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.

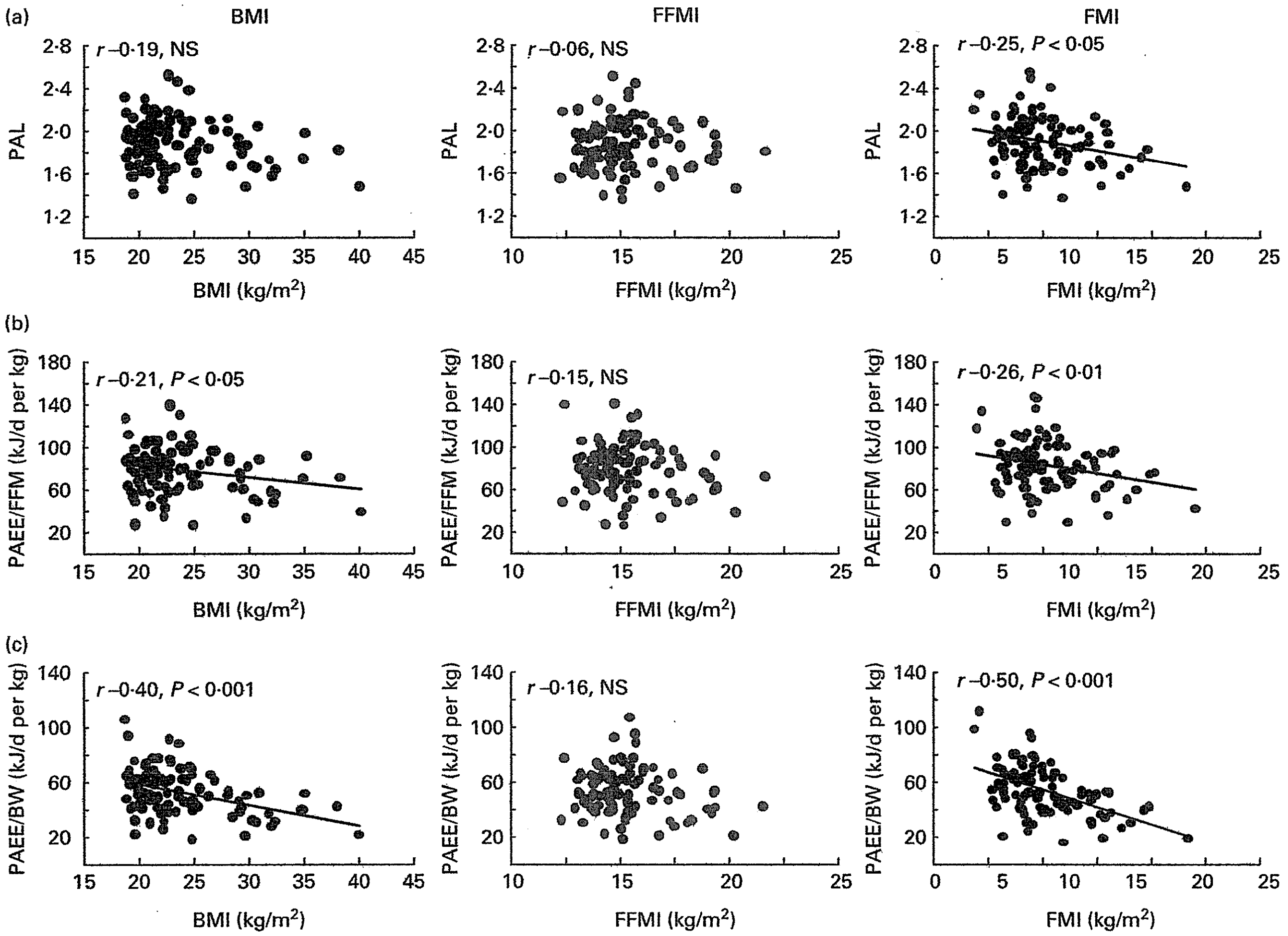

Fig. 2. Relationships between BMI, fat-free mass index (FFMI) or fat mass index (FMI) and physical activity level (PAL) (a), physical activity-related energy expenditure/fat-free mass (PAEE/FFM) (b) or PAEE/body weight (BW) (c). PAL = TEE/BMR, where TEE is total energy expenditure; PAEE = 0·9TEE − BMR; 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 < 18·5 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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Effects of Walking Speed and Step Frequency on Estimation of Physical Activity Using Accelerometers

