using the Isotope Ratio Mass Spectrometry (IRMS) *DELTA Plus* equipment (Thermo Electron Corporation, Bremen, Germany) and calibrated using Vienna Standard Mean Ocean Water (V-SMOW), 302B, and the Greenland Ice Sheet Precipitation (GISP) standard provided by the International Atomic Energy Agency. Each measurement of samples and the corresponding references was performed in duplicate. The average s.d. through the analyses were 0.5‰ for ^2H and 0.03‰ for ^{18}O.

TEE (kcal/day) calculation was performed using a modified Weir's formula Weir, 1949 based on rCO_2 (mol/day) and food quotient (FQ):

$$TEE = 3.9\times(rCO_2/FQ) + 1.1\times(rCO_2)$$

FQ was derived from the dietary assessment data (g/day) of DHQ using an equation of Black *et al.* (1986). The average value of all subjects (0.867) was used for all subjects to estimate TEE.

Assessment of other variables possibly related to the rEI

Lifestyle, behavioral and psychological variables possibly related to the rEI were obtained from the four-page questionnaire as follows: educational attainment, alcohol drinking, history of diet experiences, desire for body weight change, and difference between ideal and measured body weight.

A physical activity level was calculated as TEE divided by basal metabolic rate (BMR). BMR was estimated according to the 6th Recommended Dietary Allowances for Japanese Ministry of Health Welfare (1999).

Statistical analysis

We excluded 17 subjects who was non-Japanese ($n=1$), who was obese ($n=1$), who did not complete at least first or second DHQ ($n=2$), who had left more than 40 items blank in the questions regarding frequency for 121 selected food and beverage items in DHQ ($n=4$), who rEI outside the range of 3.0–16.0 MJ/day ($n=2$), or who did not provide sufficient urine sample volume ($n=7$). Thus, 140 subjects (67 men and 73 women) were included in the present analysis.

As we monitored the body weight change during the assessment period of rEI by second DHQ (rEI_{DHQ2}), we estimated EI (eEI) from TEE_{DLW} with a correction for change in body energy store during the survey period (Bathalon *et al.*, 2000):

$$eEI = TEE + (\Delta wt\times 0.03)$$

where TEE is measured as MJ/day, Δwt is measured as g/day between visits 1 and 3, and 0.03 MJ/day (7 kcal/day) is the energy cost of weight change (Saltzman and Roberts, 1995). The eEI was used for the validation of rEI_{DHQ2}. In contrast, this correction of change in body energy store was not considered for the validation of rEI_{DHQ1} because of the lack of the monitoring.

The results were expressed as the mean and s.d. Mean differences between sexes and among methods were tested by the non-paired *t*-test and paired *t*-test, respectively. The Pearson and Spearman correlation coefficient was used to examine correlations between the test and the reference methods. Furthermore, the study participants were classified into tertiles of energy intake according to the distribution of

Table 1 Characteristics of 140 Japanese men and women aged 20–59 years included in the analyses[a]

	Men (n = 67)	*Women (n = 73)*
Age (years)	39.4 ± 11.1	38.5 ± 10.4
Body height (cm)	169.3 ± 6.3	157.9 ± 6.1[e]
Body weight (kg)	67.3 ± 9.7	53.9 ± 7.3[e]
BMI (kg/m^2)[b]	23.3 ± 2.9	21.6 ± 2.7[e]
<18.5	5 (7)	10 (14)[i]
18.5–24.9	39 (58)	55 (75)
⩾25.0	23 (34)	8 (11)
Educational attainment		
High school or less	28 (42)	23 (32)[h]
Technical or professional school	5 (7)	28 (38)
University or more	34 (51)	22 (30)
History of diet experience[c]		
No	58 (87)	57 (78)
Yes	9 (13)	16 (22)
Desire for weight change		
Reduction	37 (55)	50 (68)
No change	20 (30)	20 (27)
Increase	10 (15)	3 (4)
Difference between ideal and measured body weight (kg)[d]	−4.2 ± 6.7	−4.5 ± 4.3
Frequency of alcohol intake (times/week)	2.6 ± 2.7	1.0 ± 1.9[e]
Physical activity level	1.70 ± 0.21	1.69 ± 0.27
Body weight change during survey (g/day)	−23 ± 55[j]	−2 ± 45[g]
TEE_{DLW} (MJ/day)	10.7 ± 1.7	8.3 ± 1.2[e]
eEI_{DLW} (MJ/day)	10.0 ± 2.1	8.2 ± 2.0[e]
rEI_{DHQ1} (MJ/day)	8.8 ± 2.4	7.7 ± 1.7[f]
rEI_{DHQ2} (MJ/day)	8.9 ± 2.5	7.4 ± 1.5[e]

Abbreviations: BMI, body mass index; DHQ, diet history questionnaire; DHQ1, first measurement of DHQ before dose of DLW; DHQ2, second measurement of DHQ 2 weeks after dose of DLW; DLW, doubly labeled water method; eEI, estimated energy intake = TEE_{DLW} + (body weight change during survey × 0.03); rEI_{DHQ}, reported energy intake assessed with self-administered DHQ; TEE_{DLW}, total energy expenditure measured by DLW.

[a]Mean ± s.d. or *n* (%).

[b]The categorization was based on the Japan Society for the Study of Obesity (Matsuzawa *et al.*, 2000).

[c]Dieting was defined as at least 2 kg intentional reduction of body weight within 1 month.

[d]Ideal body weight was evaluated by the following question: how many kilograms is your ideal body weight? Difference between ideal and measured body weight was calculated, as ideal body weight (kg)—measured body weight (kg), to evaluate the degree of desire for body weight change.

[e–g]Difference between sexes by non-paired *t*-test: [e]$P<0.001$, [f]$P<0.01$, [g]$P<0.05$.

[h,i]Significant difference between sexes in all categories by χ^2 test: [h]$P<0.001$, [i]$P<0.01$

[j]Difference within sexes from 0 by paired *t*-test: $P<0.01$.

the test and the reference methods, and the proportions of subjects classified into the same, adjacent or opposite tertiles were determined.

To evaluate the prevalence of under- or over-reporters, we calculated 95% confidence limits of rEI_{DHQ1}/TEE_{DLW} and rEI_{DHQ2}/eEI_{DLW} as a cutoff value proposed by Livingstone and Black (2003). Then, subjects with rEI_{DHQ1}/TEE_{DLW} and rEI_{DHQ2}/eEI_{DLW} smaller than 0.84 or larger than 1.16 were considered as under- or over-reporters, respectively.

A stepwise multiple regression analysis was performed to evaluate the influence of sociodemographic, lifestyle, behavioral and psychological factors on rEI_{DHQ1}/TEE_{DLW} and rEI_{DHQ2}/eEI_{DLW}, simultaneously. The following potential factors were entered into the model as the independent variables: age, BMI, body height, residential area, educational attainment, physical activity level, frequency of alcohol drinking, desire for body weight change, difference between ideal and measured body weight, and history of diet experience.

To examine the reproducibility, we compared mean rEIs between first and second DHQs (DHQ1 and DHQ2, respectively). Furthermore, the Pearson correlation coefficients were used to compare the rEIs assessed with DHQ1 and DHQ2.

All statistical analyses were performed using version 8.2 of the SAS software package (SAS Institute Inc., Cary, NC, USA). The test was considered significant at a P-value of <0.05.

Results

Basic characteristics of the study subjects, the mean TEE_{DLW}, eEI, first and second measurements of rEI by the DHQ (rEI_{DHQ1} and rEI_{DHQ2}) are shown in Table 1. Men had the higher BMI than women (23.3 versus 21.6 kg/m^2, $P<0.001$). Twenty-three of 67 men and eight of 73 women were overweight (BMI $\geq$25 kg/m^2). This table also shows body weight change during the TEE measurement, between visits 1 and 3. Mean body weight in men, although not in women, significantly changed by -23 ± 55 g/day ($P<0.01$ by paired t-test). Mean rEI_{DHQ1} was significantly lower than mean TEE_{DLW} by 1.9 ± 2.4 MJ/day (16.4%, $P<0.001$) for men and 0.6 ± 1.9 MJ/day (6.0%, $P<0.01$) for women. Mean rEI_{DHQ2} was also significantly lower than mean eEI_{DLW} by 1.1 ± 2.7 MJ/day (9.1%, $P<0.001$) for men and 0.8 ± 2.4 MJ/day (4.6%, $P<0.01$) for women.

Table 2 shows reporting accuracy of energy intake assessed with DHQ expressed as rEI_{DHQ1}/TEE_{DLW} and rEI_{DHQ2}/eEI_{DLW}. The rEI_{DHQ1}/TEE_{DLW} and rEI_{DHQ2}/eEI_{DLW} was 0.84 and 0.91 for men and 0.94 and 0.95 for women, respectively, resulting in a significantly lower rEI_{DHQ1}/TEE_{DLW} ratio for men than for women ($P<0.05$). There was a wide range in reporting accuracy of DHQ1; 31 and 51% were identified as acceptable, and 58 and 32% as under-, and 10 and 18% as over-reporters for men and women, respectively.

The rEI_{DHQ1} and TEE_{DLW} were significantly correlated only for men (Pearson correlation coefficient = 0.34, Spearman correlation coefficient = 0.33), but not for women (0.22 and 0.16, respectively). Forty-one, 45 and 14% of the subjects were cross-classified into the same, the adjacent and the opposite tertiles of the respective distributions of rEI_{DHQ1} and TEE_{DLW}, respectively (Figure 1a). The results of the correlation between rEI_{DHQ2} and eEI_{DLW} were similar (Figure 1b).

