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methods

Assessment of energy expenditure for physical activity using a triaxial accelerometer

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ABSTRACT

BOUTEN, C. V., K. R. WESTERTERP, M. VERDUIN, and J. D. JANSSEN. Assessment of energy expenditure for physical activity using a triaxial accelerometer. *Med. Sci. Sports Exerc.*, Vol. 26, No. 12, pp. 1516–1523, 1994. A triaxial accelerometer was used to evaluate the relationship between energy expenditure due to physical activity (EE_{act}) and body acceleration during different types of activity. In a laboratory experiment, 11 male subjects performed sedentary activities and walked on a motor driven treadmill (3–7 $km \cdot h^{-1}$). EE_{act} was calculated from total energy expenditure (EE_{tot}), as measured by indirect calorimetry, and sleeping metabolic rate (SMR): $EE_{act} = EE_{tot} - SMR$. Body accelerations were measured with a triaxial accelerometer at the low back. Special attention was paid to the analysis of unidirectional and three-directional accelerometer output. During sedentary activities a linear relationship between EE_{act} and the sum of the integrals of the absolute value of accelerometer output from all three measurement directions (IAA_{tot}) was found ($r = 0.82$, $P < 0.001$, $S_{y,x} = 0.22\ W \cdot kg^{-1}$). During walking EE_{act} was highly correlated with the integral of absolute accelerometer output in antero-posterior direction (IAA_x; $r = 0.96$, $P < 0.001$, $S_{y,x} = 0.53\ W \cdot kg^{-1}$). When all examined activities were included in a regression analysis, a strong linear relationship between EE_{act} and IAA_{tot} was found ($r = 0.95$, $P < 0.001$, $S_{y,x} = 0.70\ W \cdot kg^{-1}$). Using this relationship, EE_{act} during sedentary activities as well as EE_{act} during walking could be estimated with an accuracy of about 15%. Although sedentary activities and walking represent a large part of normal daily physical activity, the validity and usefulness of the triaxial accelerometer—measuring IAA_{tot}—to predict EE_{act} in daily life must be studied under free-living conditions.

BODY ACCELERATION, METABOLISM, WALKING, SEDENTARY ACTIVITIES

The assessment of physical activity in free-living subjects is central to a complete understanding of the relationship between daily physical activity and health (5,21). Therefore, a wide range of methods for the measurement of physical activity has been developed, including questionnaires, diary techniques, heart rate recording, doubly labeled water, and mechanical or electronic motion sensors. All of these methods have their own benefits and limitations under normal daily conditions and focus on physical activity from different points of view (12,17). In this study physical activity is regarded as body movement, produced by skeletal muscles and resulting in energy expenditure (7).

In the last decade there has been a growing interest in the assessment of daily physical activity using electronic accelerometers (12,14,16). These motion sensors register accelerations and decelerations of the body and, in this way, provide an objective and direct measure of the frequency and intensity of movements during physical activity. Data from studies on gait analysis and ergonomics have demonstrated a linear relationship between the integral of the absolute value of body acceleration and oxygen consumption or energy expenditure (6,8,11,19), initiating the development of accelerometers to estimate energy expenditure during physical activity. Wong et al. (30) developed a uniaxial accelerometer that could be worn on the waist and measured accelerations along the vertical axis of the trunk. In this device absolute acceleration curves were integrated and summed for the time it was worn. A correlation of 0.74 between accelerometer output and oxygen consumption was reported in subjects

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performing different exercises under laboratory conditions (16). In free-living subjects, a correlation of 0.87 between accelerometer readings and total daily energy expenditure, as determined with doubly labeled water over a 10-d period, was found (10). Meijer et al. (15) developed a portable accelerometer device with a triaxial sensor. Acceleration signals from all directions were summed, rectified and integrated over time intervals of 1 min. Validation against doubly labeled water during a 7-d period showed a correlation of 0.88 between accelerometer output and the metabolic cost of physical activity (13).

Although significant correlations between energy expenditure and accelerometer readings are found in laboratory studies and under free-living conditions, the relationship between these parameters using uniaxial accelerometers varies between different types of activity (23). It is not known whether this is the same in triaxial accelerometers. Furthermore, considering the basic laws of physics, the linearity of the relationship is unclear. The integral of the absolute value of acceleration, though not mathematically representing velocity, may be expressed in units of velocity ($m \cdot s^{-1}$). The mechanical energy required to accelerate a frictionless body with mass m_b to velocity v is $\frac{1}{2} m_b v^2$. Since mechanical energy estimates are directly related to the metabolic energy cost of movement (29), it can be argued that the relationship between energy expenditure and the integral of absolute accelerometer output—expressed in units of velocity—is quadratic rather than linear (Appendix A: A11–A15).