Jonghoon Park[1)], Kazuko Ishikawa-Takata[1)], Shigeho Tanaka[1)], Yuko Mekata[1)] and Izumi Tabata[1),2)]

1) Health Promotion and Exercise Program, National Institute of Health and Nutrition
2) Faculty of Sport and Health Science, Ritsumeikan University

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 m·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·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 ($kg \cdot m^{-2}$)	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 ($kcal \cdot min^{-1}$)	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)			
$55 m \cdot min^{-1}$	57.2±5.2 (50.9–66.3)	58.2±5.9 (51.4–67.9)	57.2±5.2 (50.9–67.9)
$75 m \cdot min^{-1}$	67.7±4.2 (60.0–74.3)	69.0±4.9 (59.5–74.0)	67.7±4.2 (59.5–74.3)
$95 m \cdot min^{-1}$	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			
$55 m \cdot min^{-1}$	96.8±8.5 (83–108)	95.3±9.5 (81–107)	96.8±8.5 (81–108)
$75 m \cdot min^{-1}$	111.1±7.1 (101–125)	109.2±8.3 (101–126)	111.1±7.1 (101–126)
$95 m \cdot min^{-1}$	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 (β=0.32, p< 0.001 for the LC; β=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 (β=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.

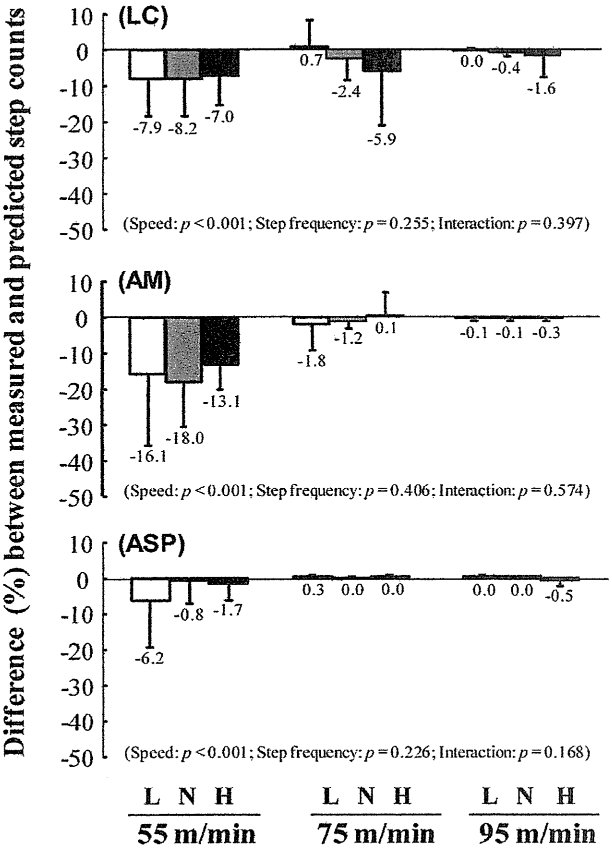

Fig. 1 Difference between measured (video records) and predicted step counts (LC, Kenz Lifecorder; AM, Actimarker; ASP, Active Style Pro) across conditions altered by three step frequencies (L, Low step frequency; N, Normal step frequency; H, High step frequency) at each walking speed (55, 75, and 95 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

