(Chen and Bassett, 2005; Matthews, 2005). However, little data on PA intensity, especially in preschool-aged children in free-living conditions, has been obtained using triaxial accelerometers (see reviews by Oliver et al. (2007) and Hinkley et al. (2008)). In addition, a recent study of ours has shown that discrimination between ambulation and play in preschool children (e.g., ball tossing) using a triaxial accelerometer (ActivTracer, GMS) contributes to better evaluation of PA intensity (Tanaka et al., 2007a). Similar results were reported in adults (Midorikawa et al., 2007). These studies suggest that relationships between PA intensity and acceleration counts are different between locomotion and the other types of PA, and that previous studies (even with a triaxial accelerometer) did not assess types of PA other than locomotion. However, the ActivTracer is expensive (about $2,000 (USD)) and does not have specific software to calculate energy expenditure for evaluating PA. Thus, for research studies with large sample sizes, more convenient devices such as pedometers are more useful than the triaxial accelerometer, although pedometers cannot evaluate levels of PA.

Two recommendations for the average daily number of steps have been suggested for elementary school-aged children (Tudor-Locke et al., 2004; Vincent and Pangrazi, 2002). Vincent and Pangrazi (2002) recommended 13,000 steps/day for boys and 11,000 steps/day for girls. Tudor-Locke et al. (2004, 2008) recommended 15,000 and 12,000 steps/day, respectively. Eisenmann et al. (2007) examined the utility of these recommendations in predicting childhood adiposity. They found that the likelihood of being classified as overweight was greater for subjects who did not meet the recommendation for steps per day than for those who did meet it. Locomotion is one of the important parts of PA in free-living conditions and daily step counts have been used as an index of PA in many studies. However, data on daily PA and total steps in representative samples of preschool-aged children using the accelerometer remain insufficient, particularly for Japanese (Cardon and De Bourdeaudhuij, 2007; Fisher et al., 2005; Jackson et al., 2003; Montgomery et al., 2004; Pate et al., 2004), and data on the relationship between total steps and minutes of engagement in moderate-to-vigorous physical activity (MVPA), except for data reported by Cardon and De Bourdeaudhuij (2007), are lacking. Cardon and De Bourdeaudhuij (2007) found a relatively strong correlation ($r=0.73$) between daily step counts and minutes of engagement in MVPA using a uniaxial accelerometer (MTI Actigraph) in 4- and 5-year-old children. However, accelerometers with a single regression equation based on locomotive activity underestimate the energy expenditure of nonlocomotive activities in adults (Matthews, 2005) and young children (Tanaka et al., 2007a). Unlike adults, children engage in types of PA other than locomotion (Oliver et al., 2007). Therefore, the present study used a vertical/horizontal counts ratio as a classification criterion and to discriminate between different types of medium-intensity activities including walking and nonlocomotive activities (Tanaka et al., 2007a).

The purposes of this study were 1) to describe the patterns of PA classified according to intensity using a triaxial accelerometer (ActivTracer, GMS), which can discriminate locomotive from nonlocomotive activities, and 2) to measure total daily number of steps using uniaxial accelerometry (Lifecorder EX, Suzuken) in Japanese preschool children. We also examined the relationship of daily step counts (a simple method for measuring PA) to minutes of engagement in MVPA.

Methods

Subjects

The subjects were 212 four- to six-year-old Japanese preschool children (85 girls and 127 boys; mean age 5.8 ± 0.6 years, range 4.5–6.8 years), living in the Tokyo metropolitan area and attending kindergarten or nursery school. All of the subjects reported being in good health, without any anamnesis of conditions affecting energy expenditure, such as abnormal thyroid gland function. Informed consent was obtained from a parent, and the Ethical Committee of J. F. Oberlin University approved the study protocol.

Measurement items and methods

Body height and weight were measured to the nearest 0.1 cm and 0.1 kg, respectively. Habitual PA was measured using a triaxial accelerometer (ActivTracer, GMS, Tokyo) and a uniaxial accelerometer (Lifecorder EX, Suzuken, Nagoya). The subjects wore a 57-gram ActivTracer and a 60-gram Lifecorder EX on the left side of the waist, as previously described (Tanaka et al., 2007a, b). The ActivTracer was set to record in 1-min epochs; the Lifecorder EX was set to measure exercise intensity in 4-sec epochs and step counts in 1-min epochs. PA was monitored continuously for 6 days (generally, 4 weekdays plus 2 weekend days). Subjects were requested to wear these devices except during unavoidable circumstances, such as dressing and bathing. The times that the subjects did not wear the equipment and sleeping times were recorded by their parents. The Lifecorder EX records a signal of 0.5 or 1 to 9 every 4 seconds while being worn, even if the subjects are asleep. When no signal was detected for more than one hour by the Lifecorder, the period was regarded as nonwearing time for both the ActivTracer and Lifecorder. We excluded days during which more than 2 hours of non-wearing time had accrued, not counting time allowed for the above-mentioned unavoidable reasons, and days during which subjects were absent from kindergarten or nursery school. Subjects with at least two weekdays and at least one weekend were used in the analyses. As a result, PA was measured successfully in 157 of 212 children (74%).

Synthetic activity counts were recorded every 1 min by the ActivTracer, and PAR (physical activity ratio), a multiple of basal metabolic rate, was estimated as previously described (Tanaka et al., 2007a). When the synthetic activity counts were in the range corresponding to medium-intensity activities (between 130 and 600 mG), classification criteria using the vertical/horizontal counts ratio (as previously described) were used to discriminate different types of medium-intensity activities, because the PAR for some medium-intensity activities (i.e., non-locomotive activities) are underestimated (Tanaka et al., 2007a): The vertical/horizontal ratio for 1) walking is ≥1.19 and for 2) nonlocomotive activities, <1.19.

Furthermore, daily step counts were evaluated using a Lifecorder EX. With this device, if the second step is not recognized within 1.5 seconds, the first step is not counted.

Analyses

Average number of weekday and weekend minutes spent in MVPA (PAR ≥3), PAR ≥4, and medium-intensity activities, number of steps, and physical activity level (PAL; total energy expenditure/basal metabolic rate) were calculated for each individual, and then the average weekly values were calculated by weighting for 5 weekdays and 2 weekend days. The relationship between the two variables was evaluated by Pearson's correlation and a linear regression model. A Student's t-test was carried out to assess the influence of gender. All results are shown as the mean±standard deviation (SD). Statistical analyses were performed with SPSS version 15.0J for Windows (SPSS Inc, Japan, Tokyo). All statistical tests were regarded as significant when the p-values were less than 0.05.

Results

The physical characteristics of the subjects are shown in Table 1. Most of the subjects in the present study were of normal weight. The numbers of overweight girls and boys based on body mass index (Cole et al., 2000) were 2 and 5, respectively. One girl was obese. Morphological variables did not show a gender difference.

Table 1 Physical characteristics of subjects

Variable	All subjects (n=157) Mean±SD	Girls (n=69) Mean±SD	Boys (n=88) Mean±SD
Age (yr)	5.9±0.5	5.9±0.5	5.9±0.5
Height (cm)	112.0±5.6	112.3±4.7	111.8±6.2
Weight (kg)	19.0±2.8	18.9±2.6	19.0±3.0
Body mass index (kg/m^2)	15.1±1.3	15.0±1.4	15.1±1.2

Times in MVPA and PAR ≥4, step counts, and PAL are shown in Table 2. All values for boys were significantly higher than those for girls. The daily step counts of subjects in the present study were normal based on the step count cutoff values suggested by Tudor-Locke et al. (2008).

Figures 1 and 2 show the relationship between MVPA minutes or minutes of PAR ≥4 and step counts. Strong significant correlations were observed between MVPA minutes and step counts (r=0.833, $p<0.001$). The daily step counts corresponding to 60 min, 100 min, and 120 min of MVPA were 9,934, 12,893, and 14,373 steps, respectively, and 92.4%,

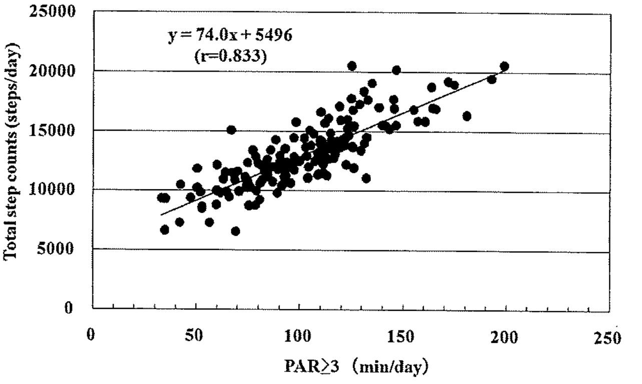

Fig. 1 Relationship between minutes engaged in moderate-to-vigorous physical activity (PAR ≥3) and daily step counts.

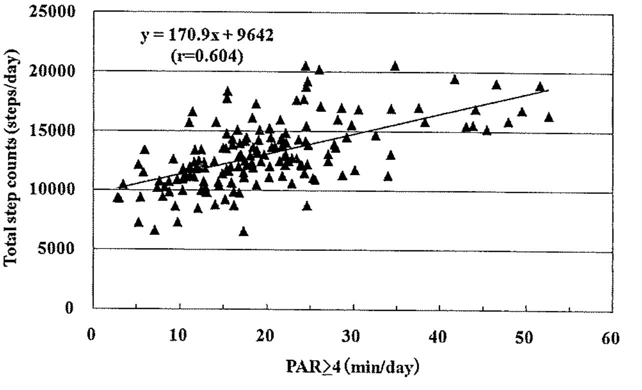

Fig. 2 Relationship between minutes engaged in PAR ≥4 activity and daily step counts.

