Table 4. Odds ratios and 95% confidence intervals for participants who perceived higher barriers to exercise, after evaluation by multiple logistic regression analyses

	Discomfort			Lack of motivation			Lack of time			Lack of social support			Poor environment		
	OR	95% CI	*P* value	OR	95% CI	*P* value	OR	95% CI	*P* value	OR	95% CI	*P* value	OR	95% CI	*P* value
Sex															
Male	1.32	0.95–1.84	0.096	1.06	0.75–1.49	0.749	0.78	0.55–1.09	0.148	1.22	0.88–1.69	0.241	1.08	0.78–1.50	0.649
Female	1.00			1.00			1.00			1.00			1.00		
Age, years															
20–39	1.13	0.68–1.86	0.640	2.31	1.34–3.99	0.003	2.52	1.47–4.32	0.001	1.11	0.67–1.82	0.693	1.01	0.61–1.67	0.955
40–59	1.22	0.79–1.89	0.375	1.74	1.08–2.82	0.023	2.22	1.39–3.56	0.001	1.00	0.64–1.54	0.983	0.56	0.36–0.87	0.010
60–	1.00			1.00			1.00			1.00			1.00		
Location of residence															
Tsukuba	0.92	0.57–1.47	0.712	1.05	0.64–1.74	0.842	0.97	0.59–1.58	0.897	1.13	0.70–1.80	0.620	0.92	0.57–1.48	0.735
Koganei	0.79	0.50–1.24	0.302	0.81	0.50–1.31	0.393	0.78	0.49–1.26	0.312	1.03	0.65–1.62	0.907	0.66	0.41–1.04	0.072
Shizuoka	0.72	0.45–1.15	0.173	0.90	0.55–1.48	0.676	0.88	0.54–1.43	0.609	0.85	0.54–1.35	0.495	0.81	0.51–1.28	0.361
Kagoshima	1.00			1.00			1.00			1.00			1.00		
Education, years															
≥13	0.99	0.70–1.40	0.959	1.63	1.13–2.34	0.009	1.29	0.91–1.84	0.158	0.84	0.59–1.18	0.304	0.95	0.67–1.33	0.747
<13	1.00			1.00			1.00			1.00			1.00		
Marital status															
Not married	0.93	0.61–1.41	0.724	0.85	0.55–1.33	0.487	1.21	0.78–1.88	0.386	1.03	0.67–1.56	0.908	0.93	0.61–1.41	0.728
Married	1.00			1.00			1.00			1.00			1.00		
Employment status															
Employed	0.87	0.58–1.29	0.478	0.96	0.63–1.47	0.866	2.77	1.81–4.25	<0.001	0.97	0.65–1.43	0.862	1.07	0.72–1.59	0.752
Not employed	1.00			1.00			1.00			1.00			1.00		
Living with a child or person in need of care															
Yes	0.73	0.51–1.03	0.072	0.86	0.60–1.24	0.425	1.20	0.84–1.72	0.307	0.98	0.69–1.38	0.889	1.09	0.77–1.54	0.634
No	1.00			1.00			1.00			1.00			1.00		
Self-rated health															
Fair or poor	1.64	1.20–2.25	0.002	1.88	1.35–2.61	<0.001	1.03	0.74–1.42	0.881	1.42	1.04–1.93	0.029	1.19	0.87–1.63	0.270
Good	1.00			1.00			1.00			1.00			1.00		
BMI, kg/m^2															
≥25	1.53	1.03–2.27	0.037	1.08	0.72–1.62	0.712	1.04	0.69–1.56	0.865	1.90	1.28–2.82	0.001	1.79	1.21–2.65	0.004
<25	1.00			1.00			1.00			1.00			1.00		

Abbreviations: BMI, Body mass index; CI, confidence interval; OR, odds ratio.
Odds ratios were calculated after adjustment for all variables listed in the table.

background. Employment status was also related to lack of time in the present study. For those who have little discretionary time for exercise, time-saving interventions such as lifestyle intervention rather than structured exercise programs, internet programs rather than face-to-face counseling, and individual counseling rather than group programs may be more effective.

Discomfort was significantly associated with fair or poor self-rated health and overweight, which suggests that exercise programs of proper intensity that are adjusted to a participant's fitness level and do not induce discomfort such as muscle soreness may be effective among individuals who are overweight or in poor health. Other relationships between sociodemographic variables and barriers indicated that certain population groups have their own profile of barrier perception.

