population and included detailed questions on occupational work, housework, and leisure-time physical activity.

The doubly labeled water (DLW) method is an excellent method for measuring TEE in free-living subjects over a period of 1 to 2 weeks[8] and is often used as a gold standard to validate field methods of assessing physical activity levels. However, to our knowledge, only our previous study[5] has used it to examine the validity of a questionnaire used for the Japanese population.

The primary objective of this study was to use the DLW method as the gold standard to validate a physical activity questionnaire developed for the Japanese population. To aid in the development of a valid physical activity questionnaire for Japanese, the secondary objective was to identify the physical activity component that had the greatest impact on physical activity level (PAL).

METHODS

Subjects

The study participants were 226 Japanese men and women age 20 to 83 years (mean ± standard deviation, 50.4 ± 17.1 years) who volunteered at community health care centers and workplaces or enrolled via the internet homepage of our institute. The inclusion criteria of the present study were as follows: absence of any condition affecting energy or water metabolism (eg, thyroid or kidney disease), not pregnant or breast-feeding, residence in home prefecture 2 weeks before and during the study, not on weight-loss or treatment diet, and not consuming more than 40 grams of alcohol per day. The occupations of the participants were homemaker ($n = 59$), office worker ($n = 57$), shipbuilder ($n = 17$), shop assistant ($n = 14$), no regular work ($n = 14$), nurse ($n = 13$), teacher ($n = 11$), salesperson ($n = 11$), factory worker ($n = 6$), clinical examination technician ($n = 5$), physiotherapist ($n = 4$), and other ($n = 12$, cleaner, gardener, dietitian, priest, sports instructor, carpenter, etc.). We were unable to randomly select subjects according to physical activity level. Over the entire assessment period, the participants were carefully instructed to maintain their normal daily activities and eating patterns and to make no conscious effort to lose or gain weight.

Study protocol

This study was approved by the Ethics Committee of the National Institute of Health and Nutrition in Japan. All subjects gave their informed consent in writing before the investigation was begun. TEE was estimated over 1 or 2 weeks, depending on the 2 half-lives of the isotopes used in the DLW method. Body mass and height were measured in the fasting state before administering the dose of DLW and on the last day of the study. On the first day of the study period, baseline urine was collected, and measurements of resting metabolic rate (RMR) and DLW dosing were obtained. The physical activity questionnaire and dietary assessment were completed between the 10th and 12th day of the study period and were checked by the researchers on the last day.

Measurement of resting metabolic rate

Subjects were instructed to refrain from moderate to vigorous physical activity for 24 hours, to fast at least 12 hours, and to get sufficient sleep before the measurements. They were instructed to arrive at the laboratory between 8AM and 9AM. After arrival, they rested quietly in the supine position for 30 minutes before the measurements. Using a mask connected to a Douglas bag, expired gas was collected twice for 10 minutes, with a 1-minute interval between collections. During all RMR measurements, the room temperature was maintained at approximately 24°C. Subjects were lying down and fully awake during the measurements. They were also free from emotional stress and were familiar with the apparatus used. The volume of expired air was measured with a certified gas meter (DC-5, Shinagawa, Tokyo, Japan), the accuracy and precision of which were maintained within 1% of the coefficient of variation (CV). Concentrations of oxygen and carbon dioxide were measured with a mass spectrometer (ARCO-1000, Arco Systems, Chiba, Japan). The precision of expired gas measurement was 0.02% for oxygen and 0.06% for carbon dioxide. RMR was calculated using Weir's equation.[9]

DLW energy measurement

After providing a baseline urine sample, a single dose of approximately 0.06 g/kg body weight of ^2H_2O (99.8 atom%, Cambridge Isotope Laboratories, MA, USA) and 1.4 g/kg body weight of $H_2{}^{18}O$ (10.0 atom%, Taiyo Nippon Sanso, Tokyo, Japan) was given orally to each subject. Then subjects were asked to collect urine samples at 8 predetermined times during the study period, at the same time of day. Except for the baseline collection, all urine samples were collected by the participant, and the time of sampling was recorded. All samples were stored by freezing at −30°C in airtight parafilm-wrapped containers and then analyzed in our laboratory.

Gas samples for the isotope ratio mass spectrometer (IRMS) were prepared by equilibration of the urine sample with a gas. CO_2 was used to equilibrate ^{18}O, and H_2 was used for ^2H. Pt catalyst was used for equilibration of ^2H. The gas sample of the CO_2 and H_2 was analyzed by IRMS (DELTA Plus; Thermo Electron Corporation, Bremen, Germany). Each sample and the corresponding reference were analyzed in duplicate. The average standard deviations for the analyses were 0.5‰ for ^2H and 0.03‰ for ^{18}O. TEE was expressed as mean TEE per day over the study period.

Calculations of isotopic abundance and TEE

The ^2H and ^{18}O zero-time intercepts and elimination rates (k_H and k_O) were calculated using a least-squares linear regression on the natural logarithm of isotope concentration as a function of the elapsed time from dose administration. 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 ^2H divided by 1.041 and that of ^{18}O divided by 1.007. The mean ko/kd of the present study was 1.28 ± 0.06 (range, 1.15–1.56). All ko/kd values were maintained within the recommended range (1.1 to 1.7) for quality control of the analysis, as recommended by the International Atomic Energy Agency.[10] rCO_2 was calculated as follows: $rCO_2 = 0.4554 \times TBW \times (1.007ko - 1.041k_H)$. Calculation of TEE (kcal/day) was performed using a modified Weir's formula based on the CO_2 production rate (rCO_2) and food quotient (FQ).[9] FQ was calculated from the dietary survey during the study period. The calculation assumed that under conditions of perfect nutrient balance, the FQ must equal the respiratory quotient (RQ).[11–13] The average FQ of each occupational group was used for each group (FQ = 0.85–0.95). However, FQ values stratified by occupational group, sex, and age were not significantly different. Physical activity level (PAL) was calculated as TEE/RMR.

Physical activity questionnaire

The physical activity questionnaire developed for the Japan Arteriosclerosis Longitudinal Study (JALSPAQ) was used in this study.[6,7] This questionnaire comprises 14 questions on occupation, locomotion, housework, sleep time, and leisure-time physical activities. In this questionnaire, occupational work was assessed as duration of sitting, standing, walking, and heavy work. Heavy work was defined as lifting more than 10 kg or manual labor of similar intensity. Leisure-time physical activity was assessed by type, duration, and frequency. Questionnaire data were converted to the intensity of each physical activity expressed in metabolic equivalents (METs), according to the Compendium by Ainsworth et al, and summarized as METs·h/day and energy expenditure.[14] In the present study, we used TEE per day, METs·h/day, and PAL as indices of physical activity level from JALSPAQ. Duration of light (<3 METs), moderate (3–5.9 METs), and vigorous (≥6 METs) physical activities was calculated for all physical activities (including occupational activity, housework, and leisure-time physical activity), as well as for leisure-time physical activity only. Working time, including occupational and housework time, was divided into the duration of sitting (<2 METs), standing (2 to <3 METs), walking (3 to <6 METs), and heavy work (≥6 METs), including housework. We calculated the durations of occupational activity and housework together because their frequencies and durations were quite complicated.

Dietary assessment

Dietary habits were assessed by using a brief self-administered diet history questionnaire (BDHQ)—a 4-page structured questionnaire that requested information on the consumption frequencies for a total of 56 food and beverage items, with specified serving sizes described in terms of the servings commonly consumed in the general Japanese population.[15] Energy and macronutrient intakes were calculated using a computer algorithm for the BDHQ, which was based on the Standard Tables of Food Composition in Japan. FQ was calculated by using the equation of Black et al.[11]

Statistical analysis

Statistical analyses were performed using SPSS for Windows (version 16.0J; SPSS Inc., IL, USA). Physical characteristics are classified using the sex and age groups outlined in the Dietary Reference Intake (DRI) of Japan. The estimated energy expenditure data were generally not normally distributed; therefore, medians and interquartile ranges are used to describe these results. Sex and age-group differences were compared using 2-way analysis of covariance. The Bonferroni procedure was used as the post-hoc test. The relation between TEE as estimated by DLW and JALSPAQ was expressed as Spearman correlations, intraclass correlation coefficient (ICC), and 95% limits of agreement (95% LOA: mean difference ± 2 × SD of the mean difference). Bland-Altman plots were also created to evaluate the differences between the 2 methods. To examine the type of physical activities that affected physical activity level, we used 1-way analysis of covariance, Pearson's correlation coefficients, and partial correlation coefficients adjusted for sex and age group.