Table 2 Characteristics of daily physical activity

Activity	All subjects (n=157) Mean±SD	Girls (n=69) Mean±SD	Boys (n=88) Mean±SD
Time in MVPA (min/day)	102.0±32.0	88.8±28.9	112.3±30.7*
Time in PAR ≥4 (min/day)	19.9±10.1	16.4±9.0	22.6±10.1*
Step counts (counts/day)	13037±2846	12255±2823	13650±2726*
PAL	1.54±0.08	1.51±0.07	1.55±0.08*

MVPA: moderate-to-vigorous physical activity, PAR: physical activity ratio, PAL: physical activity level, *: girls vs boys $p<0.05$.

51.6%, and 27.4% of the children attained these levels of MVPA, respectively. Furthermore, a significant correlation was also observed between minutes of PAR ≥4 and step counts (r=0.604, $p<0.001$). The daily step count corresponding to 30 min of PAR ≥4 activity (engaged in by 12.7% of the children) was 14,768 steps. When synthetic activity counts corresponding to medium-intensity activity (between 130 and 600 mG) were obtained, the amount of time spent in walking-type and nonlocomotive-type activities was 74±41 min/day and 167±47 min/day, respectively.

Discussion

Comparison with previous studies

This study evaluated MVPA using triaxial accelerometry in preschool-aged Japanese children. The association between daily step counts measured by uniaxial accelerometry and minutes of engagement in MVPA was also examined, as the uniaxial accelerometer is a more conventional method for measuring PA. Tanaka et al. (2007a) defined an MVPA cutoff point of PAR ≥3 for preschool-aged children; the average value of PAR for normal walking is 2.6. Therefore, in the present study, MVPA would have consisted of activities such as brisk walking, ball tossing, or more vigorous activities.

The current international guidelines recommend at least 60 min or more per day of MVPA for children's health maintenance (Biddle et al., 1998; National Association for Sport and Physical Education, 2002, 2004; Strong et al., 2005). In the present study, 92.4% of the children spent ≥60 min/day in MVPA, and 51.6% of the children spent ≥100 min/day in MVPA. The average amount of MVPA was 102±32 min/day. To our knowledge, this is the first report to examine Japanese children's PA level using a triaxial accelerometer. In a previous study (Montgomery et al., 2004), direct observation of 2.6- to 6.9-year-old children showed that they spent most of their time engaged in sedentary activities (girls: 79%, boys: 73%) and only small amounts of time in MVPA (3% and 4%, respectively) as measured by a CSA/MTI uniaxial accelerometer. Reilly et al. (2004) also observed that the median time spent in MVPA was only 4% at 5 years of age as measured by a CSA/MTI uniaxial accelerometer. Alhassan et al. (2007), using an ActiGraph uniaxial accelerometer, showed that the average total daily time spent in MVPA at age 3.6±0.5 years was 2.0±1.6% in the intervention group and 1.4±0.9% in the control group. However, the results of the present study coincided closely with results in other previous studies of youth activity level measured by heart-rate monitor or accelerometer (Andersen et al., 2006; Epstein et al., 2001). Andersen et al. (2006), using an ActiGraph uniaxial accelerometer, showed that the average time spent at levels above 4 km/h at age 9 years was 116 min and at 15 years 88 min. On the other hand, Epstein et al. (2001), using a heart rate monitor, found that youths aged 3 to 17 years engaged in MVPA for 60–120 min. However, it should be noted that the present data were recorded at 1-min epochs, which may not be sensitive enough to pick up short bursts of vigorous activity (Nilsson et al., 2002). As Freedson et al. (2005) pointed out, a major and as yet unresolved problem of comparing studies is the lack of a consensus on how the activity intensity cutoff points are defined.

Our previous study showed that linear and nonlinear regression equations using vertical acceleration counts overestimated PAR for very low-intensity activities and underestimated PAR for nonlocomotive activities (such as ball tossing and stair climbing) more than the other models for preschool-aged children (Tanaka et al., 2007a). However, all models underestimated PAR while ball tossing and stair climbing to the same degree. Therefore, an additional analysis was applied in the present study to distinguish these activities from walking. The results show that the present subjects were engaged in walking-type activities for 74±41 min/day and in nonlocomotive-type activities for 167±47 min/day. Thus, adjustment of the values predicted by the regression equations using the vertical/horizontal counts ratio improved the underestimation of PAR for nonlocomotive activities such as ball tossing. The obtained average percentage difference was improved from −32.1±18.9% to −4.7±15.5%. The results also suggest that the previous algorithms for evaluation of PA intensity using accelerometers may lead to erroneous estimations of PA intensities. In addition, some of the previous studies (Montgomery et al., 2004, Reilly et al., 2004) were based on cutoff values applied to accelerometer output that was validated against direct observation in 3- to 5-year-olds (Reilly et al., 2003; Sirard et al., 2005). Therefore, the difference in daily time spent in MVPA between our data and previous studies might be explained by different cutoff points and algorithms.

Relationship between period of engagement in moderate-to-vigorous physical activity and daily step counts

The average daily step count in the present study was 13,037±2,846 steps/day in 4- to 6-year-old children. On the other hand, Cardon and De Bourdeaudhuij (2007) reported that the average daily step count in 4- to 5-year-olds was 9,980±2,605 steps/day, and concluded that daily step counts in preschool-aged children were low. There are two recommendations regarding the number of steps per day for elementary school children (Tudor-Locke et al., 2004; Vincent and Pangrazi, 2002). Vincent and Pangrazi (2002) recommended 11,000 steps/day for girls and 13,000 steps/day for boys. Tudor-Locke et al. (2004) recommended 12,000 and 15,000 steps/day, respectively. The average values of the present study were similar to all recommended values, except the value for boys recommended by Tudor-Locke. Nakae et al. (2008) recently reported that a spring-levered pedometer underestimates step counts at the slow and normal paces of young children by more than 20%, whereas piezo-electric pedometers are much more accurate. Cardon and De Bourdeaudhuij (2007) used a spring-levered pedometer (Yamax Digiwalker) while we used a piezo-electric pedometer

(Lifecorder EX), which may be the main reason for the considerably different average step counts. Thus, the average step counts for preschool-aged children might be higher than that measured by the previous study (Cardon and De Bourdeaudhuij, 2007).

Locomotion comprises one of the important parts of physical activity in free-living conditions, and daily step counts have been used as an index of physical activity in many studies. However, the relationship between daily step counts and MVPA engagement time has not been examined except by Cardon and De Bourdeaudhuij (2007). In the present study, a strong and significant correlation was observed between minutes of MVPA and step counts (r=0.833, $p<0.001$). The daily step counts in 60 min, 100 min, and 120 min of moderate-to-vigorous physical activity were 9,934, 12,893, and 14,373 steps, respectively, and 92.4%, 51.6%, and 27.4% of the children attained these step count levels, respectively. The relationship between minutes of MVPA and step counts was in agreement with the results reported by Cardon and De Bourdeaudhuij (2007) (r=0.73, $p<0.001$). However, only 8% of their subjects reached the daily step count level corresponding to 60 min of MVPA per day. Thus, the percentage of children achieving this level was higher in the present study than in their study. Though differences in categorization of moderate-intensity activities might influence the results, both studies categorized, as similar, activities with the same intensity level; namely, they also categorized brisk walking as a moderate-intensity activity. The present study categorized brisk walking as a moderate-intensity activity because our previous study revealed that the PAR for normal-speed walking in 6-year-olds was 2.60±0.49 (Tanaka et al., 2007a). However, other differences in cutoff points might help explain the disparate results.

A significant correlation was also observed between minutes of PAR ≥4 and step counts (r=0.604, $p<0.001$), and 12.7% of the children engaged in 30 min or more of PAR ≥4 activity. The correlation coefficient was slightly lower than that for PAR ≥3. Because the PAR for normal walking is 2.60±0.49 (Tanaka et al., 2007a), it is estimated that PAR ≥4 activities such as very brisk walking and running comprised a small percentage of overall locomotion, which may be the main reason for the weaker correlation. Thus, total number of steps may be a good index for moderate-intensity PA, though not for relatively high-intensity PA.

The estimated average time engaged in locomotion was 106 min, as calculated by average daily step counts in the present study (13,037 steps) and by the average step rate (122.7 steps/min) in our calibration study (Tanaka et al., 2007b). However, the percentage of time in nonlocomotive type activities was much larger than that spent in walking type activities, in the range of synthetic activity counts corresponding to medium-intensity activity. In addition, only brisk (but not normal) walking and running are included in MVPA, judging from the average PAR for normal walking in the calibration study (Tanaka et al., 2007a). Therefore, it should be noted that less than half of the 106 min was spent in MVPA in the present study. Nevertheless, the average amount of time engaged in MVPA as measured by triaxial accelerometry was almost 100 min and was strongly correlated with total daily number of steps. These results indicate that young children who engage in a substantial amount of MVPA have high daily step counts, even though prolonged locomotion does not comprise a large part of total MVPA.

In conclusion, this study suggests that daily step counts give valid information on daily physical activity for preschool-aged children. These children need to take 12,893 steps/day to attain the recommended 100 min/day of MVPA or 14,758 steps/day to attain 30 min/day of PAR ≥4 activity.

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Classifying household and locomotive activities using a triaxial accelerometer

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ABSTRACT

The purpose of this study was to develop a new algorithm for classifying physical activity into either locomotive or household activities using a triaxial accelerometer. Sixty-six volunteers (31 men and 35 women) participated in this study and were separated randomly into validation and cross-validation groups. All subjects performed 12 physical activities (personal computer work, laundry, dishwashing, moving a small load, vacuuming, slow walking, normal walking, brisk walking, normal walking while carrying a bag, jogging, ascending stairs and descending stairs) while wearing a triaxial accelerometer in a controlled laboratory setting. Each of the three signals from the triaxial accelerometer was passed through a second-order Butterworth high-pass filter to remove the gravitational acceleration component from the signal. The cut-off frequency was set at 0.7 Hz based on frequency analysis of the movements conducted. The ratios of unfiltered to filtered total acceleration (TAU/TAF) and filtered vertical to horizontal acceleration (VAF/HAF) were calculated to determine the cut-off value for classification of household and locomotive activities. When the TAU/TAF discrimination cut-off value derived from the validation group was applied to the cross-validation group, the average percentage of correct discrimination was 98.7%. When the VAF/HAF value similarly derived was applied to the cross-validation group, there was relatively high accuracy but the lowest percentage of correct discrimination was 63.6% (moving a small load). These findings suggest that our new algorithm using the TAU/TAF cut-off value can accurately classify household and locomotive activities.