Table 3 shows the results of multiple regression analysis with rEI_{DHQ1}/TEE_{DLW} and rEI_{DHQ2}/eEI_{DLW}, as the dependent variables to examine the prediction of accuracy of reporting energy intake. For men, frequency of drinking alcohol, the difference between ideal and measured body weight, and history of diet experience correlated significantly and

Table 2 Reporting accuracy of energy intake determined by the self-administered diet history questionnaire[a]

	DHQ1			*DHQ2*		
	All (n = 140)	*Men (n = 67)*	*Women (n = 73)*	*All (n = 140)*	*Men (n = 67)*	*Women (n = 73)*
Reporting accuracy[b]	0.89 ± 0.22	0.84 ± 0.21	0.94 ± 0.22[c]	0.93 ± 0.30	0.91 ± 0.26	0.95 ± 0.33
Underreporters (*n* (%))	62 (44)	39 (58)	23 (32)[d]	64 (46)	30 (45)	34 (47)
Acceptable reporters (*n* (%))	58 (41)	21 (31)	37(51)	48 (34)	27 (40)	21 (29)
Overreporters (*n* (%))	20 (14)	7 (10)	13 (18)	28 (20)	10 (15)	18 (25)
Pearson's correlation coefficient	0.40[e]	0.34[f]	0.22	0.36[e]	0.35[f]	0.11
Spearman correlation coefficient	0.35[e]	0.33[f]	0.16	0.36[e]	0.41[e]	0.07

Abbreviations: DHQ1, first measurement of DHQ before dose of DLW; DHQ2, second measurement of DHQ 2 weeks after dose of DLW; DLW, doubly labeled water; eEI, estimated EI.

[a]Mean ± s.d. or *n* (%).

[b]Reporting accuracy was assessed as the ratio of energy intake to total energy expenditure (rEI_{DHQ1}/TEE_{DLW}) and the ratio of energy intake to estimated energy intake (rEI_{DHQ2}/eEI_{DLW}), respectively. eEI was determined by using a correction for change in body energy during the measurement period, as TEE ± (body weight change during survey × 0.03). Under-, acceptable, and over-reporters were defined as the ratio rEI_{DHQ}/TEE_{DLW} and rEI_{DHQ}/eEI_{DLW} <0.84, 0.84–1.16 and >1.16, respectively.

[c]Difference between sex by non-paired t-test: $P<0.01$.

[d]Significant difference between sexes in all categories by χ^2 test: $P<0.01$.

[e,f]Correlation coefficients between two methods: [e]$P<0.001$, [f]$P<0.01$.

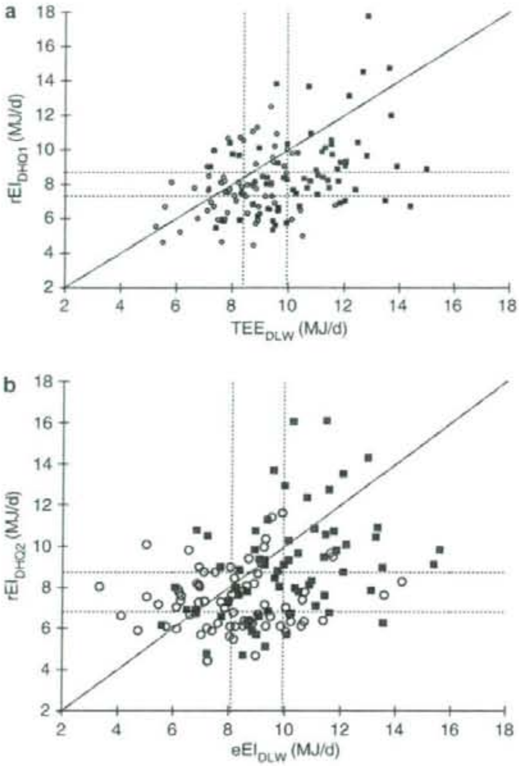

Figure 1 (**a**) Comparison of the first measurement of energy intake determined by the self-administered diet history questionnaire (rEI_{DHQ1}) with total energy expenditure measured by the doubly labeled water method (TEE_{DLW}) (■ = 67 men, ○ = 73 women). The dotted lines divide intake according to the tertiles of distribution. A straight line is $y=x$. Pearson and Spearman correlation coefficient was 0.40 and 0.35, respectively (both $P<0.001$). (**b**) Comparison of the second measurement of energy intake determined by the self-administered diet history questionnaire (rEI_{DHQ2}) with estimated energy intake (eEI_{DLW}) determined by a correction of body weight change during survey period, as TEE + (Δwt × 0.03), (■ = 67 men, ○ = 73 women). The dotted lines divide intake according to the tertiles of distribution. A straight line is $y=x$. Pearson and Spearman correlation coefficient was both 0.36 ($P<0.001$).

positively, and physical activity level negatively with rEI_{DHQ1}/TEE_{DLW}. For women, age and educational attainment correlated significantly and positively, and BMI negatively with rEI_{DHQ1}/TEE_{DLW}. We also conducted the same analysis with rEI_{DHQ2}/eEI_{DLW}. Body height, BMI and physical activity level significantly and negatively correlated with rEI_{DHQ2}/eEI_{DLW} for women. On the other hand, no factors attained the significance level for men.

The Pearson correlation coefficients between rEI_{DHQ1} and TEE_{DLW} slightly improved in both sexes after adjustment for the above-mentioned related factors (0.42 for men and 0.37 for women).

We also examined reproducibility of energy intake between DHQ1 and DHQ2. The rEI_{DHQ2} was significantly lower than rEI_{DHQ1} for women (the difference was -0.3 ± 1.1 MJ/day, $P=0.03$), but not for men. The Pearson correlation coefficient between rEI_{DHQ1} and rEI_{DHQ2} was 0.79 for men and 0.76 for women.

Discussion

To our knowledge, this is the first report in a non-Western country to validate energy intake estimated with a dietary assessment questionnaire against TEE measured by DLW method. Moreover, the sample size was relatively large compared to the previous studies with the same purpose and method (Sawaya *et al*., 1996; Kroke *et al*., 1999; Andersen *et al*., 2003).

The mean rEI_{DHQ1} was 11.0% less (16.4% for men and 6.0% for women) than the mean TEE_{DLW}. Several validation studies have shown that dietary assessment instruments underestimated daily energy intake (Livingstone *et al*., 1990; Hill and Davis, 2001). The degree of such error, under- or overestimation, has also been examined using TEE measured by the DLW method (Sawaya *et al*., 1996; Kroke *et al*., 1999; Andersen *et al*., 2003; Livingstone and Black, 2003). Average underreporting in the previous studies between EI from dietary assessment questionnaires and TEE measured by DLW ranged from 10 to 38% (Sawaya *et al*., 1996; Subar *et al*., 2003), which depends on sample size and subjects (Trabulsi and Schoeller, 2001).

For the individual ranking, the rEI_{DHQ1} significantly and positively correlated with TEE_{DLW} ($r=0.40$, $P<0.001$), showing a correlation similar to or relatively higher than those observed in the previous studies ($r=0.06$–0.48) (Kroke *et al*., 1999; Bathalon *et al*., 2000). Acceptable reporting was observed in 41% of the subjects, whereas 44% underreported and 14% over-reported. Underreporting of energy intake therefore seems to be a more serious problem than over-reporting.

In this study, the mean rEI_{DHQ1}/TEE_{DLW} ratio was significantly lower in men than in women. Further, the rate of underreporting was higher in men than in women. In a previous analysis of individual data from 21 studies, in contrast, the proportion of underreporters did not statistically differ between sexes (Black, 2000). In our previous study using semi-weighed diet records in 4 days × 4 seasons, the mean value of the ratio of rEI to BMR estimated from sex, age and body weight was not statistically different between sexes (Okubo *et al*., 2006). In the DHQ, the portion sizes of food items are standardized regardless of sex, for example as 'one small cup'. The subjects then select the relative portion size from the five categories given except for rice, bread, noodles, other wheat foods and miso soup. This structure

Table 3 Result of multiple regression analysis by stepwise procedure with the ratio of energy intake to total energy expenditure ($rEID_{HQ1}/TEE_{DLW}$ and rEI_{DHQ2}/eEI_{DLW}) as dependent variables[a]

Independent variable[b]	*Men (n = 67)*						*Women (n = 73)*					
	DHQ1			*DHQ2*			*DHQ1*			*DHQ2*		
	Partial regression coefficient[c]	*s.e.*[d]	*P-value*	*Partial regression coefficient*[c]	*s.e.*[d]	*P-value*	*Partial regression coefficient*[c]	*s.e.*[d]	*P-value*	*Partial regression coefficient*[c]	*s.e.*[d]	*P-value*
Age (years)	—	—	—	—	—	—	0.005	0.002	0.04	—	—	—
BMI (kg/m^2)	—	—	—	—	—	—	−0.036	0.009	<0.001	−0.049	0.015	<0.01
Body height (cm)	—	—	—	—	—	—	—	—	—	−0.016	0.006	0.02
Residential area	—	—	—	—	—	—	—	—	—	—	—	—
Educational attainment, (more than University versus high school or less as reference)	—	—	—	—	—	—	0.145	0.053	<0.01	—	—	—
Physical activity level	−0.356	0.120	<0.01	—	—	—	—	—	—	−0.480	0.154	<0.01
Frequency of drinking alcohol (times/week)	0.026	0.009	<0.01	—	—	—	—	—	—	—	—	—
Desire for body weight change	—	—	—	—	—	—	—	—	—	—	—	—
Difference between ideal and measured body weight (kg)	0.013	0.003	<0.01	—	—	—	—	—	—	—	—	—
History of diet experience (yes versus no as reference)	0.170	0.071	0.02	—	—	—	—	—	—	—	—	—

[a] TEE_{DLW}, total energy expenditure measured by doubly labeled water method (DLW); rEI_{DHQ}, reported energy intake assessed with self-administered diet history questionnaire (DHQ); DHQ1, first measurement of DHQ before dose of DLW; DHQ2, second measurement of DHQ 2 weeks after dose of DLW. Reporting accuracy were assessed as the ratio of energy intake to total energy expenditure (rEI_{DHQ1}/TEE_{DLW}) and the ratio of energy intake to estimated energy intake (rEI_{DHQ2}/eEI_{DLW}), respectively. Estimated EI (eEI) was determined by using a correction for change in body energy during the measurement period, as TEE + (body weight change during survey × 0.03).

