Evaluation of a triaxial accelerometer for the assessment of daily physical activity

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EVALUATION OF A TRIAXIAL ACCELEROMETER FOR THE ASSESSMENT OF DAILY PHYSICAL ACTIVITY

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Abstract - The present study deals with the evaluation of a body fixed triaxial accelerometer for the assessment of daily physical activity. The method is based on the relationship between acceleration, as measured on the human body, and energy expenditure due to physical activity (EE_{act}). This relationship is studied during different types of activities. Accelerometer output is analyzed in various ways to find the best predicting variable of EE_{act}. The most accurate variable, the sum of the integrals of absolute acceleration in three measurement directions, was implemented in a portable data acquisition unit, allowing the method to be used in free living subjects. A first evaluation of the accelerometer and data acquisition unit during a standardized activity protocol in a respiration chamber, showed that the method can be used to predict long term EE_{act} under daily living conditions.

INTRODUCTION

Quantitative measurements of the level of daily physical activity in health related research require an objective and accurate method for the assessment of activity to be used under free living conditions. A promising technique for this purpose is the use of electronic accelerometers. When fixed to the human body, the output of the motion sensors is a direct measure of body movement and can be used to predict EE_{act}. Several authors have reported on a linear relationship between energy expenditure or oxygen consumption and the integral of absolute acceleration, measured on the human body with uniaxial as well as triaxial accelerometers (Heyman et al., 1991; Meijer et al., 1989; Montoye et al., 1983). However, the relationship between EE_{act} and accelerometer readings seems to vary for different types of activities when uniaxial accelerometers are used (Servais et al., 1984). It is unknown whether the relationship can be improved using a triaxial accelerometers. Furthermore, the linearity of the relationship is unclear and the question is whether the integral of absolute acceleration provides the best estimation of EE_{act} or that other ways of data processing result in better predictions. For instance: the integral of absolute acceleration, though not mathematically representing velocity, may be expressed in units of velocity. The mechanical energy required to accelerate a frictionless body with mass m to velocity v is $\frac{1}{2}mv^2$. Since mechanical energy estimates are directly related to the metabolic energy cost of movement a quadratic relationship between EE_{act} and the integral of absolute acceleration is expected. Also the calculation of kinetic energy from accelerometer output may be used to predict EE_{act} (Sun and Hill, 1993). The primary aim of this study was to evaluate the relationship between body acceleration and EE_{act} during different types of activity in a laboratory experiment. Body accelerations were measured with a triaxial accelerometer (TA), based on three orthogonally mounted uniaxial accelerometers. Special attention was paid to the relative contribution of different measurement directions to the estimation of EE_{act}. Acceleration signals were analyzed in various ways to find the most accurate and practical estimator of EE_{act}. The computation of this estimator was implemented in a portable data acquisition unit for online calculation of 'activity counts'. The validity of the triaxial accelerometer and data acquisition unit for the assessment of long-term EE_{act} was then evaluated under simulated daily living conditions in a respiration chamber.