This study was conducted using a community-based random sample from residents living in 4 cities in Japan. Participants were randomly selected from the registry of residential addresses, from a list encompassing the entire population of each city. The response rate was 21.6%. One reason for this low rate was that we included a 7-day accelerometer survey for other purposes of this project. To estimate the representativeness of this sample, we compared the age-adjusted prevalence of overweight individuals, exercisers, and employees in our sample with those in the national survey. The prevalence of overweight participants (BMI ≥25.0) was 28.4% in men and 12.8% in women in this study, while the age-adjusted prevalence in the sample of the Japanese National Health and Nutrition Survey 2005[2] was 29.6% in men and 19.0% in women. The prevalence of overweight persons in this study was similar in men and 6.2% lower in women. There are 2 possible reasons for this lower prevalence of overweight among women. One is that this sample of women was relatively healthier than the general population of Japanese. Another is that the assessment of BMI in this study was based on self-reports and women tend to report a lower weight than their actual body weight.[21,22] As for exercise habits (≥3days/week), 19.4% of men and 22.3% of women in this study were exercisers, while 20.4% of men and 18.2% of women were reported to be exercisers (≥3days/week) in the national survey.[2] Although the survey methods were different, the sample of this study seems to include a slightly higher percentage of women exercisers. Regarding employment status, 85.6% of men and 64.9% of women in the present study had gainful employment, while 76.3% of men and 55.2% of women worked full-time or part-time in the national survey.[23] The participants of this study may have included more employed persons, which indicates that our sample was slightly different from the general population. Therefore, we cannot exclude the possibility of selection bias. This study sample may have been slightly healthier and higher in socioeconomic status. If we assume that this bias in our population results in behavioral skills that are more likely to overcome the actual barriers caused by sociodemographic status, as compared to an unhealthier population with lower socioeconomic status, then this study would underestimate the influence of sociodemographic status on barrier perceptions.

This study possesses several strengths. First, we used a sample from the general population, whereas most previous studies of perceived barriers were conducted using certain populations such as students, employees, and research volunteers. Therefore, this study contributes to the understanding of the perception of barriers in the general population, and the difference in barriers among specific population groups. Second, most studies of exercise barriers were conducted in Western countries. There have been few reports from Japan, which has important cultural differences from Western countries. Our results have implications for exercise promotion strategies developed specifically for Japanese. Third, our analysis integrated a large variety of sociodemographic attributes. Most studies examined barriers by sex, age, and a few other attributes such as BMI and employment status, but the present study investigated a larger number of attributes. Finally, the reliability and validity of the barrier scale were comprehensively examined and confirmed in a previous study.[20]

However, some limitations of the present study should be acknowledged. First, the response rate was relatively low. As discussed above, this low rate could result in selection bias. However, there have been few previous studies that have addressed perceived barriers to exercise, with respect to a variety of sociodemographic variables, among the general population. Thus, we believe that our results are useful for understanding the psychological aspects of exercise behavior. Second, we examined barriers to exercise, but did not investigate other domains of physical activity such as work activity, commuting, and household work, which are also beneficial to health. The perception of barriers to exercise and to other domains of physical activity may be different. In the future, research on barriers to specific domains of physical activity would be useful in understanding determinants of physical activity.

In spite of these limitations, the results of this study helped to identify subgroups that perceive specific barriers to exercise among Japanese, and to gain a better understanding of the psychological aspects of exercise behavior. Characteristics of specific population groups should be considered in the development of exercise promotion strategies.

CONCLUSION

Perception of barriers to exercise varied in a Japanese population characterized by age, educational attainment, employment status, self-rated health, and BMI. These results should prove helpful in developing population-specific interventions, such as time-saving interventions for younger and employed populations and, for groups with poorer health, exercise programs that are adjusted to the participants' fitness level. The results of this study highlight the importance of adjusting exercise promotion strategies to match the characteristics of the target population.

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Original Article

Use of Doubly Labeled Water to Validate a Physical Activity Questionnaire Developed for the Japanese Population

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ABSTRACT

Background: No study has attempted to use the doubly labeled water (DLW) method to validate a physical activity questionnaire administered to a Japanese population. The development and refinement of such questionnaires require that physical activity components related to physical activity level be examined.

Methods: Among 226 Japanese men and women 20 to 83 years of age, total energy expenditure (TEE) was assessed using the Japan Arteriosclerosis Longitudinal Study Physical Activity Questionnaire (JALSPAQ), and the results were compared with TEE measured by the DLW method as a gold standard. Resting metabolic rate (RMR) was measured using the Douglas Bag method.

Results: The median TEE by DLW and physical activity level (PAL: TEE/RMR) were 11.21 MJ/day and 1.88, respectively, for men, and 8.42 MJ/day and 1.83 for women. JALSPAQ slightly underestimated TEE: the differences in mean and standard error were −1.15 ± 1.92 MJ/day. JALSPAQ and DLW TEE values were moderately correlated (Spearman correlation = 0.742, $P < 0.001$; intraclass correlation coefficient = 0.648, $P < 0.001$), and the 95% limit of agreement was −4.99 to 2.69 MJ. Underestimation of TEE by JALSPAQ was greater in active subjects than in less active subjects. Moderate and vigorous physical activity and physical activity during work (ie, occupational tasks and housework) were strongly related to physical activity level. However, the physical activity components that differentiated sedentary from moderately active subjects were not clear.