[b] See table 1 for the definition of each independent variable. Age (as a continuous variable), BMI (as a continuous variable), body height (as a continuous variable), residential area (Hokuriku, Shikoku, North Kyushu, and South Kyushu), educational attainment (high school or less, technical or professional school, or university or more), physical activity level (as a continuous variable), frequency of alcohol drinking (as a continuous variable), desire for body weight change (reduction, no change or increase), difference between ideal and measured body weight (as a continuous variable), history of diet experience (yes or no).

[c] Partial regression coefficient; change in dependent variable related to a 1-U change in independent variable.

[d] Standard error (s.e.) of the regression coefficient.

might have led to relative over- and underreporting of energy in women and men, respectively.

The rEI_{DHQ1}/TEE_{DLW} was significantly and independently correlated with several anthropometric and behavioral factors (Table 3). Several previous studies have already examined non-dietary factors, such as physiological (Zhang *et al.*, 2000; Livingstone and Black, 2003) and psychological (Johansson *et al.*, 1998; Bathalon *et al.*, 2000; Tooze *et al.*, 2004) factors associated with reporting accuracy of energy intake. After adjusting for these variables, the validity slightly improved (Pearson correlation coefficient was 0.42 for men and 0.37 for women). Therefore, these non-dietary factors are needed to consider when evaluating rEI.

This study has several limitations. First, FQ was derived from dietary assessment data by DHQ. Therefore, TEE was not theoretically independent of EI. Second, the surveyed period for the first measurement of EI by DHQ (DHQ1) was ahead of, and not overlapping with, TEE measurement by the DLW method. Third, we used the TEE as gold standard for the validation of DHQ1 without any consideration for a possible body weight change during the assessment period because of lack of the data. Fourth, we used the TEE with a correction for change in body weight during the survey period as gold standard for the validation of DHQ2, because the body weight has significantly changed in men. Fifth, the change in body composition, such as change in fat mass and fat-free mass, is probably the better indicator than the change in body weight for the correction of energy content for the study purpose. Sixth, the rEI_{DHQ1} was significantly lower than the rEI_{DHQ2} for women. Intentional or non-intentional intervention effect might have influenced dietary behaviors between the first and the second measurement. As shown in Table 3, the factors affecting reporting accuracy of energy intake were different between the two measurements. This may be one of the reasons. Seventh, we applied a two-point rather than multipoint method for the measurement of TEE_{DLW}. Eighth, the subjects were not randomly sampled from the general Japanese population. Moreover, the survey areas were not equally distributed over the country but were rather selected mostly from the Western parts of Japan.

In summary, the energy intake assessed with DHQ correlated low to modestly with TEE measured by DLW. In addition, DHQ underestimated energy intake at a group level. Caution is needed when energy intake was evaluated by DHQ at both individual and group levels.

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ORIGINAL ARTICLE

Light-intensity activities are important for estimating physical activity energy expenditure using uniaxial and triaxial accelerometers

Yosuke Yamada · Keiichi Yokoyama · Risa Noriyasu · Tomoaki Osaki · Tetsuji Adachi · Aya Itoi · Yoshihiko Naito · Taketoshi Morimoto · Misaka Kimura · Shingo Oda

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Abstract This study evaluated the validity of the total energy expenditure (TEE) estimated using uniaxial (ACCuni) and triaxial (ACCtri) accelerometers in the elderly. Thirty-two healthy elderly (64–87 years) participated in this study. TEE was measured using the doubly labeled water (DLW) method (TEE_{DLW}). TEE_{ACCuni} (6.79 ± 1.08 MJ day^{-1}) was significantly lower than TEE_{DLW} (7.85 ± 1.54 MJ day^{-1}) and showed wider limits of agreement (-3.15 to 1.12 MJ day^{-1}) with a smaller correlation coefficient ($r = 0.703$). TEE_{ACCtri} (7.88 ± 1.27 MJ day^{-1}) did not differ from TEE_{DLW} and showed narrower limits of agreement (-1.64 to 1.72 MJ day^{-1}) with a larger correlation coefficient ($r = 0.835$, $P < 0.001$). The estimated intensities of light activities were significantly lower with ACCuni. Greater mediolateral acceleration was observed during 6-min walk tests. The results suggest that ACCtri is a better choice than ACCuni for assessing TEE in the elderly.

Keywords Doubly labeled water · Elderly · Physical activity level · Triaxial accelerometer · Total energy expenditure

Y. Yamada · K. Yokoyama · R. Noriyasu · T. Osaki · S. Oda (✉)
Laboratory of Sports Science and Human Motor Control, Graduate School of Human and Environmental Studies, Kyoto University, Yoshidanihonmatu, Sakyo-ku, Kyoto 606-8501, Japan
e-mail: m54899@sakura.kudpc.kyoto-u.ac.jp

T. Adachi
Department of Medical and Sport Sciences, Kyoto Interdisciplinary Institute of Community Medicine, Kyoto, Japan

A. Itoi
Department of Human Life Studies, Kobe Women's Junior College, Hyogo, Japan

Y. Naito
Department of Food Science and Nutrition, School of Human Environmental Science, Mukogawa Women's University, Hyogo, Japan

T. Morimoto · M. Kimura
Kyoto Prefectural University of Medicine, Kyoto, Japan

Introduction

The last half century has witnessed a dramatic increase in the world's population aged 60 years and greater (United Nations Department of Economic and Social Affairs-Population Division 2007). The aged, however, are not just older adults, as aging is frequently associated with a diminished ability to maintain a stable energy balance and a decrease in physical activity. These generally lead to fat and weight gain compared to younger adults, but also to muscle atrophy. This tends to progress with aging and can eventually lead to malnutrition, which contributes to further decline of bodily functions and the development of age-associated chronic degenerative diseases (Meydani 2001; Blanc et al. 2004).

Given the negative effects of physical inactivity, assessing the physical activity energy expenditure (PAEE), total energy expenditure (TEE), and physical activity level (PAL) accurately in the elderly is important (Manini et al. 2006). The doubly labeled water (DLW) method is one of the most accurate and valid tools used for evaluating TEE under free-living conditions (Schoeller et al. 1986), and it can also be used to assess PAEE and PAL with a simultaneous measurement of the resting metabolic rate (RMR) (Manini et al. 2006; Ishikawa-Takata et al. 2007).

However, access to the DLW method is limited due to the costs of the isotopes and the methodological effort involved. Moreover, the method does not provide any information about the type, intensity, and duration of each physical activity (Koebnick et al. 2005; Plasqui and Westerterp 2007). Hence, accurate alternative methods, validated using the DLW method, are necessary for epidemiological or interventional studies.

Physical activity monitoring using accelerometers obviates many of the limitations of the DLW method and may be very useful for obtaining objective information for estimating the free-living TEE with few interventions (Wong et al. 1981; Bouten et al. 1996; Davis and Fox 2007; Fox et al. 2007). Recently, several conversion algorithms for accelerometer information have been developed in laboratory settings using indirect calorimetry and validated under free-living conditions using the DLW method (Bouten et al. 1996; Westerterp 1999; Plasqui et al. 2005). However, most of the development and validation were performed in healthy young adults. This is a concern because the elderly differ from the young in terms of the kinetics and kinematics of locomotion (Murray et al. 1969; Judge et al. 1996; Dean et al. 2007). Therefore, this study tested whether the use of accelerometers and calibrations based on studies of young adults are valid in the elderly.

The two major classes of accelerometers described in the literature are the uniaxial accelerometer (ACCuni), which measures vertical acceleration only, and the triaxial accelerometer (ACCtri), which measures accelerations in three-dimensional space. ACCuni and ACCtri have recently been compared in adults or children (Chen and Sun 1997; Kumahara et al. 2004b; Plasqui et al. 2005; Tanaka et al. 2007a, b), but to our knowledge, no study has compared them in elderly participants. This is important because the elderly have less lateral stability and greater variability of lateral movement during walking (Dean et al. 2007), and the lateral instability influences the energy cost of movement (Donelan et al. 2004; Dean et al. 2007). We compared the accelerometers in a free-living environment using DLW as the criterion method, and assessed the accelerations in the anteroposterior, mediolateral, and vertical axes during a 6-min walk in a laboratory environment.

Methods

Participants

Data were obtained from 32 healthy elderly participants (18 women and 14 men, 64–87 years) recruited from participants in an ongoing health study conducted at Kyoto Prefectural University of Medicine during 2005–2006. The participants were invited to attend an information meeting and those interested in participating provided written informed consent. The eligibility criteria for the participants were as follows: not taking prescription medications that could interfere with the study and no history of alcohol abuse. The participants were evaluated by a physician to ensure that they were in good health with no signs or symptoms of metabolic disease or endocrine disorders. The study protocol was approved by the Medical Ethics Committee of Kyoto Prefectural University of Medicine.

Anthropometric measurements were obtained in the morning before the study period. Body weight was measured on an electronic scale to the nearest 0.1 kg. Height was measured to the nearest 0.1 cm. Predicted total body water (pTBW) was measured using a segmental bioelectrical impedance analysis (Muscle-α, Kyoto, Japan) (Miyatani et al. 2001; Ishiguro et al. 2006) to determine the DLW dose for each individual. No significant weight change (-0.1 ± 1.2 kg) was observed during the measurement periods.

The participants recorded a simplified physical activity record (sPAR) during the DLW measurement period, which was validated in an adult population in a study by Koebnick et al. (2005). The sPAR was modified slightly to fit the elderly population; the number of items was reduced for easier recording by the elderly: nine items were deleted and one item (taking a bath unaided) was added.