EVALUATION OF THE RELATIONSHIP BETWEEN BODY ACCELERATION AND EE_{act}

METHOD

Eleven healthy male subjects (age: 23±2 yrs, weight: 68±10 kg, height: 183±7 cm) participated in the study. After sitting relaxed for about 15 min they 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, and 7 km . h^{-1}) on a motor driven treadmill (Quinton). Total energy expenditure was calculated from O_2 uptake and CO_2 production during the last minute of each activity stage when O_2 consumption has reached a steady state. EE_{act} ($W \cdot kg^{-1}$) was calculated as total energy expenditure minus sleeping metabolic rate, measured during an overnight stay in a respiration chamber. The TA consisted of three piezoresistive accelerometers (IC Sensors, 3031-010; size: 4x4x7 mm, weight: 0.3 gram, range: ±10 *g*; frequency response: 0 - 600 Hz, f_0: 1200 Hz) mounted at right angles onto a 12 mm^3 lightweight cube. This cube was placed on a small plate with two slits for an elastic belt by which the TA was attached to the low back, near the body centre of mass. 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 accelerometers were carried in separate housings on both hips. The accelerometers were tested with a vibration excitator (Ling Dynamic Systems, 201) and found to be valid and reliable for the measurement of accelerations corresponding to human body accelerations (≤ 6 *g*; 0 -20 Hz). Transverse sensitivity was less than 3%. Calibration of the piezoresistive accelerometers was performed by altering the orientation of the TA with respect to the gravitational vector of the earth. Amplifier gains were adjusted to produce an output of 1 V . g^{-1} per measurement direction. During the activity protocol analog accelerometer outputs from all three directions were recorded on a data recorder (Tandberg, TIR 115). Acceleration signals were digitized (100 Hz), low-pass filtered (20 Hz), and corrected for base-line shifts due to DC response. The resulting signals were processed to various accelerometer output variables over a 30 s time period during the last minute of each activity stage. The following variables were obtained: 1) the integrals of absolute acceleration in x-, y-, and z-direction, 2) the sum of these three integrals, 3) the integrals of absolute acceleration in x-, y-, and z-direction squared, 4) the sum of these squared integrals, 5) the integral of the magnitude of the total acceleration vector, 6) the integral of the acceleration vector squared, 7) mean kinetic energy (x, y, z, x+y+z), and 8) mean power, due to the rate of change in kinetic energy (x+y+z). Instantaneous power values were first rectified before a mean value was derived, assuming the metabolic energy cost of positive and negative work rates to be equal. All accelerometer output variables were used in a regression analysis with EE_{act}. Pooled (n=11) as well as individual (n=1) regression equations and correlation coefficients (Pearson's r) were calculated for sedentary activities, walking, and all activities together.

RESULTS

Analog acceleration signals were comparable in each subject, although interindividual variations were observed due to differences in performance of activity, especially during sedentary activities. During sedentary activities EE_{act} was most accurately predicted by the sum of the integrals of absolute acceleration from all three measurement directions, IAA_{tot}, given by:

$$IAA_{tot} = \int_{t=t_0}^{t_0+T} |a_x|\,dt + \int_{t=t_0}^{t_0+T} |a_y|\,dt + \int_{t=t_0}^{t_0+T} |a_z|\,dt \quad (1)$$

with a_x, a_y, and a_z the magnitude of the accelerations, measured in x, y, and z direction and T the integration interval. Individual correlations varied from 0.71 to 0.99. Using the pooled data of all subjects the correlation between EE_{act} and IAA_{tot} was 0.82 (p<0.001). The contribution of the integrals of absolute acceleration from the 3 measurement directions (IAA_x, IAA_y, IAA_z) to IAA_{tot} is shown in fig. 1. During walking the best predictor of EE_{act} was the integral of absolute acceleration measured in antero-posterior direction, IAA_x:

$$IAA_x = \int_{t=t_0}^{t_0+T} |a_x|\,dt \quad (2)$$

In each subject a strong linear relationship between EE_{act} and IAA_x was found (r=0.96-0.99). A correlation of 0.96 was found for the entire group (p<0.001). Fig. 2. shows IAA_x, IAA_y, and IAA_z during walking. Although IAA_x was the best predictor of EE_{act} for each walking velocity, the major acceleration component during each stage was in the z-direction.

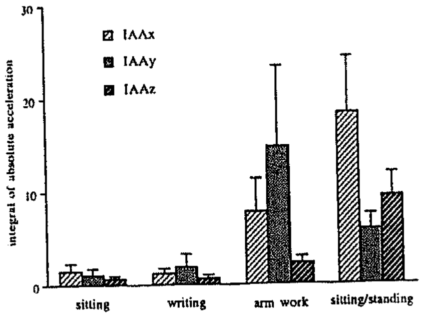

Fig. 1. IAA_x, IAA_y, and IAA_z (mean and SD) during sedentary activities.

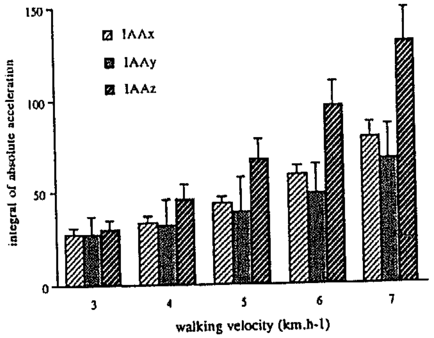

Fig. 2. IAA_x, IAA_y, and IAA_z (mean and SD) during walking.