The primary aim of the present study was to evaluate the relationship between body acceleration and energy expenditure due to physical activity (EE_{act}) during sedentary activities and walking. EE_{act} was calculated as total energy expenditure (EE_{tot}) minus sleeping metabolic rate (SMR), a measure that is frequently used for expressing physical activity. Body accelerations were measured with a triaxial accelerometer, developed at the Department of Mechanical Engineering of the Eindhoven University of Technology. This accelerometer is based on three orthogonally mounted uniaxial accelerometers, to investigate the relative contribution of different measurement directions to the estimation of EE_{act}. Acceleration signals were analyzed in different ways to find the most accurate and practical data acquisition technique for the assessment of physical activity under free-living conditions.

METHODS

Subjects

Eleven healthy male subjects, who all gave written informed consent, participated in the study. Physical characteristics of the subjects (mean, SD, range) are presented in Table 1.

TABLE 1. Subject characteristics (N = 11).

	Mean	SD	Range
Age (yr)	23.5	1.8	21–27
Height (m)	1.83	0.07	1.68–1.96
Body mass (kg)	68.6	9.9	46.8–80.5
Body mass index ($kg \cdot m^{-2}$)	20.5	1.9	16.6–23.1

Experimental Protocol

The relationship between accelerometry and energy expenditure was evaluated during sedentary activities and walking. These activities were chosen for their resemblance with normal daily activities. Together they represent the major part of normal daily physical activity in present Western society (1,18). Experiments were performed in the early morning or afternoon, and subjects were allowed to have a light meal before the measurements.

After sitting relaxed for about 15 min to reach stabilized oxygen consumption, subjects performed the following activities for 3 min each: 1) sitting relaxed, 2) sitting and writing, 3) sitting with arm work, 4) alternately sitting and standing for 10 s each, and 5–9) walking at five different speeds (3, 4, 5, 6, 7 $km \cdot h^{-1}$) on a motor driven treadmill (Quinton). Arm work was done by moving an iron disk (1.1 kg) from a shelf (height: 50 cm) on one side of the subject to a table in front of the subject and then moving the disk to a shelf on the other side. This procedure was repeated in standardized pace. Before the experiments, subjects walked for approximately 5 min on the treadmill to get acquainted with this kind of exercise. To standardize the effect of footwear on acceleration levels, all subjects wore sneakers. During the activities continuous measurements of EE_{tot} and analog accelerometer output were made. In a separate experiment SMR was measured, permitting the calculation of EE_{act}.

Energy Expenditure

EE_{tot} was calculated according to Weir (27) from O_2 consumption and CO_2 production, measured with an automated respiratory gas analyzer (Oxyconbeta, Mijnhardt). EE_{tot} was calculated over the last min of each activity stage when oxygen consumption had reached a steady state. SMR was determined during an overnight stay in a respiration chamber (22) over a 3-h interval between 2:00 a.m. and 7:00 a.m. with the lowest level of physical activity, as indicated with Doppler radar. The energy compartment EE_{tot} minus SMR consists of EE_{act} and diet induced thermogenesis. As the experiments were performed at a standardized time interval after breakfast or lunch (1.5–2 h), the thermogenic effect of food was assumed to show only little variance between subjects (24,28). Therefore, all variance in EE_{tot} minus SMR was ascribed to differences in EE_{act}. To normalize the effect of body mass on energy expenditure EE_{act} was expressed as $W \cdot kg^{-1}$.

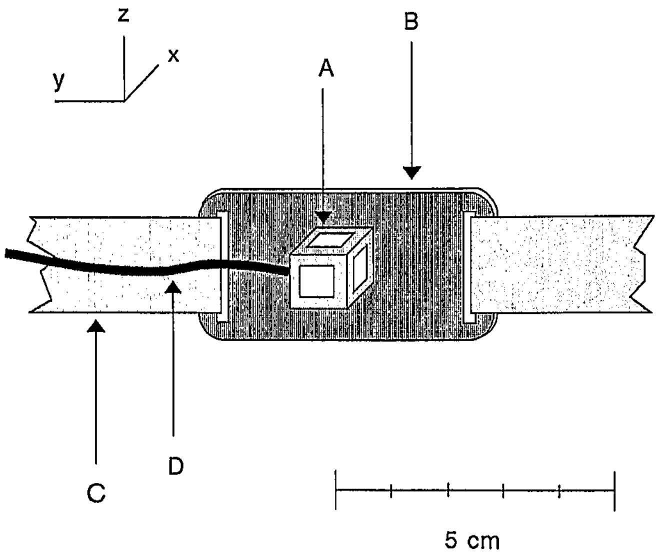

Figure 1—Schematic illustration of the triaxial accelerometer (rear view). Three piezoresistive accelerometers (x, y, and z) are mounted orthogonally on a lightweight cube (A). This cube is connected to a plate (B) that can be attached to an elastic belt (C) by means of two slits. A flexible cable (D) runs from the triaxial accelerometer to amplifier and battery units.

