The use of uniaxial accelerometry for the assessment of physical-activity-related energy expenditure: a validation study against whole-body indirect calorimetry

Hideaki Kumahara1,2, Yves Schutz1*, Makoto Ayabe2, Mayumi Yoshioka3, Yutaka Yoshitake4, Munehiro Shindo5, Kojiro Ishii6 and Hiroaki Tanaka5

1 Institute of Physiology, Faculty of Medicine, University of Lausanne, Lausanne, Switzerland
2 Laboratory of Human Performance and Fitness, Graduate School of Education, Hokkaido University, Sapporo, Hokkaido, Japan
3 Molecular Endocrinology and Oncology Research Center, Laval University Medical Center and Laval University, Quebec, Canada
4 Department for Interdisciplinary Studies of Lifelong Sport and Physical Activity, National Institute of Fitness and Sports in Kanoya, Kanoya, Kagoshima, Japan
5 Laboratory of Exercise Physiology, Faculty of Sports and Health Science, Fukuoka University, Fukuoka, Japan

Assessing the total energy expenditure (TEE) and the levels of physical activity in free-living conditions with non-invasive techniques remains a challenge. The purpose of the present study was to investigate the accuracy of a new uniaxial accelerometer for assessing TEE and physical-activity-related energy expenditure (PAEE) over a 24 h period in a respiratory chamber, and to establish activity levels based on the accelerometry ranges corresponding to the operationally defined metabolic equivalent (MET) categories. In study 1, measurement of the 24 h energy expenditure of seventy-nine Japanese subjects (40 (SD 12) years old) was performed in a large respiratory chamber. During the measurements, the subjects wore a uniaxial accelerometer (Lifecorder; Suzuken Co. Ltd, Nagoya, Japan) on their belt. Two moderate walking exercises of 30 min each were performed on a horizontal treadmill. In study 2, ten male subjects walked at six different speeds and ran at three different speeds on a treadmill for 4 min, with the same accelerometer. 

The energy expenditure (EE) associated with physical activity has a negative relationship with the prevalence of obesity and its related diseases (i.e. diabetes, hypertension, CVD etc.), and it plays a major role in the prevention and treatment of these diseases (Weinsier et al. 1998; Levine et al. 1999; Ravussin & Bogardus, 2000). When treatment strategies, including nutritional education, for those diseases are developed, quantitative information related to physical activity is required to provide more effective goals. Hence, information on physical activity is considered to be useful, not only for researchers and healthcare workers, but also for the general public, in order to prevent and treat these diseases more effectively.

Activity monitoring based on an accelerometry sensor is one of the useful methods for obtaining objective information on physical activity patterns and for estimation

**Abbreviations:** EE, energy expenditure; MET, metabolic equivalent; PAEE, physical-activity-related energy expenditure; PAEE_{Acc}, physical-activity-related energy expenditure estimated by the accelerometer; PAEE_{Acc-excl.TEF}, physical-activity-related energy expenditure estimated by the accelerometer excluding thermic effect of food; PAEE_{Chamber}, physical-activity-related energy expenditure measured by the respiratory chamber; PAEE_{Chamber-excl.TEF}, physical-activity-related energy expenditure measured by the respiratory chamber excluding thermic effect of food; SEE, standard error of the estimate; TEE, total energy expenditure; TEE_{Acc}, total energy expenditure estimated by an accelerometer; TEE_{Chamber}, total energy expenditure measured by the chamber; TEF, thermic effect of food.