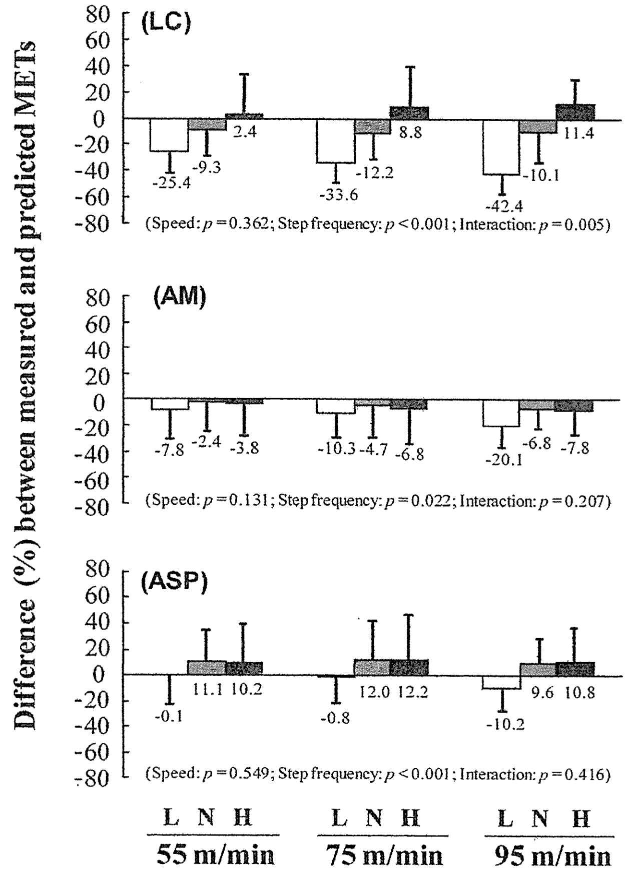

Fig. 2 Difference between measured (Douglas bag) and predicted METs (LC, Kenz Lifecorder; AM, Actimarker; ASP, Active Style Pro) across conditions altered by three step frequencies (L, Low step frequency; N, Normal step frequency; H, High step frequency) at each walking speed (55, 75, and 95 m/min). 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		β	p-value
			B	Standard error		
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.

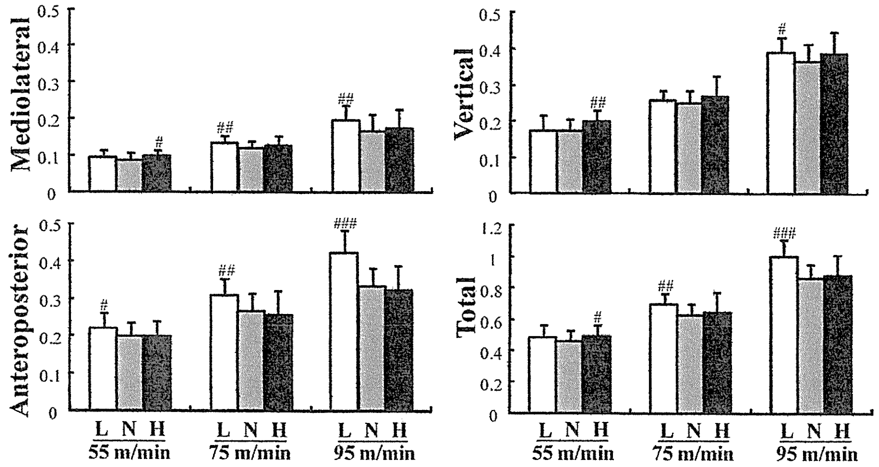

Fig. 3 Absolute accelerations in the mediolateral, vertical, anteroposterior, and total directions measured by the Actimarker across conditions altered by three step frequencies (L, Low step frequency; N, Normal step frequency; H, High step frequency) at each walking speed (55 m/min, 75 m/min, 95 m/min).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

frequency at 75 and 95 m/min.

Discussion

This is the first study to investigate whether changes in step frequency have independent effects on the validity of step-count functions and predicted energy cost assessed by accelerometers. The LC underestimated the step counts at normal or high step frequency at low walking speed. The AM also underestimated them at all step frequencies at low walking speed, whereas the ASP did not across any of the trials. The degree of the percentage error of the step counts in all accelerometers was affected by speed, but not by step frequency. The LC underestimated METs at the low or normal step frequency at all walking speeds, whereas overall underestimation was less across trials in the AM and ASP.

The present study clearly demonstrated that LC, AM, and ASP have very accurate step-count functions at normal walking speed with normal step frequency at which each subject feels comfortable walking. Schneider et al. (2003) demonstrated that LC had more accurate step-count functions compared with 7 other pedometers during a 400-m track walk at self-selected speeds for adults, and its error in detecting actual steps taken was within±3%. Actually, Cao et al. (2010) reported no significant differences between LC and AM in daily walking step counts for adults. The error of −2.4% (LC), −1.2% (AM), and 0.0% (ASP) at normal walking speed with normal step frequency in the present study meet the Japanese Industrial Standard set by the Ministry of Industry and Trading criteria indicating that error should be within 3% (3 steps of 100) (Hatano, 1993). Therefore, it is considered that LC, AM, and ASP are among the pedometers which are very accurate and sufficiently reliable to administer to large groups.