Measurement of Acceleration

The triaxial accelerometer (TA) consisted of three uniaxial piezoresistive accelerometers (ICSensors, type 3031–010; size: 4 × 4 × 3 mm; weight: 0.3 g; range: ±10 g; frequency response: 0–600 Hz, f_0: 1200 Hz) mounted orthogonally onto a 12×12×12 mm lightweight cube. Piezoresistive accelerometers are especially suited for detection of human movement due to their sensitivity to very low frequencies. The piezoresistive accelerometers used in this study were tested with a vibration excitator (Ling Dynamic Systems, type 201) and found to be valid and reliable for the measurement of accelerations corresponding to human body accelerations, usually smaller than 6 g (4) and with frequencies below 20 Hz (2,25). Transverse sensitivity of the accelerometers was less than 3%. Calibration of the separate accelerometers in the TA was performed by the so-called "turnover technique": due to the DC response of piezoresistive accelerometers, differences in accelerometer output up to 2 *g* were produced by altering the orientation of the TA with respect to the gravitational vector of the earth.

The TA was placed on a plate with two slits for an elastic waist belt (Fig. 1). With this belt the TA was attached to the low back. Accelerations were measured in a body fixed system of reference with measurement directions in antero-posterior (x), medio-lateral (y), and vertical (z) direction. Bridge amplifiers and batteries for the three piezoresistive accelerometers were carried in separate units (200 g and 310 g, respectively) on both hips. Connections between the TA and the separate parts were established via a 12-conductor shielded cable. Amplifier gains were adjusted to produce an output of 1 $V \cdot g^{-1}$ for each measurement direction. After the sensor was placed in position on the low back, accelerometer output was set to zero with the subject standing motionless. Using a flexible cable leading from the amplifier unit to a four-channel FM data recorder (Tandberg, type TIR 115), accelerations from all three directions were continuously recorded and stored on tape for further analysis.

Analysis of Accelerometer Output

Analog accelerometer output was digitized (100 Hz), converted to acceleration units ($m \cdot s^{-2}$), and read into a computer. Signals were filtered using a fourth order low-pass zero phase Butterworth filter with frequency cut-off at 20 Hz to attenuate the effect of frequencies that cannot be expected to arise from voluntary movement. Subsequently, base line shifts in accelerometer output due to changes in DC response were eliminated from the signals. Corrected and filtered acceleration signals from a 30-s interval at the end of each activity stage were processed to various accelerometer output variables. The 30-s interval was always started at a standardized moment of the activity stage, e.g., at heelstrike during walking.

Integrals of the absolute value of accelerometer output from x, y, and z directions were obtained by rectification and integration of the signals over the 30-s time interval, resulting in the variables IAA_x, IAA_y, and IAA_z. The sum of these variables was calculated to get IAA_{tot}. To test the hypothesis of a quadratic relationship between the integral of absolute accelerometer output and EE_{act}, the computed variables were squared (IAA_x^2, IAA_y^2, IAA_z^2, and IAA_{tot}^2). The magnitude of the total acceleration vector was obtained by squaring the output from each accelerometer and extracting the square root of the sum of these values. Next, the integral of the magnitude of the acceleration vector (IAV) was computed. This variable was squared to obtain IAV^2. The last processing method involved the estimation of kinetic energy (KE_x, KE_y, KE_z, KE_{tot}) and power (P) due to the rate of change of total kinetic energy at the point of attachment of the TA. These variables are directly related to the metabolic energy cost of movement and might be used to describe the relationship between metabolic (EE_{act}) and mechanical (acceleration) phenomena during physical activity. As accelerometers measure linear accelerations, only kinetic energy due to translational motion could be calculated from accelerometer output. Acceleration signals were integrated over time, resulting in instantaneous velocity. The signals thus obtained were squared and multiplied by $\frac{1}{2}m_b$, with m_b representing the subject's body mass, to calculate instantaneous kinetic energy curves for each measurement direction. Summation of these curves resulted in total kinetic energy. By taking the time derivative of the total energy curve, total instantaneous power

TABLE 2. Mean, SD, and range of energy expenditure due to physical activity (EE_{act}) for separate activities (N = 11).