Resting metabolic rate

The RMR was measured with an indirect calorimeter (AE-300S; Minato Medical Science, Osaka, Japan) for 30 min in the early morning between 05:00 and 07:00 h, after an overnight stay in the facility. Before the study began, each participant was familiarized with the procedures and equipment used in the RMR analysis. RMR was measured under standard conditions with the participant having fasted for over 12 h and lying at complete rest immediately after sleeping (Turley et al. 1993). A $\dot{V}O_2$ variation of less than 25 ml min^{-1} was used to determine whether the collection was acceptable (Turley et al. 1993). Each participant was monitored periodically to ensure that they remained awake. Data collection took place in a thermally regulated environment with minimal light and noise. The calorimeter system was calibrated before the measurement of each participant. The predicted basal metabolic rate (BMR) was also calculated using the equation of the Recommended Dietary Allowances for Japanese (Health Promotion and Nutrition Division-Health Service Bureau Ministry of Health and Welfare 1995), as in previous studies (Rafamantanantsoa et al. 2002; Ishikawa-Takata et al. 2007).

Doubly labeled water

The TEE was measured using the DLW method over a 14-day period. Participants arrived on day 0, and a urine sample was acquired to measure the baseline ^2H and ^{18}O enrichment. Between 07:00 and 08:00 h, a premixed dose containing approximately 0.12 g kg^{-1} pTBW of ^2H_2O (99.8 atom%; Taiyo Nippon Sanso, Tokyo, Japan) and 2.5 g kg^{-1} pTBW of $H_2{}^{18}O$ (10.0 atom%; Taiyo Nippon Sanso) was given to each participant to drink. Urine samples were collected 4 h after dosing, approximately 24 h after dosing, and on the morning of day 15. Aliquots of the urine samples were stored frozen at −15°C for later analysis using isotope ratio mass spectrometry (Europa Scientific ANCA-G and Hydra 20–20 IRMS for ^{18}O; Europa Scientific ANCA-GSL and GEO 20–20 IRMS for ^2H; Europa Scientific, Crewe, UK). The gas used for equilibrating the ^{18}O was CO_2 and that used for ^2H was H_2. A Pt catalyst was used to equilibrate the ^2H. Isotope analyses were carried out at the Iso-Analytical Laboratory (Iso-Analytical Limited, Sandbach, UK). Each sample and the corresponding reference were analyzed in duplicate. The average standard deviations in the analyses were 0.7% for ^2H and 0.05% for ^{18}O.

The ^{18}O and ^2H dilution spaces (N_O and N_d) were determined by dividing the dose of the tracer administered (as moles of ^2H- or ^{18}O-water) by the intercept (^2H and ^{18}O enrichment at time zero, respectively) (Coward 1990) due to the influence of delayed isotopic equilibration on the accuracy of the DLW method in the elderly (Blanc et al. 2002, 2004; Manini et al. 2006). In this study, N_d/N_O was 1.038 ± 0.009 (mean ± SD; range 1.017–1.051), which concurred with most previous studies (Racette et al. 1994). Therefore, TBW (mol) was calculated as the mean of N_d (mol) divided by 1.041 for the dilution space estimated using ^2H and N_O (mol) divided by 1.007 for the dilution space estimated using ^{18}O (Racette et al. 1994).

The rate of CO_2 production (rCO_2) was determined as $0.4554 \times TBW \times (1.007 \times {}^{18}O$ elimination rate $- 1.041 \times {}^2H$ elimination rate), in which we assumed isotope fractionation applying only to breath water using equation A6 of Schoeller et al. (1986) with the revised dilution space constant of Racette et al. (1994). TEE (kcal day^{-1}) was calculated using a modified Weir's formula (Weir 1949) based on rCO_2 (mol day^{-1}) and the food quotient (FQ), which was calculated from the daily record of the food intake during the 14-day study period using a method described elsewhere (Rafamantanantsoa et al. 2002). This assumes that under conditions of perfect nutrient balance, FQ must equal the respiratory quotient (RQ) (Black et al. 1986). The mean FQ of the participants was 0.86 ± 0.04 (mean ± SD) in this study, which is very similar to the value of 0.87 ± 0.03 for 20- to 59-year-old Japanese healthy adults in a previous study (Ishikawa-Takata et al. 2007).

The PAEE was calculated as (TEE × 0.90) − RMR × (24 − Sleeping time)/24 − 0.95 × RMR × (Sleeping time)/24, thereby removing energy expenditure from the thermal effect of meals and subtracting the energy devoted to basal metabolism, which assumes a 5% difference between RMR and the sleeping metabolic rate. Sleeping time was estimated using sPAR (Mean and SD; 8.3 ± 1.2 h per day). In addition, the PAL was calculated as TEE/BMR (Manini et al. 2006).

Accelerometers

A uniaxial accelerometer (Kenz Activity Monitor Lifecorder EX; Suzuken, Nagoya, Japan) and a triaxial accelerometer (Panasonic Electric Works Co., Ltd, Osaka, Japan) were attached to an elastic belt and worn at the back of the waist for entire 2 weeks, and the data ware trimmed to fit the DLW period. Participants were instructed to wear the accelerometers during waking hours for 2 week, exclusive of time spent bathing or when in water. The daily wearing time and number of days worn were assessed by comparison with the result of the sPAR. If the difference in the non-water activity time of sPAR and the accelerometers data exceeded 3 h in a day, that day was excluded from the analysis.

The uniaxial accelerometer measured 72.5 × 41.5 × 27.5 mm and weighed 60 g, including the battery. The technical and estimation equation details of the uniaxial accelerometer have been described elsewhere (Saito et al. 2004; Kumahara et al. 2004a). It has a linear frequency response with a band pass filter and is drip-proof (not waterproof). It assesses values ranging from zero to two times the acceleration of gravity, and the intensity of physical activity is calculated by calculating the metabolic equivalent (MET) intensity levels of physical activities, which are counted every 4 s using the activity level (1.0–9.0) from the acceleration intensity (Kumahara et al. 2004a). In addition, the energy expenditures due to very small trunk movements and posture effects (e.g., sitting to standing, light desk-work) are calculated by multiplying the BMR by a constant (Kumahara et al. 2004a).

The triaxial accelerometer measures 60 × 35 × 13 mm and weighs 24 g, including the battery. The technical and estimation equation details of the triaxial accelerometer have been described elsewhere (Hara et al. 2006; Matsumura et al. 2008). It has a linear frequency response with a low pass filter and is drip-proof (not waterproof). It samples the acceleration at 20 Hz with a range from zero to two times the acceleration of gravity. It stores the standard deviation of the vector norm of the composite acceleration (K_m) in the three dimensions each minute as follows:

$$K_m = \sqrt{\frac{1}{n-1}\left[\left(\sum_{i=0}^{n} x_i^2 + \sum_{i=0}^{n} y_i^2 + \sum_{i=0}^{n} z_i^2\right) - \frac{1}{n}\left\{\left(\sum_{i=0}^{n} x_i\right)^2 + \left(\sum_{i=0}^{n} y_i\right)^2 + \left(\sum_{i=0}^{n} z_i\right)^2\right\}\right]}$$

where n is number of data for 1 min ($n = 1{,}200$), and Σx, Σy, and Σz are the sums of the accelerations for 1 min. It does not round down to store K_m. In a study of healthy male young adults (Matsumura et al. 2008), K_m was highly correlated ($R^2 = 0.86$) with the oxygen uptake ($\dot{V}O_2$) while walking or running at seven speeds ranging from 40 to 160 m min^{-1}) and during seven daily activities: performing self-care while standing, changing clothes, cooking, simulating eating supper, washing dishes, doing laundry, and using a vacuum cleaner (Fig. 1). The metabolic equivalent (MET) intensity levels of physical activities are calculated using a simple linear regression of K_m. The accelerometers collected minute-by-minute data for the entire 2 weeks, and the data were trimmed to fit the measurement period. The 24-h PAL was calculated for each day as follows:

$$PAL_{ACC} = \frac{1}{n}\sum_{i=0}^{n} METs_i$$

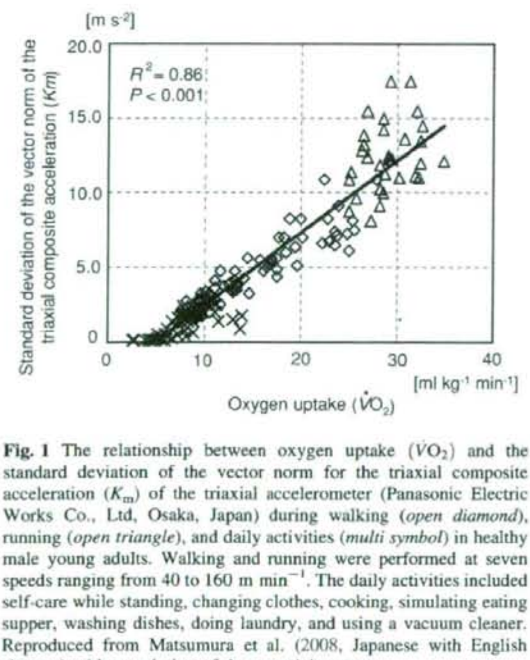

Fig. 1 The relationship between oxygen uptake ($\dot{V}O_2$) and the standard deviation of the vector norm for the triaxial composite acceleration (K_m) of the triaxial accelerometer (Panasonic Electric Works Co., Ltd, Osaka, Japan) during walking (*open diamond*), running (*open triangle*), and daily activities (*multi symbol*) in healthy male young adults. Walking and running were performed at seven speeds ranging from 40 to 160 m min^{-1}. The daily activities included self-care while standing, changing clothes, cooking, simulating eating supper, washing dishes, doing laundry, and using a vacuum cleaner. Reproduced from Matsumura et al. (2008, Japanese with English abstract) with permission of the copyright owner

where n is number of data ($n = 1{,}440$) during 24 h. TEE was calculated as PAL multiplied by RMR or BMR.