At low walking speed, the LC underestimated the step counts at the normal and high frequency while the AM underestimated them at all step frequencies. In contrast, the ASP had accurate step-count functions across all trials. The present results correspond with those of other studies using electronic pedometers that underestimated step counts at walking speeds slower than about 55 m/min (Crouter et al., 2003; Le Masurier and Tudor-Locke, 2003; Le Masurier et al., 2004). Thus, the impact on the accelerometers (sensitivity) during slow walking for the LC and AM might be too weak to detect a "threshold" of capturing a step, whereas ASP had better reliability in detecting step counts even with slow walking. It was difficult to determine why the ASP had better accuracy than the AM in detecting step counts; however, the difference in the filtering system between the AM and the ASP might explain this. Even so, speed significantly contributed to the degree of the percentage error in all three accelerometers. Therefore, we suggest that accelerometers should be carefully used when assessing daily step counts, especially for persons who walk slowly.

The present study revealed that the LC underestimated METs at the low and normal step frequency at all walking speeds, and gross underestimation was found especially at low step frequency of high walking speeds. One possible explanation for the LC error is its own proprietary data-analyzing process, in which intensity levels are categorized using both the step counts and the maximum amplitude of vertical acceleration every four seconds. In this study, although higher energy cost was demanded at a low step frequency especially at a higher walking speed, the number of step counts by the LC would have conversely decreased due to the greater step length (lower step frequency). Therefore, a decrease in step counts at the low step frequency might cause the LC underestimation. The possibility that step frequency could strongly affect the validation of the LC was supported by the following results: Step frequency was the strongest predictor ($\beta=0.87$) and speed was the second strongest ($\beta=-0.51$) of the error between the measured and predicted METs in the multiple regression analysis. Therefore, changes in step frequency would individually and markedly affect the accuracy of the LC.

Another possible reason for the LC underestimation may be that in the data-analyzing process, it uses only four thresholds from maximum amplitudes of vertical acceleration when determining the intensity levels (i.e., noncontinuous variables). For example, if the maximum amplitudes of vertical acceleration during walking altered by both low and normal step frequency at a fixed walking speed are between 0.15–0.76 G, the difference in intensity levels between the low and normal step frequency will be determined by the difference in the step counts. However, as mentioned above, the number of step counts by the LC would have been decreased due to the low step frequency, despite the higher energy cost. This might be one explanation for the LC error.

Compared with the results of the LC, the AM and ASP showed less error in measuring METs across trials. Multiple regression analysis indicated that step frequency did not affect AM accuracy. Although ASP accuracy was affected by step frequency, it only explains 10% of the error. Better validity of the AM and ASP compared with the LC might be partly due to the higher capability of the triaxial accelerometers in assessing multiple-directional accelerations as continuous variables. In the earlier studies, anteroposterior or vertical acceleration contributed to a highly accurate estimation of physical activity under normal walking conditions in which step frequency was concurrently changed with an increment in speed (Bouten et al., 1994; Kumahara et al., 2004). However, in our experimental protocol (i.e., various step frequencies altered at a fixed walking speed), the difference in vertical acceleration between the low and normal step frequency was much less than the difference between the low and normal step frequencies in the METs measured by the Douglas bag method. Moreover, the major acceleration component at a low step frequency was in the anteroposterior direction, but in the vertical direction at a high step frequency. Based on our results, we suggest that the AM and ASP assure more accuracy than the LC for estimating intensity or energy costs under various walking conditions.

