution, Kruskal–Wallis analysis was used to compare the variables among quartiles, and the Mann–Whitney *U* test was used for multiple comparisons.

Table 3. Participant characteristics, energy expenditure components and physical activity variables by fat mass index (FMI) grouping (Mean values and standard deviations)

FMI quartiles‖…	1st (2·94–6·39)		2nd (6·49–7·52)		3rd (7·55–9·73)		4th (9·82–19·49)			
	Mean	SD	Mean	SD	Mean	SD	Mean	SD	*P* (ANOVA)	*r*
Physical characteristics										
Age (years)	49·9	10·9	52·4	12·2	51·4	11·6	53·5	10·3	0·713	0·085
Height (m)	1·56	0·05	1·56	0·05	1·56	0·05	1·56	0·06	0·921	0·138
Weight (kg)¶	48·3	4·5	51·7	4·5	56·7††‡‡	4·4	72·8††‡‡§§	13·5	<0·001	0·897***
BMI (kg/m^2)¶	19·9	1·2	21·3††	1·2	23·2††‡‡	1·7	29·6††‡‡§§	4·2	<0·001	0·943***
%BF¶	26·4	4·2	32·9††	1·5	37·1††‡‡	1·7	42·9††‡‡§§	3·9	<0·001	0·916***
FFM (kg)¶	35·6	3·9	34·9	4·0	35·7	3·3	41·5††‡‡§§	7·1	0·001	0·565***
FM (kg)¶	12·8	2·4	17·0††	1·3	21·0††‡‡	1·7	30·9††‡‡§§	7·2	<0·001	0·982***
FMI (range) (kg/m^2)	5·3	0·9	7·0	0·3	8·6	0·7	12·6	2·3	<0·001	1
Energy expenditure										
TEE (kJ/d)	8810	1097	8782	1258	9049	1346	9607	1576	0·110	0·352***
TEE/BW (kJ/d per kg)	183·4	25·4	170·0†	20·7	159·4††	17·2	133·3††‡‡§§	16·7	<0·001	−0·696***
BMR (kJ/d)	4586	375	4584	457	4760	559	5503††‡‡§§	971	<0·001	0·610***
PAL	1·91	0·22	1·93	0·28	1·91	0·21	1·76†‡§	0·19	0·036	−0·254*
PAEE (kJ/d)	3343	847	3320	1082	3384	914	3143	876	0·827	−0·017
PAEE/FFM (kJ/d per kg)	94·3	23·6	95·9	31·3	94·3	21·1	76·8†‡‡§	20·4	0·024	−0·258**
PAEE/BW (kJ/d per kg)	69·6	19·0	64·2	19·5	59·4†	14·0	43·9††‡‡§§	11·7	<0·001	−0·502***
Accelerometer										
Step counts (per d)	8508	2034	9724	2154	8866	3387	7200‡‡§	2777	0·011	−0·293**
Light (<3 METs) (min/d)	56·5	17·0	63·0	21·2	61·3	26·5	51·7	17·8	0·224	−0·156
Moderate (≥ 3 and < 6 METs) (min/d)	24·9	9·7	30·3	13·2	25·7	14·6	19·3‡‡	11·0	0·021	−0·265**
Vigorous (≥ 6 METs) (min/d)	3·8	3·5	3·5	3·0	2·3	2·1	1·8†‡	2·7	0·042	−0·282**

%BF, body fat percentage; FFM, fat-free mass; FM, fat mass; TEE, total energy expenditure; BW, body weight; PAL, physical activity level (= TEE/BMR); PAEE, physical activity energy expenditure (= 0·9TEE − BMR); METs, metabolic equivalents.

* Significant correlation with FMI: * $P<0·05$, ** $P<0·01$, *** $P<0·001$.

Mean value was significantly different from that for the 1st quartile: † $P<0·05$, †† $P<0·01$.

Mean value was significantly different from that for the 2nd quartile: ‡ $P<0·05$, ‡‡ $P<0·01$.

Mean value was significantly different from that for the 3rd quartile: § $P<0·05$, §§ $P<0·01$.

‖ Subjects were categorised by quartile. There are twenty-five subjects in each quartile.

¶ Because some variables in physical characteristics did not follow a normal distribution, Kruskal–Wallis analysis was used to compare the variables among quartiles, and the Mann–Whitney *U* test was used for multiple comparisons.

Table 4. Participant characteristics, energy expenditure components and physical activity variables by body fat percentage (%BF) grouping
(Mean values and standard deviations)