EE_{act} was highly correlated to both IAA_x and IAA_{tot} when data from all activities were used. Individual correlations ranged from 0.97 to 0.99 for EE_{act} versus IAA_x and from 0.96 to 0.99 for EE_{act} versus IAA_{tot}. Pooled correlations were 0.97 and 0.95 respectively. However, the unidirectional variable IAA_x underestimated EE_{act} during sedentary activities on the average by 60%, while IAA_x estimated EE_{act} during walking within 4% accuracy. Using the three-directional variable IAA_{tot} individual EE_{act} during sedentary activities as well as walking was estimated with an accuracy of 15%. Fig. 3. shows the pooled scattergram for EE_{act} versus IAA_{tot}. Separate regression lines for sedentary activities, walking, and all activities together are indicated. Although the prediction of EE_{act} in walking is less accurate using IAA_{tot} instead of IAA_x, the three-directional variable meets the multidirectional characteristics of human movement. Moreover, a single regression equation between EE_{act} and IAA_{tot} can be used to assess the metabolic cost of both sedentary activities and walking in the individual. Since these activities represent the major part of normal daily physical activity, it was suggested that the TA could be used to predict EE_{act} in free living subjects. Therefore, a portable data acquisition unit - calculating IAA_{tot} - was developed to study the validity and usefulness of the method under daily living conditions. Note that regression lines for walking and all activities together coincide.

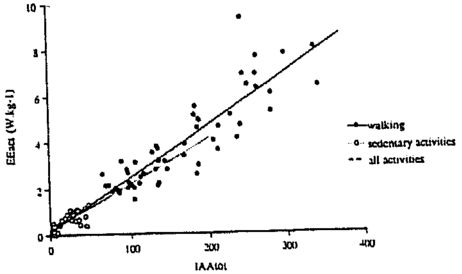

Fig. 3. Pooled scattergram and regression lines for EE_{act} vs IAA_{tot} during sedentary activities (..), walking (-), and all activities together (-). Regression lines for all activities and walking coincide.

VALIDATION OF THE METHOD DURING STANDARDIZED DAILY ACTIVITY

METHOD

Eight young adult male subjects (age: 25±3 yrs; weight: 83±11 kg; height: 185±5 cm) stayed in a respiration chamber for two nights and the intervening day. This chamber is provided with equipment to determine O_2 and CO_2. It measures 14 m^3 and is furnished with a bed, chair, table, TV, radio, telephone, wash-bowl, and toilet facilities. During daytime [8:30 - 22:00 h] the subjects followed a standardized activity protocol, consisting of sedentary activities (desk work, TV watching), household activities (making the bed, cleaning, dish washing), and some exercise tests (bench stepping, walking, moving objects). All activities were performed for 30 min. Mean total energy expenditure was determined for each activity. Mean EE_{act} ($W \cdot kg^{-1}$) for each activity was calculated from total energy expenditure minus sleeping metabolic rate. After the exercise tests subjects sat quietly or laid down on the bed to allow oxygen consumption to return to resting values. Body accelerations were measured with the TA on the low back from getting up in the morning until bedtime. Accelerometer output was modified and stored in a portable data acquisition unit (15x8x3 cm; 340 gram). A block diagram showing the data acquisition is given in fig. 4. Shortly, acceleration signals from all three measurement directions are amplified and high- (0.11 Hz) and low-pass (20 Hz) filtered to attenuate DC-response and frequencies that cannot be expected to arise from voluntary human movement. Next, acceleration signals are rectified and summed. Signals are integrated using a voltage-to-frequency converter. Each 67.1 s the output of the converter - referred to as 'activity counts' - is determined with a counter and stored in a 2kB, 8 bit memory chip. The integration interval is controlled by a timer and depends on the crystal (1.0 MHz; $T=1/[1.0\ MHz/2^{26}]$) in the timer. To calibrate the accelerometers in the TA the high-pass filter can be switched off, using the DC response to obtain the sensitivity per *g*.
Activity counts can be read out with a parallel interface and further processed on a computer. Two 9V, 500 mAh batteries for the accelerometers and the data acquisition are carried within the housing of the unit.
Mean activity count (counts · min^{-1}) was calculated for each activity and correlated against EE_{act}. Pooled (n=8) as well as individual (n=1) regression equations between activity counts and EE_{act} for the total activity protocol were calculated.

