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A triaxial accelerometer for the assessment of daily physical activity in relation to energy expenditure

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Abstract - The use of accelerometers for the assessment of daily physical activity looks promising. This method is based on a demonstrated relationship between energy expenditure due to physical activity and acceleration measured on the human body. A triaxial accelerometer, based on three uniaxial piezoresistive accelerometers, was developed to evaluate the relationship between accelerometry and energy expenditure during sedentary activities and walking. Special attention was paid to the analysis of unidirectional and three-directional accelerometer output. It was concluded that the sum of the integrals of absolute acceleration from the three measurement directions can be used for the assessment of energy expenditure due to physical activity in situations of daily living. This variable was highly correlated with energy expenditure when all examined activities were considered together ($r = 0.95$). It was a good estimator of energy expenditure during walking ($r = 0.88$) and during sedentary activities ($r = 0.82$), which represent the major part of the daily physical activity pattern.

INTRODUCTION

Investigation of the relationship between daily physical activity and health requires an objective, valid and reliable technique for measuring physical activity under free living conditions with minimal discomfort to subjects. Regarding these demands, the use of recently developed accelerometers looks promising [1]. Data from previous research suggest a linear relationship between energy expenditure due to physical activity (EEact) and the integral of absolute acceleration measured on the human body [2], [3]. However, this relationship seems to vary between different types of activities [4]. Furthermore, from a theoretical point of view the linearity of the relationship is questionable. 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 more directly related to the metabolic energy cost of movement, a quadratic relationship between the integral of absolute acceleration and EEact is expected. The primary aim of this study was to evaluate the relationship between accelerometry and EEact during different types of activity and to find a way of analyzing accelerometer output that can be used to assess EEact in free living subjects. This was done in a laboratory experiment, in which subjects performed sedentary and walking activities. Accelerations were measured with a new developed triaxial accelerometer (TA), based on three orthogonally mounted uniaxial accelerometers, to investigate the relative contribution of different measurement directions to the estimation of EEact.

METHODS

Eleven healthy male subjects (age $23 \pm 2$ yr, weight 68 ± 10 kg, height 183 ± 7 cm) performed the following activities for 3 min each: 1) sitting relaxed, 2) sitting and writing, 3) sitting and lifting a 1.1 kg iron disk alternately with left and right arm, 4) alternately sitting and standing for 10 s each, 5-9) walking at five different speeds (3, 4, 5, 6, 7 km·h$^{-1}$) on a motor driven treadmill. During the activities continuous recordings of $O_2$ consumption, $CO_2$ production and TA output were made. Gross energy expenditure during the activities was determined from mean $O_2$ and $CO_2$ during the last min of each activity stage. By subtraction of the sleeping metabolic rate, as determined in an overnight sleep in a respiration chamber, EEact ($J \cdot s^{-1} \cdot kg^{-1}$) was calculated.

Fig. 1. Triaxial accelerometer

The TA [Fig. 1] consisted of three piezoresistive accelerometers (ICSensors 3031-010, size 4 x 4 x 7 mm, weight 0.3 gram, range ± 10 g, frequency response 0-600 Hz, $f_p$ 1200 Hz), mounted orthogonally onto a lightweight cube (A), which was placed on a small plate (B) with two slits for an elastic belt (C), worn around the waist. Using this belt the TA was firmly attached to the low back. Accelerations were measured in medio-lateral (x), antero-posterior (y), and vertical direction (z).
Bridge amplifiers and batteries were carried in separate units on both hips. Interconnection to the TA was established via a 12 conductor shielded cable (D). Amplifier gains were adjusted to produce an output of 1 V · g⁻¹ for each measurement direction. Analog accelerometer output of all three directions was digitized (100 Hz), low-pass filtered (20 Hz), corrected for DC-response, and processed in various ways over a 30 s time interval of each activity stage to obtain: 1) the integral of absolute acceleration in x, y, and z direction, and the sum of these three integrals, 2) the integral of absolute acceleration in x, y, and z direction squared, and the sum of these squared integrals, 3) the integral of the total acceleration vector, 4) the integral of the total acceleration vector squared, 5) mean kinetic energy (x, y, z sum), and 6) mean power due to the total change in kinetic energy. All accelerometer output variables were correlated against EEₜ₉. Regression equations were calculated for sedentary activities, walking, and all activities together.

RESULTS AND CONCLUSION

During sedentary activities the highest correlation was found between EEₜ₉ and the sum of the integrals of absolute acceleration from all three measurement directions, IAAₜ₉ (r = 0.82, p < 0.001), defined as:

$$IAA_{tot} = \int_0^{30} a_x \, dt + \int_0^{30} a_y \, dt + \int_0^{30} a_z \, dt$$  (I)

where aₓ, aᵧ, and aₑ represent acceleration in x, y, and z direction and integration is performed over a 30 s time interval.

EEₜ₉ during walking could be predicted by the integral of absolute acceleration in antero-posterior direction, IAAₓ (r = 0.96, p < 0.001), defined as:

$$IAA_x = \int_0^{30} a_x \, dt$$  (II)

Both accelerometer output variables were highly correlated with EEₜ₉ when pooled data of all examined activities were used in a regression analysis (r = 0.97 and r = 0.95 respectively, p < 0.001). However, the regression equation between EEₜ₉ and IAAₓ for all activities underestimated energy expenditure due to sedentary activities by more than 60 %, while energy expenditure due to walking was estimated with an accuracy of 3%. When the regression equation between EEₜ₉ and IAAₜ₉ for all activities was used, energy expenditure due to sedentary activities as well as walking could be estimated with an accuracy of about 15%. The relationship between EEₜ₉ and IAAₜ₉ is shown in Fig. 2.

Besides IAAₓ and IAAₜ₉ no other accelerometer output variable was found to show a clear relationship with EEₜ₉, thus no evidence was found for the hypothesis of a quadratic relationship between accelerometer output and EEₜ₉. The accelerometer output variable that can be used for the assessment of physical activity under free living conditions seems to be IAAₜ₉. A single regression equation between this three-directional variable and EEₜ₉ can be used to assess the metabolic cost of walking and of sedentary activities, which represent the major part of daily physical activity in modern Western society [5]. Based on this conclusion the prototype of a portable data acquisition and memory unit is designed to validate the method under daily living conditions.

Fig. 2. Scattergram and regression line for energy expenditure (EEₜ₉) versus the sum of the integral of absolute acceleration in x, y, and z direction (IAAₓ).

* : sedentary activities, ■ : walking

The regression line is determined using data of all activities (n = 98, r = 0.95, $S_{xy} = 0.7 \, J \cdot s^{-1} \cdot kg^{-1}$).

REFERENCES