RESULTS

The physical characteristics of the subjects are shown in Table 1. Body weight did not change significantly during the study period ($P = 0.313$). Among all subjects, 2.8% of men and 6.8% of women were classified as lean (body mass index [BMI] <18.5 kg/m^2), and 31.5% of men and 17.8% of women were classified as obese (BMI >25 kg/m^2) according to the criteria for Japanese.[16] The average TBW was 37.3 ± 7.1 kg in men and 25.9 ± 2.8 kg in women. When 73.2% was defined as the proportion of water in fat-free mass, the percent of fat mass was 24.3 ± 6.1% in men and 33.4 ± 7.0% in women.[17] Three men aged 30 to 49 years had a body weight higher than 100 kg; however, they were fit and their percent of fat mass was less than 25%. In addition, in the assessment of TEE by DLW and JALSPAQ, they did not significantly differ from other subjects.

The medians plus interquartiles for RMR, TEE, and PAL by DLW, TEE by questionnaire, and the differences between the 2 methods are shown by sex and age group in Table 2. The respective medians of TEE and PAL were 11.21 MJ/day and 1.88 for men and 8.42 MJ/day and 1.83 for women. PAL significantly differed by age group, but not by sex. PAL in subjects older than 70 years was significantly higher than in those aged 30 to 49 years ($P = 0.016$) and 50 to 69 years

Table 1. Characteristics of study subjects

Age group, years	n	Age (years)	Height (cm)	Body weight			BMI (kg/m²)	TBW (kg)
				pre (kg)	post (kg)	change (kg)		
Male								
20–29	18	25.0 ± 2.5	171.5 ± 6.0	62.1 ± 7.9	62.3 ± 8.0	0.2 ± 0.7	21.1 ± 2.0	36.4 ± 3.7
30–49	42	36.7 ± 5.3	173.8 ± 6.6	74.8 ± 16.7	74.9 ± 16.6	0.0 ± 1.1	24.6 ± 4.7	41.8 ± 8.3
50–69	31	60.2 ± 6.5	163.8 ± 6.6	63.9 ± 8.1	64.0 ± 8.3	0.1 ± 0.9	23.8 ± 2.4	34.5 ± 4.1
≥70	17	75.1 ± 4.0	162.1 ± 5.0	60.7 ± 8.1	60.8 ± 8.2	0.2 ± 0.9	23.1 ± 2.7	32.0 ± 4.2
Female								
20–29	8	25.3 ± 2.4	157.0 ± 3.9	51.3 ± 2.5	51.2 ± 2.5	−0.1 ± 0.8	20.9 ± 1.6	25.5 ± 1.5
30–49	42	38.7 ± 4.4	158.0 ± 5.4	53.7 ± 8.3	53.7 ± 8.3	0.0 ± 0.7	21.5 ± 3.2	26.9 ± 3.1
50–69	49	62.0 ± 5.1	154.0 ± 4.6	54.6 ± 7.8	54.7 ± 7.9	0.1 ± 0.7	23.0 ± 3.2	25.8 ± 2.7
≥70	19	73.4 ± 3.9	148.0 ± 4.4	50.2 ± 6.1	50.1 ± 6.1	0.1 ± 0.6	22.9 ± 2.8	24.1 ± 2.0

All values are mean ± SD, unless otherwise indicated.
BMI: body mass index; TBW: total body water measured by doubly labeled water method.

Table 2. Resting metabolic rate (RMR) and total energy expenditure (TEE) measured by doubly labeled water (DLW) method and questionnaire

Age group, years		RMR (MJ/day)	TEE by DLW (MJ/day)	PAL	TEE by JALSPAQ (MJ/day)	Difference between DLW and JALSPAQ	
						(MJ/day)	(%)
Male							
	20–29	6.27 (0.92)	12.00 (0.19)	1.89 (0.35)	9.60 (2.12)	−1.69 (2.89)	−15.7 (23.0)
	30–49	6.72 (1.53)	12.88 (4.64)	1.87 (0.45)	11.14 (2.85)	−1.18 (3.30)	−9.5 (20.3)
	50–69	5.50 (1.30)	10.81 (2.11)	2.08 (0.55)	9.18 (1.61)	−2.02 (1.99)	−18.1 (17.5)
	≥70	5.76 (1.41)	11.76 (3.59)	2.11 (0.52)	8.03 (1.65)	−0.97 (2.34)	−12.2 (21.0)
Female							
	20–29	4.73 (0.27)	8.10 (1.18)	1.86 (0.22)	7.43 (1.01)	−1.09 (1.85)	−13.2 (22.3)
	30–49	4.83 (0.82)	8.82 (1.80)	1.84 (0.32)	7.33 (1.75)	−1.26 (1.73)	−14.9 (19.1)
	50–69	4.58 (0.95)	8.53 (1.42)	1.86 (0.37)	8.12 (1.28)	−0.43 (1.76)	−5.3 (20.4)
	≥70	4.62 (0.99)	8.56 (0.86)	1.86 (0.41)	7.08 (1.33)	−0.36 (1.68)	−5.2 (23.3)
P value	Sex	<0.001	<0.001	0.067	<0.001	0.003	0.071
	Age group	<0.001	<0.001	<0.001	<0.001	0.335	0.370
	Sex by age	0.010	0.004	0.481	<0.001	0.591	0.188

All values are median (interquartile), unless otherwise indicated.
PAL: physical activity level (TEE/RMR); JALSPAQ: Japan Arteriosclerosis Longitudinal Study Physical Activity Questionnaire.

($P < 0.001$). JALSPAQ slightly underestimated TEE, with differences in mean and standard error of the mean of −1.15 ± 1.92 MJ/day and −0.020 ± 0.030 MJ/kg/day. TEE values by JALSPAQ and DLW were moderately correlated (Spearman correlation = 0.742, $P < 0.001$; ICC = 0.648, $P < 0.001$). The 95% LOA was −4.99 to 2.69 MJ. The absolute difference between TEE values by DLW and JALSPAQ was significantly greater in men than in women, but the percent difference was not significantly different. The Spearman correlation coefficient and ICC for PAL were 0.423 ($P < 0.001$) and 0.332 ($P < 0.001$), respectively, and the 95% LOA for PAL was −0.86 to 0.46. Use of Bland-Altman plots to compare TEE and PAL by DLW and JALSPAQ suggested that TEE tended to be underestimated in subjects with higher TEE (Spearman correlation, −0.201; $P = 0.002$); however, most values were within the 2 SD of the difference in TEE as determined by the 2 methods (Figure). PAL was not underestimated even in subjects with higher PALs (Spearman correlation, −0.011; $P = 0.866$); however, individual differences were widely distributed.

Using PAL determined using TEE measured by DLW, the subjects were divided into 3 groups according to Dietary Reference Intake (Table 3).[18] The proportions of active (PAL >1.9), moderately active (PAL 1.6 to <1.9), and sedentary (PAL <1.6) individuals were 45.4%, 43.5%, and 11.1% in men, respectively, and 40.7%, 41.5%, and 17.8% in women. TEE by JALSPAQ in the sedentary group was significantly lower than in moderately active and active adults. Total METs assessed by JALSPAQ was lower in sedentary and moderately active individuals than in active individuals. The differences between the 2 methods in the TEE of sedentary and moderately active adults were significantly smaller than in active adults. The total duration of each intensity of physical activity, including occupational and housework activity and leisure-time physical activity, was compared among physical activity levels. The duration of moderate and vigorous