%BF quartiles‖...	1st (15·9–31·0)		2nd (31·4–34·5)		3rd (34·6–38·8)		4th (39·1–54·3)			
	Mean	SD	Mean	SD	Mean	SD	Mean	SD	*P* (ANOVA)	*r*
Physical characteristics										
Age (years)	48·7	10·6	53·8	12·3	50·3	11·3	53·8	10·2	0·596	0·138
Height (m)	1·56	0·06	1·55	0·04	1·56	0·05	1·57	0·06	0·839	0·112
Weight (kg)¶	49·0	5·4	53·4†	6·5	54·8††	4·3	72·3††‡‡§§	13·9	<0·001	0·710***
BMI (kg/m^2)¶	20·1	1·3	22·1††	2·2	22·6††	2·0	29·3††‡‡§§	4·5	<0·001	0·749***
%BF¶	26·2	4·1	32·7††	0·9	37·0††‡‡	1·2	43·2††‡‡§§	3·4	<0·001	1
FFM (kg)¶	36·1	4·2	36·0	4·5	34·5	2·6	41·0‡§§	7·2	0·005	0·278**
FM (kg)¶	12·9	2·7	17·5††	2·4	20·3††‡‡	1·8	30·9††‡‡§§	7·2	<0·001	0·889***
Energy expenditure										
TEE (kJ/d)	8845	1091	9326	1375	8600	1090	9477	1657	0·074	0·122
TEE/BW (kJ/d per kg)	182·1	26·9	175·0	19·4	156·6††‡‡	13·1	132·4††‡‡§§	15·5	<0·001	−0·725***
BMR (kJ/d)	4640	372	4727	530	4680	556	5385††‡‡§§	1041	<0·001	0·368***
PAL	1·90	0·22	1·98	0·26	1·85‡	0·22	1·78‡‡	0·19	0·013	−0·243*
PAEE (kJ/d)	3321	861	3666	1072	3059	806	3144	872	0·099	−0·124
PAEE/FFM (kJ/d per kg)	92·5	24·5	102·6	29·6	88·2‡	20·6	77·9‡‡	20·6	0·006	−0·244*
PAEE/BW (kJ/d per kg)	68·5	19·8	68·7	18·1	55·5††‡‡	12·8	44·4††‡‡§	12·0	<0·001	−0·515***
Accelerometer										
Step counts (per d)	8675	2082	9449	2173	9067	3288	7107†‡‡§	2869	0·013	−0·293**
Light (<3 METs) (min/d)	58·0	16·2	64·9	23·1	59·2	24·6	50·4	18·1	0·113	−0·168*
Moderate (≥ 3 and < 6 METs) (min/d)	25·7	10·2	26·4	11·2	28·7	15·7	19·4	11·8	0·057	−0·154
Vigorous (≥ 6 METs) (min/d)	3·4	3·4	3·9	3·0	2·3	2·3	1·8	2·7	0·052	−0·287**

FFM, fat-free mass; FM, fat mass; TEE, total energy expenditure; BW, body weight; PAL, physical activity level (= TEE/BMR); PAEE, physical activity energy expenditure (= 0·9TEE − BMR); METs, metabolic equivalents.
* Significant correlation with %BF: * $P<0·05$, ** $P<0·01$, *** $P<0·001$.
Mean value was significantly different from that for the 1st quartile: † $P<0·05$, †† $P<0·01$.
Mean value was significantly different from that for the 2nd quartile: ‡ $P<0·05$, ‡‡ $P<0·01$.
Mean value was significantly different from that for the 3rd quartile: § $P<0·05$, §§ $P<0·01$.
‖ Subjects were categorised by quartile. There are twenty-five subjects in each quartile.
¶ Because some variables in physical characteristics did not follow a normal distribution, Kruskal–Wallis analysis was used to compare the variables among quartiles, and the Mann–Whitney *U* test was used for multiple comparisons.