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1. Introduction

The modern lifestyle with reduced physical activity and a dietary intake greater than needed for daily energy expenditure is closely related to an increasing proportion of obese people. Low levels of physical activity are also associated with cardiovascular diseases [1], type 2 diabetes mellitus [2,3], and osteoporosis [4,5]. In order to prevent and control obesity and other diseases, moderate-intensity physical activity is recommended [6–8]. It has been reported that occupational, leisure-time, and household activities are also effective in the prevention of obesity and related diseases [9,10]. In fact, energy expenditure (EE) induced by these activities is much larger than exercise-induced EE when measured throughout the day [11]. In addition, a large inter-individual variation is observed in EE for these activities [10,11]. Therefore, it would be very useful for obesity research to measure both locomotive and household activities accurately.

There are several methods for evaluating short- and long-term physical activities under free-living conditions [12,13]. Accelerometers are currently used by some groups as monitoring tools because they are small, non-invasive, and relatively inexpensive [14]. Although several prediction equations have been developed, a single regression equation based on walking and jogging underestimates the EE of moderate-intensity household activities [15]. In contrast, a single regression equation based on household activity overestimates the EE of sedentary and light activities and underestimates the EE of vigorous activities [15,16]. Therefore, recent studies have attempted to classify physical activity into locomotive and household activities using an accelerometer. Although techniques for correct discrimination have been examined, their validity and usefulness for improving the accuracy of EE prediction have not been sufficiently proven. In addition, household activity comprises some part of total physical activity and non-exercise activity thermogenesis (NEAT). However, most studies have focused on locomotive activities such as walking and jogging, and the degree to which household activity contributes to the total amount (duration and EE) of physical activity under free-living conditions remains unclear.

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Accelerometers with a DC (direct current) response are capable of measuring acceleration due to movement and gravitational acceleration [17]. Therefore, filter processing that removes gravitational acceleration is performed to detect dynamic movements and gravitational acceleration is used to discriminate static postures such as lying and standing. Although the discrimination of posture is important in understanding behavior patterns, it is also necessary to determine what kinds of activities a person is performing under sitting or standing conditions. We hypothesized that information from the gravitational acceleration signal may contribute not only to discrimination of posture but also to classification of physical activity into locomotive or household activity, because household activities tend to involve a change in inclination of the upper body in addition to movement.

The purpose of this study was to develop a new algorithm for quick and accurate classification of physical activity into either locomotive or household activity using a triaxial accelerometer and to compare the accuracy of the algorithm with a previously proposed method.

2. Methods

2.1. Subjects

Sixty-six volunteers (31 men and 35 women) participated in this study. The subjects were separated randomly into a validation group ($n = 44$) and a cross-validation group ($n = 22$). Physical characteristics of the subjects are shown in Table 1. Before measurements, the purpose and procedure of the study were explained in detail. Written informed consent was obtained from all subjects. When we recruited subjects, participants were excluded from the study if they had any contraindications to exercise or if they were physically unable to complete the activities. This study protocol was approved by the Ethical Committee of the National Institute of Health and Nutrition in Japan.

2.2. Protocol

Before testing, height and weight were measured with subjects in light clothing without shoes using a stadiometer and a physician's scale. Height and weight were measured to the nearest 0.1 cm and 0.1 kg, respectively. Body mass index was calculated as weight (kg) divided by height squared (m^2).

All 66 subjects performed 12 sequences of normal daily movements in a controlled laboratory setting while wearing a triaxial accelerometer on the left side of the waist. The testing procedure was the same for all subjects. Participants performed each activity for 3–7 min with a break of a few minutes between each activity. The selected activities were personal computer (PC) work, laundry, dishwashing, moving a small load (5 kg), vacuuming, 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 speed (Table 2). These activities were chosen as representative activities of daily life and were based on our observations for 3 days in free-living conditions. The preliminary study was performed using the activity records of 93 subjects living in the Tokyo metropolitan area.

2.3. Triaxial accelerometer device

In order to perform this experiment, we used a triaxial accelerometer device with 4 GB of memory (Omron Healthcare, Kyoto, Japan) consisting of a MEMS-based accelerometer (LIS3LV02DQ; ST-Microelectronics) which responds to both acceleration due to movement and gravitational acceleration. The sensor is built in a plastic case designed to be clipped onto a waist belt. The device measures 80 mm × 20 mm × 50 mm and weighs 60 g, including batteries. During the experiment, the device was attached at waist level on the left side using an elastic belt. A commercial device (Omron Healthcare, Active Style Pro HJA-350IT) has been developed from the device used in the present study.

Table 1
Physical characteristics of subjects.

	Men	Women	Total
Validation group			
n	21	23	44
Age (years)	42.2 ± 14.4	43.0 ± 13.1	42.6 ± 13.7
Height (cm)	170.2 ± 5.8	159.3 ± 5.4	164.5 ± 7.8
Weight (kg)	68.3 ± 15.1	55.6 ± 9.8	61.6 ± 14.1
BMI (kg/m²)	23.4 ± 4.2	21.9 ± 3.7	22.6 ± 4.0
Cross-validation group			
n	10	12	22
Age (years)	41.9 ± 14.3	42.0 ± 11.4	42.0 ± 12.8
Height (cm)	170.2 ± 7.5	156.9 ± 5.2	162.9 ± 9.2
Weight (kg)	68.2 ± 11.9	54.9 ± 7.6	61.0 ± 11.8
BMI (kg/m²)	23.4 ± 3.2	22.3 ± 2.9	22.8 ± 3.1

Values are means ± SD; BMI, body mass index.

Table 2
Household and locomotive activities performed in this study.

PC work: typing with a personal computer (7 min)
Laundry: carrying clothes from a laundry basket and hanging up clothes (6 min)
Dishwashing: washing the dishes (6 min)
Moving a small load: lifting a small load of 5 kg and unloading it after a few steps (5 min)
Vacuuming: cleaning the floor with a vacuum cleaner (6 min)
Slow walking: walking at 55 m/min around a track (6 min)
Normal walking: walking at 70 m/min around a track (5 min)
Brisk walking: walking at 100 m/min around a track (5 min)
Walking while carrying a bag: walking at 70 m/min around a track while carrying a bag of 3 kg (5 min)
Jogging: jogging at 140 m/min around a track (4 min)
Ascending stairs: walking up stairs at a self-selected speed (3 min)
Descending stairs: walking down stairs at a self-selected speed (3 min)

2.4. Analysis of acceleration signal

Anteroposterior (x-axis), mediolateral (y-axis), and vertical (z-axis) accelerations were obtained from the triaxial accelerometer during each activity at a sampling rate of 32 Hz. The acceleration data are expressed relative to g ($1\,g = 9.81\,m/s^2$). With a 12-bit analog-to-digital converter, the maximum scaling of the acceleration data was $\pm 6\,g$ (resolution: 0.003 g). The acceleration data were uploaded to a personal computer. The signals obtained from the triaxial accelerometer were processed as follows. Each of the three signals from the triaxial accelerometer was passed through a second-order Butterworth high-pass filter to remove the gravitational acceleration component from the signal. The cut-off frequency was chosen based on frequency analysis of movements conducted. The power spectrum of each direction was calculated by fast Fourier transform (FFT) for a temporal window that contained 256 samples of the signal. This was normalized to the maximum power of each window, and the normalized power spectrums of the three directions were composited. We calculated the integral of the absolute value of the accelerometer output of each of the three axes using acceleration signals (X, Y, Z) over a 10-s time interval. The interval size was determined based on physiological aspects and the processing performance of the CPU; it has been reported that the use of 10-s epochs does not result in a significant underestimation of high-intensity activity relative to 5-s epochs whereas longer epochs do [18]. Then, the calculated horizontal acceleration in the X–Y plane (horizontal acceleration filtered, HAF) and the calculated total three-dimensional acceleration (total acceleration filtered, TAF) were determined. In addition, total acceleration using an unfiltered acceleration signal (total acceleration unfiltered, TAU) was calculated. Finally, the ratios of unfiltered to filtered total acceleration (TAU/TAF) and of filtered vertical acceleration (VAF) to HAF (VAF/HAF), as proposed by Midorikawa et al. [16], were calculated. When TAU/TAF was calculated, the phases of TAU and TAF were matched in consideration of the phase shift of the high-pass filter. The acceleration signals from six 10-s epochs in the middle of each activity were processed to various acceleration output variables.

2.5. Statistical analysis

Statistical analyses were carried out using *SPSS* Version 14.0 for Windows (*SPSS*, Inc., Chicago, IL). All results are shown as the mean ± SD. $P < 0.05$ was considered statistically significant.

To assess the cut-off value for classification of household and locomotive activities, receiver-operating characteristic (ROC) curve analysis was applied to the acceleration data. We calculated the sensitivities and specificities using the TAU/TAF and VAF/HAF ratios. The sensitivity was multiplied by the specificity, and the point with the maximum product of sensitivity and specificity was considered to be the most valid discrimination cut-off value. The triaxial accelerometer signals from the validation group were used to identify the optimum cut-off value of parameters to classify physical activity. This cut-off value was then applied to the cross-validation group and the accuracy of discrimination was evaluated.