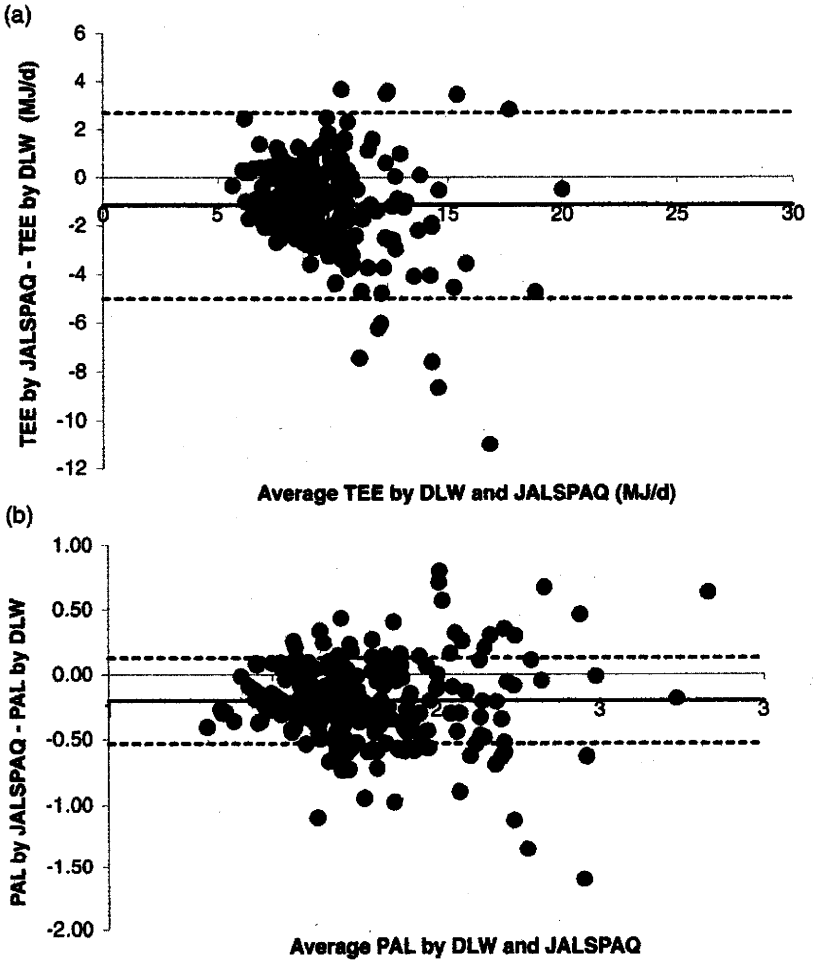

Figure. Bland-Altman plots of total energy expenditure (TEE) and physical activity level (PAL). (a) Comparison of mean TEE estimated by the doubly labeled water (DLW) method and the Japan Arteriosclerosis Longitudinal Study Physical Activity Questionnaire (JALSPAQ), and the difference in TEE as estimated by the 2 methods. (b) Comparison of mean PAL by DLW and JALSPAQ, and the difference in PAL as estimated by the 2 methods. Solid lines indicate the mean difference, and the broken lines indicate 2 SD limits.

physical activity in sedentary and moderately active adults was significantly shorter than in active adults. When we compared only leisure-time physical activity, there was no difference in duration of physical activity. Regarding physical activity during work, duration of walking was significantly shorter in sedentary individuals than in moderately active and active individuals. In addition, walking duration was significantly shorter in moderately active adults than in active adults. The proportion of heavy work differed significantly among groups; greater activity was associated with heavier work.

Regarding the types of physical activity that were correlated with PAL, correlation coefficients and partial correlation coefficients adjusted for sex and age group are shown in Table 4. Duration of total, moderate, and vigorous physical activity were weakly correlated with PAL. However, duration of leisure-time physical activity was not correlated with PAL. During working time, duration of standing, walking, and heavy work were weakly correlated with PAL.

DISCUSSION

This study used the DLW method as a gold standard to examine the validity of a physical activity questionnaire designed for the Japanese population in a large number of subjects with widely varying physical activity levels. With the DLW method as the gold standard, JALSPAQ estimated TEE relatively well, but underestimation was more frequent at higher physical activity levels.

The body height and weight of the present subjects were similar to the standard values for the Japanese population.[18] RMR was also similar to the standard RMR values for the Japanese population presented in Dietary Reference Intake.[18] Thus, we conclude that the present subjects had the general physical characteristics of the Japanese general population. However, the physical activity level of the present subjects was higher than that noted in our previous studies: 42.9% of the present subjects were classified as active, using the definition in the Dietary Reference Intake.[18] We recruited

Table 3. Total energy expenditure (TEE) and duration of each activity among groups by physical activity level

	Physical activity level			
	I Sedentary	II Moderately active	III Active	P
TEE by DLW (MJ/day)	8.11 (1.39)^{a,b}	9.18 (2.29)^{b}	10.76 (4.25)	<0.001
TEE by questionnaire (MJ/day)	7.78 (1.21)^{b,c}	8.45 (2.87)	8.90 (3.06)	0.006
Total METs (METs·h/day)	33.5 (4.1)^{b}	34.4 (4.8)^{b}	35.8 (6.4)	<0.001
Difference in TEE between DLW and PAQ (MJ/day)	−0.07 (0.50)^{b}	−0.80 (1.62)^{b}	−2.02 (2.23)	<0.001
Difference in TEE between DLW and PAQ (%)	−0.9 (15.3)^{b}	−8.4 (17.6)^{b}	−19.1 (19.0)	<0.001
Total duration of physical activity (h/day)				
Light (<3 METs)	3.41 (3.58)	4.14 (3.50)	4.16 (3.72)	0.155
Moderate (3–5.9 METs)	1.65 (1.81)^{b}	2.06 (2.07)^{b}	2.53 (3.89)	<0.001
Vigorous (≥6 METs)	0.00 (0.09)^{b}	0.00 (0.20)^{a}	0.0 (0.54)	0.007
Duration of leisure-time physical activity (h/day)				
Light (<3 METs)	0.00 (0.26)	0.00 (0.07)	0.00 (0.09)	0.766
Moderate (3–5.9 METs)	0.01 (0.17)	0.02 (0.23)	0.03 (0.27)	0.965
Vigorous (≥6 METs)	0.00 (0.08)	0.00 (0.02)	0.00 (0.00)	0.556
Duration of work (h/day)				
Sitting	0.00 (2.86)	1.55 (4.61)	0.00 (4.29)	0.129
Standing	1.75 (2.20)	1.42 (2.14)	2.00 (2.85)	0.176
Walking	0.25 (0.86)^{b,c}	0.54 (1.90)^{b}	1.00 (3.07)	<0.001
Proportion of subjects participating in heavy work (%)	6.1	24	36.1	0.003

TEE: total energy expenditure; DLW: doubly labeled water; MET: metabolic equivalent; PAQ: physical activity questionnaire.
All values are median (interquartile), unless otherwise indicated.
$^{a}P < 0.05$ as compared with physical activity level III.
$^{b}P < 0.01$ as compared with physical activity level III.
$^{c}P < 0.01$ as compared with physical activity level II.

Table 4. Correlation coefficients for physical activity level (as measured by doubly labeled water method) and duration of physical activities

	Correlation coefficient	P value	Partial correlation coefficient	P value
Total duration of physical activity (h/day)				
Light (<3 METs)	0.034	0.608	0.022	0.746
Moderate (3–5.9 METs)	0.257	<0.001	0.225	0.001
Vigorous (≥6 METs)	0.354	0.481	0.330	<0.001
Duration of leisure-time physical activity (h/day)				
Light (<3 METs)	−0.018	0.790	0.008	0.910
Moderate (3–5.9 METs)	0.002	0.978	0.000	0.996
Vigorous (≥6 METs)	−0.048	0.474	−0.072	0.286
Duration of work (h/day)				
Sitting	−0.064	0.337	−0.133	0.047
Standing	0.165	0.013	0.256	<0.001
Walking	0.271	<0.001	0.239	<0.001
Heavy	0.376	<0.001	0.354	<0.001

MET: metabolic equivalent; TEE: total energy expenditure.
Partial correlation coefficients are adjusted for sex and age group.

subjects at worksites requiring vigorous physical activity (ie, shipbuilding and hospitals). This may explain the higher physical activity level of the subjects.

Neilson et al reviewed a validation study of a physical activity questionnaire and suggested that, at the group level, the mean difference in TEE ranged from −800 to 1589 kcal/day (−3.35 to 6.65 MJ/day) and that the Spearman correlation coefficient for TEE ranged from 0.15 to 0.51.[2] As compared with these results, JALSPAQ showed a smaller negative mean difference of −1.15 MJ/day and a higher correlation (Spearman correlation, 0.742; $P < 0.001$). A comparison of individual-level agreement indicates that the width of the 95% LOA in our study (7.68 MJ/day) was smaller than that in most other questionnaires described in the review of Neilson and colleagues (1133 to 17 948 kcal/day; 4.74 to 75.09 MJ/day).[2] The relatively good agreement in this study partly resulted from the greater number of subjects ($n = 226$ in the present study vs $n = 13$ to $n = 65$ in previous studies) and the wide variation in TEE. Standard deviation was 2.77 MJ in the present study and 0.35 to 3.51 MJ in previous studies. A study by Racette showed the lowest 95% LOA (−2.42 to 0.16 MJ/day).[19] However, that study was part of an investigation of a 17-week outpatient weight loss treatment, so the subjects were thought to be highly motivated and to have answered the questionnaire carefully. One reason why TEE is assumed to have greater accuracy than the existing questionnaire is that it is believed to have more detailed questions regarding occupational activity, housework, and leisure-time physical activity.

