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Accelerometry and Energy Expenditure in Obese Adults and Normal Weight Controls

Accelerometrie und Energieverbrauch bei adipösen Erwachsenen und normalgewichtigen Kontrollpersonen

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ZUSAMMENFASSUNG

Fragestellung: Die Studie evaluiert ein neues triaxiales Accelerometer zur Vorhersage des Energieverbrauchs, gemessen als VO_2/kg, bei adipösen und normalgewichtigen Erwachsenen während Alltagsaktivitäten. Methoden: 37 adipöse Erwachsene (Body Mass Index (BMI) 37±5,4) und 17 normalgewichtige Kontrollpersonen (BMI 23±1,8)) führten acht verschiedene Aktivitäten während 5 bis 8 Minuten durch. Dabei trugen sie am rechten Oberschenkel (unterhalb Hüftgelenk) ein triaxiales Accelerometer zur Messung der bewegungsinduzierten Accelerometereinheiten (AE) (DiaTrace System). Zeitgleich erfolgte die Messung der Sauerstoffaufnahme (VO_2) und Kohlendioxidabgabe (VCO_2) mittels eines tragbaren Spiroergometrie-Systems. Die Beziehung zwischen AE und VO_2/kg wurde mittels Spline-Regression und linearen gemischten Modellen analysiert. Ergebnisse: Für alle Aktivitäten wiesen die Adipösen eine niedrigere VO_2/kg auf als die Normalgewichtigen. Für beide Gruppen zeigte sich eine lineare Beziehung zwischen AE und VO_2/kg für AE-Werte zwischen 0 und 300 Einheiten/min mit einer Zunahme des VO_2/kg von 3,7 ml/min (95%-Vertrauensintervall (VI) 3,4-4,1) bei adipösen und 3,9 ml/min (95%-VI 3,4-4,3) pro 100 AE bei normalgewichtigen Personen. Die lineare Modellierung des gesamten AE-Wertebereiches zeigt grosse Vorhersage-Intervalle von ±6,3 ml/min bei Adipösen und ±7,3 ml/min VO_2/kg bei Normalgewichtigen. Fazit: Es ist bei Adipösen wie Normalgewichtigen nur begrenzt möglich, mittels AE den Energieverbrauch, definiert als VO_2/kg, für Alltagsaktivitäten von variierenden Intensitäten und Formen der Muskelarbeit vorauszusagen.

Schlüsselwörter: Accelerometrie, Alltagsaktivitäten, Energieverbrauch, Adipositas.

SUMMARY

Objective: To evaluate a new triaxial accelerometer device for prediction of energy expenditure, measured as VO_2/kg, in obese adults and normal-weight controls during activities of daily life. Subjects and methods: Thirty-seven obese adults (Body Mass Index (BMI) 37±5.4) and seventeen controls (BMI 23±1.8) performed eight activities for 5 to 8 minutes while wearing a triaxial accelerometer on the right thigh. Simultaneously, VO_2 and VCO_2 were measured using a portable metabolic system. The relationship between accelerometer counts (AC) and VO_2/kg was analysed using spline regression and linear mixed-effects models. Results: For all activities, VO_2/kg was significantly lower in obese participants than in normal-weight controls. A linear relationship between AC and VO_2/kg existed only within accelerometer values from 0 to 300 counts/min, with an increase of 3.7 (95%-confidence interval (CI) 3.4-4.1) and 3.9 ml/min (95%-CI 3.4-4.3) per increase of 100 counts/min in obese and normal-weight adults, respectively. Linear modelling of the whole range yields wide prediction intervals for VO_2/kg of ±6.3 and ±7.3 ml/min in both groups. Conclusion: In obese and normal-weight adults, the use of AC for predicting energy expenditure, defined as VO_2/kg, from a broad range of physical activities, characterized by varying intensities and types of muscle work, is limited.

Key Words: Accelerometer, physical activity, energy expenditure, obesity.