3. Results

FFT analysis showed that for locomotive activities, peak power appeared at a frequency of 1.0 Hz or more and the frequency of the peak increased with an increase in walking pace. For household

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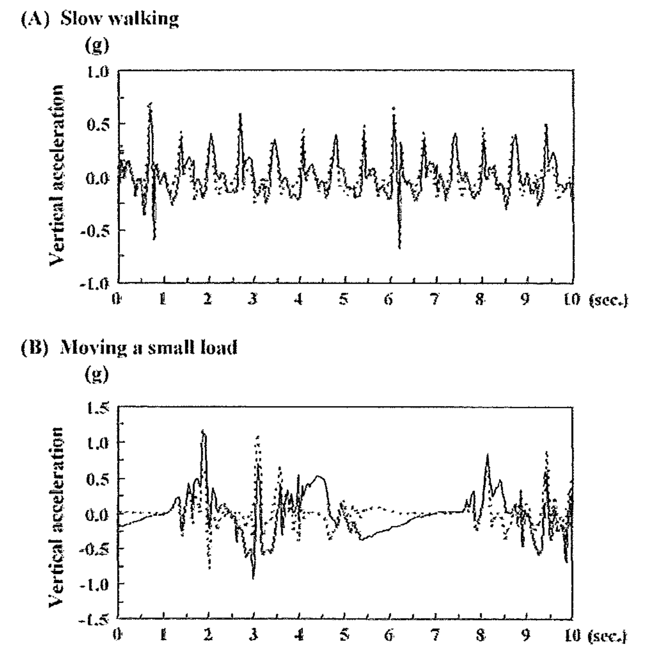

Fig. 1. Typical examples of a vertical acceleration signal during slow walking (A) and while moving a small load (B). Dotted line is before high-pass filtering, and solid line is after high-pass filtering.

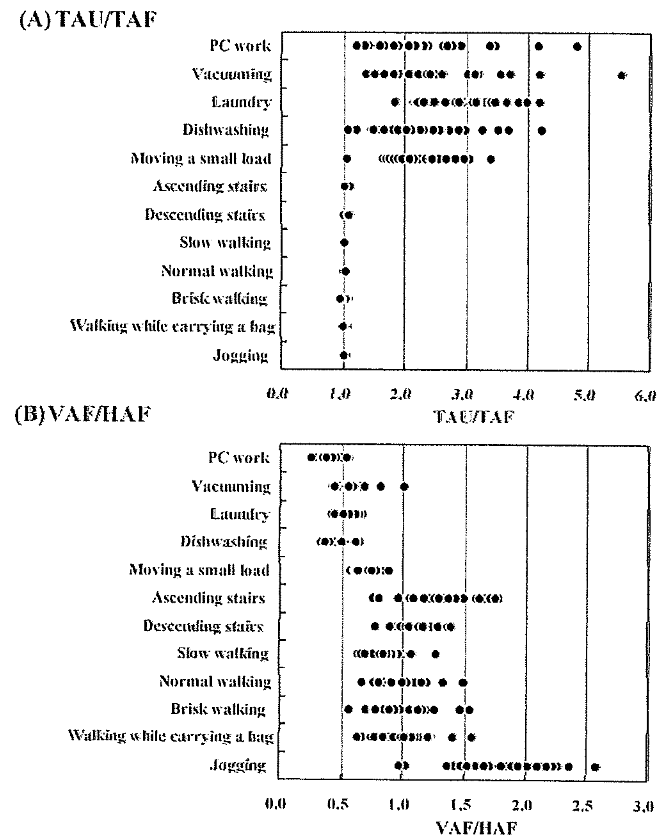

Fig. 2. The ratio of unfiltered to filtered total accelerations (TAU/TAF) (A) and the ratio of filtered vertical to filtered horizontal accelerations (VAF/HAF ratio) (B) during each activity in the validation group ($n = 44$).

activities, peak power appeared at 1.0 Hz or less and the mean frequency of the peak was 0.29 ± 0.19 Hz. Therefore, the cut-off frequency for the high-pass filter was set at 0.7 Hz (mean + 2SD).

Fig. 1 shows typical examples of a vertical acceleration signal before and after high-pass filtering during slow walking (Fig. 1A) and moving a small load (Fig. 1B). TAU during moving a small load (0.34 *g*) was larger than that during slow walking (0.23 *g*). TAF during both physical activities was similar (0.22 *g* and 0.22 *g*, respectively). Therefore, TAU/TAF during moving a small load (1.55) was larger than that during slow walking (1.04).

Fig. 2A shows TAU/TAF in the validation group. As in the case illustrated in Fig. 1, the average TAU/TAF during locomotive activities was 1.03 ± 0.03 (range 0.96–1.12). In contrast, the average TAU/TAF during household activities was 2.46 ± 0.73 (range 1.19–5.53). The product obtained by multiplying the sensitivity and specificity from the TAU/TAF data was 1.0 when TAU/TAF was between 1.13 and 1.19. Therefore, the discrimination cut-off value was set at 1.16, which is the mid-point for the TAU/TAF data. When the discrimination cut-off value derived from the validation group was applied to the cross-validation group, the percentage of correct discrimination was over 95.5% (Table 3).

The VAF/HAF ratio in the validation group is shown in Fig. 2B. The average VAF/HAF during locomotive activities was 1.13 ± 0.36 (range 0.56–2.58) and that during household activities was 0.55 ± 0.13 (range 0.32–0.99). The largest product of sensitivity and specificity using the VAF/HAF data was 0.74. Table 3 shows the results from applying the discrimination cut-off value to the cross-validation group. Vacuuming, doing laundry, dishwashing, and normal walking while carrying a bag were correctly classified by the VAF/HAF cut-off ratio. Percentages of correct discrimination for other activities ranged from 63.6% to 95.5%.

4. Discussion

Our major finding in this study is that locomotive and household activities can be accurately classified from the analysis of both unfiltered and filtered acceleration signals. We used the ratio of TAU/TAF to classify physical activities into either locomotive or household activities. The TAU/TAF ratios obtained during locomotive activities (around 1.0) and household activities (>1.0) were entirely different. Since the distinction between locomotive, household and light activities is important for accurate estimation of energy expenditure using an accelerometer, various classification methods have been proposed in previous studies [16,19]. Light activities can be discriminated from locomotive or household activities by using only total acceleration, because a lower total acceleration is observed for light activities than for the other two types of activities [16]. However, locomotive and household activities could not be clearly distinguished by a previously reported method [19]. It is very important to estimate EE accurately, including the proportion of time spent in household activities throughout the day, which is a large component of NEAT.

Table 3
Percentage of correct discrimination in cross-validation group ($n = 22$).

	TAU/TAF (%)	VAF/HAF (%)
PC work	100	100
Vacuuming	100	100
Laundry	100	100
Dishwashing	100	100
Moving a small load	100	63.6
Ascending stairs	100	90.9
Descending stairs	95.5	90.9
Slow walking	95.5	81.8
Normal walking	95.5	95.5
Brisk walking	100	95.5
Normal walking while carrying a bag	100	100
Jogging	100	100

TAU/TAF, ratio of unfiltered to filtered total acceleration; VAF/HAF, ratio of vertical to horizontal acceleration.

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Therefore, our findings are very pertinent to future research in this area.

The compendium of physical activities [20] is a common source of information regarding the intensities of various activities. The EEs of both normal walking and vacuuming are similar according to the compendium listings, whereas in this study the total acceleration for vacuuming was 1/4 that for normal walking. These results are consistent with previous reports that household activities have a higher oxygen cost, at the same total acceleration, compared with walking and running [19,21]. The increased EE during household activities is due to arm movements, lifting and carrying objects, climbing hills and stairs, and changing directions in the horizontal plane [21]. Therefore, different prediction equations are needed for accurate estimation of household and locomotive activities.

The acceleration signal was passed through a high-pass filter to remove the gravitational acceleration component in order to examine the actual relation of acceleration to physical activity [22]. In the present study, total acceleration was calculated from both the filtered and the unfiltered signals. If the acceleration signal is derived from locomotive activity which consists of only dynamic movement, the TAU/TAF ratio is mostly found to be 1.0. In contrast, if the acceleration signal is derived from household activity which consists of dynamic movement and gravitational acceleration, the TAU/TAF ratio is found to be larger than 1.0. The change in the gravitational acceleration component indicates a change in the inclination of the acceleration sensor. Because the acceleration sensor is attached to the waist of the subject, TAU/TAF reflects dynamic changes in body posture. The waist is not in the upper body, but the inclination of the upper body accompanies that of the waist in most instances. Therefore the gravitational acceleration signal at the waist reflects postural changes of the upper body to some degree. The cut-off value for classification was set at 1.16 in the present study, as a slight postural change at the waist seems sufficient to capture the postural changes of the upper body. Previous studies have reported a classification method for physical activity using the gravitational component of the triaxial accelerometer [23,24]. However, most such classification methods only discriminate static postures such as sitting and standing.

The TAU/TAF ratio was around 1.0 during locomotive activities regardless of the speed and was above 1.0 during household activities. This result suggests that there is a characteristic dynamic change in posture, such as inclining the upper part of the body forward, during household activities. While mainly the lower limbs move during locomotive activities such as walking and jogging, movement of the arms while lifting and pushing accompany household activities. Therefore, some researchers have attempted to classify and quantify the different types of physical activities using both trunk acceleration and wrist acceleration [25–27]. However, using multiple sensors can have disadvantages such as increased monetary cost and reduced convenience. If classification can be done with a single acceleration sensor, those disadvantages can be avoided. It has been reported that wrist-worn accelerometer signals can explain only a small part of the variance in EE [25,26]. In addition, it has been reported that the EEs of upper limb movements in activities such as deskwork were not different from the resting level, whereas self-care tasks accompanied by trunk movements approximately doubled the resting level [25]. Therefore, measurements of changes in posture are more important for discrimination of household activity intensity than measurements of upper arm movements.