In the present study, the degree of the percentage error of METs was affected by step frequency both in the AM and ASP. Significant underestimation was found in AM at all low step frequencies of all walking speeds, but in ASP only at low step frequency of high walking speed. As shown in the raw data of the three accelerations, the total values using the output of the three accelerations at the high walking speed was around 16% higher at the low step frequency than at the normal step frequency. However, the difference in the measured METs from the Douglas bag at the high walking speed was around 25% higher at the low step frequency than at the normal step frequency. The discrepancy of 16% and 25% might therefore result in higher error at the low step frequency of high walking speed in the AM and ASP. Furthermore, the present study showed that METs estimated by the AM tended to be entirely underestimated across trials compared with METs estimated by the ASP (Fig. 2). Because the minimum amplitude of the acceleration sensor was similar between the AM (4 mG) and the ASP (3 mG), the sensitivity of the minimum amplitude of the acceleration sensor did not affect the error of the AM. Therefore, we consider that AM accuracy may be improved by using more suitable equations to precisely measure energy costs altered by the various walking patterns.

The present study has the following limitations. First, our results using young healthy subjects might not be readily generalized to children or older adults due to different characteristics such as the length and mass of legs and body movement. In addition, the elderly have been known to walk and step so slowly that their walking movements are greater in mediolateral directions (Dean et al., 2007). Therefore, further research is needed to evaluate the accuracy of an accelerometer for other aged subjects under the same conditions and to calibrate for more accurate estimations. Second, we cannot exclude differences between walking on a treadmill indoors and freely walking outdoors. However, in general, the energy costs of treadmill and over-ground walking on a firm surface are similar (Hall et al., 2004). Hence, we thought that using the treadmill in our experimental protocol was adequate to obtain more precise and reliable data as a basic study.

In conclusion, these results suggest that accelerometers can cause errors in step-count functions at a low walking speed. Furthermore, in the measurement of energy costs, LC may cause great errors especially for the group with various step frequency and speed, whereas AM and ASP, which are tri-axial accelerometers, cause fewer errors but the degree of the percentage error is affected by step frequency.

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Correspondence to: Jonghoon Park, Health Promotion and Exercise Program, National Institute of Health and Nutrition, 1–23–1 Toyama, Shinjuku-ku, Tokyo 162–8636, Japan
Phone: +81–3–3203–8061
Fax: +81–3–3203–1731
e-mail: jonghoon@nih.go.jp

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Validity of Predictive Equations for Basal Metabolic Rate in Japanese Adults

Rieko MIYAKE, Shigeho TANAKA, Kazunori OHKAWARA, Kazuko ISHIKAWA-TAKATA,
Yuki HIKIHARA, Emiko TAGURI, Jun KAYASHITA and Izumi TABATA

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Validity of Predictive Equations for Basal Metabolic Rate in Japanese Adults

Rieko MIYAKE[1,2], Shigeho TANAKA[1,*], Kazunori OHKAWARA[1], Kazuko ISHIKAWA-TAKATA[1],
Yuki HIKIHARA[3], Emiko TAGURI[2,4], Jun KAYASHITA[5] and Izumi TABATA[1,6]

[1] *Department of Health Promotion and Exercise, National Institute of Health and Nutrition, 1–23–1 Toyama, Shinjuku-ku, Tokyo 162–8636, Japan*
[2] *Graduate School of Humanities and Sciences, Ochanomizu University, Tokyo 112–8610, Japan*
[3] *Faculty of Engineering, Chiba Institute of Technology, Narashino 275–0023, Japan*
[4] *Health Insurance Naruto Hospital, Tokushima 772–8503, Japan*
[5] *Graduate School of Comprehensive Scientific Research, Prefectural University of Hiroshima, Hiroshima 734–8558, Japan*
[6] *Faculty of Sport and Health Sciences, Ritsumeikan University, Shiga 525–8577, Japan*