* Corresponding author: Dr Yves Schutz, fax +41 21 692 55 95, email Yves.Schutz@iphysiol.unil.ch
of the related EE (Schutz et al. 2001; Ebina et al. 2002), since it can continuously measure the intensity, duration and frequency of activities. Previous activity monitors (Bouten et al. 1994; Freedson et al. 1998) have been designed to detect accelerations due to body movements, such as walking and running. However, the EE associated with certain movements (upper body) are not adequately assessed, especially when slow or small erratic movements were performed when sedentary and during very low levels of activity (Bouten et al. 1994; Nichols et al. 1999). One possible cause is a calculation algorithm that may have inherent limitations, since the equation was derived from regression equations of acceleration vs. EE during structured activities such as walking and running (Bouten et al. 1994; Fehling et al. 1999). Previous studies (Bray et al. 1994; Chen & Sun, 1997) indicated that EE was underestimated by most devices in comparison with respiratory chamber values, because of the difficulty in evaluating sedentary activities. Since running and walking activities constitute major movements in man, as do sedentary and low-intensity activities (Bouten et al. 1996; Meijer et al. 2001), EE should be accurately assessed under volitional activity (structured exercise) as well as under involuntary activity (non-structured activity) to evaluate the total EE (TEE) in free-living conditions.

Recently, an activity monitor based on a uniaxial accelerometry sensor was made commercially available (Lifecorder; Suzuken Co. Ltd, Nagoya, Japan). This activity monitor is based on a previous activity monitor developed by the same company (Kenz-accelerometer; Suzuken Co. Ltd) (Yamada & Baba, 1990; Bassett et al. 2000). Although both devices adopt quite similar accelerometric sensors and algorithms for calculating EE, the new device is superior for several reasons. It is small (0.062 × 0.046 × 0.026 m, 40 g) and the external plastic cover makes the unit very rugged. Data, including total EE, total step frequencies and raw data based on accelerometry, can be stored for 6 weeks. The data can be downloaded via a personal computer, and then a summary report can be generated. An internal real-time clock also helps to discriminate activity patterns. It is also noteworthy that the device has a unique algorithm for assessment of EE, especially non-structured activities (described later). In studies using the older device (Kenz-accelerometer; Suzuken Co. Ltd), Yamada & Baba (1990) reported that the device assessed EE during running and walking well when compared with indirect calorimetry, and it also effectively measured EE in free-living conditions when compared with physical activity recall (Suzuki et al. 1997). To further expand the benefits of this device and to use it to quantify energy EE in free-living conditions, the new device needs to be validated against indirect calorimetry.

The respiratory chamber is a precise and accurate method for quantifying daily EE under controlled conditions, during which free-living activities can be mimicked (i.e. walking on the treadmill; Jequier & Schutz, 1983). The primary purpose of the present study was to investigate the accuracy of the activity monitor for the assessment of EE over 24 h in a respiratory chamber. Epidemiological studies showing the relationship between physical activity and obesity often categorize activities into metabolic equivalent (MET) intensities, i.e. classifying it to light (<3.0 MET), moderate (3.0–6.0 MET) and vigorous (>6.0 MET) intensity activity (Pate et al. 1995). A secondary purpose of the present study was to develop and categorize the various activities based on accelerometry into corresponding EE levels expressed as MET.

Methods

Subjects

In study 1, twenty-eight healthy Japanese males and fifty-one healthy Japanese female subjects (18–64 years old) participated in this study. Eighty-five percent of the subjects had been living in Switzerland for >6 months and the others were considered to be tourists. The latter group were all asked to maintain their normal diet. The effect of jet lag was minimized since the measurements were performed 2–13 d after moving to Europe. Ten Japanese healthy males subjects (21–32 years old) who live in Japan participated in study 2.

The study protocol was approved by the Ethical Committee of the University of Lausanne. After the experiment was explained, each subject signed an informed consent statement.

Study design and variables

Study 1: experiment in the respiratory chamber. In order to investigate the validity of the assessment of daily EE using an activity monitor based on a uniaxial accelerometry sensor (Lifecorder; Suzuken Co. Ltd), the following study was performed. The subjects stayed in a large respiratory chamber for 24 h (floor surface area 13 m², volume 31 m³). The physical activity was not restrained but it was spontaneous, excluding the two prescribed walking exercises on the horizontal treadmill (3.9 and 5.1 km/h, 30 min each). However, access to the treadmill was not permitted except during the imposed walking session. The habitual daily activities in the chamber included watching television, reading, deskwork, going to the toilet and washing, hobby-like activities and walking around. The activity monitor was rigidly fixed on the belt around. The activity monitor was rigidly fixed on the belt during the daytime (for 16 h). The sleeping period was controlled (for 8 h), and the sleeping metabolic rate was averaged when sleeping over a 6 h interval, with confirmation of no physical activity by Doppler radar (Schutz et al. 1982).