The percentage of correct discrimination between locomotive and household activities by the VAF/HAF ratio was over 63.6% in the present study. Midorikawa et al. [16] reported that the sensitivity and specificity for discriminating between housework and walking using the VAF/HAF ratio was over 90%. This discrepancy may be due to differences between the protocols. Although 12 activities were chosen in the present study, only four types of activity (sitting, standing, housework, and walking) were performed in the study of Midorikawa et al. [16]. Moving a small load, which is a dynamic activity, complicated by lifting and walking, had the lowest discrimination accuracy of the 12 activities and slow walking had the lowest discrimination accuracy among the locomotive activities. The VAF/HAF ratio reflects the main direction of movement and may be associated with differences in movement between the upper body and the lower body. In the above two activities (moving a small load and slow walking), movement of both the upper and lower body occur to some degree and there may be large inter-individual differences. Therefore, the VAF/HAF ratio may tend to misclassify dynamic household activities and light locomotive activities.

Crouter et al. [19] attempted to distinguish walking and running from all other activities by calculating the coefficient of variation from Actigraph data. Because locomotive activities yielded a consistent minute-to-minute count, the coefficient of variation during locomotive activities was lower than that of other activities. They used six 10-s epochs of data to calculate the coefficient of variation for each minute. Therefore, it is necessary to keep a constant speed for at least 1 min for an accurate discrimination of walking with their method. Although it is possible to maintain an even pace in experimental conditions using a treadmill, speed is more variable in free-living walking because of pauses for traffic lights or walking on curved roads. Therefore, it is preferable that the discrimination be done over shorter time periods. In contrast, we could discriminate with 10-s epochs of data using TAU/TAF. Further research is required to determine the effectiveness of our approach for measurements of daily life EE.

In addition, it is possible that TAU/TAF may increase even during locomotive activities due to soft tissue movement or loosening of the belt that attaches the device to the waist. Since our study included only five subjects whose BMI was more than 30, we do not know the degree to which soft tissue may influence the results. It would be necessary to confirm whether our new algorithm can be adjusted for subjects with abdominal obesity.

In conclusion, we have shown that it is possible to classify locomotive and household activities using a single waist-mounted triaxial accelerometer. By analyzing raw acceleration data, changes in gravitational acceleration could be evaluated. The TAU/TAF ratio during household activities was larger than that during locomotive activities.

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Conflicts of interest

I declare that I have no conflict of interest.

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二重標識水法を用いたエネルギー摂取量評価への応用

髙田和子*

はじめに

二重標識水(Doubly labeled water：DLW)法は，水素(O)と酸素(H)の安定同位体を用いてエネルギー消費量(energy expenditure：EE)を測定する方法で，現時点では日常生活におけるEEの測定方法のうち最も精度が高いとされている．体重変化のない状態では，EEはエネルギー摂取量(energy intake：EI)に等しくなるので，食事摂取基準における推定エネルギー必要量は，DLW法によって測定されたEEのデータをもとに策定されている．

本稿では，DLW法の測定原理，測定の実際を紹介するとともに，EI評価のツールとしてのDLW法について考察する．

DLW法の測定原理

安定同位体とは，原子番号(陽子数)が同じで質量数(陽子と中性子の数の和)が異なる物質(同位体)のうち，原子核が安定し放射性をもたないもので，酸素には^{16}O，^{17}O，^{18}Oの3種，水素には^{1}Hと^{2}Hの2種がある．DLW法では，^{18}Oと^{2}Hを自然界に存在する比率よりも多く含む水(OとHの二重に印がつけられた水＝二重標識水：DLW)を，体重当たりで一定の割合で摂取する．この水は4～8時間程度で体全体の水分にまんべんなくいきわたる．その後，酸素は水(尿・汗・呼気中の水蒸気)と呼気ガス中の二酸化炭素として，水素は水としてのみ排出される．その結果，酸素の同位体の排泄の速度は，水素の同位体の排

表-1　二重標識水法による測定時の仮定

1.	測定期間中の体水分量は一定である
2.	測定期間中の水分の流入と，水分および二酸化炭素の流出の速度は一定である
3.	体内において安定同位体は，水と二酸化炭素のみにラベルされる
4.	安定同位体は，体内からは水分と二酸化炭素としてのみ排出される
5.	体内から排出される水と二酸化炭素中の安定同位体比は，同時点での体内の水分中の安定同位体比と同じである
6.	体内から排出された水と二酸化炭素が，再び体内に戻ることはない
7.	測定期間中の安定同位体の自然存在比，あるいはバックグラウンドは一定である

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泄速度よりも速くなり，その差が二酸化炭素の排出量となる．別の方法から呼吸商(Respiratory Quotient ： RQ)を推定し，それを利用して酸素消費量を推定する．この値から，間接熱量測定と同様に，Weir の式[1]を用いて EE を計算する．DLW 法における測定は，**表-1**に示す仮定のもとになりたっている．

測定の実際

1．投与量，投与方法と測定期間

投与量と測定期間は，安定同位体が測定終了後において，DLW の投与直後より十分に低下していること，バックグラウンドよりも十分に高く測定可能な程度であることの両方を満たすものとなる．投与量は，体水分当たり0.12g/kg の^2H_2Oと0.3g/kgの$H_2{}^{18}O$がよく使用される量である．投与する DLW は，市販の$H_2{}^{18}O$ (10.0atom％)と^2H_2O (99.9atom％)を混合して使用している．国産品ができてから，それぞれの価格はかなり安くなったが，2009年５月現在で，10atm％ $H_2{}^{18}O$が500g で50万(税別)，99.9atom％の^2H_2Oが100g で約１万５千円(税別)である．体重60kgの人に投与する場合で，約11万５千円になる．

測定の期間は，安定同位体の半減期の１～３倍とされているので，EE が多い対象や水分代謝の激しい対象では測定期間を短くする．一方で，人の日常生活は１週間の単位で変動することが多いので，EE の多い対象や小児では７日間，成人では14日間とすることが多い．

2．サンプリング

測定するサンプルは，体水分の一部であればよいので，血液，尿，唾液が使用可能である．採取のしやすさの点からは，唾液または尿を使用することが多い．普段の体水分中の^2Hや^{18}Oの濃度は，摂取している液体や食物によって個人差があるので，まず，DLW 投与前のサンプルを採取する．

その後のサンプリングについては，２ポイント法とマルチポイント法の２種がある．２ポイント法では，DLW 投与後，安定同位体が体水分と平衡状態に達する４時間程度のところで，サンプルを採取する．その後，翌日と７日または14日後の２回，同じ時刻のサンプルを採取する．そのため，投与後のサンプル数は最低で３回となる．しかし，平衡状態の確認や，その後の安定同位体濃度の変化を確実にとらえるために，時間をずらしてそれぞれ２回，採取し，計６回程度のサンプルを採取する場合が多い．

一方，マルチポイント法は，DLW 投与後当日のサンプル採取はせず，翌日から測定終了(７日または14日後)までの間に毎日(あるいは複数回)の同時刻にサンプル採取を行う方法である．

測定期間中は，対象者はサンプル採取以外は生活の拘束はなく，普段通りの生活(活動量，食事とも)を続ける．

3．分　析

採取したサンプルは，凍結して保存したのち，安定同位体存在比質量分析計(*Isotope Ratio Mass* Spectrometer ： IRMS)を用いて，^{18}Oと^{16}Oの存在比($^{18}O/^{16}O$)と^2Hと^1Hの存在比($^2H/^1H$)を測定する．サンプルは液体なので，酸素の測定時には二酸化炭素ガスで，水素の測定時には水素ガスで前処理を行い，気体中の安定同位体存在比を測定する．サンプル中の安定同位体存在比は，基準となる物質における存在比との比率(δ‰)でもとめる．基準となる物質としては，国際原子力機構(International Atomic Energy Agency ： IAEA)が管理している V-SMOW に対する比率で示すことが多い．筆者らの研究所では自らサンプルの分析を行っているが，国内での外注も可能である．外注での価格は１サンプルの水素と酸素の安定同位体存在比の測定で２万円になる．２ポイント法で最低のサンプル数でも４回(投与前，投与後４時間程度，翌日，最終日)，２ポイント法でも確実さを増したり，マルチポイント法とするとサンプル数はもっと多くなる．そのため，１人当たりの分析費用は最低でも８万円程度になる．

4．エネルギー消費量の算出

得られたデータから投与前の安定同位体比を除き，マルチポイントで得られた変化量をグラフにプロットすると対数曲線を描いて減少していく(**図-1a**)．この値を自然対数に変換した後の図が**図-1b**である．マルチポイント法での値を計算す

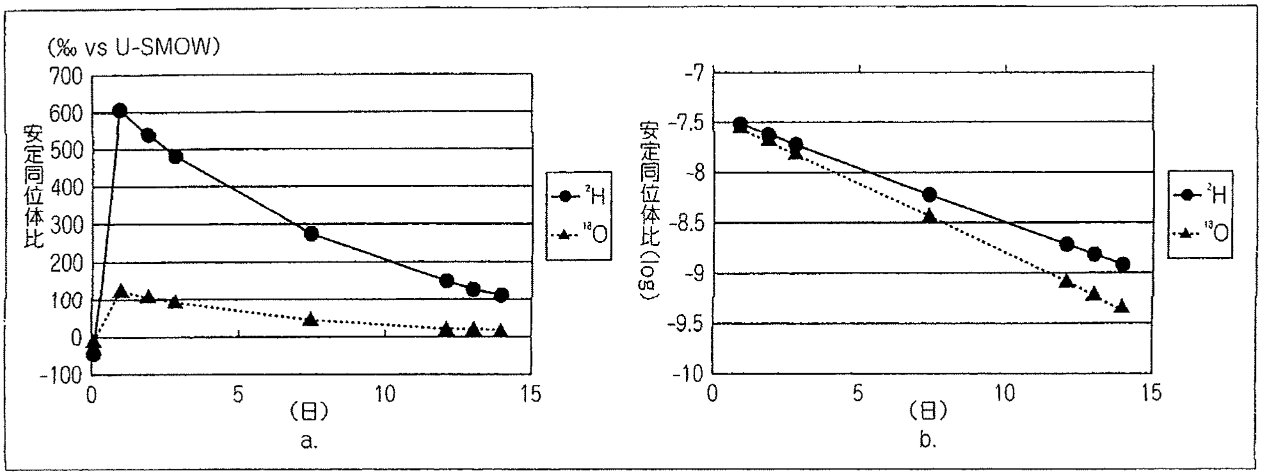

図-1 サンプル中の安定同位体比の変化(a)と対数変換後の値(b)