INTRODUCTION

Accelerometers provide a measure of physical activity and are increasingly being used in research and in the population (20). Previous studies calibrated records of accelerometer counts (AC) in a given time interval against measured energy expenditure (VO_2; METs [metabolic equivalent]) during a variety of activities (15,21). Regression equations to estimate MET values from AC were created and categories defining sedentary, easy, moderate and vigorous activity were generated (8,19). However, despite the widespread use of accelerometers, the relation between AC and exercise energy expenditure in obese adults has rarely been assessed in obese adults (6,14). Recently a triaxial accelerometer has been developed for integration into a mobile phone. The phone is equipped with specialized software (DiaTrace System (2)) that allows the recording of acceleration data and offers mobile assistance in supporting exercise behaviour in daily life.

This study sought to evaluate a new triaxial accelerometer device for prediction of energy expenditure, measured as VO_2/kg, by

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accelerometer counts (AC) in obese adults and normal weight controls during eight activities of daily life.

SUBJECTS AND METHODS

The Fraunhofer-Institut für Graphische Datenverarbeitung, Rostock, Germany provided the recording software (DiaTrace System) for the assessment of triaxial accelerometer data (2).

Study population

Thirty-seven obese adults were recruited from a 3-year outpatient weight loss program of the University of Bern. Seventeen normal weight individuals served as control group (Table 1). Inclusion criteria were: Age 18 to 63 years; Body mass index (BMI) 30 to 50 for the obesity group and BMI 20 to 25 for the control group. Exclusion criteria were: Diagnosed coronary artery disease with exercise induced myocardial ischemia; diagnosed left ventricular dysfunction, heart failure and symptomatic peripheral occlusive vascular disease; reduced haemoglobin level; untreated arterial hypertension; obstructive lung problems (FEV_1%VC < 70); musculoskeletal disorders that limit physical activities to be assessed; significant atrial and/or ventricular arrhythmia.

Study procedures

The study protocol was approved by the local Ethics Committee of the University of Bern, Switzerland. Prior to participation, obese and normal weight individuals signed an informed consent.

Physical activities

Physical activities to be assessed (Table 2) were performed in a random order. The activities were chosen to provide a variety of intensities from sedentary to moderate-vigorous, and to reflect typical activities of daily life, including "lifestyle" activities, general housework activities and leisure activities for relaxation. Between activities, a resting phase of 10 minutes was inserted.

Equipment and parameters assessed

The hardware of the accelerometer features an STMicroelectronics triaxial sensor (ST LIS302DL), a sampling rate of 20 Hz, 2^6bit/g quantization and a measuring range of ±2 g (2). The data assessment software (DiaTrace System) provides sensor raw data and in addition a metric for physical activity without the offset of gravity or influence of orientation. The accelerometer measures the physical force at the fixation point for each axis (ax, ay, az), subtracts the gravity influence and computes the physical force in AC by the following equation:

$$AC = \frac{\sqrt{a_x - \bar{a}_x)^2 + (a_y - \bar{a}_y)^2 + (a_z - \bar{a}_z)^2}}{t}$$

The gravity offset can be achieved by the moving average operation for each axis:

$$\bar{a}_{xn} = (1 - m) * a_{xn-1} + m * a_x$$

For the sampling rate of 20 Hz we defined m = 0.01 which allows a dynamic offset compensation. For further processing, all recorded acceleration raw data tuples were stored with a time stamp. Because the acceleration sensor provides only discrete data, the AC were normalized to a second and summarized in an epoch of 3.2 seconds. The AC is SI-conform and measured in m/s3:

$$AC = \sum_{n=1}^{64} \frac{\sqrt{a_{xn} - \bar{a}_x)^2 + (a_{yn} - \bar{a}_y)^2 + (a_{zn} - \bar{a}_z)^2}}{20}$$

The most frequent location of carrying a mobile phone is the front trouser pocket (13). Therefore, participants wore the accelerometer attached to a belt at the right thigh 15 cm below the Spina iliaca anterior superior during all activities.