Six-minute walk test

In the laboratory, the participants walked for a total of 6 min under two conditions: they were told to walk faster than their usual walking speed under the fast condition, and slower than their usual walking speed under the slow condition. The order of the speed and direction of walking (clockwise or counterclockwise) were counterbalanced, with a 6-min rest between the two trials. The participants walked continuously around an oval 35-m track. They wore identical shoes that we provided to eliminate the effect of sole type. The triaxial accelerometer was attached to an elastic belt and worn at the back of the waist. We compared the results with those for healthy young individuals 10–32 years old. To assess the magnitude of the acceleration in each axis, the standard deviations of the accelerations in each axis (AP, anteroposterior; ML, mediolateral; V vertical) were calculated from 15 s after starting to 15 s before stopping to exclude the effect of gait initiation and termination. Since the walking speed affected the magnitude of the accelerations (Iwashita et al. 2003), the comparison of acceleration needs standardization of walking speed. All regressions of accelerations in the AP, ML, and V axes on walking speed returned nonsignificant intercepts in the linear regression analysis ($P = 0.192$–0.667). Therefore, the accelerations divided by the walking speeds were used for the analysis. The ratio of the accelerations of ML to V was also calculated for further analysis.

Statistical analysis

All analyses were performed using SPSS 12.0 for Windows (SPSS Inc., Chicago, IL, USA). The results are given as the means ± SD and range. For all of the analyses, an alpha of 0.05 was used to denote statistical significance. The relationships among TEE_{DLW}, TEE_{ACCuni}, and TEE_{ACCtri} were examined using linear regression analysis. Pearson correlation coefficients were compared statistically using the methods described by Meng et al. (1992). To eliminate the effects of weight, height, age, percent body fat, and gender on the relationship between TEE_{DLW} and TEE estimated using the accelerometers, partial correlation coefficients were calculated adjusted by those variables. Multiple stepwise linear regression analysis was also applied to examine the significance of the accelerometer data in the estimation of TEE. Bland–Altman plot analyses (1995) were performed to compare TEE_{ACCuni}, TEE_{ACCtri}, and TEE_{DLW} in the elderly. The differences between elderly and young individuals were examined using one-way analysis of variance (ANOVA). To appreciate the variability in the relationship between gait speed and the accelerations, linear regression analysis was applied and the standard error of the estimate (SEE) of gait speed from the magnitude of the accelerations was calculated in young adults and elderly, respectively.

Results

The physical characteristics of the participants are shown in Table 1. The measured PAL ranged from 1.34 to 2.20 in individual participants, with a mean of 1.66. PAL was not significantly correlated with age in either men ($r = -0.057$, $P = 0.847$) or women ($r = 0.144$, $P = 0.570$). In the participants, the predicted BMR was highly correlated with the measured RMR ($r = 0.937$, $P < 0.001$), the slope of the regression line did not differ significantly from 1.0 (95% confidence interval (CI): 0.98–1.30), and the intercept did not differ significantly from zero (95% CI: −1.35 to 0.15). Eleven participants reported riding a bicycle at least once in the measurement period and the average time spent riding was 16.0 ± 28.7 min day^{-1} for all participants. Eight participants reported swimming at least once in the measurement period and the average time spent swimming was 5.2 ± 9.9 min day^{-1} for all participants.

The total energy expenditure (TEE) measured using DLW, ACCuni, and ACCtri, both with the measured RMR and predicted BMR, are shown in Table 2. The correlation between the daily average ACCuni and ACCtri output was moderate ($r = 0.691$, $P < 0.001$). Although the correlation between TEE_{ACCuni} and TEE_{ACCtri} was very high ($r = 0.941$, $P < 0.001$), ACCuni significantly underestimated TEE compared to DLW, for both the measured RMR and predicted BMR (−11.7 and −12.5%). In contrast, TEE_{ACCtri} did not differ significantly from TEE_{DLW} with either the measured RMR or predicted BMR (2.5 and 1.6%). All of the correlation coefficients were significant ($P < 0.001$), although the correlation coefficients between TEE_{ACCuni} and TEE_{DLW} ($r = 0.695$ and 0.703) were significantly lower ($P < 0.05$) than the correlation coefficients between TEE_{ACCtri} and TEE_{DLW} ($r = 0.819$ and 0.835). The correlation coefficient between PAL_{ACCuni} and PAL_{DLW} ($r = 0.328$, $P > 0.05$) was not significant, but was significantly lower ($P < 0.05$) than the correlation coefficient between PAL_{ACCtri} and PAL_{DLW} ($r = 0.621$, $P < 0.001$).

We evaluated the influence of body weight and other physical characteristics on the relationship between the results using the DLW and accelerometer methods. The correlation coefficient between TEE_{ACCuni} divided by body weight and TEE_{DLW} divided by body weight ($r = 0.554$, $P < 0.01$) was significantly smaller ($P < 0.05$) than the correlation coefficient between TEE_{ACCtri} divided by body weight and TEE_{DLW} divided by body weight ($r = 0.760$, $P < 0.001$). The partial correlation between TEE_{ACCuni} and TEE_{DLW} adjusted for gender, age, weight, height, and percent body fat was not significant ($r = 0.163$, $P = 0.437$). In contrast, the partial correlation between TEE_{ACCtri} and TEE_{DLW} adjusted for gender, age, weight, height, and percent body fat was still significant ($r = 0.617$, $P < 0.001$). The results of the stepwise regression analysis for TEE are shown in Table 3. The output of ACCuni did not contribute significantly to estimating TEE, while the output of ACCtri contributed significantly to estimating TEE independent of the physical characteristics.

The linear regressions of TEE_{DLW} against TEE measured using the uni- and triaxial accelerometers with the predicted BMR (TEE_{ACCuni} and TEE_{ACCtri}) are shown in Fig. 2a and b. The slopes of the regression did not differ significantly from 1.0 for both the uni- and triaxial accelerometers. The intercept was significantly different from zero for ACCuni, but did not differ significantly from zero for the regressions obtained using ACCtri. The Bland–Altman agreement plots between TEE_{DLW} against TEE_{ACCuni} and TEE_{ACCtri} are shown in Fig. 2c and d. The limit of agreement was −3.15 to 1.12 MJ day^{-1} between TEE_{DLW} and TEE_{ACCuni}, and −1.64 to 1.72 MJ day^{-1} between TEE_{DLW} and TEE_{ACCtri}. The limit of agreement between TEE_{DLW} and TEE_{ACCtri} (3.36 MJ day^{-1}) was

Table 1 Physical characteristics of participants ($n = 32$)

	Mean ± SD (range)
Age	74 ± 6 (64–87)
Weight (kg)	53.5 ± 9.1 (37.1–76.5)
Height (cm)	154.9 ± 8.9 (141.8–175.4)
BMI (kg/m^2)	22.2 ± 2.5 (17.0–27.5)
Percent body fat (%)	31.9 ± 6.9 (14.7–43.5)
Measured RMR (MJ day^{-1})	4.74 ± 0.75 (3.50–6.41)
Estimated BMR (MJ day^{-1})	4.66 ± 0.61 (3.56–5.87)
TEE (MJ day^{-1})	7.85 ± 1.54 (5.25–11.23)
PAEE (MJ day^{-1})	2.41 ± 0.99 (0.94–4.59)
PAL	1.66 ± 0.24 (1.34–2.20)

BMI body mass index, *RMR* resting metabolic rate, *BMR* basal metabolic rate, *TEE* total energy expenditure, *PAEE* physical activity energy expenditure, *PAL* physical activity level

Table 2 Summary of total energy expenditure (TEE) estimated by accelerometers in the elderly

Estimation methods	TEE (MJ day^{-1})[a]	%difference[b]	r^c
DLW	7.85 ± 1.54 (5.25–11.23)		
ACCuni × mRMR	6.88 ± 1.22 (5.00–9.61)***	−11.7 ± 14.3% (−42.4–12.9%)	0.695
ACCuni × pBMR	6.79 ± 1.08 (5.09–9.39)***	−12.5 ± 14.0% (−40.8–12.4%)	0.703
ACCtri × mRMR	8.02 ± 1.45 (5.70–10.57)	2.5 ± 11.5% (−19.8–23.2%)	0.819
ACCtri × pBMR	7.88 ± 1.27 (5.74–10.33)	1.6 ± 11.1% (−18.3–28.2%)	0.835

DLW doubly labeled water, *ACCuni* uniaxial accelerometer, *ACCtri* triaxial accelerometer, *mRMR* measured resting metabolic rate, *pBMR* predicted basal metabolic rate

[a] Values are means ± SD; range in parentheses

[b] Percent difference from TEE measured by DLW. Values are means ± SD; range in parentheses

[c] Correlation coefficients with TEE measured by DLW

*** Significantly smaller than TEE measured by DLW: $P < 0.001$

Table 3 Multiple stepwise linear regression analysis for predicting total energy expenditure measured by DLW

Predicted variables	Coefficients							
	The uniaxial accelerometer				The triaxial accelerometer			
	Standardized	Unstandardized		P	Standardized	Unstandardized		P
	β	B	SEE		β	B	SEE	
ACC output				0.950	0.508	4.825	0.892	<0.001
Gender				0.524	−0.420	−1.296	0.378	<0.01
Age				0.877				0.718
Weight				0.452	0.467	0.079	0.021	<0.001
Height	0.777	0.133	0.020	<0.001				0.289
BMI				0.997				0.316
Percent body fat				0.783				0.534
(Constant)		−12.740	3.096	<0.001		−3.812	2.085	0.078

BMI body mass index, *ACC output* the average METs of the measurement period obtained by uni-axial and tri-axial accelerometers

Average METs were calculated solely as just a function of acceleration intensity (for details, see the "Methods" section)

Height was excluded and replaced by weight in the final step of the analysis using the triaxial accelerometer

The final models explained 62 and 77% of the TEE in the analysis using the uniaxial and triaxial acceleromters, respectively

smaller than that between TEE_{DLW} and TEE_{ACCuni} (4.27 MJ day^{-1}). The differences among TEE_{ACCuni}, TEE_{ACCtri}, and TEE_{DLW} were not significantly correlated with age, weight, height, BMI, TBW, percent body fat, total muscle mass, or BMR ($r = -0.325$ to 0.211, $P > 0.05$). None of these variables increased the validity of TEE obtained by conventional methods from the linear regression models when added to the model. The Bland–Altman agreement plots between PAEE estimated using DLW ($PAEE_{DLW}$), and those using ACCuni and ACCtri ($PAEE_{ACCuni}$ and $PAEE_{ACCtri}$) had similar results to TEE (Fig. 2e, f).