Both O₂ consumption and CO₂ production were measured, and EE was then calculated. The configuration of the chamber and the method of gas analysis have been described by Jequier & Schutz (1983). The subjects ingested three standard experimental meals (breakfast, lunch and dinner). The energy intake (8399 ± 1266 kJ/d) was not significantly different from the daily EE measured by the respiratory chamber (TEEchamber). The % body fat was assessed by a skinfold thickness method and an independent bioelectrical impedance method. The body density was estimated from the sum of triceps and subscapular skinfold thicknesses and a Japanese formula (Nagamine & Suzuki, 1964), and the
% body fat was then calculated using the equation of Brozek et al. (1963). A handle (arm-to-arm) type device (model 
HBF-302; Omron Hatsusaka Co. Ltd, Tokyo, Japan) was 
used as the impedance method. This device displays the % 
body fat from personal data (i.e. age, height and weight) 
and bioelectrical impedance. The skinfold thickness and % 
body fat were averaged and reported in the results section. 
In a subsample of fifty-nine subjects, the body composition 
estimate was compared with the air-displacement 
plethysmography method (BodPod®; Life Measurement 
Instruments, Concord, CA, USA) (Fields et al. 2002) and 
there was a strong correlation (r = 0.89, P < 0.001).

Study 2: experiment using a motorized treadmill. Study 2 
was performed in order to determine a more precise 
relationship between the accelerometry output measured 
by the activity monitor and EE during ambulatory physical 
activities. The subjects performed 4 min of each of the 
following exercise conditions using a motor-driven treadmill: 
walking at 2·4, 3·3, 4·2, 5·1, 6·0 and 6·9 km/h, and running 
at 7·8, 8·7 and 9·6 km/h (the slope was horizontal). Each 
grade condition was separated by a 2 min rest period.

\[ V_0 \] was measured during the last minute of each steady-
state condition from the mixed expired gases collected by 
the Douglas bag method using a mouthpiece and a nose-
clip. The volume of expired air was quantified with a 
twin-drum-type respirometer (CR-20; Fukuda Irika, 
Tokyo, Japan), and both the \( O_2 \) and \( CO_2 \) concentrations 
were analysed using MS (Arco; Arco System, Tokyo, 
Japan). The analyser was calibrated before the test using 
verified gases of known concentration. MET were calcu-
lated by dividing the steady-state \( V_0 \) by 3·5 ml/kg per 
min (equivalent to 1·0 MET), since, in contrast to study 
1, RMR could not be measured.

Accelerometer features

The activity monitor measures acceleration in the vertical 
(\( z \)) direction. According to technical details provided by 
the manufacturer (Suzken Co. Ltd), it samples the accelera-
tion at 32 Hz and assesses values ranging from 0·06 to 
1·94 \( g \) (1·00 \( g \) is equal to the acceleration of free fall). 
The acceleration signal is filtered by an analogue bandpass 
filter and digitized. A maximum pulse over 4 s is taken as 
the acceleration value, and the activities are categorized 
into eleven activity levels (0·0, 0·5, and 1·0–9·0; level 
0·0 corresponds to < 0·06 \( g \)) based on the pattern of the 
accelerometric signal. The activity levels are subsequently 
converted by an algorithm to calculate EE (kcal) based on 
the following principle: when the sensor detects three 
acceleration pulses or more for four consecutive seconds, 
the activities are recognized as physical activity, and then 
categorized into one of nine activity levels (levels 
1·0–9·0). EE due to these activities (EE\(_{Act} \)) are calculated 
and counted every 4 s, using body weight (W) and a factor 
\( Ka \) which depends upon the activity level:

\[
EE_{Act}(\text{kcal}) = Ka \times W \text{ (kg)}.
\]  
The factor \( Ka \) is not provided here, since it is the proprie-
tary information of the manufacturer and is therefore 
confidential.