Activity	EE_{act} ($W \cdot kg^{-1}$) Mean	SD	Range
Sitting	0.17	0.10	0.02–0.37
Writing	0.17	0.15	0.02–0.49
Arm work	0.70	0.26	0.42–1.29
Sitting/standing	0.87	0.23	0.39–1.13
Walking, 3 km · h^{-1}	2.09	0.36	1.52–2.79
Walking, 4 km · h^{-1}	2.53	0.40	2.02–3.19
Walking, 5 km · h^{-1}	3.31	0.42	2.59–3.90
Walking, 6 km · h^{-1}	4.69	0.55	3.66–5.53
Walking, 7 km · h^{-1}	7.02	1.12	5.31–9.37

due to the rate of change of kinetic energy was obtained. To correlate instantaneous energy and power curves against EE_{act}, it is necessary to calculate mean values for these parameters. This was done by integration of the curves over the 30-s time interval and dividing the result by 30. Power curves were first rectified before a mean value was derived, assuming metabolic energy cost of positive and negative work rates to be equal. Equations describing the accelerometer output variables may be found in Appendix A.

Statistics

All accelerometer variables were used separately in a simple regression analysis with EE_{act} during sedentary activities, walking, and all activities together. For each of these activity conditions regression equations, correlation coefficients (Pearson's r), and standard errors of estimate ($S_{y,x}$) were calculated for individual as well as pooled data of all subjects.

RESULTS

EE_{act} (mean, SD, and range) for each activity is shown in Table 2.

During sedentary activities the highest correlations were found for the linear relationship between EE_{act} and IAA_{tot}. Individual correlations ranged from 0.71 to 0.99 with a mean of 0.91. The mean standard error of estimate was 0.12 $W \cdot kg^{-1}$, with a range of 0.02–0.39 $W \cdot kg^{-1}$. Using pooled data of all subjects the correlation between EE_{act} and IAA_{tot} was 0.82 ($P < 0.001$, $S_{y,x} = 0.22$ $W \cdot kg^{-1}$). The contribution of the integral of absolute accelerometer output in x, y, and z direction to IAA_{tot} during the sedentary activities is illustrated in Figure 2.

During walking the most accurate predictor of EE_{act} was IAA_x. In each subject a strong linear relationship between EE_{act} and IAA_x was found. The average individual correlation was 0.99 (range: 0.96–0.99). Mean individual $S_{y,x}$ was 0.29 $W \cdot kg^{-1}$ (range: 0.06–0.88 $W \cdot kg^{-1}$). A correlation of 0.96 was found for the entire group ($P < 0.001$, $S_{y,x} = 0.53$ $W \cdot kg^{-1}$). Figure 3 shows the integral of the absolute value of accelerometer output in x, y, and z direction during walking with different velocities. Although IAA_x was the best predictor of EE_{act} for each velocity stage, the major acceleration component during each stage was in the z direction.

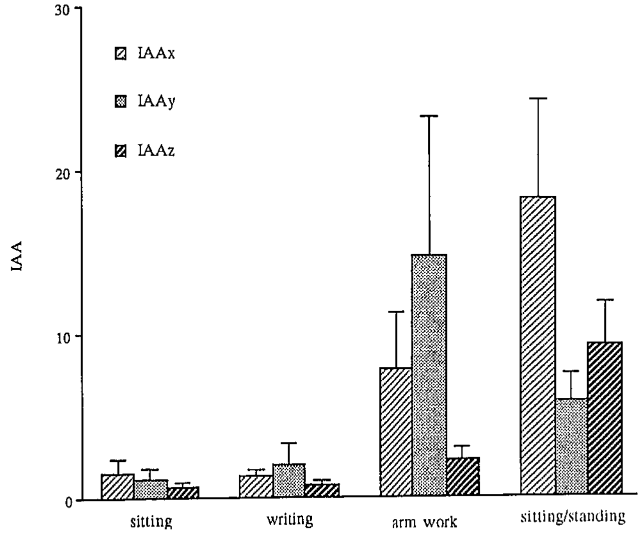

Figure 2—Integral of the absolute value of accelerometer output (IAA) in x, y, and z direction (mean and SD) during sedentary activities.

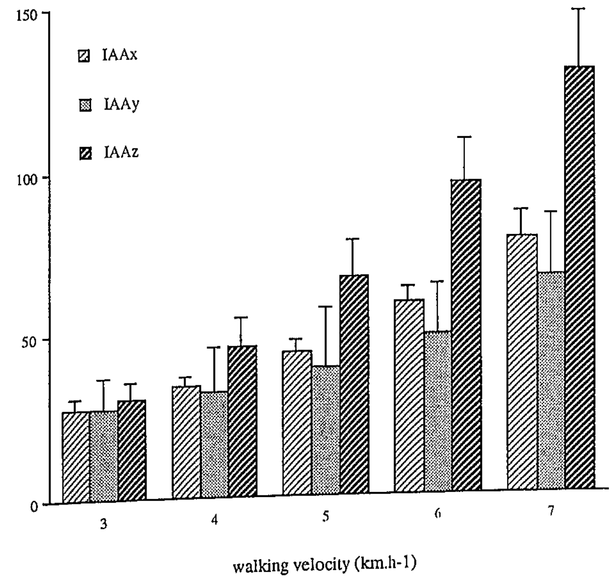

Figure 3—Integral of the absolute value of accelerometer output (IAA) in x, y, and z direction (mean and SD) during walking at different velocities.