Figure 3 shows the estimated duration of activities at each intensity using ACCuni and ACCtri. No significant differences were observed in the moderate (3–5.9 METs) and vigorous (>6.0 METs) activities. In contrast, ACCuni showed a significantly shorter duration for 2–2.9 MET activities ($P < 0.001$), and a significantly longer duration for 1.1–1.9 MET activities compared to ACCtri ($P < 0.001$).

Figure 4 shows the magnitude of the acceleration in each axis and the ratio of the magnitude of the mediolateral acceleration to the vertical acceleration during slow and fast walking in the young and elderly individuals. No significant main effects of age and no significant interactions were observed for the magnitude of the acceleration in the vertical (V) and anteroposterior (AP) axes (Fig. 4a, c). Conversely, the magnitude of the acceleration in the mediolateral (ML) axis was greater in the elderly (significant main effect for age group with no significant interactions) (Fig. 4b). Furthermore, the acceleration ratio of ML to V had a significant main effect of age ($P < 0.01$) with no significant interaction ($P = 0.377$) and no significant main effect of gait speed ($P = 0.148$) in the two-way ANOVA (age groups × gait speeds) (Fig. 4d).

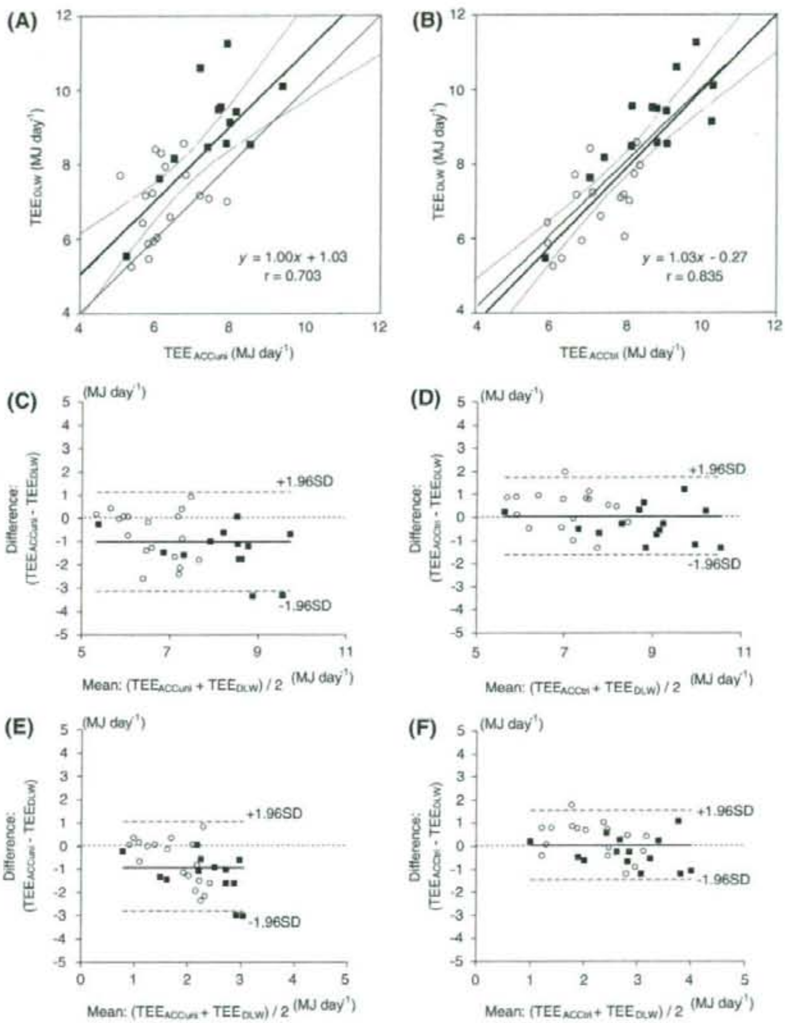

Fig. 2 The linear regressions of the total energy expenditure measured using doubly labeled water (TEE$_{DLW}$) against the total energy expenditure estimated using the (**a**) uniaxial (TEE$_{ACCuni}$) and (**b**) triaxial (TEE$_{ACCtri}$) accelerometers for healthy male (*filled square*) and female (*open circle*) elderly participants ($n = 32$). Bland–Altman agreement plots showing the difference between the total energy expenditure measured using doubly labeled water (TEE$_{DLW}$) and estimated using the (**c**) uniaxial (TEE$_{ACCuni}$) and (**d**) triaxial (TEE$_{ACCtri}$) accelerometers. A negative sign for the difference indicates an underestimation and a positive sign denotes an overestimation. TEE$_{ACCtri}$ did not differ significantly from TEE$_{DLW}$, but TEE$_{ACCuni}$ was significantly lower than TEE$_{DLW}$. Bland–Altman agreement plots indicated that the estimation of physical activity energy expenditure (PAEE) had similar results to those of TEE (**e**, **f**)

In the linear regression analysis, the SEE of gait speed was 0.12 m s^{-1} ($R^2 = 0.692$, $P < 0.001$) with the magnitude of V acceleration as a predictor, 0.15 m s^{-1} ($R^2 = 0.522$, $P < 0.001$) with the magnitude of AP acceleration, 0.17 m s^{-1} ($R^2 = 0.413$, $P < 0.001$) with the magnitude of ML acceleration, and 0.11 m s^{-1} ($R^2 = 0.735$, $P < 0.001$) with the magnitude of the vector norm of the composite acceleration from ACCtri. The correlations of gait speed with the uniaxial accelerations were significantly lower in the elderly ($r = 0.569$–0.755, $P < 0.001$, in each axis) than in the young adults ($r = 0.813$–0.917, $P < 0.001$, in each axis). The correlation of gait speed with the triaxial composite acceleration did not differ from the correlations of gait speed against the V acceleration in young adults ($r = 0.917$ vs. $r = 0.917$), but was slightly higher than the correlation of gait speed with the V acceleration in the elderly ($r = 0.808$ vs. $r = 0.755$).

Discussion

We compared the validity of ACCuni and ACCtri for estimating TEE and PAEE in the elderly population. Compared to the DLW method, ACCtri had more accuracy and precision for estimating TEE and PAEE than ACCuni

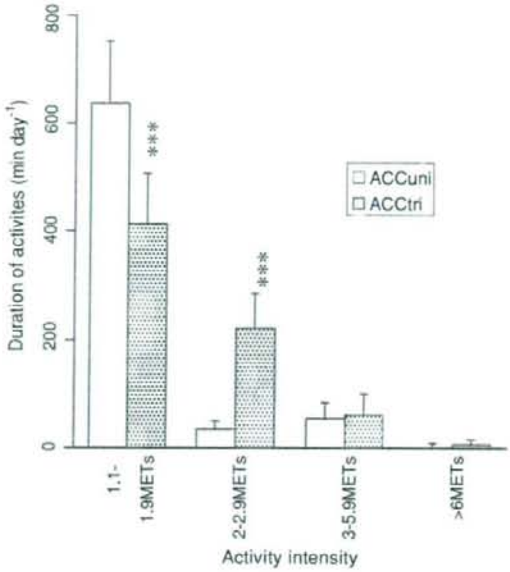

Fig. 3 The estimated duration of activities at each intensity using both ACCuni and ACCtri in the elderly participants. A significant difference between ACCuni and ACCtri was observed for light activities (1.1–2.9 METs)

(Fig. 3). This can be explained by the underestimated intensities of sedentary activities with ACCuni (Fig. 4). Furthermore, the output of ACCtri, but not ACCuni, contributed significantly to estimating TEE independent of gender, age, weight, height, and percent body fat (Table 3).

The number of commercial accelerometers for assessing energy expenditure has increased dramatically. We selected the devices used in this study for the following reasons: ACCuni and ACCtri have same measurement range of acceleration, are similar in size, use simple regression models to convert acceleration into PAL, do not need any individual calibrations, and have been calibrated with Japanese healthy young adults. In this study, the correlation between TEE_{ACCuni} and TEE_{ACCtri} was high ($r = 0.941$, $P < 0.001$), and it was reasonable to compare the two instruments. Although the correlation between the two was high, the accuracy and precision were significantly higher for ACCtri than ACCuni.

Several studies using the DLW method have validated the use of accelerometers for estimating energy expenditure in the elderly. Starling et al. (1999) examined Caltrac, a uniaxial accelerometer, and found that it significantly underestimated PAEE in participants between 45 and 84 years old (−50 to −55%). Meijer et al. (2001) examined Tracmor, a triaxial accelerometer, and found that it agreed with PAEE measured using the DLW method with a high correlation in 55–74-year-old participants. The results in our study agree with those studies, and suggest that ACCtri is a more suitable device than ACCuni in the elderly. Moreover, compared to conventional questionnaire methods in the literature (Morio et al. 1997; Rothenberg et al. 1998; Bonnefoy et al. 2001; Seale et al. 2002;

Fig. 4 The accelerations divided by the walking speed during level walking at slow and fast paces (**a**) in the vertical (*V*), **b** mediolateral (*ML*), and **c** anteroposterior axes in young and elderly participants. Only the variability of the ML acceleration had a significant main effect of group. The ratio of the variability of the ML acceleration to the variability of the V acceleration (**d**) also had a significant main effect of group