JALSPAQ tended to greatly underestimate TEE in more active subjects, possibly because the algorithm for the calculation of TEE for JALSPAQ only includes duration of time spent sitting, standing, and walking. These activities were scored on a scale from 1.5 to 4.0 METs. Even when there was a question regarding carrying heavy objects or engaging in activity of similar intensity, such activity was not used to calculate TEE. Thus, underestimation would be greater in subjects who expended considerable energy at work. In the present study, 16 subjects were engaged in shipbuilding, and the differences between TEE by DLW and JALSPAQ ranged from −10.98 to 0.34 MJ/day; TEE was overestimated by JALSPAQ in only 2 subjects.

Although TEE estimated by JALSPAQ showed a relatively good correlation with TEE by DLW, RMR accounted for a large part of TEE. To lessen the contribution of RMR, PAL was compared between the two methods. The results for PAL were poor, and individual differences were widely distributed. Therefore, JALSPAQ must either be improved or another new questionnaire should be developed to assess individual PAL.

We also attempted to identify a physical activity that characterized physical activity level. Our results showed that total time spent in moderate physical activity was significantly greater in the active group. In addition, moderate and vigorous physical activity had a weak but significant correlation with PAL. Thus, moderate physical activity is an important component of physical activity level, as Westerterp has suggested.[20] However, the duration of moderate physical activity did not differ in the sedentary and moderate groups. Wareham et al used a very brief questionnaire that only included physical activity during work and recreational activities and found that physical activity ratio (daytime energy expenditure/resting metabolic rate), which was estimated using a heart rate monitor, did not differ between inactive and moderately inactive groups, even though VO_{2max} was different between these groups.[21] Another method of classifying physical activity in sedentary subjects should thus be considered.

The present results also suggest that intensity and duration of physical activity during work (including occupational activity and housework) strongly affect PAL, whereas leisure-time physical activity does not. Both work and leisure-time physical activity play fundamental roles in total physical activity, which explains why previous brief physical activity questionnaires assessed only physical activity during work and leisure time.[21,22] In the present study, because the mean duration of all leisure-time physical activity was 22 ± 21 minutes per day, the effect of leisure-time physical activity on TEE might be very small.

The most significant limitation of this study was that subjects were not selected randomly: they joined the study as volunteers. Hence, as compared with the general population, they might have remembered their physical activities better and completed the questionnaire more carefully. In addition, the variation in their physical activity level might differ from that of the general Japanese population. However, we were unable not determine the nature or extent of error that resulted from these subject characteristics. A second limitation is that the study periods for DLW and JALSPAQ were not identical. The DLW method determined the average TEE over 1 or 2 weeks. In contrast, JALSPAQ assessed typical physical activity over 1 month. This discrepancy could affect the validation of JALSPAQ. Finally, the relatively small proportion of sedentary subjects made it difficult to characterize the sedentary population. Although we tried to collect subjects with a broad range of physical activities, we could not collect comparable numbers of sedentary and active subjects.

In conclusion, PAL by JALSPAQ weakly correlated with PAL by DLW, although TEE by JALSPAQ was better correlated with TEE by DLW than with TEE assessed by the questionnaires used in previous studies. TEE underestimation was greater in active subjects than in sedentary and moderately active subjects. In addition, in this population, total moderate physical activity and physical activity during work were related to physical activity level, whereas leisure-time physical activity was not. To improve the physical activity questionnaire, an algorithm for heavy work should be added. In addition, to better differentiate sedentary subjects form moderate subjects, additional questionnaire items should be added or the algorithm should be reevaluated.

ACKNOWLEDGMENTS

This study was partly supported by Health and Labour Sciences Research Grants from the Japanese Ministry of Health, Labour and Welfare. The authors gratefully acknowledge the generous assistance of the working group for the development of a physical activity survey of the Japan Arthrosclerosis Longitudinal Study Group. The authors also thank the Japan Arteriosclerosis Prevention Fund, which supports the Japan Arteriosclerosis Longitudinal Study.

Conflicts of interest: The authors have no conflicts of interest to report.

REFERENCES

1. Shephard RJ. Limits to the measurement of habitual physical activity by questionnaires. Br J Sports Med. 2003;37:197–206; discussion.
2. Neilson HK, Robson PJ, Friedenreich CM, Csizmadi I. Estimating activity energy expenditure: how valid are physical activity questionnaires? Am J Clin Nutr. 2008;87:279–91.
3. Prince SA, Adamo KB, Hamel ME, Hardt J, Gorber SC, Tremblay M. A comparison of direct versus self-report measures for assessing physical activity in adults: a systematic review. Int J Behav Nutr Phys Act. 2008;5:56.
4. Westerterp KR. Assessment of physical activity: a critical appraisal. Eur J Appl Physiol. 2009;105:823–8.
5. Ishikawa-Takata K, Tabata I, Sasaki S, Rafamantanantsoa HH, Okazaki H, Okubo H, et al. Physical activity level in healthy free-living Japanese estimated by doubly labelled water method and International Physical Activity Questionnaire. Eur J Clin Nutr. 2008;62:885–91.
6. Naito Y, Harada A, Inoue S, Kitabatake Y, Arao T, Ohashi Y. Report of the physical activity research of the Japan Arteriosclerosis Longitudinal Staudy. Research in Exercise Epidemiology. 2003;5:1–7.

7. Japan Arteriosclerosis Longitudinal Study (JALS) Group. Japan Arteriosclerosis Longitudinal Study-Existing Cohorts Combine (JALS-ECC): rationale, design, and population characteristics. Circ J. 2008;72:1563–8.
8. Melanson EL Jr, Freedson PS. Physical activity assessment: a review of methods. Crit Rev Food Sci Nutr. 1996;36:385–96.
9. Weir JB. New methods for calculating metabolic rate with special reference to protein metabolism. J Physiol. 1949;109:1–9.
10. International Atomic Energy Agency. Assessment of body composition and total energy expenditure in humans using stable isotope techniques. Vienna, Austria: International Atomic Energy Agency; 2009.
11. Black AE, Prentice AM, Coward WA. Use of food quotients to predict respiratory quotients for the doubly-labelled water method of measuring energy expenditure. Hum Nutr Clin Nutr. 1986;40:381–91.
12. Jones PJ, Leitch CA. Validation of doubly labeled water for measurement of caloric expenditure in collegiate swimmers. J Appl Physiol. 1993;74:2909–14.
13. Surrao J, Sawaya AL, Dallal GE, Tsay R, Roberts SB. Use of food quotients in human doubly labeled water studies: comparable results obtained with 4 widely used food intake methods. J Am Diet Assoc. 1998;98:1015–20.
14. Ainsworth BE, Haskell WL, Whitt MC, Irwin ML, Swartz AM, Strath SJ, et al. Compendium of physical activities: an update of activity codes and MET intensities. Med Sci Sports Exerc. 2000;32:S498–504.
15. Satoshi S. Development and evaluation of dietary assessment methods using biomarkers and diet history questionnaires for individuals. In: Heizo T, editor. Research for evaluation methods of nutrition and dietary lifestyle programs held on Healthy Japan 21: Summary report. Ministry of Health, Labour and Welfare, Japan; 2004. p. 10–44.
16. Matsuzawa Y. New criteria for 'obesity disease' in Japan. Circ J. 2002;66:987–92.
17. Vivian HH, Dale WR. Body composition reference methods. Applied body composition assessment. Champaign, IL: Human Kinetics; 2004. p. 22–47.
18. Ministry of Health Labour and Walfare, Japan. Dietry Reference Intakes for Japanese, 2010. Ministry of Health, Labour and Welfare, Japan; 2010.
19. Racette SB, Schoeller DA, Kushner RF. Comparison of heart rate and physical activity recall with doubly labeled water in obese women. Med Sci Sports Exerc. 1995;27:126–33.
20. Westerterp KR. Pattern and intensity of physical activity. Nature. 2001;410:539.
21. Wareham NJ, Jakes RW, Rennie KL, Schuit J, Mitchell J, Hennings S, et al. Validity and repeatability of a simple index derived from the short physical activity questionnaire used in the European Prospective Investigation into Cancer and Nutrition (EPIC) study. Public Health Nutr. 2003;6:407–13.
22. Johansson G, Westerterp KR. Assessment of the physical activity level with two questions: validation with doubly labeled water. Int J Obes (Lond). 2008;32:1031–3.