IAA_x and IAA_{tot} were both highly correlated with EE_{act} when regression analysis was performed on data of all activities. Individual correlations varied between 0.97 and 0.99 for EE_{act} vs IAA_x ($0.15 \leq S_{y,x} \leq 0.72$, mean $S_{y,x} = 0.39$ $W \cdot kg^{-1}$). For EE_{act} vs IAA_{tot} correlations ranged from 0.96 to 0.99 ($0.07 \leq S_{y,x} \leq 0.64$, mean $S_{y,x} = 0.30$ $W \cdot kg^{-1}$). Correlations for the entire group were 0.97 for IAA_x ($P < 0.001$, $S_{y,x} = 0.51$ $W \cdot kg^{-1}$) and 0.95 for IAA_{tot} ($P < 0.001$, $S_{y,x} = 0.70$ $W \cdot kg^{-1}$). As individual calibration adds little to the accuracy for predicting EE_{act} from IAA_x or IAA_{tot}, pooled regression equations can be used to estimate individual EE_{act}. For all

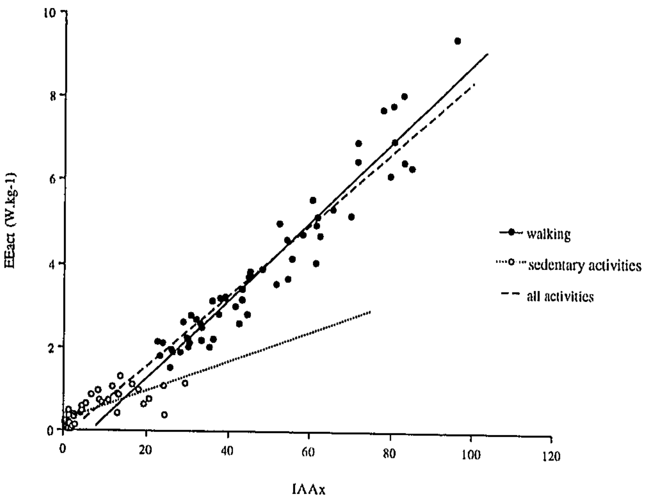

Figure 4—Scatter plot for energy expenditure due to physical activity (EE_{act}) vs the integral of the absolute value of accelerometer output in antero-posterior direction (IAA_x) of the pooled data of 11 subjects during sedentary activities and walking. Separate regression lines for the relationship between EE_{act} and IAA_x are shown for sedentary activities (*dotted line*, $r = 0.76$, $S_{y,x} = 0.24\ W \cdot kg^{-1}$), for walking (*solid line*, $r = 0.96$, $S_{y,x} = 0.53\ W \cdot kg^{-1}$), and for all activities together (*dashed line*, $r = 0.97$, $S_{y,x} = 0.51\ W \cdot kg^{-1}$).

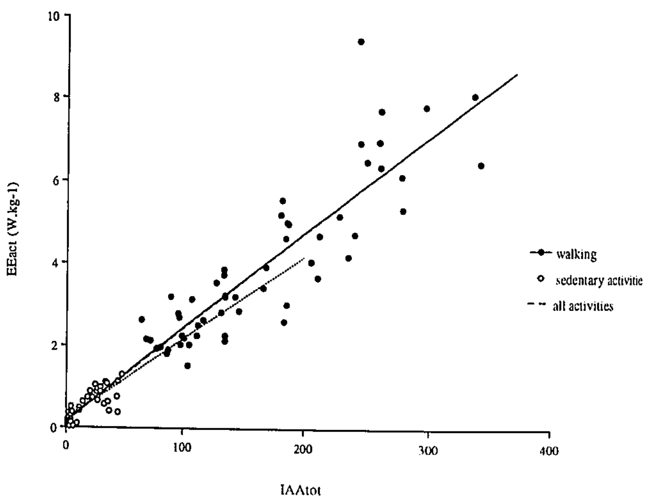

Figure 5—Pooled scatter plot and regression lines for energy expenditure due to physical activity (EE_{act}) vs the sum of the integrals of absolute accelerometer output from three orthogonal measurement directions (IAA_{tot}) during sedentary activities and walking. Regression line for sedentary activities: *dotted line* ($r = 0.82$, $S_{y,x} = 0.22\ W \cdot kg^{-1}$). Regression lines for walking (*solid line*, $r = 0.88$, $S_{y,x} = 0.92\ W \cdot kg^{-1}$) and for all activities together (*dashed line*, $r = 0.95$, $S_{y,x} = 0.70\ W \cdot kg^{-1}$) coincide.