Conclusions: Physical activity level values on JALSPAQ and DLW were weakly correlated. In addition, estimation of TEE in active subjects should be improved, and the use of a questionnaire to differentiate activity in sedentary and moderately active subjects must be reassessed.

Key words: physical activity questionnaire; doubly labeled water; physical activity; energy expenditure

INTRODUCTION

Accurate assessment of physical activity level is fundamental in epidemiological studies that examine the effect of physical activity on disease prevention and health promotion. Although there are several methods for estimating physical activity level, questionnaires are the most common assessment tool in such studies. Many types of physical activity questionnaires are used in epidemiological studies, but a validation study of such questionnaires suggested that the reliability and validity of measurements of habitual physical activity are quite low.[1–3] In addition, Neilson et al suggested that the ability of physical activity questionnaires to predict total energy expenditure (TEE) is limited. Westerterp et al suggested that questionnaires are satisfactory as an instrument for ranking physical activity level, but not as tools for assessing absolute TEE.[4] We previously examined the International Physical Activity Questionnaire (IPAQ) and reported that it was difficult to distinguish sedentary from moderately active individuals in the Japanese population.[5] Although the IPAQ was developed for international use, we maintain that questionnaires designed to suit each country or culture would increase the validity of assessments of physical activity level. The Japan Arteriosclerosis Longitudinal Study Physical Activity Questionnaire (JALSPAQ) was developed to assess physical activity in the Japan Arteriosclerosis Longitudinal Study.[6,7] This questionnaire was developed using data from physical activity records for the Japanese

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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 ^{2}H 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 $\pm 2 \times$ 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

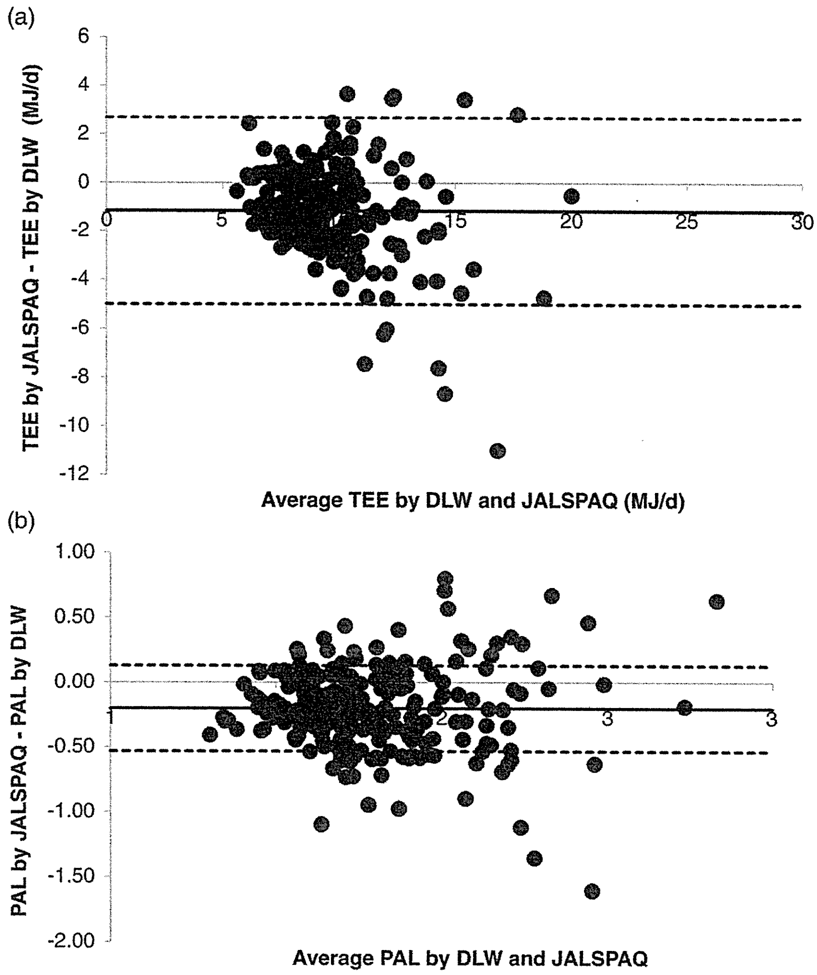

Figure. Bland-Altman plots of total energy expenditure (TEE) and physical activity level (PAL). (a) Comparison of mean TEE estimated by the doubly labeled water (DLW) method and the Japan Arteriosclerosis Longitudinal Study Physical Activity Questionnaire (JALSPAQ), and the difference in TEE as estimated 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			*P*
	I Sedentary	II Moderately active	III Active	
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.

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

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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.
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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).

Calculation of the PAIs

We consider the PAIs to be a convenient and practical index. The PAIs were calculated for each subject and activity by dividing EE by either BW (EE/BW; kcal·min^{-1}/kg), L-RMR (EE/L-RMR; kcal·min^{-1}/kcal·min^{-1}), S-RMR (EE/S-RMR; kcal·min^{-1}/kcal·min^{-1}), or FFM (EE/FFM; kcal·min^{-1}/kg). Therefore, the EE/L-RMR for lying and the EE/S-RMR for sitting quietly were equal to 1.00.