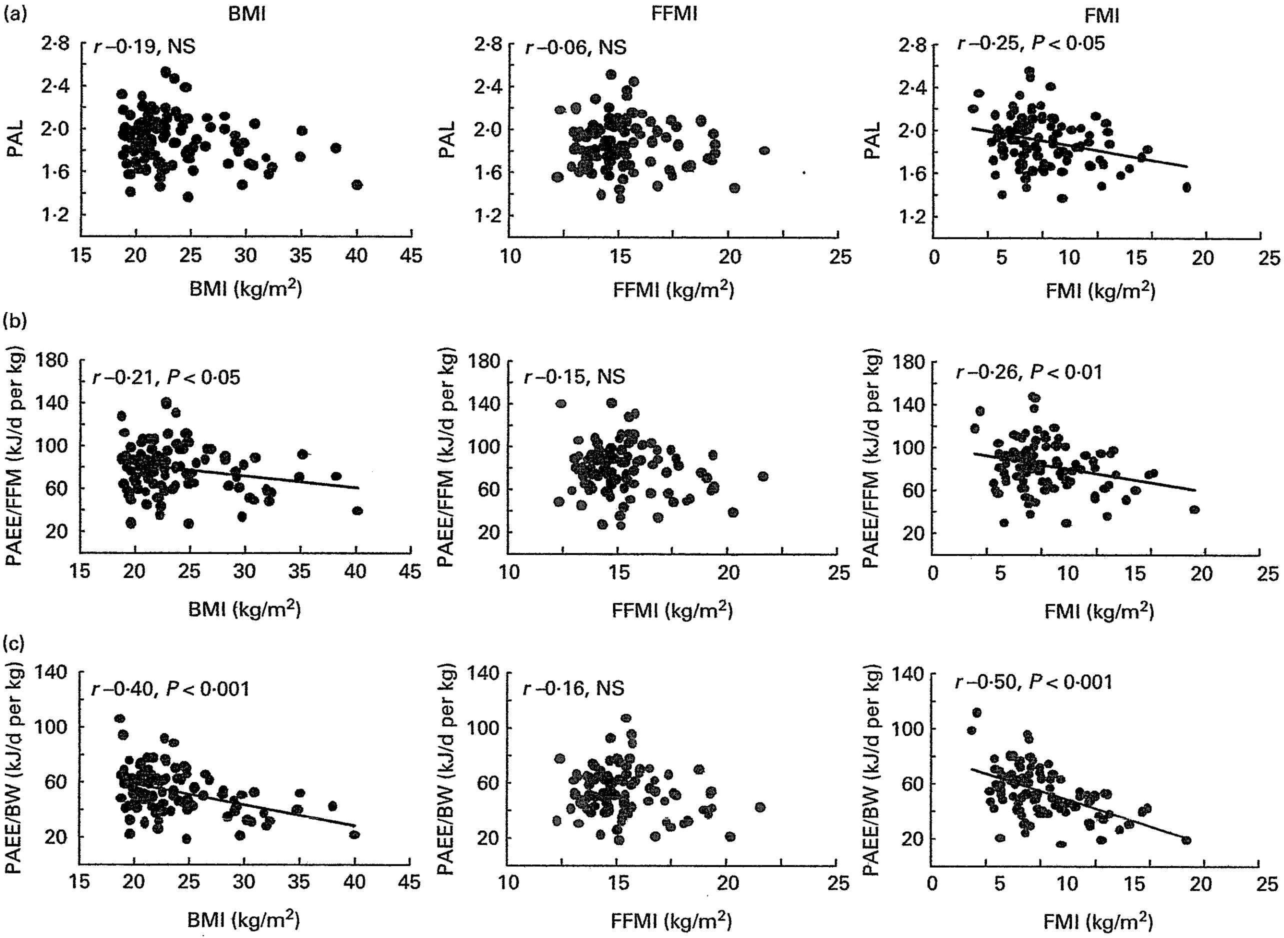

Fig. 2. Relationships between BMI, fat-free mass index (FFMI) or fat mass index (FMI) and physical activity level (PAL) (a), physical activity-related energy expenditure/fat-free mass (PAEE/FFM) (b) or PAEE/body weight (BW) (c). PAL = TEE/BMR, where TEE is total energy expenditure; PAEE = 0·9TEE − BMR; 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 ≥ 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 ≥ 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 $< 18{\cdot}5\,\text{kg/m}^2$).

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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Effects of Walking Speed and Step Frequency on Estimation of Physical Activity Using Accelerometers

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Abstract This study evaluated the accuracy of assessing step counts and energy costs under walking conditions altered by step frequency changes at given speeds using uni- (LC) and tri-axial accelerometers (AM, ASP). Healthy young men and women ($n=18$) volunteered as subjects. Nine tests were designed to manipulate three step frequencies, low (−15% of normal), normal, and high (+15%), at each walking speed (55, 75, and 95 m/min). A facemask connected to a Douglas bag was attached to subjects, who wore accelerometers around their waist. LC underestimated the step counts at normal or high step frequency at 55 m/min and AM also at all step frequencies at 55 m/min, whereas ASP did not in all trials. LC underestimated metabolic equivalents (METs) at low or normal step frequency at all walking speeds. AM underestimated METs at low step frequency at all walking speeds and at high step frequency of 95 m/min. ASP gave underestimates only at low step frequency of 95 m/min. The degree of the percentage error of METs for AM and ASP was affected by step frequency. Significant interaction between step frequency and speed was found that for LC. These results suggest that LC and AM can cause errors in step-count functions at a low walking speed. Furthermore, LC may show low accuracy of the METs measurement during walking altered according to step frequency and speed, whereas AM and ASP, which are tri-axial accelerometers, are more accurate but the degree of the percentage error is affected by step frequency. *J Physiol Anthropol 30(3): 119–127, 2011* http://www.jstage.jst.go.jp/browse/jpa2
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Keywords: accelerometers, step frequency, step counts, energy costs

Introduction

Walking is the most basic form of human locomotion and one of the most important components of many daily physical activities. An increased amount of energy expended in daily walking reportedly has significant effects on suppressing the progress of various diseases (Hakim et al., 1999; Lee and Buchner, 2008). Thus, walking represents a significant index of human health. Generally, human walking is complexly composed of the multidirectional characteristics of movements altered by combinations of speed and step frequency. Therefore, it would be of great value to accurately assess the number of steps or energy costs expended by various walking movements.

Pedometers are the simplest and the most inexpensive method that has been used for objective assessment of physical behaviors (Crouter et al., 2003; Schneider et al., 2004). Pedometers, especially, have the great advantage of providing immediate information on accumulated step counts as a real-time feedback tool to be more physically active (Bravata et al., 2007). Pedometers have been popularly used for normal subjects and certain epidemiological studies in Japan (Hatano 1993; Mitsui et al., 2008) and mechanisms have gradually been developed for detecting a step from using a spring-suspended lever arm (metal-on-metal contact) to using a magnetic reed proximity switch or accelerations (accelerometer). On the other hand, accelerometers are increasingly used to allow researchers to assess energy costs, and they are considered superior to other methods of measuring various physical activity categories, e.g., low or moderate-intensity activities like walking spread throughout the day (Plasqui and Westerterp, 2007; Bassett et al., 2008). Given the importance of quantifying step counts, most accelerometers made in Japan provide information not only on energy costs but also step counts. The Kenz Lifecorder EX (LC; Suzuken Co., Ltd., Nagoya, Japan), a uniaxial accelerometer using vertical acceleration, is already popular in many countries due to its reasonable cost and reliability for measuring the energy cost of walking or daily physical activity (Kumahara et al., 2004; McClain et al., 2007a, b). More recently, the Actimarker (AM; Panasonic Electronic Works Co., Ltd., Osaka, Japan) and the Active Style Pro (ASP; Omron Health Care Co., Ltd., Kyoto, Japan), newer triaxial accelerometers, have just become commercially available. Tri-axial accelerometers for measuring daily physical activity are considered more accurate than uni-accelerometers (Plasqui and Westerterp, 2007; Yamada et al., 2009).