Oxygen uptake and CO_2 production were measured breath by breath by means of a portable metabolic unit (Metamax; Cortex Company, Leipzig, Germany). The heart rate was measured by a Polar heart rate transmitter unit. Additionally, rating of perceived exertion (RPE; Borg scale 6-20) was assessed at the end of each activity, except for resting and sitting/watching TV.

Table 1: Characteristics of obese and normal weight participants.

	Obese participants (N = 37)		Normal weight controls (N = 17)		
	Mean (SD)	Range	Mean (SD)	Range	p value
Age (years)	41 ± 11	22-63	37 ± 15	18-60	0,24
Height (cm)	166 ± 7	147-180	167 ± 8	154-182	0,63
Weight (kg)	103 ± 15	76-136	63 ± 6	50-74	< 0.001
Circumference (cm)	114 ± 12	90-141	83 ± 7	71-94	< 0.001
BMI (kg/m²)	37.1 ± 5.4	30-49	22.6 ± 1.8	20-25	< 0.001

Table 2: Description of physical activities with total exercise time in brackets.

Activity	Description
Lying	Lying on bed, semi-supine position, awake; dimly lit, quiet room (8 min)
Watching TV	Quiet sitting in a chair, watching television (8 min)
Vacuum cleaning	Vacuum cleaning (40 m² carpet using vacuum cleaner), speed as used to do (8 min)
Slow walking	Treadmill, plane level, 3.0 km/h (8 min)
Walking at slope	Treadmill, 5 % grade, 3.0 km/h (8 min)
Cycling	Cycle ergometer, steady state, 60-65 % peak VO_2 (8 min)
Carrying 2 grocery bags while walking	Weight load of each bag is 2.5 kg, self-determined walking speed (5 min)
Push-ups at wall	Standardized performance, one repetition per 5 sec (5 min)

Study preparation

Prior to study entry, all participants underwent a ramp treadmill test (Woodway, Weil/Germany) to determine peak VO_2. Three hours prior to assessment, participants were not allowed to smoke or eat, except drinking fruit tea and water. One hour before starting the measurements, participants were introduced to the study equipment and procedure. Before starting the assessment, the accelerometer and the metabolic unit were synchronized. Accelerometer data, data on gas exchange and data on heart rate were documented every three seconds. During all study activities, participants were accompanied by two trained staff members, who were responsible for speed and/or intensity control of the exercise.

Data preparation

All data were checked for correct synchronization between AC and

VO_2/kg measures. To assure a steady-state phase of all measurements during each activity, values collected during the first two minutes and the last 30 seconds of each 5- and 8-minute activity were discarded. To address measurement errors of the heart rate transmitter, heart rate values above 180 beats/min (0.2 % of all observations) and values below 50 beats/min for resting activities (lying; watching TV) or 60 beats/min for remaining activities (0.7 % of all observations) were discarded.

For biological reasons, there is a time lag between the activity as immediately measured by the accelerometer and the resulting energy expenditure. Therefore, averages of each measurement were calculated for the constant phase of each activity within each patient and then used for the statistical analysis.

Statistical analysis

Baseline characteristics, AC and VO_2/kg of obese and normal weight participants were compared using unpaired t-tests. To characterize the relationship between AC and VO_2/kg over a range of activities of different intensities, an explorative cubic spline regression with knots at 0, 200, 400, 600, and 1000 counts/min was calculated and plotted separately for both groups. Linear mixed-effects regression analyses were performed for both groups accounting for the dependence among repeated measurements within the same subject and controlling for age and BMI, once for an accelerometer range of 0 to 300 counts/min and once for the whole range. A scatter plot was drawn with separate linear regression lines and corre-sponding 95 %-prediction intervals for each group. The effect of the different types of activities on the relationship between AC and VO_2/kg is depicted by a scatter plot with different markers for each type of activity. Moreover, a linear mixed-effects regression was calculated that also accounted for the type of activity. All P-values and 95 %-confidence intervals (CI) are two-sided. P-values < 0.05 are considered significant. All analyses were done using Stata 11 (Stata Corporation, College Station, Texas).