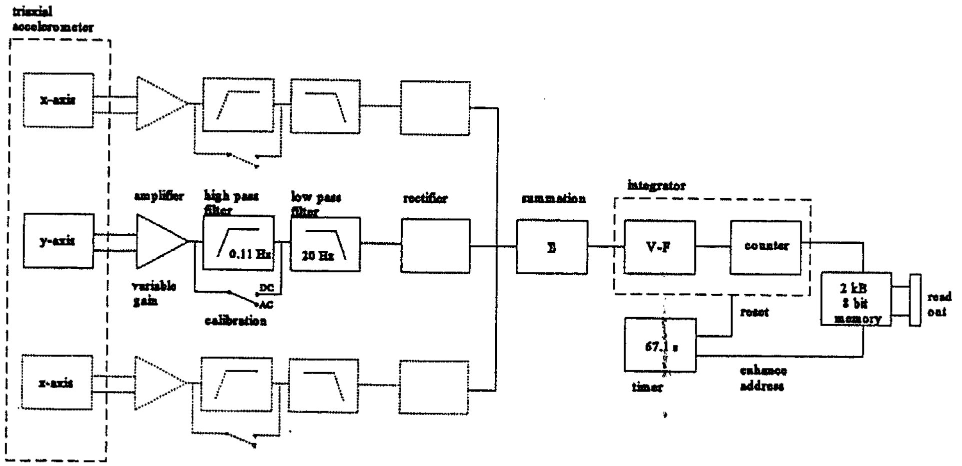

Fig. 4. Block diagram of the data acquisition unit

RESULTS

Although the activity protocol was standardized, the performance of some activities, especially household activities, differed among subjects. Therefore relatively large interindividual variations in EE_{act} as well as activity counts were seen. Individual correlations between EE_{act} and activity counts ranged from 0.73 to 0.94. Pooled correlation for EE_{act} versus activity counts was 0.89. Using the individual regression equations between EE_{act} and activity counts 0.54 to 90% of the variance in EE_{act} could be explained from accelerometer output. Using the pooled regression equation 80% of the energy cost for physical activity could be explained from activity counts. The pooled scattergram for EE_{act} versus activity counts is shown in fig. 5.

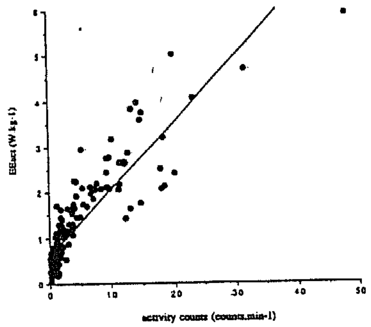

Fig 5. Pooled scattergram and regression line for EE_{act} vs activity counts during the standardized activity protocol.

DISCUSSION

This study was conducted to evaluate the relationship between EE_{act} and body accelerations registered during sedentary activities and walking and to validate the use of a body fixed triaxial accelerometer for the assessment of EE_{act} during standardized daily physical activity. The best predictor of EE_{act} was obtained by integration of absolute accelerometer output. The results did not support the hypothesis of a quadratic relationship between EE_{act} and the integral of absolute acceleration being superior to a linear relationship between these variables. Also, EE_{act} could not be predicted from measures of kinetic energy or power. This might be due to the fact that kinetic energy due to rotation or work against gravity cannot be calculated from accelerometer output. In addition, the sensitivity of the accelerometers to gravitational acceleration prevents the calculation of velocity from simple integration. During sedentary activities the most accurate estimation of EE_{act} was obtained by IAA_{tot}. It is not surprising that this three-directional variable provided the best prediction of EE_{act}, as movements in three planes were incorporated in the activities. During walking the most accurate prediction of EE_{act} was achieved by IAA_x. In earlier studies IAA_z was used for the assessment of EE_{act} in exercises like walking and running, because the major acceleration component during these activities is in the vertical direction (Haymes & Byrnes, 1991; Wong et al., 1981). Although we agree that the major acceleration component during walking is in the vertical direction (fig. 2.), EE_{act} during walking is better predicted from the integral of absolute acceleration in antero-posterior direction. The high accelerometer output in vertical direction can be explained from peak accelerations occurring during heel strike, which are more prominent in z- than in x-, and y- directions. Peak accelerations are caused by the impact between foot and walking surface and not produced by voluntary movement, resulting in energy expenditure. Therefore, EE_{act} might not be proportional to IAA_z. Different relationships between EE_{act} and accelerometer output were found for sedentary activities and walking when EE_{act} was correlated against the unidirectional variables IAA_x, IAA_y, and IAA_z. These findings correspond with Servais et al. (1984) who report that calibration of a uniaxial accelerometer, measuring IAA_z over a range of activities, is different for each activity. When the three-directional variable IAA_{tot} was used in our study, more similarity between EE_{act} versus accelerometer output relationships during sedentary activities and walking was obser-