Many investigators have assessed the accuracy and reliability of pedometers and accelerometers, respectively, under various walking conditions (Crouter et al., 2003; Schneider et al., 2004). Pedometers or accelerometers are found to be less accurate in capturing step counts precisely at slow speeds below around $55\,\mathrm{m \cdot min^{-1}}$ (Crouter et al., 2003; Le Masurier and Tudor-Locke, 2003; Le Masurier et al., 2004). Pedometers or accelerometers have their own vertical acceleration 'threshold' to capture a step. So far, low walking speed is the only factor known to lower accuracy in measuring steps; however, it remains unknown whether or not step frequency changes at a fixed walking speed (especially a slower walking speed) would affect accuracy in measuring step counts.

With respect to measuring energy costs, the uni- (vertical) or tri-axial (vertical, anteroposterior, and mediolateral) accelerometers have clearly demonstrated that output has a strong linear relationship with increasing walking speed (Bouten et al., 1994; Kumahara et al., 2004; Rowlands et al., 2007). However, in these studies, step frequency increased concurrently with walking speed. The rate of body movement changed by step length (step frequency) is likely to be proportional to the displacement in the anteroposterior direction (Dillman, 1975). In this case, a triaxial accelerometer using the integral of three accelerations (vertical, anteroposterior, and mediolateral) would be an appropriate method to quantify the energy cost from the multidirectional characteristics of human movement during walking. However, it remains unclear how much step frequency changes at a fixed walking speed would independently affect the accuracy of measuring energy costs with any accelerometer.

Accordingly, the purpose of the present study was to evaluate the accuracy of measuring step-count functions and energy costs from these three accelerometers under walking conditions altered by step frequency changes at given speeds.

Methods

Subjects

We recruited 18 healthy adult participants (9 male and 9 female, 23–41 yr) who work at the same worksites and did not have any physical impairment that affected ambulation. The descriptive characteristics of the subjects are presented in Table 1. All aspects of this study were approved by the Ethical Committee of the National Institute of Health and Nutrition. All subjects signed an informed consent document before the investigations were conducted.

Experimental Protocol

The resting metabolic rate (RMR) was measured 3 hr after each subject had lunch. Each subject became accustomed to walking on a motor-driven treadmill until it became natural. Afterward, the normal step frequency (step counts$\cdot$min^{-1}) at which each subject feels comfortable walking (normal step frequency for each subject) was assessed by a researcher using a hand-tally counter at speeds of around 55, 75, and 95 m/min, which were generally used as low, normal, and high (brisk) walking speeds, respectively (Le Masurier and Tudor-Locke, 2003; Midorikawa et al., 2007). A low step frequency for each subject was calculated as -15% of normal step frequency and a high step frequency as $+15\%$. The 15% change in step frequency during walking on a treadmill was chosen based on the range of stride length that can be easily performed and is sufficient to significantly increase metabolic costs (Holt et al., 1991; Russell et al., 2010). Before starting the measurements, each subject practiced walking while matching it to the tempo (frequency) of an electronic metronome sound. Afterward, a facemask connected to the Douglas bag was worn by subjects with three accelerometers equipped on their waist; they then took a 5-minute rest while sitting on a chair mounted on the treadmill. The experimental procedure started at a 55 m/min pace, and then was repeated at 75 and 95 m/min in order. Three trials of normal, high, and low frequency were included at each walking speed (i.e., a total of nine tests were performed). The order of the nine tests was not randomized in order to assess them from lower to higher metabolic cost. A 15% decrease in stride length, i.e., increased step frequency, requires more energy expenditure compared with normal stride length (Russell et al., 2010) and longer steps at given walking speeds increase metabolic cost even more (Cavagna and Franzetti, 1986). The subject took a 5-min rest while seated between settings of step frequency and a 30-min rest between settings of walking speed. Also, we recorded the number of steps counted by three accelerometers during each trial and recorded all trials using a digital video recorder for precise counting later.

Measurement of resting metabolic rate and metabolic equivalents

Three hr after lunch, each subject sat relaxed for 30 min to reach stable oxygen consumption. RMR was then measured using a mask and Douglas bag for 20 min (10 min×2 with a 1-minute intermission). Energy expenditure during walking was measured using a mask and Douglas bag. Each subject walked for 6 min at 55 m/min and 5 min at 75 or 95 m/min, and respiratory measurements were made during the last 3 min and 2 min at 55 m/min and 75 or 95 m/min, respectively. O_2 and CO_2 concentrations of expired gas were measured using a gas analyzer (ARCO-1000A; Arco System, Kashiwa, Japan). Before each measurement, the gas analyzer was calibrated using room air and a certified gas. Expired gas volume was measured with a certified dry gas meter (SHINAGAWA DC-5, Tokyo, Japan). Energy expenditure (kcal) was calculated from O_2 consumption and CO_2 production using Weir's equation (Weir, 1949). The metabolic equivalents (METs) were determined by energy expenditure (kcal) obtained during walking divided by the measured RMR.