Statistical analysis

The data are presented as means±SD, unless otherwise stated. Differences were considered to be statistically significant if the P value was less than 0.05. We regarded a PAI as an appropriate adjustment for body size when there was no significant correlation between the PAI and BW. The independent associations between the PAIs and BW were tested using a general linear model (GLM) that examined the effects of age, sex, and sex–BW interaction, given that men have a greater body weight than women. In addition, the activity styles may also be related to age and sex, although the L-RMR, S-RMR, and FFM measured in the present study already reflected the effects of age and sex. Therefore, the effects of age and sex were considered in the relationship between all the PAIs and BW. If the sex–BW interaction term was not statistically significant in the GLM, the interaction term was excluded in the subsequent analyses, and the errors in the PAIs caused by size were estimated from the regression models using the average age and a fixed value for sex (0.5). If the interaction term was significant, the errors were estimated in a similar way, but for each sex. The errors were calculated as percentages of the predicted PAIs for an average BW ($PAIs_{(ave.)}$). For example, error (%)$=B\times x/PAIs_{(ave.)}\times 100$, where B is the regression coefficient of the relationship between PAI and BW from GLM adjusted for age and sex and x is the difference from average BW. All the statistical analyses were performed using SPSS Version 15.0J for Windows (SPSS, Inc., Chicago, IL, USA).

Results

The majority of the 78 subjects weighed between 40–80 kg, although 2 subjects weighed more than 100 kg and were outside the 98th percentile BMI for the Japanese population. As L-RMR or S-RMR data for five subjects were not obtained, these subjects were excluded from all the analyses. The physical characteristics of the remaining 71 subjects are summarized in Table 1.

The means, SDs, and coefficients of variations of PAI for all activities are presented in Table 2. Several data are missing due to difficulties in adequately collecting expired gas in the steady state or performing the activity following the prescribed speed and duration. We confirmed in respective activities there was no bias with respect to age, BW, or BMI. S-RMR/L-RMR was 1.09±0.05 in males and 1.12±0.08 in females. Although mean PAI was different between the sexes in some activities, the sex–BW interaction term was not statistically significant for any activity except EE/FFM-walking at 70 m/min with a 3-kg load. Therefore, all the analyses included all data from both sexes. The relationships between the PAIs and BW are summarized in Table 3 and the percentage differences in PAIs caused by a 10 kg deviation from average BW are summarized in Table 4. EE/BW correlated significantly with BW in all sedentary activities. For these activities, there were −5% to −6% (5% to 6%) differences in EE/BW values when the BW was more than 10 kg above or below average (60 kg). EE/L-RMR correlated significantly with BW for walking up stairs, walking at 70 m/min, and walking at 100 m/min. For these activities, there were +3% to 5% (−3% to −5%) differences in EE/L-RMR values when the BW exceeded or was below the average by 10 kg. EE/S-RMR correlated significantly with BW for vacuuming, lifting and carrying a small load, and for the majority of the ambulant activities. For these activities, there were +3% to 6% (−3 to −6%) differences in EE/S-RMR values when BW exceeded or was below the average by 10 kg. EE/FFM correlated significantly with BW for walking up stairs only. For this activity, there was +3.7% (−3.7%) differences in EE/FFM values when BW exceeded or was below the average by 10 kg.

Discussion

In the present study, the mean values of PAIs were significantly different between the sexes for some activities.

Table 1 Characteristics of the subjects

	All (N=71)		Male (N=34)	Female (N=37)	
	Means±SD	Range	Means±SD	Means±SD	*p*-value
Age (years)	43±13	21–66	43±14	43±13	0.850
Height (cm)	163.7±8.1	149.8–183.9	169.6±6.1	158.2±5.5	<0.001*
Body weight (kg)	60.0±10.5	40.3–86.1	65.3±9.6	55.2±9.0	<0.001*
BMI (kg/m^2)	22.3±3.0	16.7–32.3	22.6±2.4	22.1±3.4	0.450
Fat-free mass	45.2±8.5	32.2–62.0	51.9±6.3	38.9±4.7	<0.001*
Body fat (%)	24.7±6.7	11.0–37.8	20.0±4.5	28.9±5.4	<0.001*

BMI: (body mass index)
* Significant difference between sexes (Student's *t*-test)