If an acceleration pulse due to physical activity (i.e. cor-
responding to the activity levels 1·0–9·0) is not immedi-
ately succeeded by another acceleration pulse, then it is 
not counted as 0·0 but a level of 0·5 is arbitrarily ascribed 
for 3 min. It is assumed that the subject is standing up and 
maintaining that state (or sitting down). The latter posture 
voyles a higher EE than resting supine position. In brief, 
isolated spurts of acceleration are assumed to be due to 
acute changes in posture (lying down, sitting and standing), 
since walking and moving around are typically rhythmical 
activities. EE due to very small trunk movements and pos-
ture effect (EE\(_{\text{minorAct}} \), i.e. sitting to standing-up position, 
light desk-work etc.) are calculated from the BMR multiple 
by a constant \( Kx \):

\[
EE_{\text{minorAct}}(\text{kcal}) = Kx \times \text{BMR}.
\]  
The value of the constant \( Kx \) is not given here, since it is 
considered to be confidential by the manufacturer.

The TEE assessed by the device (TEE\(_{Act} \)) is 
calculated from the sum of BMR, thermic effect of food 
(TEF = (1/10)TEE), EE\(_{Act} \) and EE\(_{\text{minorAct}} \):

\[
\text{TEE}_{\text{Act}} = \text{BMR} + (1/10)\text{TEE}_\text{Act} + \text{EE}_{\text{Act}} + \text{EE}_{\text{minorAct}}.
\]  
The BMR is calculated from body weight (W), height (H), 
sex and age using a standard Japanese formula 
(Health Promotion and Nutrition Division, Health Service 
Bureau, Ministry of Health and Welfare, 1996) as follows:

\[
\text{BMR} \text{(kcal)} = K_b \times \text{BSA} \times T \times (1/10000),
\]  
where \( K_b \) is the standard Japanese value which corresponds 
to age (kcal/m\(^2\) per h) (Health Promotion and Nutrition 
Division, Health Service Bureau, Ministry of Health and 
Welfare, 1996), T is time (h) and BSA is body surface 
area (cm\(^2\)) estimated using a Japanese formula (Fujimoto 
et al. 1968).

\[
\text{BSA} \text{(cm}^2\text{)} = W^{0.444}(\text{kg}) \times H^{0.663}(\text{cm}) \times 88.83.
\]

Data analysis and statistics

In study 1, the activity levels of the accelerometer were 
determined over 4 s, and the value was then averaged 
over 15 min. The EE values derived from both the acceler-
ometer and the respiratory chamber expressed as kcal were 
converted into kJ using the standard conversion factor, i.e. 
1·000 kcal = 4·184 kJ. The measured EE was normalized 
for body weight (kJ/kg per h), and also was expressed as 
measured EE/measured sleeping metabolic rate (i.e. physi-
cal measured activity ratio).

Physical-activity-related EE (PAEE) measured by the 
respiratory chamber either including or excluding TEF 
(PAEE\(_{\text{Chamber incl.TEF}} \) and PAEE\(_{\text{Chamber-excl.TEF}} \) respectively) and 
that obtained by the activity monitor (PAEE\(_{\text{Act}} \) and PAEE\(_{\text{Act-excl.TEF}} \) respectively) were calculated using the 
following formulas:

\[
\text{PAEE}_{\text{Act}} = \text{TEE}_{\text{Act}} - \text{calculated BMR by the algorithm} 
(\text{see equation 3})
and

$$\text{PAEE}_{\text{Chamber}} = \text{TEE}_{\text{Chamber}} - \text{measured sleeping metabolic rate.}$$