activities together these regression equations are given by:

$$EE_{act} = -0.176 + 0.085 IAA_x \tag{1}$$

$$EE_{act} = 0.104 + 0.023 IAAtot. \tag{2}$$

Comparison between measured and estimated EE_{act} showed that equation 1 underestimated individual EE_{act} during sitting, writing, and arm work by 35–140%, while EE_{act} during sitting down/standing up was overestimated by 70%. On the average, EE_{act} for all sedentary activities was underestimated by more than 60%. EE_{act} during walking was estimated within 4% accuracy using regression equation 1. Figure 4 shows a scatter plot for EE_{act} vs IAA_x of the pooled data of all subjects and all activities. Separate regression lines between EE_{act} and IAA_x for each activity condition are indicated. As can be seen, the slopes of the regression lines for sedentary activities and walking are different, while the regression line for all activities is dominated by data obtained during walking. When regression equation 2 was used, individual EE_{act} during sedentary activities as well as during walking could be predicted with an accuracy of about 15%. The scatter plot and regression lines for EE_{act} vs IAA_{tot} are shown in Figure 5. Here, more conformity between EE_{act} vs IAA_{tot} relationships for different activity conditions can be observed. Note that regression lines for walking and all activities coincide.

With respect to the other accelerometer output variables only IAA_x2 was found to show a clear relationship with EE_{act}. This variable was significantly correlated with EE_{act} during walking ($r = 0.90$, $P < 0.001$, $S_{y,x} = 1.03\ W \cdot kg^{-1}$). However, no such relationship was found for sedentary activities. Furthermore, prediction of EE_{act} using IAA_x^2 was less accurate than with IAA_x. Using both IAA_x and IAA_x^2 in a multiple regression with EE_{act} during walking learned that the contribution of IAA_x^2 to the estimation of EE_{act} was not significant ($P = 0.204$) in comparison with IAA_x ($P < 0.001$).

No clear relationships between EE_{act} and measures of kinetic energy or power were discovered.

DISCUSSION

The present study was conducted to investigate the relationship between EE_{act} and body acceleration, registered during sedentary activities and walking. Body accelerations in three orthogonal directions were measured at the low back and processed to various unidirectional and three-directional accelerometer output variables. Analog acceleration signals were comparable in each subject, although interindividual variations were observed due to differences in performance of activity, especially during sedentary activities (Fig. 2). Relatively large differences in EE_{act} between individuals were found during sedentary activities (Table 2). These differences might be explained by 1) the difficulty of measuring energy expenditure at these low levels of activity, 2) variations in energy expenditure corresponding to the aforementioned variations in the level and performance of physical activity, and 3) the fact that diet induced thermogenesis (DIT) was not considered. Assuming DIT to vary between 7% and 14% of EE_{tot} in our subjects (24), the estimated effect of DIT on EE_{act} during sedentary activities ranges from 16% during sitting/standing to almost 100% during sitting relaxed. However, using the individual relationships between EE_{act} and IAA_{tot} for sedentary activities, 50–98% of the variance in EE_{act} can be explained from accelerometer output ($0.50 \leq r^2 \leq 0.98$; mean $r^2 = 0.83$). Using pooled data of all subjects 67% of the variance in EE_{act} can be explained from accelerometer output. During walking, interindividual differences in accelerometer output and EE_{act} were smaller, resulting in stronger relationships between EE_{act} and accelerometer output variables. Here, the estimated effect of DIT on EE_{act} ranges from 8% during walking at 7 $km \cdot h^{-1}$ to about 20% at 3 $km \cdot h^{-1}$.

When pooled data of the 11 subjects were used to predict EE_{act} for the separate sedentary activities and walking velocities, the correlation coefficient between EE_{act} and accelerometer output varied from 0.18 for sitting relaxed to 0.57 for sitting with arm work (IAA_{tot}) and from 0.48 for walking at 3 $km \cdot h^{-1}$ to 0.71 for walking at 7 $km \cdot h^{-1}$ (IAA_x). Thus, the accelerometer output only explains 3–32% of the variance in EE_{act} during the separate sedentary activities and 23–50% of the variance in EE_{act} during the different walking velocities, implicating the low sensitivity of the method to estimate differences in EE_{act} in the separate activities.