Table 2 The means of respective physical activity indexes for all activities

2-a. The means of EE/BW for all activities

	EE/BW (kcal·min^{-1}/kg)						
	All			Male		Female	
	N	Mean±SD	CV	N	Mean±SD	N	Mean±SD
Sedentary activities							
lying quietly	71	0.0148±0.0016	10.8	34	0.0154±0.0015*	37	0.0143±0.0015
sitting quietly	71	0.0164±0.0017	10.3	34	0.0168±0.0016*	37	0.0160±0.0017
working at the computer	69	0.0181±0.0019	10.8	32	0.0187±0.0020*	37	0.0175±0.0017
Lifestyle activities							
vacuuming	69	0.0481±0.0096	19.9	34	0.0492±0.0099	35	0.0470±0.0092
hanging laundry	71	0.0367±0.0053	14.3	34	0.0378±0.0055	37	0.0358±0.0049
washing dishes	69	0.0293±0.0046	15.8	34	0.0301±0.0047	35	0.0285±0.0045
carrying a small load	71	0.0715±0.0108	15.1	34	0.0744±0.0106*	37	0.0688±0.0104
Ambulant activities							
walking up stairs	68	0.1228±0.0093	7.6	32	0.1262±0.0090*	36	0.1197±0.0086
downstairs	71	0.0512±0.0082	16.1	34	0.0534±0.0090*	37	0.0492±0.0071
walking (55 m/s)	69	0.0502±0.0064	12.7	32	0.0516±0.0070	37	0.0489±0.0056
walking (70 m/s)	69	0.0590±0.0071	12.0	33	0.0598±0.0079	36	0.0583±0.0062
walking (100 m/s)	71	0.0759±0.0115	15.1	34	0.0771±0.0129	37	0.0748±0.0100
walking (70 m/s) with a 3 kg load	71	0.0689±0.0090	13.1	34	0.0688±0.0105	37	0.0690±0.0076
jogging (140 m/s)	62	0.1557±0.0188	12.1	34	0.1624±0.0196*	28	0.1475±0.0143

2-b. The means of EE/L-RMR for all activities

	EE/L-RMR (kcal·min^{-1}/kcal·min^{-1})						
	All			Male		Female	
	N	Mean±SD	CV	N	Mean±SD	N	Mean±SD
Sedentary activities							
lying quietly	—		—		—		
sitting quietly	71	1.11±0.07	6.3	34	1.09±0.05*	37	1.12±0.08
working at the computer	69	1.23±0.11	8.6	32	1.22±0.10	37	1.23±0.11
Lifestyle activities							
vacuuming	69	3.28±0.72	21.9	34	3.21±0.71	35	3.35±0.72
hanging laundry	71	2.50±0.40	16.0	34	2.47±0.40	37	2.52±0.40
washing dishes	69	2.00±0.35	17.4	34	1.95±0.30	35	2.04±0.39
carrying a small load	71	4.85±0.79	16.2	34	4.86±0.83	37	4.85±0.75
Ambulant activities							
walking up stairs	68	8.40±0.82	9.8	32	8.29±0.81	36	8.50±0.83
downstairs	71	3.46±0.50	14.4	34	3.46±0.49	37	3.46±0.51
walking (55 m/s)	69	3.40±0.46	13.4	32	3.35±0.44	37	3.45±0.47
walking (70 m/s)	69	4.00±0.54	13.6	33	3.88±0.55	36	4.11±0.52
walking (100 m/s)	71	5.15±0.82	15.8	34	5.02±0.85	37	5.27±0.78
walking (70 m/s) with a 3 kg load	71	4.68±0.68	14.6	34	4.47±0.68*	37	4.87±0.64
jogging (140 m/s)	62	10.51±1.26	12.0	34	10.58±1.38	28	10.42±1.11

Table 2 Continued
2-c. The means of EE/S-RMR for all activities

	EE/S-RMR (kcal·min^{-1}/kcal·min^{-1})						
	All			Male		Female	
	N	Mean±SD	CV	N	Mean±SD	N	Mean±SD
Sedentary activities							
lying quietly	71	0.91±0.06	6.1	34	0.92±0.05	37	0.89±0.06
sitting quietly		—			—		—
working at the computer	69	1.11±0.08	7.1	32	1.12±0.07	37	1.10±0.09
Lifestyle activities							
vacuuming	69	2.96±0.63	21.4	34	2.95±0.68	35	2.97±0.59
hanging laundry	71	2.26±0.37	16.2	34	2.26±0.37	37	2.25±0.37
washing dishes	69	1.80±0.32	17.6	34	1.79±0.27	35	1.81±0.36
carrying a small load	71	4.39±0.69	15.7	34	4.46±0.74	37	4.32±0.64
Ambulant activities							
walking up stairs	68	7.60±0.74	9.8	32	7.60±0.73	36	7.59±0.76
downstairs	71	3.13±0.47	14.9	34	3.18±0.48	37	3.09±0.46
walking (55 m/s)	69	3.08±0.43	14.0	32	3.08±0.43	37	3.08±0.44
walking (70 m/s)	69	3.62±0.50	13.9	33	3.57±0.52	36	3.67±0.48
walking (100 m/s)	71	4.66±0.76	16.3	34	4.61±0.80	37	4.71±0.73
walking (70 m/s) with a 3 kg load	71	4.23±0.62	14.7	34	4.11±0.64	37	4.34±0.59
jogging (140 m/s)	62	9.50±1.10	11.6	34	9.72±1.29	28	9.23±0.77