A comparison between the values from these formulas was performed supposing that TEF calculated by the algorithm ((1/10)TEE$_{\text{Acc}}$) accurately assessed the true value:

$$\text{PAEE}_{\text{Acc-excl TEF}} = \text{TEE}_{\text{Acc}} - \text{(calculated BMR by the algorithm + TEF as (1/10)TEE}_{\text{Acc}})$$

(see equation 3)

and

$$\text{PAEE}_{\text{Chamber-excl TEF}} = \text{TEE}_{\text{Chamber}} - \text{(measured sleeping metabolic rate + TEF).}$$

In order to obtain a valid comparison of PAEE among methods, the TEF was calculated using an approach similar to that used for the accelerometer algorithm, i.e. 10% total energy intake. Since the subjects were close to similar to that used for the accelerometer algorithm, i.e. methods, the TEF was calculated using an approach performed supposing that TEF calculated by the algorithm was still found ($P$=0.423; SEE 503 kJ/d) with the measured value. However, there was a highly significant correlation between both ($r$=0.564; $P$<0.001, see 503 kJ/d) (Fig. 1). PAEE$_{\text{Acc}}$ was also significantly lower than TEE$_{\text{Chamber}}$ ($r$=0.38; 95% CI −1.13 (P<0.001); i.e. 92.7 (SD 17.8)% PAEE$_{\text{Chamber}}$), yet there was a significant correlation between both ($r$=0.564; $P$<0.001, see 446 kJ/d) (Fig. 2). Moreover, the differences between the measured and the estimated values were normally distributed (Figs. 1 and 2). When PAEE was calculated taking the TEF into account, it remained significantly lower when using the accelerometer ($r$=0.611–0.956). Fig. 3 shows the relationship between the activity levels and the measured EE of the pooled subjects (n 79) over the daytime. A highly significant correlation was still found ($r$=0.439; $P$<0.001, see 431 kJ/d) with the measured value.

The individual correlations between the activity levels estimated by the accelerometer were measured EE (averaged over 15 min periods in the daytime) were significant ($r$=0.611–0.956). Fig. 3 shows the relationship between the activity levels and the measured EE of the pooled subjects (n 79) over the daytime. A highly significant relationship was seen between both measurements, not only including the walking periods (r 0.808; $P$<0.001, see 1.780 kJ/kg per h), but also when obligatory walking was excluded ($r$=0.477; $P$<0.001, see 1.684 kJ/kg per h). The regression equation was based on all activities (during the daytime) as follows:

$$\text{EE (kJ/kg per h)} = 2.659x + 5.33,$$

### Results

The physical characteristics of the subjects of study 1 and 2 are shown in Table 1.

#### Table 1. Physical characteristics of the Japanese subjects* (Mean values and standard deviations)

<table>
<thead>
<tr>
<th>Study 1</th>
<th>Study 2</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Total (n 79)</td>
</tr>
<tr>
<td></td>
<td>Mean (SD)</td>
</tr>
<tr>
<td>Age (years)</td>
<td>39.7 (12.4)</td>
</tr>
<tr>
<td>Height (m)</td>
<td>1.628 (0.081)</td>
</tr>
<tr>
<td>Weight (kg)</td>
<td>58.8 (11.9)</td>
</tr>
<tr>
<td>BMI (kg/m²)</td>
<td>22.0 (3.2)</td>
</tr>
<tr>
<td>Fat (%)</td>
<td>23.5 (8.5)</td>
</tr>
</tbody>
</table>

* For details of procedures, see p. 236.
EE (kcal/kg per h) = 0.636x + 1.27,

where x is the activity level (range of score 0.5–9.0). Similarly, when measured EE was expressed as the physical activity ratio there was a highly significant relationship between the ratio and the activity levels ($r^2 = 0.801$, SEE 0.440), and the following regression equation was developed:

physical activity ratio = 0.640x + 1.27,

where x is the activity level.