Equipment

Kenz Lifecorder EX

The Kenz Lifecorder EX (LC; Suzuken Co., Ltd., Nagoya, Japan) is a uniaxial accelerometer, 70×40×25 mm in size and 30 g in mass. In this study, devices were attached on the side of the waist at the midline of the left thigh. This accelerometer samples at 32 Hz and assesses values ranging from 0.06 to 1.94 G. The LC uses only four thresholds from maximum amplitudes of vertical acceleration when determining the intensity levels. The signal is filtered by an analog bandpass filter and digitized. The maximum amplitude of the acceleration sensor and the step count generated by vertical movement determine the intensity levels. Ten intensity levels (0.5 and 1–9) are used to categorize intensities. The LC was initialized by setting the precise time and date and inputting the gender, age, height, and weight of each subject. After completing all trials, the data were downloaded using Physical Activity Analysis Software (Version 1.0, Suzuken Co., Ltd., Nagoya, Japan). The intensities obtained every 4 sec were converted into METs using Kumahara's equation obtained during progressive walking and running on a treadmill (Kumahara et al., 2004). The relationship between METs and activity level was highly significant ($r^2=0.929$):

$\mathrm{METs}=0.043x^2+0.379x+1.361$ (Kumahara et al., 2004)

where x is the intensity level (0.5, 1–9 intensities).

Actimarker

The Actimarker (AM; Panasonic Electronic Works, Ltd., Osaka, Japan) is a triaxial accelerometer, 60×35×12 mm in size, and 30 g in mass. In the present study, devices were attached on either side of the waist at the midline of the left thigh. This device was released for sale in 2008 and has field-proven reliability for estimating various activities (Yamada et al., 2009). The AM had user-friendly software providing activity intensity categories, daily energy expenditure, steps, and METs·hr. This device obtained three-dimensional accelerations with a sensitivity of 4 mG and with a band-pass filter of 0.3 to 100 Hz. The acceleration count was calculated as the average of the absolute values from acceleration in each direction for a given interval (12 sec). The acceleration data were uploaded to a personal computer, and converted into METs by the following equation:

Physical Activity Energy Expenditure (PAEE) (kcal/min) = $ax\times$[basal metabolic rate (BMR)]/1440+RMR

where a is a coefficient, and x is the output data from synthetic accelerations of 3 dimensions.

RMR is calculated by BMR×1.2

METs=PAEE/RMR.

The BMR was estimated according to the sixth Recommended Dietary Allowances for Japanese (Ministry of Welfare Japan, 1999). We also obtained the data of anteroposterior, mediolateral, and vertical accelerations from special software of the AM which was not available commercially.

Active Style Pro

The Active Style Pro (ASP; Omron Health Care Co., Ltd., Kyoto, Japan) is also a triaxial accelerometer, 80×20×50 mm in size, and 61 g in mass. The ASP was released for sale in Japan in 2008 and has proven reliability for estimating various activities (Oshima et al., 2010). In the present study, devices were attached on the right side of the waist. Anteroposterior, mediolateral, and vertical accelerations were obtained from the triaxial accelerometer during each activity with a sensitivity of 3 mG and at a sampling rate of 32 Hz. With a 12-bit analog to digital converter, the maximum scaling of the acceleration data was ±2048 counts. Acceleration data were then uploaded to a personal computer. The signals obtained from the triaxial accelerometer were processed in the following way. Each of the 3 signals from the triaxial accelerometer was passed through a high-pass filter with a cutoff frequency at 0.7 Hz to remove the gravitational acceleration component from the signal. We calculated the integral of the absolute value of the accelerometer output of each of the 3 axes using acceleration signals over a 10-sec time interval. After the synthetic acceleration was filtered, it was categorized into either lifestyle or locomotive activity using a ratio of unfiltered to filtered synthetic acceleration. Synthetic accelerations of three dimensions were converted into METs by the follow equations:

If Counts/min: $\leqq A$, Sedentary METs is $b+ax$

If Counts/min: $>A$ and Ratio: $\leqq B$, lifestyle activity formula METs is $d+cx$

If Ratio: $>B$, locomotive activity formula METs is $f+ex$

where A and B are thresholds, and a to f are coefficients.

x is output data from synthetic accelerations of 3 dimensions.

Statistics

All values are presented as means±SD. Differences were considered to be statistically significant if the *p* value was <0.05. Significant differences between men and women in the physical or gait characteristics were analyzed by an unpaired-sample *t*-test. The percentage error was calculated as [(predicted value−observed value)/observed value] ×100. Statistical comparisons of measured METs or the acceleration data obtained from the AM among step frequencies at each walking speed were performed by one-way analyses of variance (ANOVA) with repeated measures, and the Bonferroni procedure was used for *post-hoc* tests. One-way ANOVA with repeated measures was also used to compare differences between observed and predicted step counts or measured and predicted METs among accelerometers at each step frequency at a given walking speed; the Dunnett procedure was used for *post-hoc* tests. Two-way (step frequency and speed) ANOVA with repeated measures was used to determine how the factors affected the percentage error between measured and predicted METs in each accelerometer. When significant interactions were detected, simple main effect analysis was employed for each low, normal, or high step frequency to compare the effect of speed with the Bonferroni adjustment procedure. Multiple stepwise regression analysis