2-d. The means of EE/FFM for all activities

	EE/FFM (kcal·min^{-1}/kg)						
	All			Male		Female	
	N	Mean±SD	CV	N	Mean±SD	N	Mean±SD
Sedentary activities							
lying quietly	71	0.0197±0.0018	9.2	34	0.0193±0.0017	37	0.0201±0.0019
sitting quietly	71	0.0218±0.0019	8.6	34	0.0210±0.0017*	37	0.0225±0.0018
working at the computer	69	0.0242±0.0026	10.6	32	0.0236±0.0026	37	0.0247±0.0025
Lifestyle activities							
vacuuming	69	0.0643±0.0140	21.7	34	0.0617±0.0135	35	0.0669±0.0141
hanging laundry	71	0.0491±0.0081	16.6	34	0.0474±0.0074	37	0.0507±0.0086
washing dishes	69	0.0391±0.0071	18.0	34	0.0376±0.0061	35	0.0406±0.0077
carrying a small load	71	0.0954±0.0153	16.0	34	0.0935±0.0153	37	0.0972±0.0153
Ambulant activities							
walking up stairs	68	0.1646±0.0161	9.8	32	0.159±0.0143*	36	0.1698±0.0159
downstairs	71	0.0684±0.0118	17.2	34	0.0669±0.0117	37	0.0698±0.0119
walking (55 m/s)	69	0.0671±0.0100	14.9	32	0.0645±0.0092*	37	0.0693±0.0103
walking (70 m/s)	69	0.0789±0.0116	14.7	33	0.0750±0.0104*	36	0.0824±0.0116
walking (100 m/s)	71	0.1016±0.0180	17.7	34	0.0966±0.0171*	37	0.1061±0.0178
walking (70 m/s) with a 3 kg load	71	0.0923±0.0154	16.7	34	0.0862±0.0139*	37	0.0979±0.0148
jogging (140 m/s)	62	0.2040±0.0223	10.9	34	0.2035±0.0265	28	0.2045±0.0162

EE: energy expenditure, BW: body weight, L-RMR: lying resting metabolic rate, S-RMR: sitting resting metabolic rate, FFM: fat-free mass, CV: coefficient of variation.
*$p<0.05$ vs. male group (Student's t-test)

Table 3 Results from the general linear model with physical activity index as the dependent variable and body weight, age, and sex as the independent variables

	EE/BW (kcal·min^{-1}/kg)			EE/L-RMR (kcal·min^{-1}/kcal·min^{-1})			EE/S-RMR (kcal·min^{-1}/kcal·min^{-1})			EE/FFM (kcal·min^{-1}/kg)		
	Regression coefficient[1] (Estimate±SE)	Age, sex[2)]	Average EE/BW[3)]	Regression coefficient[1] (Estimate±SE)	Age, sex[2)]	Average EE/BMR[3)]	Regression coefficient[1] (Estimate±SE)	Age, sex[2)]	Average EE/BMR[3)]	Regression coefficient[1] (Estimate±SE)	Age, sex[2)]	Average EE/FFM[3)]
Sedentary activities												
lying quietly	−0.000079±0.000016**	age, sex	0.0149	—		—	0.000±0.001		0.91	−0.000020±0.000024		0.0197
sitting quietly	−0.000094±0.000017**	age, sex	0.0164	−0.001±0.001		1.11	—		—	−0.000032±0.000022	sex	0.0218
working at the computer	−0.000091±0.000022**	sex	0.0181	0.000±0.001	age	1.22	0.001±0.001	age	1.11	−0.000018±0.000029	age	0.0241
Lifestyle activities												
vacuuming	−0.000016±0.000123	age	0.0480	0.015±0.009	age	3.26	0.016±0.008*	age	2.95	0.000252±0.000173	age, sex	0.0636
hanging laundry	−0.000099±0.000062	age, sex	0.0368	0.006±0.004	age	2.49	0.007±0.004	age	2.26	0.000088±0.000089	age, sex	0.0491
washing dishes	−0.000075±0.000057	age	0.0293	0.005±0.004	age	1.99	0.006±0.004	age	1.79	0.000068±0.000084	age	0.0394
carrying a small load	−0.000139±0.000132	age, sex	0.0717	0.016±0.009	age	4.85	0.017±0.008*	age	4.39	0.000233±0.000175	age	0.0953
Ambulant activities												
walking up stairs	−0.000070±0.000119	sex	0.1230	0.035±0.010**	sex	8.37	0.035±0.009**		7.58	0.000598±0.000178*	age, sex	0.1637
downstairs	−0.000189±0.000103	sex	0.0513	0.006±0.006	age	3.46	0.007±0.006	age	3.13	0.000050±0.000147	age	0.0683
walking (55 m/s)	−0.000119±0.000083	sex	0.0503	0.011±0.006	age	3.40	0.011±0.005*	age	3.08	0.000146±0.000123	age, sex	0.0670
walking (70 m/s)	−0.000121±0.000091		0.0590	0.013±0.006*	age, sex	3.99	0.035±0.009**		7.58	0.000213±0.000135	age, sex	0.0785
walking (100 m/s)	−0.000096±0.000149		0.0760	0.021±0.010*	age, sex	5.14	0.021±0.009*	age	4.66	0.000335±0.000210	age, sex	0.1012
walking (70 m/s) with a 3 kg load	−0.000186±0.000113	age	0.0689	0.012±0.007	age, sex	4.67	0.013±0.007	age, sex	4.22	0.000159±0.000168	age, sex	0.0920
jogging (140 m/s)	−0.000339±0.000242	sex	0.1547	0.031±0.018		10.51	0.031±0.015*		9.47	0.000343±0.000308	0.2038	