British Journal of Nutrition (2011), page 1 of 11

doi:10.1017/S0007114510005441

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

Kazunori Ohkawara[1,2]*, Yoshitake Oshima[3], Yuki Hikihara[4], Kazuko Ishikawa-Takata[1], Izumi Tabata[1,5] and Shigeho Tanaka[1]

[1]*Health Promotion and Exercise Program, National Institute of Health and Nutrition, 1-23-1 Toyama, Shinjuku-ku, Tokyo 162-8636, Japan*
[2]*Center for Human Nutrition, University of Colorado Denver, Denver, CO, USA*
[3]*Research and Development Department, Omron Healthcare Company Limited, Kyoto, Japan*
[4]*Faculty of Engineering, Chiba Institute of Technology, Narashino, Japan*
[5]*Faculty of Sport and Health Sciences, Ritsumeikan University, Shiga, Japan*

(Received 14 June 2010 – Revised 18 November 2010 – Accepted 19 November 2010)

Abstract

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

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

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

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

---

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

* **Corresponding author:** K. Ohkawara, fax +81 3 3204 1761, email ohkawara@nih.go.jp

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

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

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

Subjects and methods

Subjects

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

Anthropometric measurements

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

Experimental protocol

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

Table 1. Physical characteristics of the subjects in each group

(Mean values and standard deviations)

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

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

Indirect calorimetry

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

Triaxial accelerometer

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

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

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

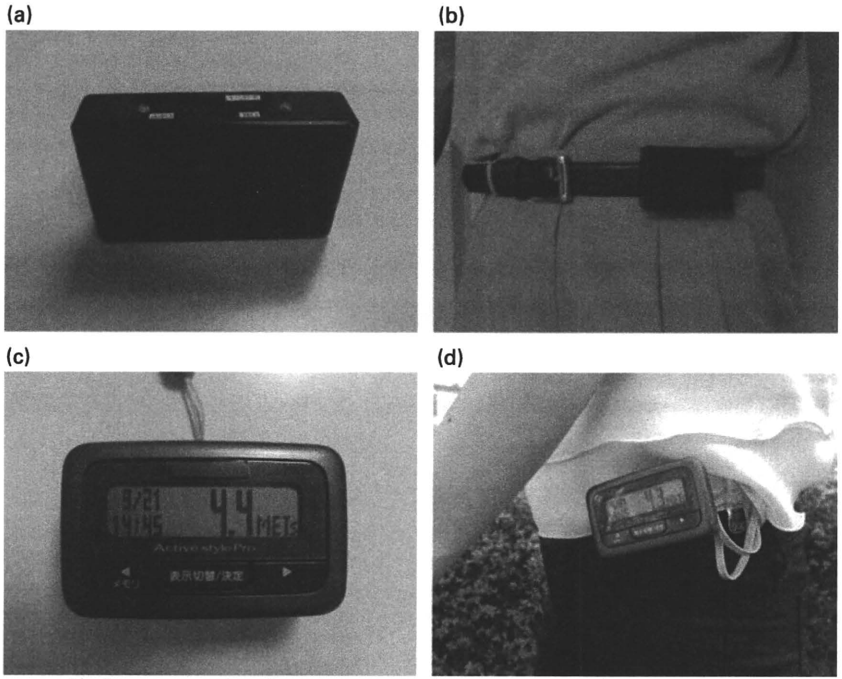

Fig. 1. Prototype accelerometer used in the present study and a commercial accelerometer based on the algorithm developed in the present study. (a) Prototype accelerometer that was used to perform all measurements; (b) subjects wore the prototype accelerometer on the waist with a clip during the entire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

Table 2. Energy expenditure, metabolic equivalents (MET), accelerations and acceleration ratios for each activity in the validation group
(Mean values and standard deviations, *n* 44)

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

* MET were calculated as energy expenditure for each activity divided by energy expenditure for resting in the sitting position.
† MET were calculated as energy expenditure for each activity divided by 4·184 kJ/kg per h.

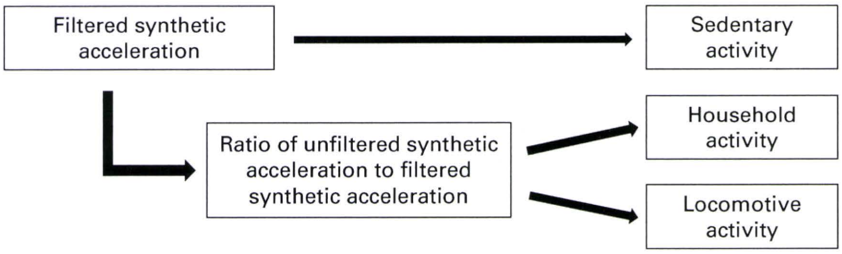

Fig. 2. Algorithm for the classification of three different activity types, using a triaxial accelerometer.

Statistical analysis

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

Results

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

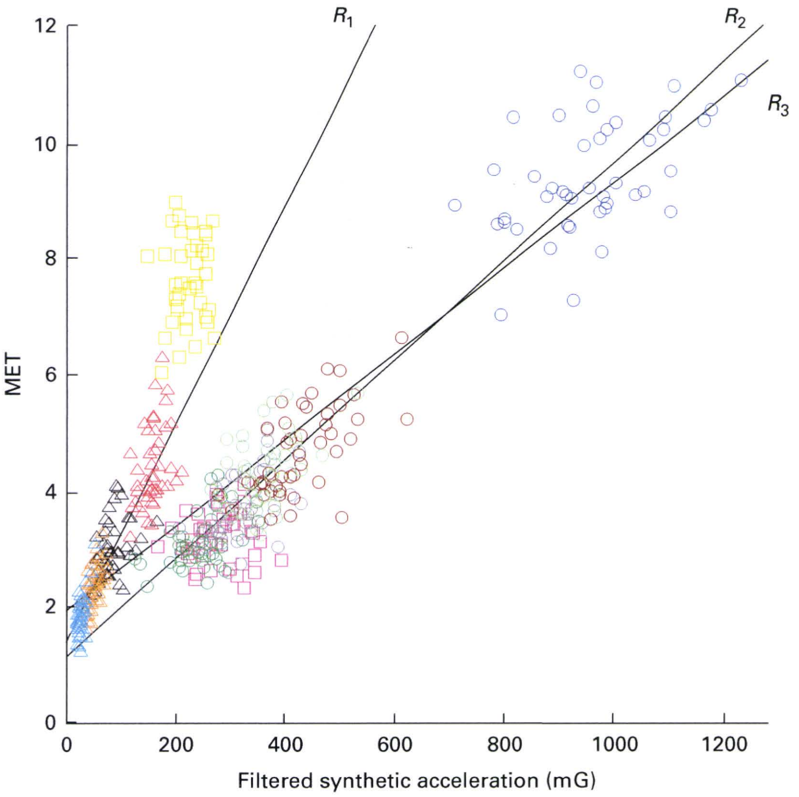

Fig. 3. Relationships between measured metabolic equivalents (MET) and filtered synthetic accelerations during locomotive and household activities in the validation group (*n* 44). R_1 (*r* 0·907, $P<0·001$), regression line for household activities only; R_2 (*r* 0·930, $P<0·001$), regression line for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

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

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

	Equation	*r*	SEE (MET)
Linear regression model			
Model 1			
Locomotive plus household activities	$MET = 1.9494 + 0.0074 \times ACC_{fil}$	0·930*	0·804
Model 2			
Locomotive activity only	$MET = 1.1372 + 0.0085 \times ACC_{fil}$	0·961*	0·658
Household activity only	$MET = 1.4023 + 0.0188 \times ACC_{fil}$	0·907*	0·460
Non-linear regression model			
Model 3			
Locomotive activity only	$MET = 0.8944 + 0.0126 \times ACC_{fil}^{0.947}$	0·961*	0·657
Household activity only	$MET = 0.8149 + 0.1014 \times ACC_{fil}^{0.701}$	0·910*	0·453
Sex-specific linear regression model			
Model 4			
Locomotive activity only (male)	$MET = 0.8766 + 0.0088 \times ACC_{fil}$	0·968*	0·634
Locomotive activity only (female)	$MET = 1.3488 + 0.0083 \times ACC_{fil}$	0·955*	0·658
Household activity only (male)	$MET = 1.4022 + 0.0181 \times ACC_{fil}$	0·911*	0·446
Household activity only (female)	$MET = 1.3951 + 0.0195 \times ACC_{fil}$	0·907*	0·470
Sex-specific non-linear regression model			
Model 5			
Locomotive activity only (male)	$MET = 0.6714 + 0.0120 \times ACC_{fil}^{0.959}$	0·968*	0·633
Locomotive activity only (female)	$MET = 0.5367 + 0.0284 \times ACC_{fil}^{0.834}$	0·956*	0·654
Household activity only (male)	$MET = 1.3172 + 0.0254 \times ACC_{fil}^{0.939}$	0·911*	0·445
Household activity only (female)	$MET = 0.2828 + 0.2393 \times ACC_{fil}^{0.563}$	0·915*	0·451

* $P<0.001$.

