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

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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. The measurements, the subjects wore a uniaxial accelerometer (LifeCorex; 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. O₂ consumption was measured during the last minute of each stage and was expressed in MET. The measured TEE was 8447 (SD 1337) kJ/d. The accelerometer significantly underestimated TEE and PAEE (91·9 (SD 5·4) and 92·7 (SD 17·8) % chamber value respectively); however, there was a significant correlation between the two values (r 0·928 and 0·564 respectively; P < 0·001). Although TEE and PAEE were systematically underestimated during the 24 h period, the accelerometer assessed energy expenditure well during both the exercise period and the non-structured activities. Individual calibration factors may help to improve the accuracy of TEE estimation, but the average calibration factor for the group is probably sufficient for epidemiological research. This method is also important for assessing the diurnal profile of physical activity.

Accelerometer: Daily energy expenditure: Physical activity: Respiration chamber

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; PAEEChamber, physical-activity-related energy expenditure measured by the respiratory chamber; PAEE_Acc-excl.TEF, physical-activity-related energy expenditure estimated by the accelerometer excluding thermic effect of food; PAEEChamber-excl.TEF, physical-activity-related energy expenditure measured by the respiratory chamber excluding thermic effect of food; TEE, total energy expenditure; TEE_Acc, total energy expenditure estimated by an accelerometer; TEEChamber, total energy expenditure measured by the chamber; TEF, thermic effect of food.

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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 v. 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 (<30 MET), moderate (30–60 MET) and vigorous (>60 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 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 (SD 1266) kJ/d) was not significantly different from the 24 h 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.

V̇O₂ 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 plethysmography method (BodPod®; Life Measurement Instruments, Concord, CA, USA) (Fields et al. 2002). A handle (arm-to-arm) type device (model HBF-302; Omron Hatsusaka Co. Ltd, Tokyo, Japan), and both the O₂ and CO₂ concentrations were analysed using MS (Arco; Arco System, Tokyo, Japan). The analyser was calibrated before the test using a clip. The volume of expired air was quantified with a plethysmography method (BodPod®; Life Measurement Instruments, Concord, CA, USA) (Fields et al. 2002). A handle (arm-to-arm) type device (model HBF-302; Omron Hatsusaka Co. Ltd, Tokyo, Japan), and both the O₂ and CO₂ concentrations were analysed using MS (Arco; Arco System, Tokyo, Japan). The analyser was calibrated before the test using a clip. The volume of expired air was quantified with a plethysmography method (BodPod®; Life Measurement Instruments, Concord, CA, USA) (Fields et al. 2002).

The factor Kx which depends upon the activity level:

\[
EE_{\text{Act}}(\text{kcal}) = Kx \times W \quad (1)
\]

The factor Kx is not provided here, since it is the proprietary information of the manufacturer and is therefore confidential.

If an acceleration pulse due to physical activity (i.e. corresponding to the activity levels 1.0–9.0) is not immediately 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 involves a higher EE than resting supine position. In brief, isolated spurts of acceleration are assumed to be due to acute changes in posture (flying down, sitting and standing), since walking and moving around are typically rhythmic activities. EE due to very small trunk movements and posture effect (EEminorAct, i.e. sitting to standing-up position, light desk-work etc.) are calculated from the BMR multiple by a constant Kx:

\[
EE_{\text{minorAct}}(\text{kcal}) = Kx \times BMR. \quad (2)
\]

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 (TEEAct) is calculated from the sum of BMR, thermic effect of food (TEF = (1/10)TEE), EEAct and EEminorAct:

\[
TEE_{\text{Act}} = BMR + \left(\frac{1}{10}\right)\text{TEE} + EE_{\text{Act}} + EE_{\text{minorAct}}. \quad (3)
\]

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:

\[
BMR \quad (\text{kcal}) = K_b \times BSA \times T \times (1/10000),
\]

where K_b is the standard Japanese value which corresponds to age (kcal/m² 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 (cm²) estimated using a Japanese formula (Fujimoto et al. 1968).

\[
BSA \quad (\text{cm}^2) = W^{0.444} \times H^{0.663} \times \text{cm} \times 88.3.
\]

Data analysis and statistics

In study 1, the activity levels of the accelerometer were determined over 4s, and the value was then averaged over 15 min. The EE values derived from both the accelerometer and the respiratory chamber expressed as kcal were converted into kJ using the standard conversion factor, i.e. 1000 kcal = 4184 kJ. The measured EE was normalized for body weight (kJ/kg per h), and also was expressed as measured EE/standard metabolic rate (i.e. physical measured activity ratio).