Treadmill exercise

Since a one-way ANOVA ($9 \times 10$, $P<0.001$) revealed a significant speed effect on MET ($P<0.001$) and on the activity levels ($P<0.001$), Scheffe’s F post hoc analysis was performed to determine the presence of any significant differences. The mean values and standard errors of MET and activity levels measured by the activity monitor for each speed are presented in Fig. 4. MET between 2.4 and 3.3 km/h and between 3.3 and 4.2 km/h were not significantly different. However, there was a significant difference at 4.2–9.6 km/h. On the other hand, the activity level was significantly different at 2.4–7.8 km/h, while it was not significantly different at >7.8 km/h. Fig. 5 shows the relationship between the activity levels and MET. The quadratic equation regression ($r^2 = 0.928$, $P<0.001$, standard error of the estimate 503 kJ/d) was calculated at a speed $\leq 7.8$ km/h, since

or expressed in kcal:

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physical activity ratio = 0.640x + 1.27,

where x is the activity level.
the activity level did not follow the energy expenditure over this velocity. The equation was as follows:

\[ \text{MET} = 0.043x^2 + 0.379x + 1.361, \]

where \( x \) is the activity level. The estimated MET from the recorded activity level was calculated by the equation, then categorized into one of three activity level defined as light (<3.0 MET), moderate (3.0–6.0 MET) and vigorous (>6.0 MET) activity (Table 2).

**Discussion**

**Validity of assessment of energy expenditure measured using the accelerometer**

The present study showed that TEE\textsubscript{Acc} was significantly underestimated by a mean value of 8%. However, a highly significant relationship was demonstrated between TEE\textsubscript{Acc} and the measured values in the chamber as shown in Fig. 1. In addition, the inter-individual variability of the relative error showed small deviation: the CV was 5.9%. These results indicated that inter-individual differences in TEE can be assessed well by the accelerometer. It was considered that the cause of the underestimation of TEE may partly stem from underestimation of basal EE, though the formula used was intended for Japanese individuals, so that ethnic differences are not the cause for such a difference: the predicted basal EE was found to be underestimated by 7 (SD 9) % (464 (SD 539) kJ/d) as compared with the measured sleeping metabolic rate, and this error contributed 66 % of the total error involved over 24 h. We tried to apply several basal EE prediction equations replacing that used by the accelerometer algorithm: those of Harris & Benedict (1919) and of the Food and Agriculture Organization/World Health Organization/United Nations University (1985). The two formulas gave more accurate results than the value obtained with the accelerometer algorithm: the recalculated TEE values averaged 96.5 (SD 6.3) and 98.0 (SD 5.8) % of the measured value respectively. The net improvements in the accuracy of estimation were therefore 4.6 and 6.0 %, although the values were still significantly lower than the measured ones. Note that the mean basal EE with these two formulas were not significantly different from measured sleeping metabolic rate. The tables of Fleisch (1951) and of Robertson & Reid (1952) classically used in the UK were also employed to recalculate basal EE. The body surface area estimation was based on a Japanese formula (Fujimoto et al. 1968). The two basal EE calculated still underestimated the measured sleeping metabolic rate: the estimated TEE values did not improve and represented 94.0 (SD 5.4) and 91.4 (SD 5.5) % true TEE value, using the Fleisch (1951) and the Robertson & Reid (1952) tables respectively. In addition, when the body surface area was based on the classical Du Bois & Du Bois (1916) formula,
estimated TEE averaged 96·1 (SD 6·0) and 93·1 (SD 5·6) % true value respectively. Note that the % body fat of a subgroup of Japanese subjects (n 22) was the same as a white group strictly matched for gender, age, height and weight (H Kumahara, H Tanaka and Y Schutz, unpublished results).

On the other hand, PAEE_{Acc} was also significantly underestimated compared with the measured value, accounting for 34 % of the total difference in TEE. When PAEE was calculated, taking into account the TEF (i.e. PAEE_{Chamber-excl.TEF} v. PAEE_{Acc-excl.TEF}), it remained significantly underestimated.