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

Fig. 3 depicts the relationship between measured MET and ACC_{fil} during household and locomotive activities performed by the validation group. The correlation coefficients for locomotive (*r* 0·961, $P<0.001$), household (*r* 0·907, $P<0.001$) and combined household and locomotive activities (*r* 0·930, $P<0.001$) were high. We developed linear and non-linear regressions for estimating the intensities of household and locomotive activities; ascending and descending stairs were excluded from developing regressions, because the relationships between MET and ACC_{fil} for ascending and descending stairs differed from the relationship for the other locomotive activities (Table 3). As a result, the linear regression calculated with combined data of household and locomotive activities had a lower *r* value compared with all other regressions for locomotive activities only. Regressions for only household activities had slightly lower *r* values than those for all activities, but the regression standard errors of estimate were improved. Table 4 shows the cross-validation for all regressions. Significant differences were observed between measured values and values estimated from model 1 for most activities. However, models 2–5 accurately estimated the intensity of most household and locomotive activities, with the exceptions of ascending and descending stairs from models 2–5 and normal walking from models 2, 4 and 5, although the differences for normal walking were relatively small. In the cross-validation group, household and locomotive activities were correctly classified 100 % of the time by the ACC_{unfil}:ACC_{fil} threshold reported previously[27]. Bland–Altman plots showed that there was improved accuracy of individual activities with models 2–5 compared with model 1 (Fig. 4). Although all models tended to underestimate higher vigorous intensity activity with significant r^2 values ($P<0.05$), household activities were clearly well estimated by models 2–5. The results of the present study remained consistent, whether estimated from linear or non-linear regressions or from sex-specific regressions.

Fig. 5 depicts the relationship between measured MET and ACC_{fil} during sedentary activities performed by the validation group. We selected three activities to represent sedentary activities. As shown in Fig. 5, we calculated the regression equation for estimating the intensity of sedentary activities by including dishwashing with the lowest MET on average in our selected household and locomotive activities. The threshold for the classification between sedentary activities and other activities was determined by the point of intersection in the linear regressions for sedentary activities and household activities (29·9 mG). With these threshold and regression equations, resting in the supine position (mean difference 0·04 (SD 0·06) MET, $P<0.01$), personal computer work (mean difference −0·03 (SD 0·09) MET, NS) and dishwashing (mean difference 0·02 (SD 0·31) MET, NS) were estimated adequately in the cross-validation group.

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

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

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

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

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

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

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

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

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

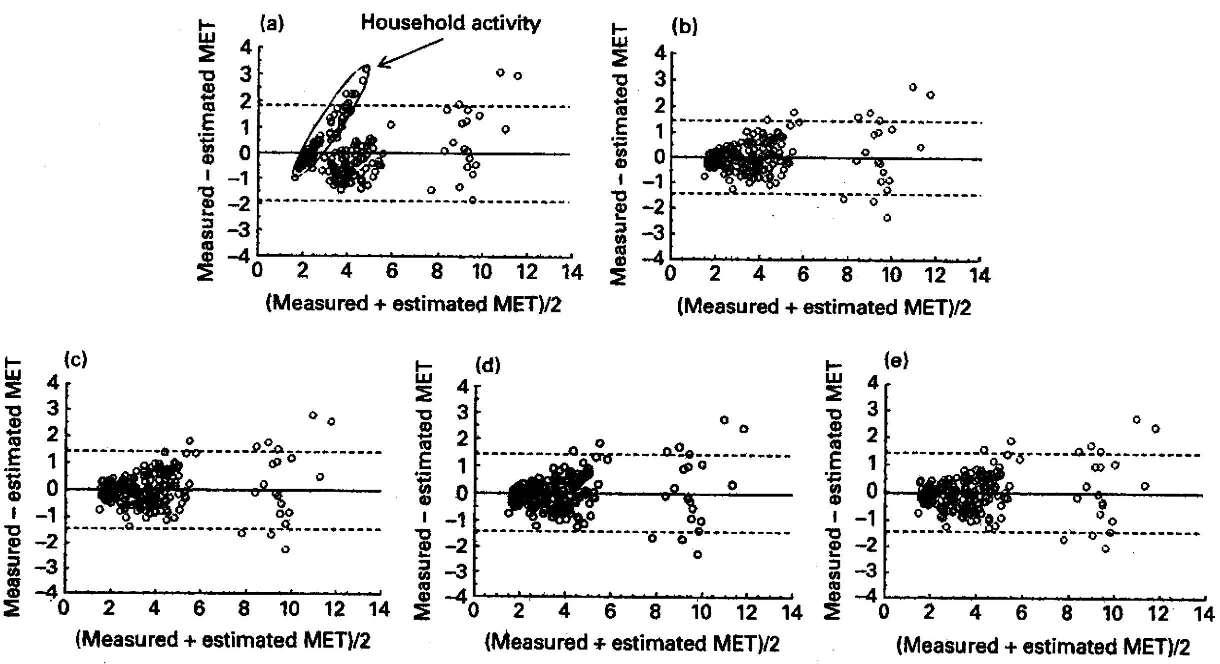

Fig. 4. Bland–Altman analysis. Differences between measured and estimated metabolic equivalents (MET) are plotted against measured and estimated mean MET for household and locomotive activities. (a) Model 1, linear regression model for estimating locomotive and household activities together (*r* 0·237);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

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

If $29{\cdot}9\,\text{mG} > \text{ACC}_{\text{fil}}$,

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

If $29{\cdot}9\,\text{mG} \leq \text{ACC}_{\text{fil}}$,

Then if $1{\cdot}16 \leq \text{ACC}_{\text{unfil}}:\text{ACC}_{\text{fil}}$ ratio.

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

Else if $1{\cdot}16 > \text{ACC}_{\text{unfil}}:\text{ACC}_{\text{fil}}$ ratio.

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

Discussion

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

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

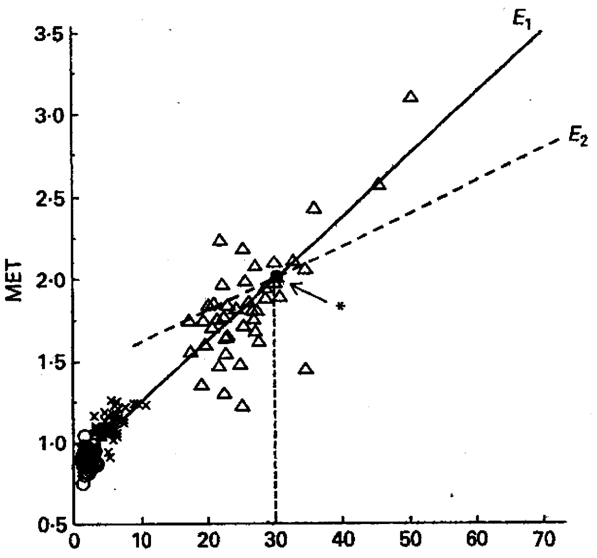

Fig. 5. Relationship between measured metabolic equivalents (MET) and filtered synthetic accelerations during sedentary activities in the validation group (*n* 44). E_1 (*r* 0·942, $P<0·001$, standard error of estimate 0·151 MET), regression line for sedentary activities; E_2, regression line for household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

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

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

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

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

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

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

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

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

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

Acknowledgements

The present study was supported by the Health and Labor Sciences Research Grants for Comprehensive Research on Cardiovascular and Life-Style Related Diseases from the Japanese Ministry of Health, Labor and Welfare (principal investigator: S. T.). Heartfelt thanks are due to the subjects who participated in the present study. We wish to thank the members of the National Institute of Health and Nutrition and Omron Healthcare Company Limited, especially Hiroko Kogure, Emiko Taguri, Rieko Miyake, Ryosuke Doi and Kaori Kawaguchi for their help in data acquisition and analysis. K. O., S. T., Y. O., Y. H., K. I.-T. and I. T. designed the study; K. O., S. T., Y. O., Y. H. and K. I.-T. performed the experiments; K. O., S. T. and Y. O. analysed the data; K. O., S. T. and Y. O. wrote a draft of the manuscript; Y. H., K. I.-T. and I. T. reviewed and edited the manuscript. None of the authors had a conflict of interest.