Physical-activity-related EE (PAEE) measured by the respiratory chamber either including or excluding TEF (PAEEChamber and PAEEChamber-excl.TEF respectively) and that obtained by the activity monitor (PAEEAct and PAEEAct-excl.TEF respectively) were calculated using the following formulas:

\[
\text{PAEE}_{\text{Act}} = TEEP = \text{calculated } BMR \text{ by the algorithm (see equation 3)}
\]
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 \((1/10)\text{TEE}_{\text{Acc}}\) accurately assessed the true value:

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

(see equation 3)

and

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

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 (0·564; \(P<0·001\)), i.e. 91·9 (SD 5·4%) TEEChamber; however, there was a highly significant correlation between the two (r 0·928; \(P<0·001\), SEE 0·503 kJ/d) (Fig. 1). PAEEAcc was also significantly lower than PAEEChamber (−238 (SD 468) kJ/d, 95% CI −342, −133 (\(P<0·001\)); i.e. 92·7 (SD 17·8%) PAEEChamber), 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 (−172 (SD 453) kJ/d, 95% CI −274, −71; i.e. 94·9 (SD 28·4%) of the chamber value), but a significant correlation was still found (r 0·423; \(P<0·001\), SEE 431 kJ/d) with the measured value.

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*

<table>
<thead>
<tr>
<th>Study 1</th>
<th>Study 2</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Total (n 79)</strong></td>
<td><strong>Men (n 28)</strong></td>
</tr>
<tr>
<td><strong>Mean</strong></td>
<td><strong>SD</strong></td>
</tr>
<tr>
<td>Age (years)</td>
<td>39·7</td>
</tr>
<tr>
<td>Height (m)</td>
<td>1·628</td>
</tr>
<tr>
<td>Weight (kg)</td>
<td>58·3</td>
</tr>
<tr>
<td>BMI (kg/m²)</td>
<td>22·0</td>
</tr>
<tr>
<td>Fat (%)</td>
<td>23·5</td>
</tr>
</tbody>
</table>

* For details of procedures, see p. 236.

Total energy expenditure in the respiratory chamber

Measured TEEChamber averaged 8451 (SD 1338) kJ/d for the whole group (men 9656 (SD 1119), women 7789 (SD 926) kJ/d). Measured PAEEChamber averaged 2557 (SD 537) kJ/d in the whole group (men 2867 (SD 423), women 2387 (SD 519) kJ/d). Measured TEEAcc was 7750 (SD 1186) kJ/d (men 8912 (SD 884), women 7111 (SD 775) kJ/d) and measured PAEEAcc was 2319 (SD 453) kJ/d (men 2605 (SD 422), women 2163 (SD 391) kJ/d). TEEAcc was significantly lower than TEEChamber (−702 (SD 502) kJ/d, 95% CI −814, −589 (\(P<0·001\)); i.e. 91·9 (SD 5·4%) TEEChamber); however, there was a highly significant correlation between the two (r 0·928; \(P<0·001\), SEE 0·503 kJ/d) (Fig. 1). PAEEAcc was also significantly lower than PAEEChamber (−238 (SD 468) kJ/d, 95% CI −342, −133 (\(P<0·001\)); i.e. 92·7 (SD 17·8%) PAEEChamber), 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 (−172 (SD 453) kJ/d, 95% CI −274, −71; i.e. 94·9 (SD 28·4%) of the chamber value), but a significant correlation was still found (r 0·423; \(P<0·001\), SEE 431 kJ/d) with the measured value.

The individual correlations between the activity levels estimated by the accelerometer v. the 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; \(P<0·001\), 1·780 kJ/kg per h), but also when obligatory walking was excluded (r 0·477; \(P<0·001\), 1·684 kJ/kg per h). The regression equation was based on all activities (during the daytime) as follows:

\[ \text{EE (kJ/kg per h)} = 2·659x + 5·33, \]
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 ($r = 0.801$, $P < 0.001$), 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 × 10, $P < 0.001$) revealed a significant speed effect on MET ($P < 0.001$) and on the activity levels ($P < 0.001$), Scheffé’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 ($r^2 = 0.929$, see 0.463 MET) was calculated at a speed $\leq 7.8$ km/h, since

**Assessment of energy expenditure**

Fig. 1. (A), Relationship between the total energy expenditure measured by the respiratory chamber (TEE$_{chamber}$) v. that measured by the accelerometer (TEE$_{Acc}$; Lifecorder, Suzuken Co. Ltd, Nagoya, Japan); (B), the difference between the two values is plotted v. the mean value of the two for each subject ($n = 79$, study 1; Bland–Altman plots (Bland & Altman, 1986)). For details of subjects and procedures, see Table 1 and p. 236. ●, Male subjects; ○, female subjects. (A), ---, line of best fit; – – –, identity line. (B), ---, mean difference between the two methods; – – –, 95% limits of agreement (+ or – 2SD). TEE$_{chamber}$ was significantly lower than TEE$_{chamber}$ (−701 (SD 502) kJ/d; $P < 0.001$); however, there was a significant correlation ($r = 0.928$; $P < 0.001$, standard error of the estimate 503 kJ/d).