Previous studies found that TEE was also significantly underestimated by 13 % using uniaxial accelerometers (Caltrac; Hemokinetics Inc., Madison, WI, USA) (Bray et al. 1994) and by 17 % using a triaxial accelerometer (Trirac-R3D; Hemokinetics Inc.) (Chen & Sun, 1997), but the physical activity included use of a stationary bicycle, which is not sensed by accelerometry, compared with measured TEE in a respiratory chamber. Basal EE was overestimated by 7–9 %. Most of the previously commercially available activity monitors have difficulty in detecting small changes in EE due to sedentary and low-intensity activities since the device output is not proportional to the increase in EE (Bouten et al. 1994). Consequently, EE is largely underestimated by such accelerometers, since PAEE measured within the confinement of a respiratory chamber was restricted to relatively sedentary activities. Moreover, since low-level activity (i.e. <3 MET) accounts for 65–82 % total daily activity in free-living conditions (Meijer et al. 2001), EE due to spontaneous activity should be also fully assessed in order to accurately evaluate TEE in free-living conditions. In our present study, the activity levels measured by the activity monitor showed a highly significant correlation with the measured EE, not only during the active part of the day (r 0·807; P<0·001), but also during sedentary activities, when walking periods were excluded (r 0·477; P<0·001).

The SEE calculated from these relationships were 1·784 kJ (0·426 kcal)/kg per h (i.e. 0·43 MET) during the active part of the day and 1·684 kJ (0·402 kcal)/kg per h (i.e. 0·40 MET) during sedentary activities, giving a greater CV at lower activity levels. These absolute values were lower than those reported in previous studies (Meijer et al. 1989; Bouten et al. 1994; Freedson et al. 1998; Nichols et al. 1999) using a triaxial accelerometry sensor, even though in the present study the activities in the chamber were not strictly regimented activities as compared with previous structured ones (i.e. walking and running). Bouten et al. (1994) indicated that the integral of the acceleration in the three directions (antero-posterior, medio-lateral and vertical planes) is more valid than a uniaxial acceleration (only vertical plane) when sedentary movements are considered. Because each of the three acceleration directions contributes to EE, depending on the type of activity such as sitting, standing and walking, only uniaxial acceleration direction will fail to distinguish EE associated with the various types of small movements.

In the present study, the activity levels were calculated from the amplitude of accelerations and step frequency during a time period by means of the manufacturer’s algorithm (unknown). Consequently, it was supposed that the algorithm might work adequately to detect variations of EE. The calculation of EE due to small movements (corresponding to activity level 0·5) is obviously different from active movements such as walking (corresponding to activity levels 1·0–9·0): the EE due to small movements are calculated based on a physiological hypothesis (see equation 2) in contrast to that of active movements that are based on a biomechanical hypothesis (see equation 1). It therefore probably helps to distinguish different EE due to type of activity.

Some studies (Levine et al. 1999; Martinez-Gonzalez et al. 1999; Esparza et al. 2000) have indicated that the EE induced by very small movements (i.e. involuntary activity) may have an important relationship to lifestyle-related diseases. Therefore, an evaluation of physical activity on a long-term basis is required and is assessed not only for vocation-related activities (structured exercise), but also involuntary activities (non-structured activity) to prevent and to treat obesity and its related diseases.

Since the accelerometer could assess the PAEE well, the device is likely to detect not only ambulatory movements, but also spontaneous low-level activities.

Classification of the activity levels corresponding to intensity of metabolic equivalents

In the present study, we demonstrated that activity levels measured by the accelerometer increased in proportion to increase in MET for 2·4–7·8 km/h. However, no significant difference was observed for 7·8–9·6 km/h, despite the fact that MET directly increased in proportion to the speed, as shown in Fig. 4. It is interesting to note that all subjects started to run at 7·8 km/h. It is likely that the activity monitor can detect changes of the speeds during walking; however, this is less successful during running. Yamada & Baba (1990) also recognized that the activity levels failed to follow treadmill speeds accurately above 8·0 km/h. This result thus indicated that the acceleration in the vertical plane is not able to correctly estimate EE during running. One possible reason for this is that the accelerometry sensor of our device detects vertical acceleration due to body movement up to 1·94 g. In fact, the centre of gravity during running as measured by the accelerometry sensor attached to the waist readily exceeded the threshold of the present sensor (i.e. 1·94 g) (P. Terrier, personal communication). As a result, our sensor was unable to assess variations in acceleration due to changing running speed, because the magnitude of the acceleration during running may exceed the highest limit recorded by the accelerometer. Therefore, we must pay attention to the wide range of measurements regarding the acceleration signal as well as the accuracy of measurement of this variation. We need a device that can measure physical activities with a high accuracy from light to moderate intensities, since vigorous intensity activities (like running) constitute a small percentage of the total daily activity in the free-living population (Meijer et al. 2001).