Table 1 Physical characteristics of subjects

	Men (N=9)	Women (N=9)	All subjects (N=18)
Age (yr)	31.0±4.9 (24–37)	28.1±5.9 (23–41)	29.6±5.5 (23–41)
Height (cm)	171.6±2.2 (167.6–173.9)	161.5±5.9 (151.4–167.9)*	166.5±6.8 (151.4–173.9)
Body mass (kg)	71.2±6.5 (62.3–78.2)	52.7±6.2 (45.3–59.2)*	71.2±6.5 (45.3–78.2)
BMI ($\mathrm{kg \cdot m^{-2}}$)	24.2±2.1 (20.9–26.5)	20.1±1.6 (18.0–23.3)*	24.2±2.1 (18.0–26.5)
RMR ($\mathrm{kcal \cdot min^{-1}}$)	1.1±0.3 (0.77–1.59)	0.9±0.1 (0.76–1.01)	1.1±0.3 (0.76–1.59)
Step length (cm)			
55 $\mathrm{m \cdot min^{-1}}$	57.2±5.2 (50.9–66.3)	58.2±5.9 (51.4–67.9)	57.2±5.2 (50.9–67.9)
75 $\mathrm{m \cdot min^{-1}}$	67.7±4.2 (60.0–74.3)	69.0±4.9 (59.5–74.0)	67.7±4.2 (59.5–74.3)
95 $\mathrm{m \cdot min^{-1}}$	79.4±4.9 (70.4 - 85.6)	78.3±6.1 (64.6 - 82.6)	79.4±4.9 (64.6–85.6)
Step frequency			
55 $\mathrm{m \cdot min^{-1}}$	96.8±8.5 (83–108)	95.3±9.5 (81–107)	96.8±8.5 (81–108)
75 $\mathrm{m \cdot min^{-1}}$	111.1±7.1 (101–125)	109.2±8.3 (101–126)	111.1±7.1 (101–126)
95 $\mathrm{m \cdot min^{-1}}$	120.1±7.7 (111–135)	122.1±10.6 (110–147)	120.1±7.7 (110–147)

Abbreviations: BMI, body mass index; RMR, resting metabolic rate
Values are means±s.d. (range). * indicates a significant difference from Men ($p<0.001$).

Table 2 Accuracy of step-count functions among accelerometers

walking speed	Step frequency	Visually counted steps	Step detected			p value		
			LC	AM	ASP	LC	AM	ASP
55 m/min	low	492±45	452±64	410±97	464±87	0.171	0.001	0.414
	normal	580±54	534±86	475±81	576±64	0.023	<0.001	0.984
	high	662±59	616±72	576±70	650±58	0.002	<0.001	0.695
75 m/min	low	475±31	478±47	466±48	477±32	0.968	0.693	0.997
	normal	552±40	538±49	545±43	551±40	0.069	0.590	1.000
	high	633±59	595±113	634±76	633±60	0.135	1.000	1.000
95 m/min	low	522±40	522±39	521±40	522±41	0.999	0.969	0.994
	normal	609±41	606±40	608±41	609±41	0.246	0.924	0.996
	high	705±48	692±56	702±49	701±47	0.191	0.986	0.921

Values are means±s.d. LC, Kenz Lifecorder; AM, Actimarker; ASP, Active Style Pro

was employed to determine which variables (step frequency, speed, step frequency x speed, sex, height, and body mass) contribute to the percentage error of estimating METs or step counts in each accelerometer. All statistical treatments were done using SPSS for Windows (version 16.0J; SPSS Inc., Chicago, IL, USA).

Results

The physical or gait characteristics of the subjects are shown in Table 1. Height, body mass, and BMI were significantly higher in men than in women ($p<0.001$), whereas the other factors did not differ between genders.

Accuracy of detecting step counts

The LC significantly underestimated step counts at the normal or high step frequency at 55 m/min (Table 2). The AM significantly underestimated step counts at all step frequencies at 55 m/min, whereas the ASP did not in any of the nine trials. In the percentage error between the measured and predicted step counts for each accelerometer, two-way ANOVA analysis demonstrated no significant interactions between step frequency and speed in all accelerometers (Fig. 1). Speed significantly contributed to the percentage error in all accelerometers whereas step frequency did not. A stepwise multiple regression analysis of predictors of the percentage error (including step frequency, speed, step frequency by speed, sex, height, and body mass) in the LC and AM revealed that speed was the only significant predictor ($\beta=0.32$, $p<0.001$ for the LC; $\beta=0.57$, $p<0.001$ for the AM), but no other factors were selected. The final models of the LC and AM accounted for 11% and 32% of the variance of the percentage error, respectively. In the case of the ASP, step frequency by speed was the only significant predictor ($\beta=0.21$, $p=0.007$), and the final model accounted for 5% of the variance in percentage error.

METs measured from Douglas bag method

The METs measured at low, normal, and high step frequency were shown in Table 3. There were no differences in measured METs among the three step frequencies at 55 m/min. However, at 75 and 95 m/min ($p=0.003$ and $p<0.001$, respectively), the measured METs at the low step frequency were significantly higher than those of the normal step frequency.