Fig. 2. (A), Relationship between the physical-activity-related energy expenditure measured by the respiratory chamber (PAEE$_{chamber}$) v. that measured by the accelerometer (PAEE$_{Acc}$; Lifecorder, Suzuken Co. Ltd, Nagoya, Japan); (B), the difference between the two values is plotted v. the mean value of the two for each subject ($n = 79$, study 1; Bland–Altman plots (Bland & Altman, 1986)). For details of subjects and procedures, see Table 1 and p. 236. ●, Male subjects; ○, female subjects. (A), ---, line of best fit; – – –, identity line. (B), ---, mean difference between the two methods; – – –, 95% limits of agreement (+ or – 2SD). PAEE$_{chamber}$ was significantly lower than PAEE$_{chamber}$ (−238 (SD 468) kJ/d; $P < 0.001$); however, there was a significant correlation ($r = 0.564$; $P < 0.001$, standard error of the estimate 446 kJ/d).

Fig. 3. Relationship between the daytime activity levels recorded by the accelerometer (Lifecorder; Suzuken Co. Ltd, Nagoya, Japan) and the energy expenditure (EE) of the pooled subjects ($n = 79$, study 1). For details of subjects and procedures, see Table 1 and p. 236. x, Treadmill walking periods; ---, regression line for the relationship for all activities ($r = 0.801$, $P < 0.001$, standard error of the estimate 1.780 kJ/kg per h); – – –, regression line for the relationship for all activities excluding treadmill walking ($r = 0.477$, $P < 0.001$, standard error of the estimate 1.684 kJ/kg per h).
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).

**Table 2.** The different activity levels of the accelerometer* classified into category of metabolic equivalents (MET)†

<table>
<thead>
<tr>
<th>Activity levels</th>
<th>Estimated MET</th>
</tr>
</thead>
<tbody>
<tr>
<td>Light intensity</td>
<td>1.0–1.8</td>
</tr>
<tr>
<td></td>
<td>2.0–2.3</td>
</tr>
<tr>
<td></td>
<td>3.0–2.9</td>
</tr>
<tr>
<td>Moderate intensity</td>
<td>4.0–3.6</td>
</tr>
<tr>
<td></td>
<td>5.0–4.3</td>
</tr>
<tr>
<td></td>
<td>6.0–5.2</td>
</tr>
<tr>
<td>Vigorous intensity</td>
<td>7.0–6.1</td>
</tr>
<tr>
<td></td>
<td>8.0–7.1</td>
</tr>
<tr>
<td></td>
<td>9.0–&gt;8.3</td>
</tr>
</tbody>
</table>

* Lifecorder; Suzuken Co. Ltd., Nagoya, Japan.
† The MET values were estimated using a formula derived from study 2 (for details, see p. 237).

**Discussion**

Validity of assessment of energy expenditure measured using the accelerometer

The present study showed that $\text{TEE}_{\text{ACC}}$ was significantly underestimated by a mean value of 8%. However, a highly significant relationship was demonstrated between $\text{TEE}_{\text{ACC}}$ 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 24h. 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 basal 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) %
ttrue value respectively. Note that the % body fat of a sub-
group of Japanese subjects (n 22) was the same as a white
population, strictly matched for gender, age, height and weight
(H Kumahara, H Tanaka and Y Schutz, unpublished results).

On the other hand, PAEEAcc 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. PAEEChamber-excl.TEF v. PAEEAcc-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
(Tritrac-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 previous com-
ercially 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 confine-
ment 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
accelerometer 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 run-
ing). 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 uni-
axial 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 volitional 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 moni-
tor can detect changes of the speeds during walking; how-
ever, this is less successful during running. Yamada
and 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 verti-
cal plane is not able to correctly estimate EE during run-
ing. 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

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exercises, a simple linear regression equation fitted well in study 1, whereas in study 2, a quadratic curvilinear regression equation was more appropriate. The probable reason for this is a change in net energetic efficiency of running, and a possible effect of straight extrapolation of the relationship in study 1 (Fig. 3), in which the maximum activity level in the chamber was not much greater than 6·0. The correlation of the quadratic relationship between activity level and MET was highly significant \( r^2 = 0.929, \) see 0.463 MET. Using a classical uniaxial accelerometer (Caltrac; Hemokinetics Inc.), Haymes & Byrnes (1993) showed that the strength of the relationship between the accelerometer output and measured EE was also high \( r^2 = 0.76, \) see 1.23 MET during walking (speed 3.2–8.0 km/h). Another study using a triaxial accelerometer device (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 accelerometer 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 (Lifeocorder; 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 still be 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.

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