Regarding the relationship between the activity levels assessed by accelerometry and MET during treadmill...
et al. in inability to detect external work as well as topographical to measure the intensity of physical activity. However, the useful objective tool for epidemiological studies designed corresponding to MET categories is considered to be a diminish the relative error. However, individual calibration applied to approximate the real value, but it would be conditions. The average group calibration factor found can be of the total daily physical activity and EE in free-living con-- (Lifecorder; Suzuken Co. Ltd) is useful for the assessment (Tracmor; Maastricht, The Netherlands) (Levine et al. 2001) reported that since the relationship for the group of subjects was not significant, individual regression equations are needed for each subject to determine EE based on the accelerometry output.

The MET values were calculated from the regression equation shown in Table 2. The data showed an obvious difference between the activity levels and this helped to distinguish different intensities of physical activity. It appears to be classified broadly into levels < 3.0, 4.0–6.0 and > 7.0, which corresponded to light (< 3.0 MET), moderate (3.0–6.0 MET) and vigorous (> 6.0 MET) intensity activity respectively. When the MET values were calculated from a regression equation derived from study 1 (Fig. 3) (i.e. calculated as 4.184 kJ (1 kcal)/kg per h equivalent to 1.0 MET), the values that corresponded to the activity levels for a range from 1.0 to 6.0, by step of one unit, were 1.9, 2.5, 3.2, 3.8, 4.4 and 5.1 MET respectively. Similarly, a regression equation for estimating the physical activity ratio (i.e. EE/sleeping metabolic rate) was developed in study 1. The calculated values corresponding to each activity level were almost identical. These values from study 1 are similar to the values in study 2. This information can be used to detect the difference in activity levels and objectively assess the duration and/or intensity levels in various physical activities. In addition, this device is useful for assessing the effect of lifestyle interventions related to physical activity and for providing clinical prescription for prevention and/or treatment of lifestyle-related diseases.

In conclusion, the findings of the present study suggest that our accelerometer based on uniaxial accelerometry (Lifeecorder; Suzuken Co. Ltd) is useful for the assessment of the total daily physical activity and EE in free-living conditions. The average group calibration factor found can be applied to approximate the real value, but it would be easier to improve the algorithm of the accelerometer to diminish the relative error. However, individual calibration factors may be still needed to provide more accurate estimation. Furthermore, the classification of activity levels corresponding to MET categories is considered to be a useful objective tool for epidemiological studies designed to measure the intensity of physical activity. However, the inability to detect external work as well as topographical transition (i.e. carrying a load or walking on a slope) (Bassett et al. 2000; Terrier et al. 2001) remains a limitation in the application of this technique in obtaining accurate results when the results are expressed in terms of EE.

Acknowledgements

We thank the participants for their cooperation and the following Japanese associations: The Japan Club of Geneva, The Swiss–Japanese journal Grü/ei and The Swiss Happy Net. We would also like to thank those who helped in the recruiting process of the subjects. We are grateful to assistant teacher Takuya Yahiro and the staff at the Laboratory of Exercise Physiology, Faculty of Sport and Health Science, Fukuoka University, for their assistance, as well as Philippe Terrier at the Institute of Physiology, Faculty of Medicine, University of Lausanne, for providing important advice. This research was supported by Medical Frontier Strategy Research grants H13-21th-31 from the Japanese Ministry of Health Labour and Welfare.

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