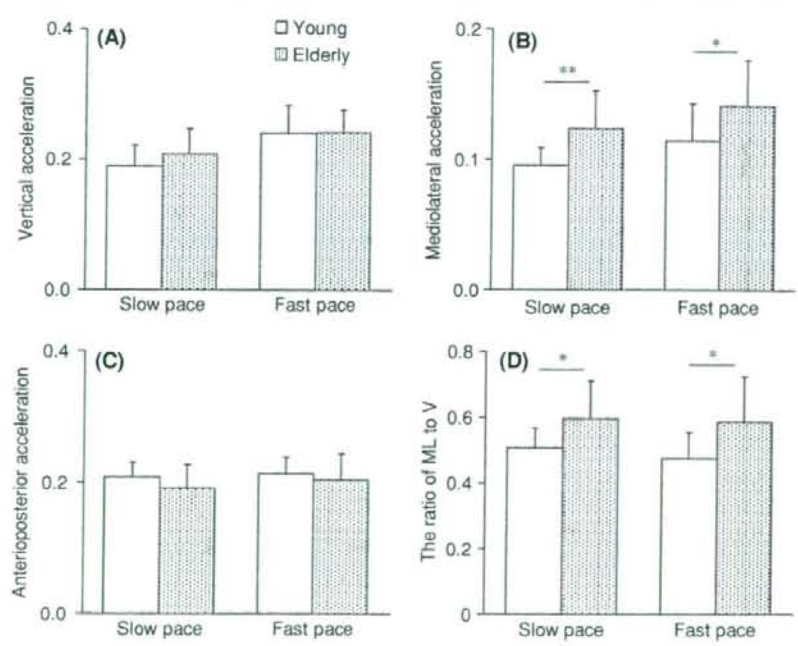

Table 4 A summary of studies comparing TEE and PAEE measured using the DLW method in which TEE and PAEE were estimated using conventional methods in the elderly or the adults including participants aged 60 year and over

Methods	Mean difference (MJ day^{-1})	Range of limits of agreement (MJ day^{-1})	*N*	Age (year)	References
PAEE					
ACCtri	0.03	3.03	14 M, 18 F	75 ± 6	This study
ACCuni-Lifecorder	−0.91*	3.84	14 M, 18 F	75 ± 6	This study
ACCuni-Caltrac	−2.75*	6.30	32 M	66 ± 11	Starling et al. (1999)
	−2.07*	3.50	35 F	67 ± 9	Starling et al. (1999)
MLPA	−3.15*	8.14	32 M	66 ± 11	Starling et al. (1999)
	−2.04*	5.84	35 F	67 ± 9	Starling et al. (1999)
	−1.31*	7.33	19 M	73.4 ± 4.1	Bonnefoy et al. (2001)
YPAS	−0.44	11.84	32 M	66 ± 11	Starling et al. (1999)
	−0.04	8.14	35 F	67 ± 9	Starling et al. (1999)
	0.38	4.64	19 M	73.4 ± 4.1	Bonnefoy et al. (2001)
College Alumni	−1.00*	7.00	19 M	73.4 ± 4.1	Bonnefoy et al. (2001)
TEE					
ACCtri	0.03	3.36	14 M, 18 F	75 ± 6	This study
ACCuni-Lifecorder	−1.06*	4.27	14 M, 18 F	75 ± 6	This study
	−2.37*	3.58	24 M	48 ± 10	Rafamantanantsoa et al. (2002)
Armband accelerometer	−0.49*	3.73	13 M, 32 F	35.1 ± 14	St-Onge et al. (2007)
Flex HR	0.70	7.23	6 M	68.8 ± 2.5	Morio et al. (1997)
	0.60	3.31	6 F	71.3 ± 2.4	Morio et al. (1997)
	−0.96*	4.66	9 F, 3 M	73 ± 0	Rothenberg et al. (1998)
	0.24	6.71	24 M	48 ± 10	Rafamantanantsoa et al. (2002)
Factorial method	−0.10	5.92	6 M	68.8 ± 2.5	Morio et al. (1997)
	−0.80	4.78	6 F	71.3 ± 2.4	Morio et al. (1997)
Activity record	−0.66	7.37	9 F, 3 M	70 ± 0	Rothenberg et al. (1998)
	−1.40*	3.13	24 M	48 ± 10	Rafamantanantsoa et al. (2002)
7-d activity recall	1.16*	11.30	19 M	73.4 ± 4.1	Bonnefoy et al. (2001)
	1.26	9.70	14 M	74.1 ± 4.1	Seale et al. (2002)
	0.07	10.77	13 F	73.5 ± 4.2	Seale et al. (2002)
QAPSE	−1.50*	9.31	19 M	73.4 ± 4.1	Bonnefoy et al. (2001)
College Alumni	6.65*	18.74	65 F	59.9 ± 7.5	Mahabir et al. (2006)
Five City Project	1.72*	7.03	65 F	59.9 ± 7.5	Mahabir et al. (2006)
$CAPS_{Typical\ Week}$	−3.35*	75.14	65 F	59.9 ± 7.5	Mahabir et al. (2006)
$CAPS_{Four\ Week}$	1.22*	24.77	65 F	59.9 ± 7.5	Mahabir et al. (2006)

* Significantly different from zero ($P < 0.05$)

Note: Any accelerometry prediction of EE (TEE or PAEE) may be highly dependent on the degree to which calibration activities resemble the activities that take place during free-living

Mahabir et al. 2006; St-Onge et al. 2007), ACCtri is generally in better agreement with DLW and less prone to significant systematical bias in the elderly (Table 4).

We examined the reasons for the discrepancy between TEE_{ACCuni} and TEE_{ACCtri} in the elderly. The primary discrepancy was that the intensities of light activities (1.1–2.9 METs) estimated using ACCuni were significantly lower than using ACCtri in the elderly. For ACCuni, the energy expenditures of very small trunk movements and posture effects (e.g., sitting to standing, light desk-work) are calculated by multiplying the BMR by a constant because ACCuni could not measure the energy expenditure during sedentary activities accurately in a laboratory environment, as shown by Bouten et al. (1994). Kumahara et al. (2004a) demonstrated that ACCuni underestimated the 24-h energy expenditure determined using whole-body indirect calorimetry and recalibrated METs from the output of ACCuni during walking. We applied this equation to our data, but

TEE_{ACCuni} was improved only 1–3% and was still lower than TEE_{DLW}.

In contrast, for ACCtri, a prediction equation was developed including sedentary activity as well as walking and running (see the Methods section and Fig. 1). In Fig. 1, sedentary activities were spread around a $\dot{V}O_2$ of 7–10.5 ml kg^{-1} min^{-1} (~2.0–2.9 METs) and around a $\dot{V}O_2$ of 3.5–7 ml kg^{-1} min^{-1} (~1.0–1.9 METs). Elderly adults engage in more sedentary and light-intensity activities than young adults (Meijer et al. 2001; Blanc et al. 2004; Harris et al. 2007); therefore, the underestimated intensities of sedentary activities with ACCuni might lead to underestimating TEE in the elderly under normal conditions. Indeed, if we calculate the average energy expenditure error associated with misclassifying 200 min day^{-1} of 2.1–2.9 MET activity as 1.1–1.9 MET activity, this accounts for about two-thirds of the underestimate.

One reason that ACCuni underestimated intensity could be the differences in the kinetics and kinematics of the locomotion between elderly and young people. In this study, the elderly had significantly higher lateral acceleration than young participants during level walking. Elderly people tend to walk with wider steps, less lateral stability, and greater variability of lateral movement during walking (Murray et al. 1969; Judge et al. 1996; Dean et al. 2007). The lateral instability adds an additional energetic cost (Donelan et al. 2004; Dean et al. 2007), and the elderly tend to have greater energetic costs during walking (Mian et al. 2006; Dean et al. 2007; Harris et al. 2007; Ortega and Farley 2007). These changes may not be reflected by the vertical acceleration. Indeed, the correlation between oxygen uptake and vertical acceleration has been reported to be weaker in the elderly than in young participants during treadmill walking (Nichols et al. 1992). The higher lateral acceleration of the elderly in our study agrees with these previous studies, and the underestimation of TEE_{ACCuni} in the elderly might be attributable to the kinetic and kinematic differences in locomotion between elderly and young participants.

Several studies of young adults and children have compared uniaxial and triaxial accelerometers simultaneously (Bouten et al. 1996; Chen and Sun 1997; Eston et al. 1998; Kumahara et al. 2004b; Plasqui et al. 2005; Tanaka et al. 2007a, b). ACCuni underestimated the energy expenditure during high-speed running, sports, and vigorous activities (Eston et al. 1998; Touno et al. 2003; Trost et al. 2006), which has been given as the primary reason for ACCuni underestimating TEE in children or active adults. In contrast, the duration of the vigorous activities did not differ significantly between ACCuni and ACCtri in our study. The underestimated intensity of vigorous activities with ACCuni might not markedly affect the estimated TEE in this population. However, note that typical accelerometers cannot assess several vigorous activities accurately, such as vigorous bicycling, swimming, and hill climbing.

Accelerometers measure body movement and the estimated energy expenditure. Therefore, RMR must be measured to calculate TEE. However, the measurement of RMR is time-consuming and not suitable for a large-scale survey. We demonstrated that the predicted BMR was highly correlated with the measured RMR and the regression line agreed with the line of identity. The accuracy and precision for estimating TEE did not differ between the measured RMR and predicted BMR, implying that TEE can be assessed using ACCtri with the predicted BMR in this population.

In this study, no significant correlation was observed between age, physical characteristics, or body composition and the residual of TEE_{DLW} and TEE estimated using accelerometers. Plasqui et al. (2005) indicated that the multiple regression analysis with age, physical characteristics, and body compositions was improved by the estimation of TEE by ACCtri (Plasqui et al. 2005). In contrast, Brage et al. (2007) reported that none of the routinely available variables (age, gender, and height) contributed significantly to estimating the physical activity intensity with the accelerometer. This difference between the studies may be due to the study population, i.e., the range of age and fatness, or the calculation equation of the accelerometers.

The range of the limit of agreement between TEE_{DLW} and TEE_{ACCtri} (3.36 MJ day^{-1}) was small in comparison with previous studies (Table 4, TEE). The range of the limit of agreement between $PAEE_{DLW}$ and $PAEE_{ACCtri}$ (3.03 MJ day^{-1}) was also small in comparison with previous studies (Table 4, PAEE). However, it is still too large for an accurate estimation at the individual level. Recently, several researchers developed a complex accelerometer algorithm for estimating the energy expenditure of various activities more accurately (Chen and Sun 1997; Westerterp 1999; Crouter et al. 2006a, b; Rothney et al. 2007; Tanaka et al. 2007a, b). Furthermore, it might be necessary to calibrate an accelerometer individually for more accurate estimations (Chen and Sun 1997; Ekelund et al. 2003). However, this would complicate our data analysis, so we just used the single regression models obtained in previous studies without individual calibration. Further research is needed to improve the estimation of TEE and PAEE at the individual level.