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Summary Many predictive equations for basal metabolic rate (BMR) based on anthropometric measurements, age, and sex have been developed, mainly for healthy Caucasians. However, it has been reported that many of these equations, used widely, overestimate BMR not only for Asians, but also for Caucasians. The present study examined the accuracy of several predictive equations for BMR in Japanese subjects. In 365 healthy Japanese male and female subjects, aged 18 to 79 y, BMR was measured in the post-absorptive state using a mask and Douglas bag. Six predictive equations were examined. Total error was used as an index of the accuracy of each equation's prediction. Predicted BMR values by Dietary Reference Intakes for Japanese (Japan-DRI), Adjusted Dietary Reference Intakes for Japanese (Adjusted-DRI), and Ganpule equations were not significantly different from the measured BMR in either sex. On the other hand, Harris-Benedict, Schofield, and Food and Agriculture Organization of the United Nations/World Health Organization/United Nations University equations were significantly higher than the measured BMR in both sexes. The prediction error by Japan-DRI, Adjusted-DRI, and Harris-Benedict equations was significantly correlated with body weight in both sexes. Total error using the Ganpule equation was low in both males and females (125 and 99 kcal/d, respectively). In addition, total error using the Adjusted-DRI equation was low in females (95 kcal/d). Thus, the Ganpule equation was the most accurate in predicting BMR in our healthy Japanese subjects, because the difference between the predicted and measured BMR was relatively small, and body weight had no effect on the prediction error.

Key Words basal metabolic rate, predictive equation, Japanese, validity

To maintain body weight, energy from food intake must equal energy expenditure. The estimated energy requirement (EER) is defined as the average dietary energy intake that is predicted to maintain energy balance in healthy adults of a given age, gender, weight, height, and level of physical activity consistent with good health (*1*).

Total energy expenditure (TEE) can be divided into basal metabolic rate (BMR), diet-induced thermogenesis, and physical activity (*2*). Calculated from the normal physical activity level (PAL=TEE divided by BMR) of about 1.75 for Japanese (*3*) and Caucasians (*4*), BMR accounts for about 60% of TEE in an adult with normal physical activity in daily life. Therefore, in healthy individuals, EER is usually BMR multiplied by physical activity level, and in unhealthy individuals (patients in clinical settings), EER is BMR multiplied by an activity factor and stress factor (*5*). Thus, it is important to accurately evaluate BMR. However, because of the relatively high cost, limited availability of equipment, the time needed for the measurements, the need for the subject to be in a fasting state, and the need for adequately trained personnel, equations that predict BMR are frequently applied in clinical and field settings instead of indirect calorimetry (*6*).

The international guidelines for nutrition treatment of the American Society for Parenteral and Enteral Nutrition recommend using the Harris-Benedict equation or indirect calorimetric measurement to evaluate BMR (*7*). However, 60% of 515 hospitals in Japan reported the calculation of EERs from body weight (*8*). In addition, only 1.9% of the hospitals carried out indirect calorimetric measurement of BMR. In the clinical setting, the patients' energy expenditure must be estimated accurately because overfeeding or underfeeding

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[*] To whom correspondence should be addressed.
E-mail: tanakas@nih.go.jp

Table 1. Physical characteristics of subjects.

	All (n=365)	Males (n=163)		Females (n=202)		p values
	Mean±SD	Mean±SD	Range	Mean±SD	Range	
Age (y)	41±17	43±15	20–79	39±18	18–76	0.041
Height (cm)	163.3±9.0	170.3±6.9	146.4–187.7	157.6±5.9	140.8–172.1	<0.001
Weight (kg)	59.5±11.9	67.1±11.2	45.5–110.2	53.3±8.2	36.1–99.1	<0.001
Body mass index (kg/m^2)	22.2±3.1	23.1±3.0	16.8–36.4	21.5±3.0	16.5–36.4	<0.001

Differences between males and females were evaluated by unpaired t-test. p values: males vs. females.

may have adverse effects, such as electrolyte imbalance and gastrointestinal problems (*9*).

BMR is usually calculated from predictive equations using data such as age, sex, height, and weight (*10*). The Harris-Benedict equation (*11*), Schofield equation (*12*), and the Food and Agriculture Organization of the United Nations/World Health Organization/United Nations University (FAO/WHO/UNU) equation (*13*) are internationally used. Harris-Benedict equations were developed from energy expenditure measurements in young Caucasian males and females in 1919 (*11*). Schofield and FAO/WHO/UNU equations were developed using a database of 7,173 subjects (aged from under 3 y to over 60 y) including approximately 45% Italian subjects (*12–15*) and about 50 young Japanese subjects (*16*). Previous studies show that the predictive equations derived mainly from measurements made on Caucasian subjects tend to overestimate BMR in Asians (*9, 10*) as well as in Caucasian subjects (*10, 17–21*). However detailed information on the validity for each sex and age group in Japanese is not available.