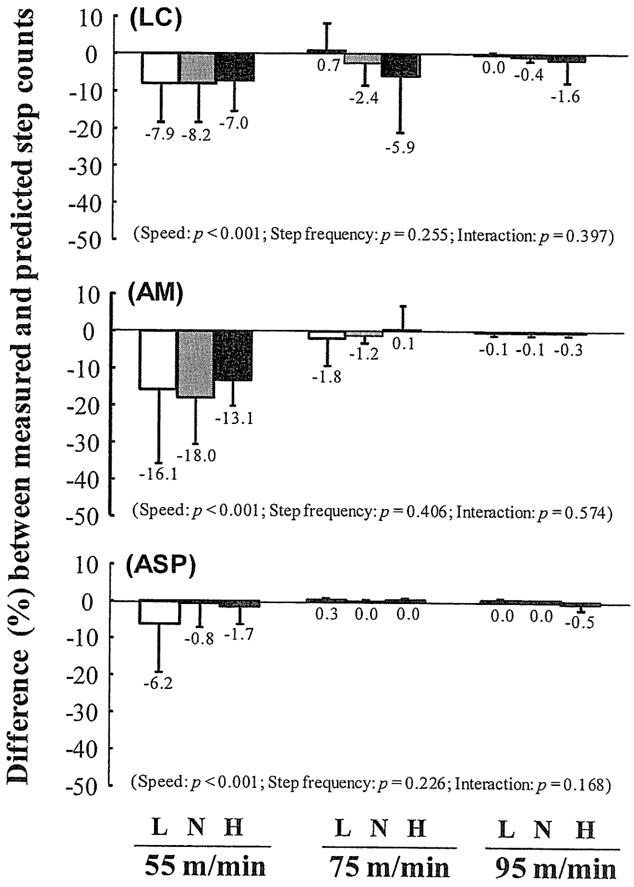

Fig. 1 Difference between measured (video records) and predicted step counts (LC, Kenz Lifecorder; AM, Actimarker; ASP, Active Style Pro) across conditions altered by three step frequencies (L, Low step frequency; N, Normal step frequency; H, High step frequency) at each walking speed (55, 75, and 95 m/min). The numbers under the bars indicate the difference (%) between measured and predicted step counts. The results of two-way ANOVA analysis were shown in parentheses for each accelerometer.

Accuracy of predicted METs in accelerometers

The LC significantly underestimated METs at the low and normal step frequencies at all walking speeds (Table 3). The AM significantly underestimated METs at the low step frequency at all walking speeds and also at the high step frequency of 95 m/min. The ASP significantly underestimated only at the low step frequency of 95 m/min. In the percentage error between the measured and predicted METs for each accelerometer, two-way ANOVA analysis demonstrated significant interaction between step frequency and speed only in the LC (Fig. 2). Simple main effect analysis in the LC showed no significant differences in the percentage errors among the three low step frequencies (55 m/min vs. 75 m/min: $p=0.788$; 75 m/min vs. 95 m/min: $p=0.647$; 55 m/min vs. 95 m/min: $p=0.060$), the three normal step frequencies (all $p=1.000$), or the three high step frequencies (55 m/min vs. 75 m/min and 75 m/min vs. 95 m/min: $p=1.000$; 55 m/min vs. 95 m/min: $p=0.612$). Step frequency significantly contributed to the percentage error in the AM and ASP, whereas speed did not. As shown in Table 4, a stepwise multiple regression analysis of predictors in the percentage error between the measured and predicted METs for each accelerometer revealed that step frequency was the strongest predictor in the LC. Speed and height were significantly associated, but step frequency by speed, sex, and body mass was not selected for the model. The final model accounted for 58% of the model variation. The percentage error in the AM showed that height and sex significantly contributed to the percentage error, but step frequency, speed, and step frequency by speed were not selected. The final model accounted for 8.8% of the model variation. With ASP, the step frequency and speed significantly contributed to the percentage error, and the final model accounted for 10% of the model variation.

Anteroposterior, mediolateral, and vertical accelerations

Figure 3 shows the absolute data of anteroposterior, mediolateral, and vertical accelerations measured by the AM. Mediolateral acceleration at 55 m/min was significantly higher at the high step frequency than at the normal step frequency. Mediolateral acceleration at 75 m/min and 95 m/min was

Table 3 Accuracy of predicted METs among accelerometers

walking speed	Step frequency	Observed METs steps	Predicted METs			*p* value		
			LC	AM	ASP	LC	AM	ASP
55 m/min	low	3.2±0.9	2.2±0.1	2.8±0.3	3.0±0.3	<0.001	0.035	0.643
	normal	2.8±0.4	2.5±0.3	2.7±0.2	3.0±0.2	0.009	0.411	0.096
	high	3.0±0.7	2.9±0.4	2.8±0.3	3.2±0.3	0.866	0.250	0.616
75 m/min	low	4.1±0.7	2.6±0.3	3.5±0.3	3.9±0.3	<0.001	0.002	0.567
	normal	3.6±0.7	3.1±0.4	3.3±0.3	3.9±0.4	0.004	0.151	0.273
	high	3.8±0.9	4.0±1.0	3.4±0.5	4.0±0.7	0.714	0.178	0.616
95 m/min	low	6.0±1.0	3.3±0.4	4.7±0.3	5.2±0.4	<0.001	<0.001	0.001
	normal	4.5±0.6	4.0±0.8	4.2±0.3	4.9±0.4	0.010	0.093	0.141
	high	4.7±0.8	5.1±0.6	4.2±0.5	5.1±0.6	0.074	0.045	0.168

Values are means±s.d. METs, Metabolic equivalents; LC, Kenz Lifecorder; AM, Actimarker; ASP, Active Style Pro