る場合は，この直線の傾きが安定同位体の排出率になる．測定期間中のすべてのRQを測定することは困難であること，長期的にみた場合，RQとFQ (food quotient)は同じであるという仮定から，調査期間中の食事調査の結果よりFQを求めて，酸素消費量を計算する[2]．DLW法で最終的に得られる結果は，7日または14日間を平均した1日の総エネルギー消費量(Total Energy Expenditure：TEE)である．

エネルギー摂取量評価への応用

1．エネルギー摂取量評価の精確さ

通常，EIの評価は，なんらかの食事調査を用いて行っている．現在，研究や健康管理の場面では，さまざまな種類の調査方法が使用されている．代表的なものとしては，食事記録法，24時間思い出し法，食物摂取頻度調査法，食事歴法があるが，それぞれ長所と短所がある．かつては，摂取量の調査方法の精度管理においては，秤量法による食事記録が基準として使われることが多かった．しかし1980年代以降，DLW法が人を対象に多く使用されるようになった後，EIの精度評価に使用されるようになった．これは，体重と身体組成が一定な条件下では，1日の総エネルギー摂取量(Total Energy intake：EI)とTEEは同じであるという原理に基づいたものである．Hillらのレビュー[3]によれば，DLW法を使用してTEI

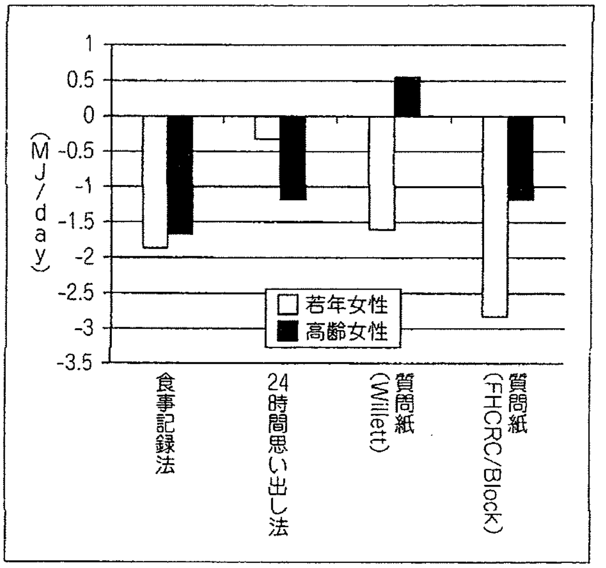

図-2 若年女性(平均25.2歳)と高齢女性(平均74.0歳)における各種調査法から推定したエネルギー摂取量とDLW法で求めたエネルギー消費量の差(文献4から筆者作製)

評価の精度を検討した研究の多くが，食事調査がTEIを過小評価していると指摘している．このレビューでは食事調査とDLW法により測定したTEEの値の差は最大で－59～19％にばらついており，食事調査から正確にEIを知ることの難しさが指摘されている．

食事調査方法の違いについては，Sawayaら[4]が若年と高齢の2グループに対して，秤量法による食事記録法，24時間思い出し法，2種類の食物摂取頻度調査法によるEI評価の精度について検

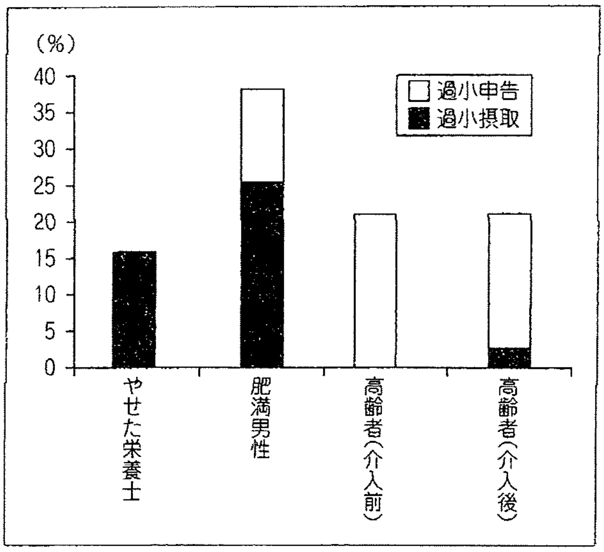

図-3　過小申告と過小摂取の割合(文献6～8より筆者作製)
DLW法を使用して検討した過小申告と過小摂取の割合.

討している(**図-2**). この研究では, 高齢者を対象にしたWillettの食物摂取頻度調査のみTEIを過大評価したが, 統計的に有意な年齢差, 調査方法による違いは認められなかった. しかしHillらは, TEIの過小評価が大きい対象の特徴として, 肥満者, 減量の経験者, 性差があることを指摘している.

Westerterpら[5]はTEIの過小評価を, 過小申告(*under-reporting*)と過小摂取(*under-eating*)に分けて検討している. 過小申告はいわゆる申告漏れで, 実際には摂取したのに記録にないことを示す. 一方で, 過小摂取は, 測定期間中になんらかの理由により摂取量が減ることを指しており, これは体重や身体組成の変化からある程度, 推測可能である. 彼らの研究からは, やせた栄養士では過小申告はなく, 摂取量の減少のみがみられたこと[6], 肥満男性では, 過小評価の約2/3が過小摂取, 1/3が過小申告であることが指摘されている[7](**図-3**). 一方, 高齢者を対象に運動に関する介入をする前後で, 食事調査の過小評価について検討したところ, 介入前の過小評価はすべて過小申告であった[8]. しかし, 介入後では過小申告は減少したが, 過小摂取がみられ, 結果的に全体の過小評価は大きくなった. とくに介入後では, 脂肪摂取量が過小に記録され, たんぱく質摂取量は過大に申告されていることから, 対象者の知識や意識により食事調査の精度が変わっていく可能性が指摘されている.

2. 過食時のエネルギー消費量

DLW法は, 現時点では自由に生活している条件において最も正確にTEEを評価する方法とされている. しかしながら, DLW法もいくつかの仮定の上に成り立つものであり, ヒューマンカロリメータ(Human Carolimeter : HC)に比べると推定精度は劣り, 確度は1～2%, 精度は5～7%程度とされている.

DLW法は, エネルギーバランスのとれた体重や体組成が変化しない状態で測定することが基本となっている. そのため, エネルギーバランスの崩れた状態では, 限られた情報しか得られないことになる. Riumalloら[9]は, 体重維持のTEIよりも1日当たり720kcal多い食事を摂った場合の体重, 体組成, TEE, TEIを比較している. その結果, 体重は－0.3～＋3.5kg, 体脂肪量は0.6～3.8kg変化したが, TEEは1週間の過剰摂取の後でも変わっておらず, TEIを反映したものにはなっていなかった. さらに, 体脂肪の蓄積量は過剰に摂取したエネルギー量の66%にとどまっており, 1日当たり約240kcalは評価不能となっていた. Riumalloらは残りの240kcalの一部は, 食事誘発性熱産生として使われているのではないかと指摘しているが, 残りの部分については不明であり, エネルギーバランスがとれていない条件では, DLW法で測定したEEがEIを反映していないとしている.

3. 体重変化時のDLW法によるTEIの評価

2007年にde Jongeら[10]はエネルギー摂取量の制限下において, DLW法で測定したTEEからTEIを評価することを検討した. 彼らの研究では, 3週間, 体重維持のTEIより30%少ないエネルギーを摂取した最後の1週間にHCとDLW法の両方でTEEを測定し, さらにその前後でdual-energy X-ray Absorptiometry (DXA)法を用いて体組成を測定している. 繰り返しになるがDLW法はエネルギー出納が取れている状態を仮定しているので, 通常は摂取エネルギー制限下では測定しない. この研究ではHCで測定したTEEとDLW法で測定したEEはよく一致し,

DLW 法による TEE は FQ を使用した場合で1.6±7.7%の過小評価，HC で測定した RQ を使用した場合で1.3±8.9%の過大評価であった．このことから，エネルギー制限下でも，DLW 法により TEE を評価しうることが指摘されている．

また，de Jonge らは DLW 法で測定した TEE と体組成の変化から推定した体に蓄積されているエネルギー量の変化から，TEI を推定した場合の精確さを評価している．すなわち，TEI は DLW 法で測定した TEE と体へのエネルギー蓄積量の変化の和で示すことができる．体組成の変化がわかればエネルギー蓄積量(energy store：ES)の変化(ΔES)は次の式から計算できる．

$$\Delta ES(kcal/day) = (9.3\times \Delta FM) + (1.1\times \Delta FFM)$$

ΔFM：体脂肪(Fat Mass)の変化量(g/day)
ΔFFM：除脂肪(Fat Free Mass)の変化量(g/day)

その結果では，推定した TEI は摂取した TEI よりも8.7±36.7%高く評価されていたが，その幅は－70～＋46%と大きかった．DLW 法により評価した EE と ES から推定した TEI は集団としては比較的よく評価できたが，個別にみると，推定誤差が大きいとまとめられている．

4. 多食と少食

1961～1993年に報告されたいくつかの論文では，標準体重でも自らを，多食(large-eating)あるいは少食(small-eating)と認識している人の存在が指摘されている．これらの研究においては，年齢，身長，体重，あるいは FFM などを調整しても，多食者は少食者の2倍の TEI があり，エネルギー利用効率のよい人と悪い人がいる可能性が指摘されている．1994年に Clark ら[11]は，多食者と少食者に対して，食事記録による TEI と活動記録による TEE の調査に加え，DLW 法で TEE の測定と，TEE と体重の変化量から推定した TEI を比較した(**図-4**)．その結果，自己記録による TEI は少食者で少なく，TEE は少食者で多かった．TEE は，多食者，少食者とも DLW 法で測定した値と活動記録がほぼ同じ結果となった．しかし，DLW 法で求めた TEE と体重変化から推定した TEI は，多食者に比べ少食者で多くなった．この研究では，少食者のうち2名に食事記録で求めた TEI の食事を3～4週間摂取したところ，体重減少が認められている．そこで，Clark らは，食事記録による TEI の信頼性は低く，エネルギー効率のよい少食者はいないのではないかと結論づけている．