RESULTS

Energy expenditure in obese compared to normal weight adults

With the exception of two exercises (cycling and push-ups), the respiratory exchange rate (RER) was always within the aerobic range (between 0.80 and 0.87) in both obese and normal weight adults. When cycling, the mean RER was 0.95 in both groups. For push-ups, the mean RER was 0.93 and 0.95 in normal weight and obese adults, respectively. For all exercises, there were no significant differences in RER between groups.

For all physical activities, including watching TV and lying down, the obese individuals demonstrated significantly higher absolute values of VO_2l/min. The mean difference was lowest for lying, at 8 %, and highest for walking at slope, at 35 %. On the contrary, except for walking at slope, obese patients exhibited significantly lower VO_2/kg values than normal weight individuals. This is also true for cycling despite the fact that both groups performed the exercise at the same relative work load (64 % of peak VO_2, Fig. 1a) and the same RPE of "somewhat hard".

For all activities, energy expenditure expressed as kJ/10min was significantly higher in the obese compared to the normal

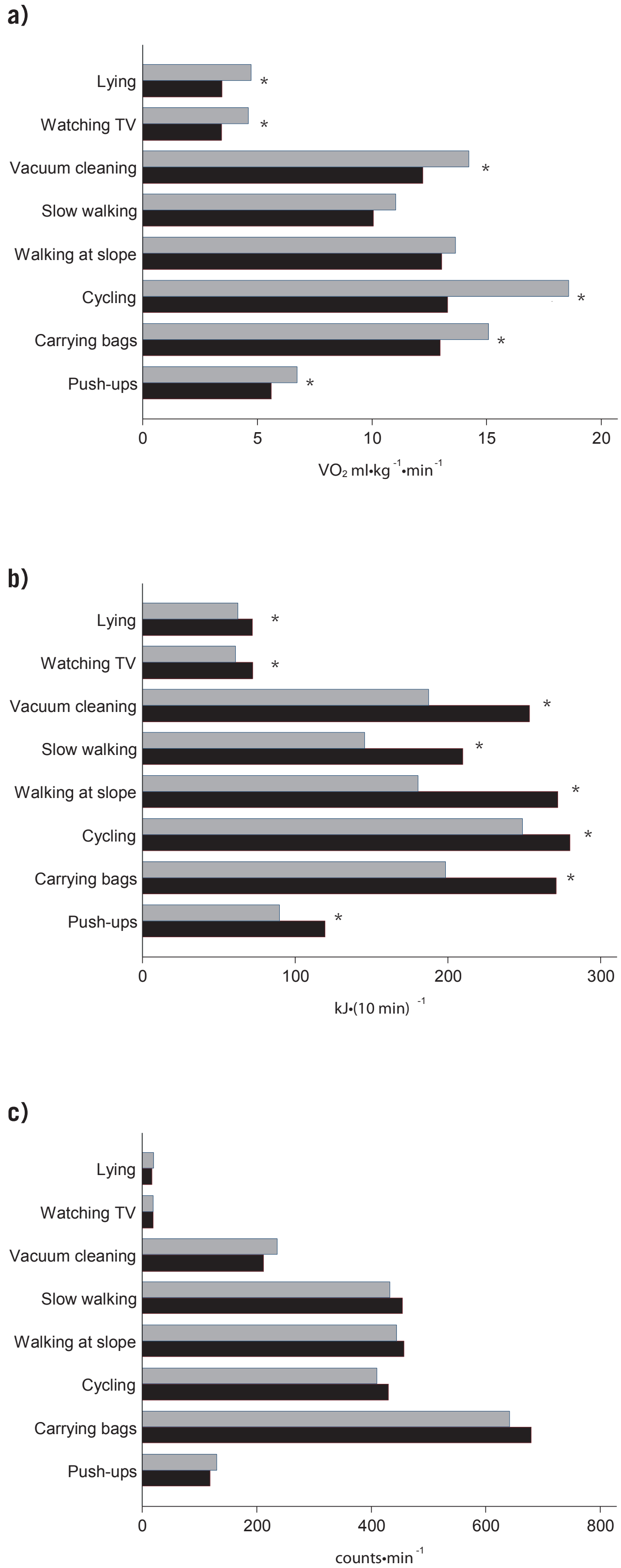

Figure 1: Comparison of measures (mean) of energy expenditure (a, b) and accelerometer activity counts (c) between obese adults (black bars) and normal weight adults (grey bars) for different activities. * denotes a significant difference between the two groups as shown by an unpaired t-test.

weight group (Fig. 1b) (range of increase between 13% for sitting and lying, and 66% for walking at slope).

AC per minute varied considerably by type of exercise, with no statistically significant difference between the obese and normal weight groups (Fig. 1c).

Relationship between physical activity and energy expenditure

A linear relationship between AC and energy expenditure (VO_2/kg) only exists at lower AC up to a threshold of about 300 counts/min (Fig. 2). An adjusted mixed-effects linear regression within this range demonstrated a significant relationship between AC and VO_2/kg in both the obese and normal weight adults (Table 3a). The VO_2/kg increased by 3.7 ml/min (95%-CI 3.4-4.1) in obese and 3.9 ml/min (95%-CI 3.4-4.3) in normal weight participants if AC increased