References

1. US Department of Health & Human Services (2008) Physical Activity Guidelines Advisory Committee Report 2008. http://www.health.gov/PAGuidelines/Report/
2. Saris WH, Blair SN, van Baak MA, *et al.* (2003) How much physical activity is enough to prevent unhealthy weight gain? Outcome of the IASO 1st Stock Conference and consensus statement. *Obes Rev* **4**, 101–114.
3. Levine JA, Eberhardt NL & Jensen MD (1999) Role of nonexercise activity thermogenesis in resistance to fat gain in humans. *Science* **283**, 212–214.
4. Levine JA, Lanningham-Foster LM, McCrady SK, *et al.* (2005) Interindividual variation in posture allocation: possible role in human obesity. *Science* **307**, 584–586.
5. Dale D, Welk GJ & Matthews CE (2002) Methods for assessing physical activity and challenges for research. In *Physical Activity Assessments for Health-related Research*, pp. 19–34 [GJ Welk, editor]. Champaign, IL: Human Kinetics Publishers.
6. Melanson EL Jr & Freedson PS (1996) Physical activity assessment: a review of methods. *Crit Rev Food Sci Nutr* **36**, 385–396.
7. Neilson HK, Robson PJ, Friedenreich CM, *et al.* (2008) Estimating activity energy expenditure: how valid are physical activity questionnaires? *Am J Clin Nutr* **87**, 279–291.
8. Chen KY & Bassett DR Jr (2005) The technology of accelerometry-based activity monitors: current and future. *Med Sci Sports Exerc* **37**, S490–S500.
9. Trost SG, McIver KL & Pate RR (2005) Conducting accelerometer-based activity assessments in field-based research. *Med Sci Sports Exerc* **37**, S531–S543.

10. Ward DS, Evenson KR, Vaughn A, *et al.* (2005) Accelerometer use in physical activity: best practices and research recommendations. *Med Sci Sports Exerc* **37**, S582–S588.
11. Richardson CR, Newton TL, Abraham JJ, *et al.* (2008) A meta-analysis of pedometer-based walking interventions and weight loss. *Ann Fam Med* **6**, 69–77.
12. Bravata DM, Smith-Spangler C, Sundaram V, *et al.* (2007) Using pedometers to increase physical activity and improve health: a systematic review. *JAMA* **298**, 2296–2304.
13. Bassett DR Jr, Ainsworth BE, Swartz AM, *et al.* (2000) Validity of four motion sensors in measuring moderate intensity physical activity. *Med Sci Sports Exerc* **32**, S471–S480.
14. Matthews CE (2005) Calibration of accelerometer output for adults. *Med Sci Sports Exerc* **37**, S512–S522.
15. Welk GJ, Blair SN, Wood K, *et al.* (2000) A comparative evaluation of three accelerometry-based physical activity monitors. *Med Sci Sports Exerc* **32**, S489–S497.
16. Rothney MP, Schaefer EV, Neumann MM, *et al.* (2008) Validity of physical activity intensity predictions by ActiGraph, Actical, and RT3 accelerometers. *Obesity (Silver Spring)* **16**, 1946–1952.
17. Chen KY & Sun M (1997) Improving energy expenditure estimation by using a triaxial accelerometer. *J Appl Physiol* **83**, 2112–2122.
18. Crouter SE & Bassett DR Jr (2008) A new 2-regression model for the Actical accelerometer. *Br J Sports Med* **42**, 217–224.
19. Crouter SE, Churilla JR, Bassett DR, *et al.* (2006) Estimating energy expenditure using accelerometers. *Eur J Appl Physiol* **98**, 601–612.
20. Crouter SE, Churilla JR & Bassett DR Jr (2008) Accuracy of the Actiheart for the assessment of energy expenditure in adults. *Eur J Clin Nutr* **62**, 704–711.
21. Crouter SE, Clowers KG & Bassett DR Jr (2006) A novel method for using accelerometer data to predict energy expenditure. *J Appl Physiol* **100**, 1324–1331.
22. Midorikawa T, Tanaka S, Kaneko K, *et al.* (2007) Evaluation of low-intensity physical activity by triaxial accelerometry. *Obesity (Silver Spring)* **15**, 3031–3038.
23. Pober DM, Staudenmayer J, Raphael C, *et al.* (2006) Development of novel techniques to classify physical activity mode using accelerometers. *Med Sci Sports Exerc* **38**, 1626–1634.
24. Rothney MP, Neumann M, Beziat A, *et al.* (2007) An artificial neural network model of energy expenditure using nonintegrated acceleration signals. *J Appl Physiol* **103**, 1419–1427.
25. Tanaka C, Tanaka S, Kawahara J, *et al.* (2007) Triaxial accelerometry for assessment of physical activity in young children. *Obesity (Silver Spring)* **15**, 1233–1241.
26. Zhang K, Werner P, Sun M, *et al.* (2003) Measurement of human daily physical activity. *Obes Res* **11**, 33–40.
27. Oshima Y, Kawaguchi K, Tanaka S, *et al.* (2010) Classifying household and locomotive activities using a triaxial accelerometer. *Gait Posture* **31**, 370–374.
28. Ohkawara K, Tanaka S, Ishikawa-Takata K, *et al.* (2008) Twenty-four-hour analysis of elevated energy expenditure after physical activity in a metabolic chamber: models of daily total energy expenditure. *Am J Clin Nutr* **87**, 1268–1276.
29. Weir JB (1949) New methods for calculating metabolic rate with special reference to protein metabolism. *J Physiol* **109**, 1–9.
30. Bland JM & Altman DG (1986) Statistical methods for assessing agreement between two methods of clinical measurement. *Lancet* **1**, 307–310.
31. Corder K, Brage S, Mattocks C, *et al.* (2007) Comparison of two methods to assess PAEE during six activities in children. *Med Sci Sports Exerc* **39**, 2180–2188.
32. Institute of Medicine (2005) *Dietary Reference Intakes for Energy, Carbohydrate, Fiber, Fat, Fatty, Acids, Cholesterol, Protein and Amino Acids.* Washington, DC: The National Academies Press.
33. Westerterp KR (2001) Pattern and intensity of physical activity. *Nature* **410**, 539.
34. Crouter SE, Kuffel E, Haas JD, *et al.* (2010) Refined two-regression model for the ActiGraph accelerometer. *Med Sci Sports Exerc* **42**, 1029–1037.
35. Bonomi AG, Plasqui G, Goris AH, *et al.* (2009) Improving assessment of daily energy expenditure by identifying types of physical activity with a single accelerometer. *J Appl Physiol* **107**, 655–661.
36. Staudenmayer J, Pober D, Crouter S, *et al.* (2009) An artificial neural network to estimate physical activity energy expenditure and identify physical activity type from an accelerometer. *J Appl Physiol* **107**, 1300–1307.
37. Maiolo C, Melchiorri G, Iacopino L, *et al.* (2003) Physical activity energy expenditure measured using a portable telemetric device in comparison with a mass spectrometer. *Br J Sports Med* **37**, 445–447.
38. McLaughlin JE, King GA, Howley ET, *et al.* (2001) Validation of the COSMED K4 b2 portable metabolic system. *Int J Sports Med* **22**, 280–284.
39. Melanson EL, Freedson PS, Hendelman D, *et al.* (1996) Reliability and validity of a portable metabolic measurement system. *Can J Appl Physiol* **21**, 109–119.
40. Wideman L, Stoudemire NM, Pass KA, *et al.* (1996) Assessment of the aerosport TEEM 100 portable metabolic measurement system. *Med Sci Sports Exerc* **28**, 509–515.
41. Duffield R, Dawson B, Pinnington HC, *et al.* (2004) Accuracy and reliability of a Cosmed K4b2 portable gas analysis system. *J Sci Med Sport* **7**, 11–22.
42. Littlewood RA, White MS, Bell KL, *et al.* (2002) Comparison of the Cosmed K4 b(2) and the Deltatrac II metabolic cart in measuring resting energy expenditure in adults. *Clin Nutr* **21**, 491–497.
43. Mc Naughton LR, Sherman R, Roberts S, *et al.* (2005) Portable gas analyser Cosmed K4b2 compared to a laboratory based mass spectrometer system. *J Sports Med Phys Fitness* **45**, 315–323.
44. Byrne NM, Hills AP, Hunter GR, *et al.* (2005) Metabolic equivalent: one size does not fit all. *J Appl Physiol* **99**, 1112–1119.
45. Jette M, Sidney K & Blumchen G (1990) Metabolic equivalents (METS) in exercise testing, exercise prescription, and evaluation of functional capacity. *Clin Cardiol* **13**, 555–565.
46. Leenders NY, Sherman WM & Nagaraja HN (2006) Energy expenditure estimated by accelerometry and doubly labeled water: do they agree? *Med Sci Sports Exerc* **38**, 2165–2172.
47. Yamazaki T, Gen-No H, Kamijo Y, *et al.* (2009) A new device to estimate VO_2 during incline walking by accelerometry and barometry. *Med Sci Sports Exerc* **41**, 2213–2219.

Journal of
PHYSIOLOGICAL
ANTHROPOLOGY

Validity of Physical Activity Indices for Adjusting Energy Expenditure for Body Size: Do the Indices Depend on Body Size?