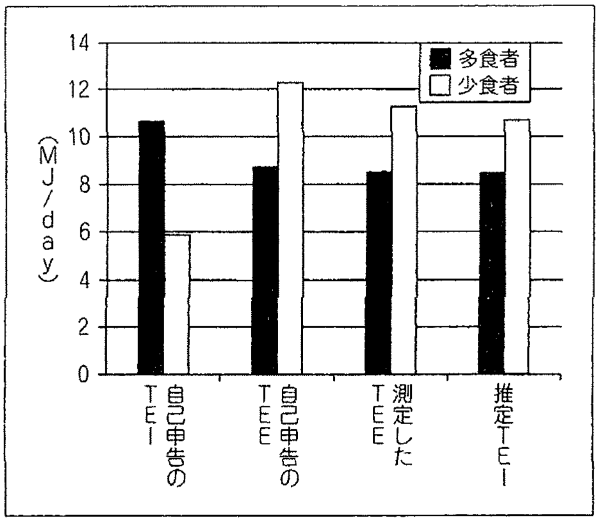

図-4 多食者と少食者のエネルギー摂取量とエネルギー消費量
(文献11より筆者作製)

5. DLW 法によるエネルギー摂取量評価

TEI の評価は，特別な場合を除き，多くが対象者自らの記録や申告によって行われる．そのため，意識的，無意識的にかかわらず，調査することが記録(申告)内容や摂取量に影響を与える場合がある．DLW 法により TEE を測定することは，唯一，客観的に TEI を評価しうる方法といえる．そのため，前章で示したような，これまで食事記録などの調査で指摘されていた結果が覆る場合がある．一方で，DLW 法は基本的には，体重や体組成が一定の期間で調査をするので，体重や体組成が変化する期間においては，その変化量を考慮する必要があり，また，体水分量の変化が DLW 法の測定において精度に影響を与える．さらに，コストや分析の手間から，DLW 法は多数を対象にした調査や，日常の診療や保健指導において使用できるものではない．DLW 法による TEI 評価は，以上のことを考慮した上で，必要に応じて使用するものと考える．

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アスレチックトレーナーのためのスポーツ医学

編集●宮永 豊(筑波大学教授)・河野一郎(筑波大学教授)・白木 仁(筑波大学講師)

❖日本体育協会によるアスレチックトレーナーの資格制度発足を踏まえ，競技現場で必要となるスポーツ医学に関するすべての事項を網羅した実践書．スポーツ医学の知識が体系的に整理されており，体育教師やコーチ，スポーツ医にも役立つ内容．

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7 適切なエネルギー消費量評価

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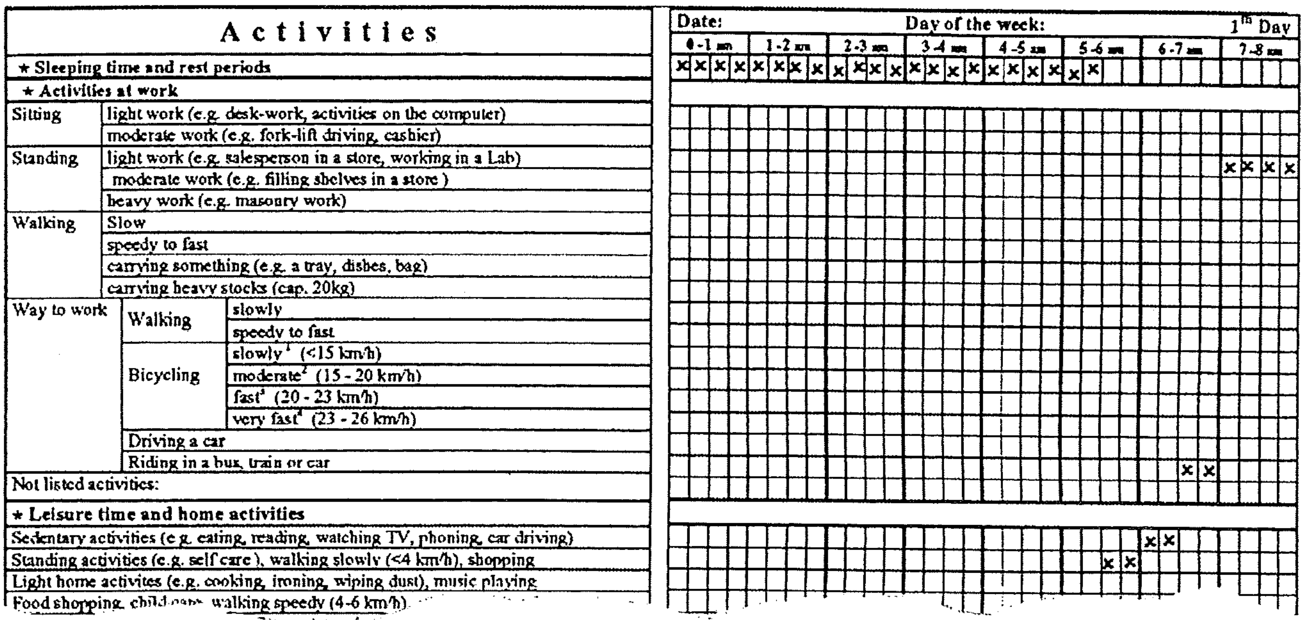
はじめに

エネルギー消費量(energy expenditure：EE)の評価方法には，さまざまな方法があるが，それぞれに特徴がある(表1)[1]．スポーツ選手を対象とした場合，練習などのスポーツ活動時のみのEEを推定する場合と，1日のEEを推定する場

表1 ／ 身体活動量調査方法の長所と短所のまとめ

身体活動量の調査方法	長所	短所
<基準となる方法>		
二重標識水法(DLW法)	正確で妥当性のあるエネルギー消費量の測定方法．小児から成人まで適用可能．自由生活下での測定ができ，身体活動の習慣に変化を及ぼさない．	高価である．分析に熟練を要する．特定の活動の情報を得ることができず，総エネルギー消費量しかわからない．大規模の調査に適さない．最低3日以上必要である．
間接的カロリメータ	短時間のエネルギー消費量測定において正確で妥当性がある．	高価である．より良い携帯型の機器ができるまでは，研究室レベルでの測定に限られる．身体活動量の間接的な測定である．
観察法	身体活動の種類と活動の内容を判断をするための最も良い記録方法．連続性のある情報が得られる．子どもにも適用可能．	時間がかかる．対象者の活動が影響を受ける可能性がある．観察時間が限られる．観察者の主観に影響を受ける．
<観察法>		
歩数計	軽く，ウエスト周囲に携帯が可能．単純で，安価．活動を制限しない．自由生活下での調査が可能．	歩行や走行の歩数のみを計測し，水平方向の移動や上体の動きの記録ができない．エネルギー消費量の推定において，妥当性が限られる．特定の活動の情報を得ることはできず，総身体活動量のみを評価．
加速度計	歩数計を参照．長時間，記録できる．動きの強度を知ることができる．特殊な活動を測定できる可能性がある．自由生活下での測定が可能．	エネルギー消費量評価の精度には，限界がある．特に一軸で腰部装着の場合，水平移動，上体の動き，荷物の運搬を記録できない．
心拍数計	軽量で持ち運び可能．身体活動への生理的な反応に直接的に関係している．長時間の詳細な記録が可能．特殊な活動を測定できる可能性がある．	ごく低強度の身体活動では，心拍数が活動と関係のない要因の影響を受けるため，適さない．個別に身体活動と心拍数の関係式を作成する必要がある．
<主観的方法>		
質問紙	疫学的研究に使用可能．集団を対象に身体活動レベルを大雑把に分類することに適している(低・中・高活動など)．	妥当性に限界がある．身体活動の詳細な情報は得られない．対象者の記憶や判断に左右される．個人レベルの身体活動量の評価には適さない．

(文献1)より改変引用)



Activities			Date: Day of the week: 1th Day — 0-1 am, 1-2 am, 2-3 am, 3-4 am, 4-5 am, 5-6 am, 6-7 am, 7-8 am
★ Sleeping time and rest periods			
★ Activities at work			
Sitting	light work (e.g. desk-work, activities on the computer)		
	moderate work (e.g. fork-lift driving, cashier)		
Standing	light work (e.g. salesperson in a store, working in a Lab)		
	moderate work (e.g. filling shelves in a store)		
	heavy work (e.g. masonry work)		
Walking	Slow		
	speedy to fast		
	carrying something (e.g. a tray, dishes, bag)		
	carrying heavy stocks (cap. 20kg)		
Way to work	Walking	slowly	
		speedy to fast	
	Bicycling	slowly[1] (<15 km/h)	
		moderate[2] (15 - 20 km/h)	
		fast[3] (20 - 23 km/h)	
		very fast[4] (23 - 26 km/h)	
	Driving a car		
	Riding in a bus, train or car		
Not listed activities:			
★ Leisure time and home activities			
Sedentary activities (e.g. eating, reading, watching TV, phoning, car driving)			
Standing activities (e.g. self care), walking slowly (<4 km/h), shopping			
Light home activites (e.g. cooking, ironing, wiping dust), music playing			
Food shopping, child care, walking speedy (4-6 km/h)			

図1 活動記録の例（文献3）より引用）

合がありうる．いずれにしても測定の目的や，費用，設備などに応じて，適切な方法を選ぶことが重要である．ここでは，選手を対象とした場合に，実際に使用可能と考えられる活動記録法，心拍数法，加速度計法について解説する．