ved. A correlation of 0.95 was found between EE_{act} and IAA_{tot} for the pooled data of sedentary activities and walking in all subjects, implicating that 90% of the variance in EE_{act} could be explained from IAA_{tot} (r^2 = 0.90). The predicted variance is higher than that reported by other authors (Meijer et al., 1989) and higher than found during the long term evaluation of the method in a respiration chamber. Here 80% of the variance in EE_{act} was explained from activity counts. During the standardized protocol EE_{act} might be underestimated in activities that involve static exercise, like making the bed or moving objects. During static exercise accelerometer output probably is not proportional to EE_{act}. Furthermore, the gravitational component superimposed on the measured body accelerations may cause over- or underestimation of EE_{act} in activities that involve bending of the trunk. Part of this effect was eliminated using the high-pass filter in the data acquisition unit, but the gravitational component might affect EE_{act} when rotations of the trunk occur frequently (f > 0.11 Hz).
Bouten et al. (unpublished data) studied the influence of the gravitational component on the estimation of EE_{act} with two accelerometers (x- and z-direction) on the low back during walking at 3 to 7 km · h^{-1}. The inclination of the accelerometers with respect to the gravitational axis of the earth was determined using video registration. Predictions of EE_{act} were on the average 4% more accurate when accelerometer output was corrected for the gravitational components before conversion to the integral of absolute acceleration. However, the rotations of the trunk during walking are relatively small (-5° to 5°) and the observations were restricted to the sagittal plane. Therefore, care must be taken in generalizing these results to normal daily activity.

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MEASUREMENT OF ENERGETIC ASPECTS OF HABITUAL PHYSICAL ACTIVITY

- development of an energy monitor -

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Abstract - In exercise physiology oxygen consumption (VO2max) measured during steady state exercise is used as the golden standard for energy output. In steady state the speed of physical activities such as walking, running and cycling, is linearly related to energy expenditure. Assuming a certain mechanical efficiency, the power output can be estimated from the oxygen uptake (VO2). However, there are several restrictions to the continuous measurement of oxygen consumption during daily physical activities. Therefore there is a great need in simple instruments to estimate power output from habitual physical activities. Accelerometers are very promising because acceleration of the whole body and/or body segments are highly correlated with the intensity and energy output of habitual physical activities. The purpose of this study is to start with a pattern recognition from accelerometry of body fixed sensors in three types of physical activities .
In a pilot experiment subjects performed (1) walking at two speeds, (2) horizontal running at three speeds, and (3) bicycling with three combinations of load and pedal revolutions. The sensors were placed on the sternum (vertical and horizontal) and on the upper leg.
The results showed that the three types of activities could be recognized. This pilot was restricted to a limited number of daily physical activities and these results have to be confirmed outside the laboratory where subjects can perform the same activities with different speeds in real life situations.

INTRODUCTION

The amount of energy spent during daily life has proven to be an important factor in the development of chronic diseases such as cardiovascular diseases, cancer, diabetes and chronic obstructive pulmonary diseases. Powell et al (1987) and Berlin et al (1990) have summarized the epidemiological evidence for an indirect or direct causal relationship between physical activity on the one side and morbidity and mortality of cardiovascular diseases on the other side. The protective mechanism of physical activity is probably not only the duration and frequency but also the intensity of the physical activities. Therefore, there is a need for measuring the energy output per time unit of physical activities. In exercise physiology oxygen consumption (VO2) is used as the golden standard for energy expenditure. In steady state exercise the intensity of daily physical activities such as walking, running, bicycling and stair climbing shows a linear relationship with VO2 (Åstrand et al, 1986) and the energy expenditure can be estimated from the caloric equivalent of VO2 (Montoye et al, 1994). However, there are several restrictions to the monitoring of VO2: it is very costly, it limits the duration of the measurement period, it hampers the subject in his own physical activity and not-steady state exercise is under - or overestimated. Therefore, there is a great need for more simple instruments to estimate energy expenditure during daily living.
Accelerometers are promising because (1) acceleration of whole body and/or body parts are highly specific for the type of physical activity and (2) acceleration of whole body and body segments are linearly related with the intensity and energy expenditure of a