In Japan, Dietary Reference Intakes for Japanese (Japan-DRI) provides BMR standards (standard BMR per unit weight) according to sex and age category, and the data for these standards were from a Japanese BMR database (*22, 23*). BMR can be calculated as BMR standards multiplied by body weight. However, the validity of the predictive equations including the predictive equations for BMR standards from the Japan-DRI and the equations for BMR standards to adjust BMR standards for individuals with relatively large or small body weight (*24*) have not been examined in healthy Japanese subjects. In addition, we recently developed new predictive equations for sleeping metabolic rate and BMR in Japanese (*25*).

In the present study, we examined the validity of applying three BMR equations used for Japanese, and three internationally used equations developed mainly from energy expenditure measurements in Caucasian subjects, to healthy Japanese adults.

MATERIALS AND METHODS

Subjects. The data used for the current analysis were collected from different experimental studies that followed a similar methodology. A total of 365 apparently healthy Japanese subjects (163 males and 202 females subjects) were enrolled through personal contact, internet communication, or poster advertisements. The subjects included students, housewives, office workers, and medical colleagues. None had diseases that might affect metabolic rate. The study protocol was explained in advance to the subjects, who were instructed to eat a normal diet and do normal, but not vigorous, physical activity beginning 1 d before measurements. All studies were carried out in the National Institute of Health and Nutrition (Tokyo) and Oita Prefecture. This 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. All of the subjects signed an informed consent form.

Anthropometric and body composition. Physical characteristics of the subjects are summarized in Table 1. Anthropometric measurements were performed according to the method of Lohman et al. (*26*). Body weight was measured to the nearest 0.1 kg using an electronic scale (YK-150D, YAGAMI, Nagoya, Japan), and body height to the nearest 0.1 cm using a stadiometer (YL-65, YAGAMI). Measurements were performed in light clothing and underwear. The light clothing was weighed and subtracted from the total to obtain body weight with minimal clothing (underwear). Body mass index (BMI: kg/m^2) was calculated as body weight (kg) divided by square of body height (m^2).

Measurements of BMR. Subjects came to the laboratory on the previous night and stayed overnight, or came in the early morning. In the latter case, they were asked to minimize walking prior to their laboratory visit and BMR measurement. Travel time was considered to be within 15 to 90 min in most cases. In most of the previous studies, especially for the Japan-DRI, Schofield, and FAO/WHO/UNU equations, BMR was measured under the latter condition (*23*). BMR was measured in the post-absorptive state (12 h or more after the last meal). Measurements were performed in a room at constant temperature (approximately 25°C). After entering the laboratory, subjects rested in the supine position for at least 30 min, and wore a face mask. In the case of overnight stay, the subjects were quietly awakened at 0700 and had a face mask attached while remaining in bed for 30 min. Two samples of expired air were collected in Douglas bags over each of two 10-min periods, and the mean of the two values was used for analysis.

Mass spectrometer (ARCO-1000 and ARCO-2000, Arco System, Kashiwa, Japan) were used to analyze the

Table 2. Predictive equations for basal metabolic rate used in the present study.