I．活動記録法

活動記録法では，対象者または記録者が対象とする活動時間(練習時間のみ，あるいは数日間)中の活動の内容と時間を記録する．それぞれの活動の時間と活動ごとのEEを乗じ合計することで，対象とする時間における総エネルギー消費量を知ることができる．EEの計算においては，基礎代謝量や安静時代謝量を推定あるいは実測した値を使用する．それぞれの活動ごとのEEについては，その競技種目独特の活動や，オリジナルな練習方法，多くの時間を占める活動については実測することが望ましいが，資料としてはAinsworthら[2]が作製した活動ごとのMETの値が適切であろう．

活動記録法による誤差は，記録者の記録ミスあるいは，EE計算時における活動ごとのEEの当てはめが不適切なことによって生じる．練習や試合などの間については，選手以外の者が記録に当たる必要があるが，活動内容が秒単位で変化することもあり，それらの動きをどの程度，細かく記録するかで精度に影響を与える．一方，練習時間以外では，選手本人に記録を依頼する必要があり，その場合，選手本人の理解や協力の程度，あるいは記録することにより活動内容が影響を受けることが精度に影響を与える．Ainsworthらの資料[2]は多種類のスポーツを網羅しているが，すべての活動を含んでいるわけではないので，完全に一致する活動を選ぶことは困難である．また，資料として作成されているものは，あくまでも代表値であり，個人の体力や技術のレベルによりEEが大きく異なることが誤差になりうる．

図1は，Koebnickらが使用した1週間の活動を15分単位で記録するための記録用紙である[3]．この方法では，休息，仕事，余暇，スポーツなどの活動について似たような強度の活動をまとめ，33種類の活動(**表2**)[3]について，該当するところにマークをいれる．この活動記録法では，二重標識水(doubly labeled water：DLW)法と比較して，4±12%の過大評価をしたが，二つの方法間

表2 ／ Koebnick C らの活動記録で使用されている活動の項目と MET

	MET		MET
睡眠時間と休息時間	1.0	余暇時間	
仕事関係の活動		静的な活動(食事，読書，テレビなど)	1.3
座位(軽い業務)	1.5	立位での活動(身支度)，ゆっくりの歩行，買物	2.1
座位(中強度の業務)	2.5	軽強度の家事(料理，アイロンかけ)，楽器の演奏	2.3
立位(軽い業務)	2.5		
立位(中強度の業務)	3.0	飲食物の買物，子どもの世話，速歩	2.8
立位(高強度の業務)	4.0	中強度の家事活動と庭仕事(窓ふき，芝刈り)	4.1
歩行(ゆっくり)	2.0	家の補修，ペンキ塗り，タイル貼り	4.5
歩行(速歩)	3.5	高強度の家事活動と庭仕事(掘る)	5.5
歩行(荷物の運搬)	4.0	かなり高強度の家事活動と庭仕事(木を切る，重い物の運搬)	6.5
歩行(重い荷物の運搬)	5.0		
職場への往復		スポーツ活動	
歩行(ゆっくり)	2.5	ボーリング，ビリヤード，サーフィン	2.8
歩行(速歩)	3.5	体操，自転車(ゆっくり)，乗馬，卓球，バレーボール	4.0
自転車(ゆっくり，<15km/h)	4.0		
自転車(中強度，15〜20km/h)	6.0	ゴルフ，ダンス	4.5
自転車(速い，20〜23km/h)	10.0	エアロビック，バスケットボール，自転車(中強度)，ハイキング	6.2
自転車(かなり速い，23〜26km/h)	12.0		
車の運転	2.5	バドミントン，インラインスケート，ボート，スキー，テニス	7.0
バス，電車，車に乗る	1.3		
		登山，アメリカンフットボール，ハンドボール，ジョギング，自転車(速い)，水泳	9.0
		柔道，スカッシュ，自転車(かなり速い)	11.3

(文献3)より引用)

の差は有意ではなかった．Koebnick らは日常の1日の生活の EE を評価しているが，練習中の主要な活動をリストアップし，短い単位時間(数秒から1分)ごとの活動内容を記録することで，同様に記録と評価ができる．

日本では，労働の EE 評価について，沼尻ら[4]による時間研究の方法の記述が詳しい．沼尻らは，調査前に実際の作業を観察し，動作内容を分解して，作業工程を区分していく方法をとっているが，同様の手法が選手におけるスポーツ活動の時間調査に応用できる．

Ⅱ．心拍数法

心拍数が中〜高強度の活動において，酸素消費量と正の相関がみられることを利用した方法である．胸部に電極を装着し，小型のモニターを手首または腰に携帯することで，数時間から数日間のデータを1分から数分単位で記録することができる．

心拍数と酸素消費量の関係は，部分的には直線的であるが，低強度の活動では，心拍数と酸素消費量の関係はなだらかで，ストレスや姿勢など他の要因の影響を受けやすい．強度によっては，心拍出量が変化するために，心拍数と酸素消費量の関係が変化する場合があり，心拍数と酸素消費量の関係式は，1本の直線回帰式，2本の直線回帰式，対数曲線などいくつかの方法で示されてきた．1980年代頃からは，個別の心拍数と酸素消費量の関係を示す方法として，flex-HR 法がよく使用されている．この方法では，安静時と標準化された最大下での運動(ステップテスト，トレッドミル，自転車エルゴメータなど)で，酸素消費量と心拍数を測定する(**図2**)[5]．安静時心拍数の最大値と運動時の心拍数の最小値の平均値を屈曲(flex-HR)点とし，屈曲点より心拍数が大きいときは，運動時の値から求めた心拍数と酸素消費量の関係式を使用し，屈曲点より心拍数が小さいと

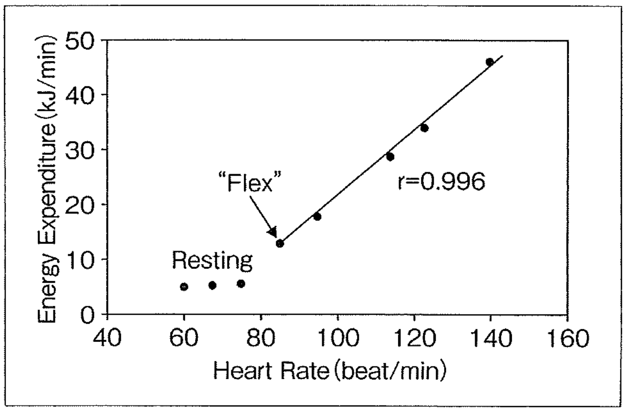


図2 ／ 心拍数とエネルギー消費量の関係（文献5）より引用）

表3 ／ 異なった式を使用して個別のエネルギー消費量を推定した値の比較

	16時間のエネルギー消費量の推定値	差
18種類の活動から個別の式を作製した場合	8,172±1,603	
9種類の活動から個別の式を作製した場合	7,882±2,075	−290±1,054 (−3,801, +2,543)
集団の式を作成した場合	8,044±1,544	−589±1,547 (−3,986, +2,097)
他の集団の式を使用した場合	7,803±1,984 (kJ/16 h)	+141±2,425 (−3,532, +5,034)

（文献6）より引用）

きには，安静時の3点の平均値を使用する．カロリメータやDLW法を基準にflex-HR法の精度を検討した1988〜1993年の論文によると，1日のエネルギー消費量推定の平均の誤差は－1％（－0.12MJ）で，2例を除くすべてが10％以内の誤差範囲にあった[5]．

心拍数からEEの推定による誤差の要因として，運動時においては，心拍数と酸素消費量の関係は活動の種類（自転車と走行など）により異なり，トレーニングのレベルによっても違うことがあげられる．また，断続的な活動の場合に，活動強度の変化に比べ心拍数の変化が遅いことが影響する可能性がある．心拍数には，身体の水分の充足度，気温，高度なども影響する．一方で，加速度計や歩数計が歩行・走行に近い動きを精度よく測定できることに比べ，心拍数からの推定は，自転車，上体の運動，水泳，坂道での歩行や走行なども評価できる可能性がある．

心拍数と酸素消費量の関係には個人内および個人間の差があるので，基本的には，心拍数と酸素消費量の関係は，個別に作成する必要がある．**表3**は，心拍数と酸素消費量の関係式の求め方によるEEの推定値の違いを示している[6]．18種類の活動により個別に関係式を作製した場合に比べ，9種類の活動から式を作製した場合には，推定値は平均で290kJ小さくなり，差は－3,801〜1,054kJにばらついていた．対象者のグループ全体から平均の関係式を作成して，個人のEEを推定した場合の誤差は－589kJであり，個別の式からEEを求める場合より差は大きくなったが，ばらつきは，個別の式を使用した場合と同程度であった．一方，他のグループで作製した式を使用した場合，差の平均値は＋141kJと小さいが，個別のばらつきは最も大きくなっており，他のグループで作製した式を使用することの困難さを示している．

心拍数を利用したEE評価として，Polar心拍計が多用されている．Polar心拍計のいくつかのモデルは，性・年齢・身長・体重・体力レベル・安静時の心拍数から個人の最大酸素摂取量と最大心拍数を推定し，さらにEEを推定することができる．Crouterらは，最大酸素摂取量と最大心拍数を付属ソフトで推定した場合と実測した場合のそれぞれから推定したEEとカロリメータで実測したEEを比較した（**図3**）[7]．その結果，男性ではEEの平均誤差は，カロリメータの実測値と推定値からの式では，－0.1kcal/min（95％信頼限界：－4.6，＋4.3kcal/min），カロリメータの実測値と実測値の式では，－0.5kcal/min（95％信頼限界：－3.2，＋2.1kcal/min）であった．女性では，推定値からの式では，－2.4kcal/min（95％信頼限界：－5.2，＋0.4kcal/min），実測値からの式では，－0.7kcal/min（95％信頼限界：－2.2，＋0.8kcal/min）であった．男女とも個別にみると，最大酸素消費量と最大心拍数の実測値からEEの推定を行う方が，個人レベルでの推定誤差