The best prediction of EE_{act} was obtained by integration of absolute accelerometer output. Our results did not support the hypothesis of a quadratic relationship between EE_{act} and the integral of absolute accelerometer output being superior to a linear relationship between these variables. Also, EE_{act} could not be predicted from measures of kinetic energy or power. Using a force platform inside a whole-room indirect calorimeter, Sun and Hill (25) found a strong linear relationship between mechanical work, performed on the body center of mass, and metabolic energy expenditure during walking and stepping exercise in 33 subjects (mean $r = 0.93$). The reason why we did not find a similar relation might be that mechanical energy due to rotation or work against gravity could not be calculated. In addition the initial velocity of the body could not be accounted for in the estimation of kinetic energy from accelerometer output.

During sedentary activities the most accurate predictor of EE_{act} was the sum of the integrals of absolute accelerometer output from all three measurement directions (IAA_{tot}). It is not surprising that the best prediction of EE_{act} was obtained from a three-directional variable, as movements in three planes were incorporated in these activities. During walking the most accurate estimation of EE_{act} was achieved by integrating the absolute value of unidirectional acceleration in antero-posterior direction (IAA_x). In earlier studies the integral of the absolute value of acceleration in vertical direction was used for the assessment of physical activity in exercises like walking and running, because the major acceleration component during these activities is in the vertical direction (9,23,30). Although we agree that the major acceleration component during walking is in the vertical (z) direction (Fig. 3), EE_{act} during walking is better predicted using the integral of absolute accelerometer output in the antero-posterior (x) direction. The relatively high accelerometer output in the vertical direction can be explained by peak accelerations resulting from heel strike, which are more prominent in the z direction than in x and y directions. Peak accelerations are caused by impact forces between foot and walking surface and are not produced by voluntary movement itself. Therefore, EE_{act} might not be proportional to the integral of absolute accelerometer output in vertical direction.

Figure 4 shows that different relationships between EE_{act} and accelerometer output were found for the different types of activity performed, when EE_{act} was correlated against the unidirectional variable IAA_x. Similar results were found when IAA_y and IAA_z were used in a regression with EE_{act}. These findings correspond with Servais et al. (23), who report that calibration of a uniaxial accelerometer, measuring the integral of the absolute value of vertical acceleration over a range of activities is different for each activity. The contribution of movement, and hence acceleration, to separate measurement directions varies for different activities. For instance, in our experiments the major acceleration component during sitting with arm work was in the y direction, during sitting and standing in the x direction, and during walking in the z direction. This might explain the discrepancies in relationships between EE_{act} and accelerometer output for different activities using a uniaxial accelerometer. When the three-directional variable IAA_{tot} was used to estimate EE_{act}, more similarity between EE_{act} vs accelerometer output relationships for sedentary activities and walking were observed (Fig. 5).

To our knowledge the contribution of different measurement directions to the estimation of EE_{act} was never studied using one and the same accelerometer. Ayen and Montoye (3) used three uniaxial accelerometers mounted at right angles on the waist to determine whether energy expenditure during a range of exercises was better estimated with this simulated triaxial accelerometer than with a single accelerometer. Their findings correspond to our conclusions in that IAA_x was a better predictor of EE_{act} ($r = 0.74$) than IAA_z ($r = 0.65$) during walking, running, and stepping exercise. Also, the estimation of energy expenditure using the output of three accelerometers ($r = 0.78$) was better than that using any of the uniaxial accelerometers.

In the present study a correlation of 0.95 was found between EE_{act} and IAA_{tot} for the pooled data of all subjects and all activities. The standard error of estimate was 0.70 $W \cdot kg^{-1}$. This error is smaller than that reported by Meijer et al. (15) who found a $S_{y,x}$ of 1.32 $W \cdot kg^{-1}$ for 16 subjects (13 males, 3 females) over a range of sedentary, walking, and running activities using a triaxial accelerometer. However, in the study of Meijer et al., energy expenditure was systematically underestimated during running. As we did not include running in our activity protocol, care should be taken in comparing the results.

Our data demonstrate that the use of a triaxial accelerometer seems to be an appropriate technique to quantify the multidirectional characteristics of human movement in relation to energy expenditure during sedentary activities and walking. A single regression equation between EE_{act} and the sum of the integrals of the absolute value of acceleration from three orthogonal measurement directions can be used to assess the metabolic cost of these activities. Also, individually established relationships for EE_{act} vs accelerometer output can be omitted as a pooled regression equation using data of several subjects can be used to estimate EE_{act} in the individual. Although sedentary activities and walking represent a large part of normal daily physical activity (1,18), activities performed under controlled laboratory conditions may differ considerably from activities performed under free-living conditions. The relationship between EE_{act} and IAA_{tot} is also likely to be dependent on personal characteristics, like age, sex, and body composition. Furthermore, given that only 11 subjects were studied and all of them were male, the results may not be generalized to daily living conditions. Therefore, the validity and usefulness of the TA to estimate energy expenditure during daily physical activity should be studied in free-living subjects.