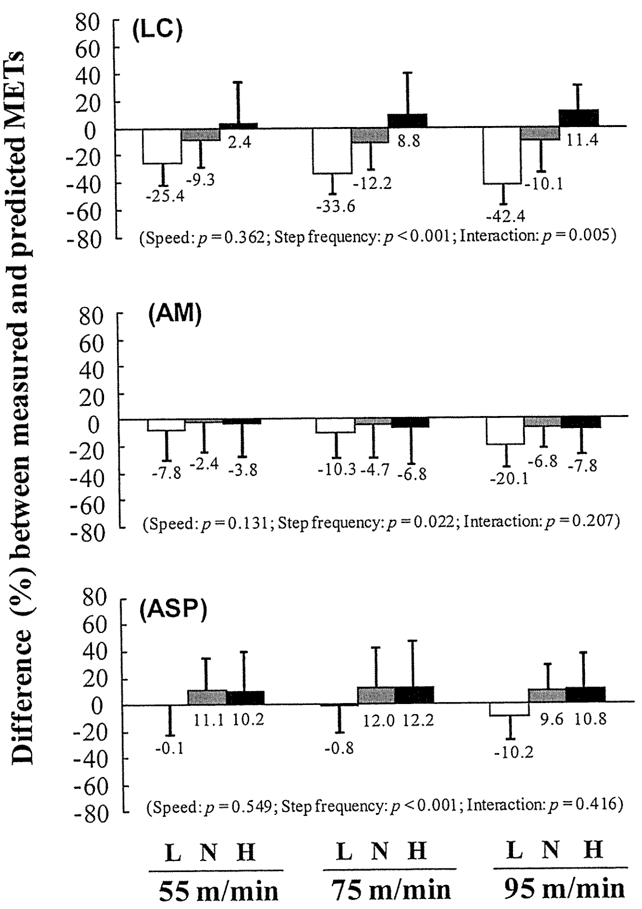

Fig. 2 Difference between measured (Douglas bag) and predicted METs (LC, Kenz Lifecorder; AM, Actimarker; ASP, Active Style Pro) across conditions altered by three step frequencies (L, Low step frequency; N, Normal step frequency; H, High step frequency) at each walking speed (55, 75, and 95 m/min). The numbers under the bars indicate the difference (%) between measured and predicted METs. The results of two-way ANOVA analysis were shown in parentheses for each accelerometer.

significantly higher at the low step frequency than at the normal frequency. Vertical acceleration was significantly higher at the high step frequency at 55 m/min or at the low step frequency at 95 m/min than at the normal frequency. Anteroposterior acceleration was significantly higher at the low step frequency at all walking speeds when compared to normal frequency. The total value of three accelerations was significantly higher at the high step frequency at 55 m/min than at the normal frequency and also higher at the low step

Table 4 Multiple regression analysis of predictors in the percentage error between the measured and predicted METs in each accelerometer

Predictors	R	R^2	Unstandardized coefficients B	Unstandardized coefficients Standard error	β	p-value
LC						
Step frequency			1.262	0.089	0.869	<0.001
Speed			−0.857	0.102	−0.514	<0.001
Height			−0.550	0.214	−0.133	<0.001
Total	0.764	0.584				<0.001
AM						
Height			−1.409	0.370	−0.452	<0.001
Sex			−11.832	4.880	−0.288	0.016
Total	0.296	0.088				<0.001
ASP						
Step frequency			0.487	0.116	0.374	<0.001
Speed			−0.396	0.134	−0.265	0.004
Total	0.322	0.103				<0.001

Abbreviations: METs, Metabolic equivalents; R, Multiple correlation coefficient; R^2, Multiple coefficient of determination; β, Standardized partial regression coefficient; LC, Kenz Lifecorder; AM, Actimarker; ASP, Active Style Pro.

Confounding factors of step frequency, speed, step frequency x speed, sex, height, and body mass were used in the analyses of each accelerometer.

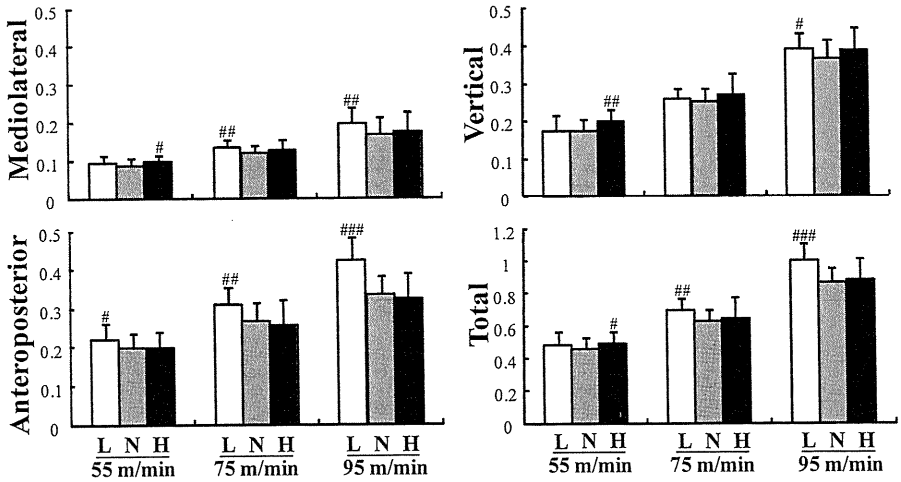

Fig. 3 Absolute accelerations in the mediolateral, vertical, anteroposterior, and total directions measured by the Actimarker across conditions altered by three step frequencies (L, Low step frequency; N, Normal step frequency; H, High step frequency) at each walking speed (55 m/min, 75 m/min, 95 m/min). Values significantly different from N (Normal step frequency) are indicated by $^{\#}p<0.05$, $^{\#\#}p<0.01$, $^{\#\#\#}p<0.001$.