EE: energy expenditure, BW: body weight, L-RMR: lying resting metabolic rate , S-RMR: sitting resting metabolic rate, FFM: fat-free mass, SE: standard error.

[1] Regression coefficient: Relationship between physical activity indices and body weight from general linear models (GLM) adjusted for age and sex.

[2] Age, sex: Significance of age and sex in the GLM. ($P<0.05$)

[3] Average physical activity indices: Physical activity index of average body weight (60.0 kg) from GLM adjusted for age (43 y) and sex (0.5).

* $P<0.05$, ** $P<0.001$: There was a significant correlation between the index and body weight.

Table 4 The errors (%) in physical activity indices caused by a 10 kg above average body weight (60.0 kg)[1].

Activities	EE/BW ($kcal\cdot min^{-1}/kg$)	EE/L-RMR ($kcal\cdot min^{-1}/kcal\cdot min^{-1}$)	EE/S-RMR ($kcal\cdot min^{-1}/kcal\cdot min^{-1}$)	EE/FFM ($kcal\cdot min^{-1}/kg$)
Sedentary activities				
lying quietly	−5.3	—		
sitting quietly	−5.7		—	
working at the computer	−5.0			
Lifestyle activities				
vacuuming			5.3	
hanging laundry				
washing dishes				
carrying a small load			3.9	
Ambulant activities				
walking up stairs		4.2	4.6	3.7
downstairs				
walking (55 m/s)			3.6	
walking (70 m/s)		3.3	4.6	
walking (100 m/s)		4.1	4.6	
walking (70 m/s) with a 3 kg load				
jogging (140 m/s)			3.2	

EE: energy expenditure, BW: body weight, L-RMR: lying resting metabolic rate, S-RMR: sitting resting metabolic rate, FFM: fat-free mass.
[1] The discrepancies were calculated as follows;
The error (%) $= B \times x / PAIs(ave.) \times 100$
B is the regression coefficient of the relationship between physical activity index and body weight from general linear models (GLM) adjusted for age and sex.
x is the difference from average body weight (60.0 kg).
$PAI_{(ave.)}$: Physical activity index for average body weight (60.0 kg) from GLM adjusted for age and sex.
Data are presented only for the significant relationship between physical activity index and body weight.
This table shows when x is +10 kg (70 kg). If x is 10 kg below average, the values of the discrepancies change from plus to minus or from minus to plus.

However, gender did not influence the correlation between PAI and BW in any activity except for EE/FFM-walking at 70 m/min with a 3-kg load. Therefore, we were able to combine the data for both sexes in most of the analyses.

Our results showed that the EE/BW was not appropriate for adjusting for body size in sedentary activities. In contrast, EE/L-RMR and EE/S-RMR were appropriate for sedentary activities, but inappropriate for the other activities. The EEs of sedentary activities were not weight-dependent and increased less than body weight. In contrast, the EEs of other activities were weight-dependent as they increased with increasing BW, whereas the observed L-RMR and S-RMR increased less with increasing BW. Therefore, EE/BW values in non-weight-dependent activities decreased and EE/L-RMR and EE/S-RMR values in weight-dependent activities increased with increasing BW. When we used EE/BW to evaluate the intensity of non-weight-dependent activities, this caused about a 20% higher estimate for 40 kg than for 80 kg BWs for the same activity. When we used EE/L-RMR or EE/S-RMR values to estimate the intensity of weight-dependent activities, this caused a 12% to 20% lower estimate for 40 kg than 80 kg BWs.

It has been reported that EE/RMR (including EE/BMR) was inappropriate for evaluation of intensity of some activities in girls and adults (Kriyan et al., 2006; Spadano et al., 2003; Haggarty et al., 1997). These researchers suggested it was necessary to take BW into consideration when using the BMR-multiple approach to estimate EE. Kuriyan et al., (2006) considered the relationship between EE/BMR, BW, and BMI. They found in three walking activities that BMI caused a 3% to 16% overestimation of EE/BMR in underweight men (BMI 16.0–18.3 kg/m^2, BW 42.3–49.8 kg) and a 3% to 11% underestimation of EE/BMR in overweight men (BMI 25.2–33.0 kg/m^2, BW 51.0–92.3 kg) when EE was estimated using the EE/BMR value for normal weight (BMI 19.1–24.3 kg/m^2, BW 46.6–66.5 kg) men. A similar tendency was observed by Haggarty et al., (1997) who showed that EE/BMR increased in a hyperbolic manner as weight increased, and that the rate of increase in EE/BMR became larger as intensity of activity rose. However, in our study the error in EE/BMR caused by BW for jogging was smaller than the difference for walking activities. This could be due to the fact that the EE of high intensity activities such as jogging was influenced not only by body size, but also by physical fitness (Margaria et al., 1963).