Emiko Taguri1),2),3), Shigeho Tanaka2), Kazunori Ohkawara2), Kazuko Ishikawa-Takata2),
Yuki Hikihara2), Rieko Miyake1),2), Shigeru Yamamoto1) and Izumi Tabata2)

1) Department of Food and Nutritional Sciences, Graduate School of Humanities and Sciences, Ochanomizu University
2) Health Promotion and Exercise Program, National Institute of Health and Nutrition
3) Health Insurance Naruto Hospital

Abstract To express intensity of physical activity, energy expenditure is often divided by either body weight, resting metabolic rate, or fat-free mass. These calculations are used widely as the physical activity index. However, it is unclear how body size influences the valid estimation of intensity of various kinds of activities. In the present study, we investigated whether these indices are able to adjust for body size when calculating energy expenditure in various kinds of activities. In addition, we examined to what extent the error of index is introduced by differences in body size. Resting metabolic rates and energy expenditure during sitting light work, 4 lifestyle and 7 ambulant activities were measured in the postabsorptive state using indirect calorimetry in 71 healthy Japanese adults. We regarded an index as an inappropriate adjustment for body size when there was a significant correlation between it and body weight. Energy expenditure normalized by body weight correlated with body weight in all sedentary states; when normalized by lying resting metabolic rate it correlated with body weight in 3 ambulant activities; when normalized by sitting resting metabolic rate it correlated with body weight in 2 lifestyle and 5 ambulant activities; and when normalized by fat-free mass it correlated with only 1 ambulant activity. The indices caused errors in estimates of activity intensity of less than±10% when body weight was more than 10 kg above average. In conclusion, the body weight-normalized index was inappropriate for sedentary activities and the other three indices were inappropriate for ambulant activities. However, the use of any of these indices introduces an error in the estimate of total energy expenditure of considerably less than±10% for body weights within the normal range.
J Physiol Anthropol 29(3): 109–117, 2010 http://www.jstage.jst.go.jp/browse/jpa2
[DOI: 10.2114/jpa2.29.109]

Keywords: intensity of activity, body weight, resting metabolic rate

Introduction

Measurements of energy expenditure (EE) and determination of intensity of physical activity are important for the assessment of human health and nutrition. Human daily life consists of various kinds of activities, with the pattern of daily activity not being constant even in the same individual. It is however possible to compare or evaluate different types of movement activities if each physical activity is expressed as intensity. It is important to note that EE becomes higher with increasing body size even if the same intensity of activity is performed. Therefore, it is necessary to adjust EE for body size in order to appropriately compare the intensity of activity. This makes it possible to compare different styles of physical activity with different body size, which is helpful for understanding the physiological polymorphisms that occur in humans.

There are several alternative approaches for determining the intensity of activity using physical activity indices (PAIs), defined as EE divided by either body weight (BW: EE/BW), resting metabolic rate (RMR) in the lying position (L-RMR: EE/L-RMR), RMR in the sitting position (S-RMR: EE/S-RMR), or fat-free mass (FFM: EE/FFM). These PAIs are used routinely throughout the world to normalize data. Adjustment for body size as multiples of the PAIs assumes that the relationship between EEs and the normalizing factors are linear and pass through the origin. However, it is uncertain to what degree these PAIs provide appropriate adjustment for body size in various kinds of activities.

Previous studies found that EE/BW overcorrected for body size (Prentice et al., 1996; Lawrence, 1988; Davies and Cole, 2003). EE/BW was greater for underweight than for overweight subjects despite their performing the same activity. In other words, if the same PAI value is used in these activities, EE is underestimated for underweight subjects and overestimated for overweight subjects. The authors suggested that the quantity EE/BW$^{0.5}$ was more appropriate for sedentary lifestyles. The basal metabolic rate (BMR) was roughly proportional to weight raised to the 0.5 power. Therefore the EE of common daily activities was more proportional to BMR than to BW (Lawrence, 1988). However, other studies found that EE/BMR was not constant for different BWs when used for lifestyle and ambulant activities (Kuriyan et al., 2006; Spadano et al., 2003; Haggarty et al., 1997). In these activities, EE/BMR was greater in overweight subjects than in underweight subjects. In some cases, BMR was substituted for RMRs (L-RMR and S-RMR). However, differences in the relationships between body size and L-RMR and S-RMR were not clarified sufficiently. There is an alternative way to adjust EE for body size, namely, EE/FFM, with previous studies in children and adolescents suggesting that FFM may be the most appropriate variable for normalization of EE during physical activities (Ekelund et al., 2004; Vermorel et al., 2005).

Intensity of daily total activity can be estimated by dividing total energy expenditure (TEE) by BW (TEE/BW) or by RMRs (TEE/L-RMR and TEE/S-RMR). These indices were shown to also be sensitive to body size even for the same physical activity (Prentice et al., 1996; Goran, 1995; Carpenter et al., 1995). As a result, it was not possible to compare intensity of daily activity between groups with different body sizes.

Unfortunately, as previous studies investigated only one of these PAIs for particular activities, it is impossible to compare the PAIs for different activities (Ferro-Luzzi, 2005). As described above, daily life consists of various kinds of activities, with these activities being classified roughly into weight-dependent, non-weight dependent and intermediate activities. In order to understand the biomechanical and physiological variability of these activities, it is necessary to adequately adjust for body size or RMR. The objectives of the present study were therefore to examine the validity of the four PAIs to characterize each daily activity in the Japanese population and to determine how body size influences the reliable estimation of activity intensity during various kinds of activities.

Materials and Methods

Subjects

Seventy-eight healthy Japanese subjects in the age range of 20–69 years (41 males and 37 females) were recruited for the study. They were recruited from various types of occupations so that the distribution of body mass index (BMI) was comparable to that in the Japanese population. All subjects were free of chronic diseases that could affect metabolism or daily physical activity. Informed consent was signed by all subjects. The study protocol was approved by the Ethical Committee of the National Institute of Health & Nutrition.

Experimental protocol

The experiments were conducted after 12 or more hours of an overnight fast and sufficient sleep. The subjects visited the laboratory between 8:00 and 9:00 am on the day of the experiment and anthropometric measurements were obtained. L-RMR and S-RMR were then determined, followed by measurement of the EEs of various physical activities. The three PAIs were calculated for each activity.

Anthropometric measurements

The anthropometric measurements included height, BW, and percentage body fat (BF, %). A digital scale (YK-150D; Yagami, Nagoya, Japan) was used to measure BW to the nearest 0.1 kg with the subjects dressed in light clothing. The weight of clothing was then subtracted. Barefoot standing height was measured to the nearest 0.1 cm using a wall-mounted stadiometer (YL-65; Yagami). The BMI was calculated as BW (kg) divided by height squared (m^2). BF was measured by a bioelectrical impedance technique (HBF-362; Omron Healthcare, Kyoto, Japan). FFM (kg) was calculated by subtracting the amount of BF (kg) from BW.

Measurement of L-RMR, S-RMR, and EE of the activities

The subjects were instructed to lie quietly for 30 minutes before the measurement of L-RMR ($kcal \cdot min^{-1}$). During the L-RMR measurement, the subject was awakened quietly and instructed not to move. The ambient room temperature was maintained at approximately 25°C. The L-RMR measurement was recorded for 2 periods of 10 minutes. Following the L-RMR measurement, the subject sat quietly in a chair and S-RMR ($kcal \cdot min^{-1}$) was then measured for a period of 10 minutes.

Based on the preliminary study using 3-day activity records of 93 subjects living in the Tokyo metropolitan area under free-living conditions, the following activities were chosen as representative activities of daily life and classified into 3 categories. Sedentary activities were lying quietly, sitting quietly, and working at the computer. Lifestyle activities were vacuuming, hanging laundry, washing dishes, and lifting and carrying a small load (loading, unloading, and carrying a 5-kg package). Ambulant activities were walking up stairs, walking down stairs, walking (55 m/min, 70 m/min, 100 m/min), walking at 70 m/min with a 3-kg load, and jogging (140 m/min). The order of these measurements was from light activities to vigorous activities. The participants performed each activity for 3 to 6 minutes to achieve steady state before the expired gas was collected, with a break of a few minutes between each activity and the next to obtain the samples.

The expired gasses were collected in a 100 L Douglas bag (Fukuda Sangyo, Chiba, Japan), and the volume measured using a dry gas meter (DC-5; Shinagawa, Tokyo, Japan). The O_2 and CO_2 concentrations were measured with a mass spectrometer (ARCO-1000; Arco System, Kashiwa, Japan). The analyzer was calibrated with room air containing 20.93% O_2 and 0.04% CO_2, and a calibration-grade standard gas containing 15.27% O_2 and 5.12% CO_2 (Takachiho Chemical Industrial, Tokyo, Japan).