In addition, several differences exist between the two accelerometers. The ACCuni acceleration data were rounded down every 4 s for nine grades, while the ACCtri acceleration data were not rounded down. The properties of their filters for accelerations are different. We could not clarify how these differences affect the results and further research into this is needed.

In conclusion, based on a comparison with the DLW method, ACCtri has more accuracy and precision than ACCuni for estimating the daily TEE and PAEE in the elderly. This study indicated plausible reasons for this finding, including the underestimated intensities of light activities with ACCuni and the difference in the mediolateral acceleration during locomotion between the elderly and young adults. The partial correlation between TEE_{DLW} and TEE_{ACCtri}, but not TEE_{ACCuni}, was still significant after adjusting for gender, age, weight, height, and percent body fat. The output of ACCtri contributed significantly to estimating TEE independent of those physical characteristics. The results suggest that ACCtri is more valid for estimating the energy expenditure in the elderly population.

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連載

運動・身体活動と公衆衛生(1)
「公衆衛生分野において運動・身体活動をどう考えるか」

武庫川女子大学生活環境学部食物栄養学科　**内藤義彦**

新しい連載を担当するに当たり，序論として，「運動・身体活動と公衆衛生」というテーマを設けた背景と今後の連載で採り上げてみたい話題および論点について簡単に触れておきます。

1.　背景と抱負

最初に指摘しておきたいのは，運動・身体活動に関する話題が，今日の公衆衛生分野において注目度が高くかつ重要な意味を持つということである。過去を振り返ってみれば，日常的な身体活動量の減少傾向は直感的には明らかであり，今後も自らが意識していないと不足状態に陥りがちな環境に置かれている人が多いと考えられる（身体活動に限らず個人の生活習慣は自己決定というよりは日々のライフスタイルの中で形成され，漸次無意識化していく）。それがため，近年，身体活動の不足が関与する疾病が増加し，公衆衛生上の大きな問題になってきている。それに警鐘を鳴らすかのように，古くは hypokinetic diseases，最近は sedentary death syndrome というような用語がシンボリックに造られてきた。そして，その延長線上にある病態として metabolic syndrome が最近の大きな話題となっており，公の対策キャンペーンでも「1に運動，2に食事……」のごとく運動・身体活動が強調されている。このような流れの中で，公衆衛生活動に関連した運動・身体活動に関する国民へのメッセージとして「健康日本21」および「エクササイズガイド」が国から示されている。

このような背景をもとに，現時点での運動・身体活動に関する公衆衛生学上の到達点を明らかにし，今後の課題について論じることは公衆衛生学雑誌の読者にとって有意義と考えられる。そこで，本連載では身体活動に関する公衆衛生学に関連した研究や実践活動・理論に詳しい専門家が分担し，そのエッセンスについて話題提供をしてもらう予定である。

2.　公衆衛生分野において身体活動をどう扱うか

要は身体活動に関連する概念や情報をどう整理し，多くの対象にどう活用していくかという問題である（身体活動は，身体活動量 physical activity とフィジカルフィットネス physical fitness の二つの観点で論じられる場合が多いが，本稿では前者を中心にした）。

上述したように，巷間では身体活動量の不足が問題視されているが，科学的根拠を踏まえた議論がなされているとは必ずしもいいがたい。そこで，疫学や公衆衛生学の視点に立って試みに論点をいくつか列挙してみた。

1)　身体活動量の評価方法の開発

身体活動とは骨格筋が収縮・弛緩すること，あるいはそのことによる一連の活動（行動）であり，身体活動量とは身体活動によって消費するエネルギー量との定義があるが，理論的な定義と実際の評価との間には乖離がある。呼気分析や二重標識水（DLW）を用いた厳密で定量的な評価値がゴールドスタンダードであるといっても，これらも本来の定義とは異なったものを評価していることに留意しなければならない。煎じ詰めれば，身体活動量を厳密に測定することは現実的には不可能であり，余分なものを評価したり，間接的指標や代替指標で評価しているに過ぎない。とはいえ，何らかの指標がないと評価することや比較することもできなくなるので，不完全ながらも使用目的に合わせた様々な身体活動量の指標が存在する。また，最近の研究テーマとしては，身体活動量が多様な側面（有酸素運動，レジスタンス運動，柔軟運動などの種類，運動強度の分布，活動内容など）から議論されるようになってきた。公衆衛生の現場のニーズとしては，健康診断や診療の場で導入しやすく，より簡便かつ経済的で妥当性の高い手段，例えば質問紙や歩数計のような計測機器などの検討が有益と考えられる。

2)　身体活動量による様々な健康事象に対する影響（効果）の解明

身体活動量の不足による影響が議論の中心になっているが，過多による悪影響の有無や付加運動として処方（介入）する場合のリスクの問題も確認しておく必要がある。また，身体活動量の総量または一定強度以上の活動時間などの身体活動量よりも不活動の時間（いかに動いているかよりもいかに動いていないか）を重視する意見もある。また，短期的影

響と長期的影響を区別して議論する必要があるだろう。ここで議論のキーとなる指標は相対危険（リスク比）になろう。

3）　母集団全体における身体活動量の分布（過不足する人の割合）の検討

時代の趨勢は身体活動量の低下方向に向かっているが，個別的には依然として身体活動量が多いサブグループがいる可能性に留意すべきだろう。いずれにせよ，分布を知ることにより集団全体における身体活動量の影響を定量的に議論することが可能になる。当初は観察研究に基づくことになるが，身体活動量レベルと疾病の有病率または罹患率の関連から，介入の必要性の議論や介入による効果の期待値の概算が可能になると考えられる。なお，議論のキーとなる指標は寄与危険（リスク差）になろう。

4）　身体活動量の過不足の改善方法の確立

正に，現在最も注目されている保健指導の領域であり，判定された問題点をどう解決していくかが大きな課題である。問題点が分かることと行動を変えることは別である。行動変容を促すには，個別的な指導手法の確立だけでなく個人を取り巻く環境全体を変えることも考慮すべきだろう。指導方法を確立するためにエビデンスレベルの高い介入研究が必要になるが，無作為化比較対照試験（RCT）であったとしても，多くの場合，研究対象の一般住民に対する代表性が保証されないので，これらの結果を広く適用する場合には注意を要する。実際の運用面では，対象集団の特性に合わせた調整（テイラーメイド化）が必要になる可能性がある。

5）　身体活動と健康・病気との関連に影響を及ぼす要因や条件の解明

運動処方における有効限界・安全限界の考え方からも示唆されるように，他の生活習慣介入よりもリスク管理への配慮が求められることが多い。どの曝露要因もそうだが，性や年齢（ライフステージ），人種，疾病の有無など対象集団の特性（交絡要因）の違いにより影響が異なる可能性を考慮する必要がある。また，長期的な身体活動量と疾病の関連だけでなく，指導による急激な身体活動量の増加におけるリスク管理も必須である。

6）　身体活動に関する政策の立案

個別的な身体活動に関する指導や支援は行動科学を活用して効果を上げる工夫がなされている。一方で，ライフスタイルは生活の中で形成されるものであり，その意味では政策が個々人のライフスタイルに広く深く影響しうる。運動指導を行うスタッフの資格，指導内容，運動指導に対する報酬，運動施設などハード面の整備，学校教育における体育への提言，生涯スポーツの再構築，地域スポーツクラブの奨励，健康日本21や運動指針などの啓発事業など，様々な場面・レベルで影響が効果ができる課題があり，海外の事例も参考になると考えられる。

7）　身体活動とスポーツとの接点の活用

スポーツには，自らの問題とは離れて多くの人々が関心を抱く。アスリートは憧憬の的であり，強い影響を受け運動に励む人々もおれば，自分には無理と単に崇めるだけという人々もいる。アスリートになるための体力・トレーニングと健康とは必ずしも一致しない。しかし，人気の高いスポーツに運動への親近感を持たすことができれば，広く国民に身体活動量の確保を意識付けることができるかもしれない。また，マスコミが煽る面もあるがその人気により，今や文化のみならず政治・経済にも影響を及ぼしている。このポテンシャルは公衆衛生上注目すべき現象と考えられる。

8）　ライフステージのよる身体活動の意義

生活習慣の基礎が形成される乳幼児期から，児童期，思春期，青年期，壮年期，そして歩んできた人生を振り返る老年期まで，各ステージにおける健康目標と身体活動の持つ意義を明確にし，ニーズに合った指導や対策を検討するべきであろう。若い世代では体力向上や記録更新などに関心が強く，青・壮年期では仕事や家事の負担にならないこと，老年期は体力維持，介護予防のための運動・身体活動に関心を示すのではないだろうか。また，各ステージにおける身体活動量の評価方法も異なり，目的に合わせた身体活動評価の視点の変更が必要になる。例えば，小児期の身体活動量の評価には，質問紙の回答を得るのが困難なので，観察または加速度センサーなどを用いた評価方法が有望になる。

9）　運動に関する科学的根拠の重視

運動・身体活動への関心が高まりつつあるにも関わらず，わが国では科学的根拠に基づく情報の整理がまだ不十分である。我が国における身体活動に関する疫学研究のレベルアップと研究者の養成を目的に，運動・身体活動研究者と医学・公衆衛生学・疫学などの研究者の接点となるべく，国内の研究者の集まりとして運動疫学研究会（現会長：荒尾　孝）が平成10年に設立された。規模は未だ小さいが，その趣旨は今後のニーズに合致していると考えられる。

以上，公衆衛生分野における身体活動の意義を考えるためのガイダンスのような拙文を思いに任せて記してみました。今後はテーマを絞った話題提供を予定しています。次回は，運動疫学の現状について，早稲田大学の荒尾　孝先生にご報告いただく予定です。