Our study indicated that S-RMR is undifferentiated from L-RMR in some cases. While the relationship between EE/L-RMR and BW was similar to the relationship between EE/S-RMR and BW, the errors caused by BW were more likely to be observed and be larger in EE/S-RMR than in EE/L-RMR. This discrepancy was probably caused by differences in the relationship between L-RMR, RMR, and BW. The difference in relationship was not statistically significant, although RMR increased less with BW compared to L-RMR.

On the other hand, EE/FFM was appropriate except for the ambulant activity of walking up stairs. We found that size-independent comparisons could be made using FFM. Moreover, previous studies succeeded in comparing physical activity using EE/FFM even between obese and nonobese adult subjects (Meijer et al., 1992) and between children and adolescents (Ekelund et al., 2004; Vermorel et al., 2005). On the basis of these results it appears that FFM has characteristics of both BW and RMRs.

Daily life consists of various kinds of activities. The average intensity of daily activity is evaluated as TEE/BW, TEE/L-RMR, or TEE/S-RMR. Some previous papers have suggested that TEE/BW (Lawrence, 1988; Margaria et al., 1963) and TEE/BMR (Goran, 1995; Carpenter et al., 1995; Goran, 2005) produced spurious differences when subjects of different size were compared across the range of TEE levels. We consider that the maximum difference from average BW was no more than $\pm$10% for a daily lifestyle in the normal BW group. For example, for an 80-kg person sitting quietly for 24 hours, the intensity of daily activity calculated using TEE/BW is about a 10% underestimation of the true intensity of daily activity. As daily activities consisted of various activities, including weight-dependent activities, the estimation errors caused by BW for particular activities become smaller than 10%. It seems unimportant that a 10% estimation error (at a maximum) can be caused by using PAIs, as intra-individual variation in TEE is approximately $\pm$10% in free-living activities for some weeks (Goran et al., 1993). In addition, there are unavoidable differences in methodology when using a physical activity record and physical activity recall. Comparing the unavoidable differences reported in a previous study (Conway et al., 2002) to the differences in our data, our maximum estimation error of 10% was about 1/3 that of the TEE estimated from the physical activity record and only 1/10 that of the TEE estimated from physical activity recall. Thus, our estimation errors in TEE appear to be considerably smaller than the other error factors. Moreover, use of PAIs may reduce errors when the intensity of daily activity is estimated using TEE/L-RMR and TEE/S-RMR to calculate physical activity levels.

It is important to note that a two-step procedure is required to predict physical activity level in general situations (Goran, 2005). In many cases, RMRs are predicted from an equation that often is based on BW. For example, the basal metabolism per unit body weight (BMR/BW) was included in the Dietary Reference Intakes for Japanese, 2010 (Ministry of Health, Labour, and Welfare, Japan, 2009). However, BMR/BW correlated negatively with BW (Takahashi et al., 2007). As BMR corresponded to L-RMR in the present study, there will be an estimation error when BMR/BW is used in the estimate of BMR. According to our study, −5% to 6% errors may occur in BMR values when the BW is more than 10 kg above average. In addition, it is also necessary to consider the effect of the errors in estimations of RMRs. As the measurement error of body weight is considerably smaller than the prediction error of BMR or RMR, different effects of the errors would occur when using the predicted values.

This study had several limitations. The coefficient of variation tended to be large, especially for lifestyle activities. This was attributed to the fact that we prescribed only the duration of the activities and did not strictly prescribe the motion of activities. In addition, we did not obtain information on the motion for each activity of each subject, and accordingly could not examine the effects of inter-individual differences. Other limitations included the fact that the methodology for determining body composition in our study was not sophisticated, as we estimated FFM using bioelectrical impedance analysis. Therefore, the results for EE/FFM would include the predictive error associated with the measurement method (Korth et al., 2007). Another limitation is that we did not take into account aerobic fitness, although we considered the influence of this factor was small, as subjects who were not athletes performed each activity for only several minutes.

In conclusion, although BW influenced EE/BW in sedentary activities and also the three alternative indices in other activities, the error in the estimate of total EE using any of these indices should be considerably less than $\pm$10% for body weights within the normal range. The PAIs are simple calculations and make it easy to compare the intensities of activity and to estimate EEs using activity diaries, recall, and direct observation data. It is most important in future studies to consider the size of the error effects of the indices. It will then be possible to properly compare physical activity among different body sizes.

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