A shortcoming of accelerometers is the underestimation of energy expenditure in activities that involve static exercise. During static exercise the accelerometer output is not proportional to the increase in EE_{act}. Saris and Binkhorst (20) and Verschuur and Kemper (26) state that this is probably not a serious limitation under free living conditions, because the contribution of static exercise t daily physical activity is negligible. However, EE_{act} during activities like walking upstairs, carrying a load, o cycling with head wind must be evaluated with caution The registration of external vibrations, not produced b the subject, may also produce artifacts. The use of a buil in low-pass filter, as in our TA, will reduce this effect The DC response of piezoresistive accelerometers ca cause serious errors in prediction of EE_{act} when the orientation of the accelerometers with respect to the gravitational force vector is altered. We eliminated DC response by hand, but under normal daily conditions this is not possible. Under these circumstances DC response can be attenuated using a high-pass filter with low frequency cut-off (<0.1 Hz). Future research should be aimed at the development of a portable accelerometer and data acquisition unit to evaluate the method under free-living conditions.

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Appendix A. Integrals of the absolute value of accelerometer output in x, y, and z direction over a time interval [t = 0, T] of 30 s, with a_x, a_y, and a_z representing measured accelerations in x, y, and z direction:

$$IAA_x = \int_{t=0}^{T} |a_x| dt \quad (A1)$$

$$IAA_y = \int_{t=0}^{T} |a_y| dt \quad (A2)$$

$$IAA_z = \int_{t=0}^{T} |a_z| dt \quad (A3)$$

Sum of the integrals of absolute accelerometer output in x, y, and z direction:

$$IAA_{tot} = IAA_x + IAA_y + IAA_z \quad (A4)$$

Squared integrals of absolute accelerometer output in x, y, and z direction:

$$IAA_x^2 = [\int_{t=0}^{T} |a_x| dt]^2 \quad (A5)$$

$$IAA_y^2 = [\int_{t=0}^{T} |a_y| dt]^2 \quad (A6)$$

$$IAA_z^2 = [\int_{t=0}^{T} |a_z| dt]^2 \quad (A7)$$

Sum of squared integrals of absolute accelerometer output in x, y, and z direction:

$$IAA_{tot}^2 = IAA_x^2 + IAA_y^2 + IAA_z^2 \quad (A8)$$

Integral of the magnitude of the total acceleration vector:

$$IAV = \int_{t=0}^{T} \sqrt{a_x^2 + a_y^2 + a_z^2}\, dt \quad (A9)$$

Squared integral of the magnitude of the total acceleration vector:

$$IAV^2 = [\int_{t=0}^{T} \sqrt{a_x^2 + a_y^2 + a_z^2}\, dt]^2 \quad (A10)$$

Mean kinetic energies due to translation in x, y, and z direction:

$$KE_x = \frac{1}{T}\int_{t=0}^{T} \frac{1}{2} m_b v_x^2 dt \quad (A11)$$

$$KE_y = \frac{1}{T}\int_{t=0}^{T} \frac{1}{2} m_b v_y^2 dt \quad (A12)$$

$$KE_z = \frac{1}{T}\int_{t=0}^{T} \frac{1}{2} m_b v_z^2 dt \quad (A13)$$

with m_b representing body mass, and the instantaneous velocities $v_x(t)$, $v_y(t)$, and $v_z(t)$ defined as:

$$\begin{aligned} v_x(t) &= \int_{\tau=0}^{t} a_x(\tau)d\tau + v_x(t=0) \\ v_y(t) &= \int_{\tau=0}^{t} a_y(\tau)d\tau + v_y(t=0) \\ v_z(t) &= \int_{\tau=0}^{t} a_z(\tau)d\tau + v_z(t=0) \end{aligned} \quad (A14)$$

where $v_x(t = 0)$, $v_y(t = 0)$, and $v_z(t = 0)$ are considered to be zero.

Mean total kinetic energy due to translation:

$$KE_{tot} = \frac{1}{T}\int_{t=0}^{T} \left(\frac{1}{2} m_b v_x^2 + \frac{1}{2} m_b v_y^2 + \frac{1}{2} m_b v_z^2\right) dt \quad (A15)$$

Mean power due to the rate of change of total kinetic energy due to translational motion:

$$P = \frac{1}{T}\int_{t=0}^{T} \left|\frac{d}{dt}\left(\frac{1}{2} m_b v_x^2 + \frac{1}{2} m_b v_y^2 + \frac{1}{2} m_b v_z^2\right)\right| dt. \quad (A16)$$