Predictive equations (kcal/d)	Age range	Males	Females
Japan-DRI (2010)	18–29	$24.0\times W$	$22.1\times W$
	30–49	$22.3\times W$	$21.7\times W$
	50–69	$21.5\times W$	$20.7\times W$
	70 over	$21.5\times W$	$20.7\times W$
Japan-DRI with adjustment for body weight (Adjusted-DRI)	18–29	$[24.0+(10.8-0.173\times W)]\times W$	$[22.1+(8.9-0.172\times W)]\times W$
	30–49	$[22.3+(10.8-0.173\times W)]\times W$	$[21.7+(8.9-0.172\times W)]\times W$
	50–69	$[21.5+(10.8-0.173\times W)]\times W$	$[20.7+(8.9-0.172\times W)]\times W$
	70 over	$[21.5+(10.8-0.173\times W)]\times W$	$[20.7+(8.9-0.172\times W)]\times W$
Harris-Benedict		$66.4730+13.7516\times W+5.0033\times H-6.7550\times A$	$655.0955+9.5634\times W+1.8496\times H-4.6756\times A$
Schofield	18–29	$(0.063\times W+2.896)\times 1{,}000/4.186$	$(0.062\times W+2.036)\times 1{,}000/4.186$
	30–59	$(0.048\times W+3.653)\times 1{,}000/4.186$	$(0.034\times W+3.538)\times 1{,}000/4.186$
	60 over	$(0.049\times W+2.459)\times 1{,}000/4.186$	$(0.038\times W+2.755)\times 1{,}000/4.186$
FAO/WHO/UNU	18–29	$(64.4\times W-113.0\times H/100+3{,}000)/4.186$	$(55.6\times W+1{,}397.4\times H/100+146)/4.186$
	30–59	$(47.2\times W+66.9\times H/100+3{,}769)/4.186$	$(36.4\times W-104.6\times H/100+3{,}619)/4.186$
	60 over	$(36.8\times W+4{,}719.5\times H/100-4{,}481)/4.186$	$(38.5\times W+2{,}665.2\times H/100-1{,}264)/4.186$
Ganpule		$(0.0481\times W+0.0234\times H-0.0138\times A-0.4235)\times 1{,}000/4.186$	$(0.0481\times W+0.0234\times H-0.0138\times A-0.9708)\times 1{,}000/4.186$

W: weight (kg), H: height (cm), A: age (y).

oxygen and carbon dioxide concentrations. The volume of expired air was determined using a dry gas volume meter (DC-5, Shinagawa, Tokyo, Japan) and converted to the volume under conditions of standard temperature, pressure, and dry gas (STPD). Gas exchange results were converted to BMR (kcal/d) using Weir's equation (*27*). To examine whether overnight stay before the BMR measurement caused a significant difference in the observed BMR, analysis of covariance with BMR as the dependent variable and gender, age, height, and body weight as covariates was employed. No significant effect of the measurement conditions was observed (stayed overnight: 1,275±15 kcal/d (mean±SE), came in the early morning on the day: 1,268±6 kcal/d (mean±SE), $F=0.163$, $p=0.687$).

Predictive equations of BMR. Predictive BMR was calculated using the Japan-DRI (*22*), Harris-Benedict (*11*), Schofield (*12*), FAO/WHO/UNU (*13*), and Ganpule (*25*) equations (Table 2). For the Japan-DRI equations, the Ministry of Health and Welfare proposed adjusting for the effect of body weight (*24*). Therefore, the equations with this adjustment (Adjusted-DRI) were also examined.

Statistical analysis. Results are presented as the mean±standard deviation (SD). Statistical significance was set at $p<0.05$ for all predictors. Differences between males and females were evaluated by an unpaired t-test. In addition to the mean±SD of the difference, total error (TE) was used to determine how accurately predicted BMR matched measured BMR. This statistic includes two sources of variation, one attributable to the lack of association between the two sets of measurement (standard error of estimate) and one attributable to the difference between the means (*28*). Statistical significance of differences between measured and predicted values was analyzed by one-way analysis of variance (ANOVA) and Dunnett's post hoc test. The relationship between difference of BMR (predicted minus measured BMR) and weight was examined using Pearson's correlation. Statistical analyses were performed using SPSS for Windows (version 15.0; SPSS Inc., Chicago, IL, USA).

Table 3. Measured basal metabolic rate (kcal/d and kcal/kg weight/d) in each sex and age group.

Age range	BMR (kcal/d) Mean±SD	BMR (kcal/kg weight/d) Mean±SD
Males ($n=163$)		
All	1,452±219	21.8±2.4
18–29	1,492±151	23.5±2.2
30–39	1,532±250	22.0±2.2
40–49	1,489±222	21.0±2.0
50–59	1,395±184	21.7±2.8
60–69	1,321±142	20.6±2.0
70–79	1,220±170	20.2±1.5
Females ($n=202$)		
All	1,122±136	21.2±2.4
18–29	1,132±122	22.2±2.6
30–39	1,168±122	21.6±2.4
40–49	1,196±161	21.3±1.9
50–59	1,090±114	19.6±1.8
60–69	1,085±110	20.1±1.7
70–79	968±107	20.1±1.9

RESULTS

The average weight and height of subjects in each age and gender group were comparable to national standard heights and weights (*29*) (Table 1). Average