by 100 counts/min. Age and BMI had a significant effect on the AC only in obese patients. When modelling the whole AC range linearly (Table 3b and Fig. 2), the relationship with VO_2/kg remained highly significant in both groups, with narrow confidence intervals around the regression lines (±0.5 and ±0.9 ml/min in obese and normal-weight participants, respectively), but rather wide prediction intervals (±6.3 and ±7.3 ml/min, respectively).

When additionally correcting for the type of activity in the regression analysis, the association between AC and VO_2/kg diminished, and the extent of energy expenditure was mostly explained by age, BMI and type of activity for obese subjects and by type of activity for normal weight adults (data not shown). Compared to lying down, all activities except watching TV resulted in an increase in energy expenditure in both groups. Fig. 3 shows the distribution of the different types of ac-tivities in relation to AC and VO_2/kg. In both groups, lying and watching TV resulted in low AC and low VO_2/kg. Vacuum cleaning resulted in rather low AC but fairly high VO_2/kg. Comparing the distributions of slow walking with walking at slope reveals that both activities resulted in similar AC (approximately 450 counts/min), but led to very different VO_2/kg values (Fig. 3).

Table 3: Relationship between accelerometer counts (AC) and energy expenditure (VO_2/kg) for obese and normal weight participants assessed by mixed-effects linear regression. The effects show the increase in VO_2/kg (ml/min) per increase in the dependent variables (AC, age and BMI).

	Obese participants (N = 37)		Normal weight controls (N = 17)	
	Effect (ml/min) (95%-CI)	p value	Effect (ml/min) (95%CI)	p value
3a) Adjusted for age and BMI within an AC range of 0-300 counts/min				
AC [per 100 counts/min]	3.74 (3.39 to 4.09)	< 0.001	3.88 (3.44 to 4.32)	< 0.001
Age [per 10 years]	0.38 (0.03 to 0.73)	0,03	-0.18 (-0.52 to 0.17)	0.31
BMI [per unit]	-0.13 (-0.20 to -0.05)	0.001	0.11 (-0.16 to 0.39)	0,42
3b) Adjusted for age and BMI over the whole AC range				
AC [per 100 counts/min]	1.40 (1.26 to 1.53)	< 0.001	1.80 (1.53 to 2.07)	< 0.001
Age [per 10 years]	0.59 (0.13 to 1.05)	0,01	-0.11 (-0.73 to 0.52)	0.74
BMI [per unit]	-0.16 (-0.26 to -0.07)	0.001	-0.10 (-0.59 to 0.40)	0.71

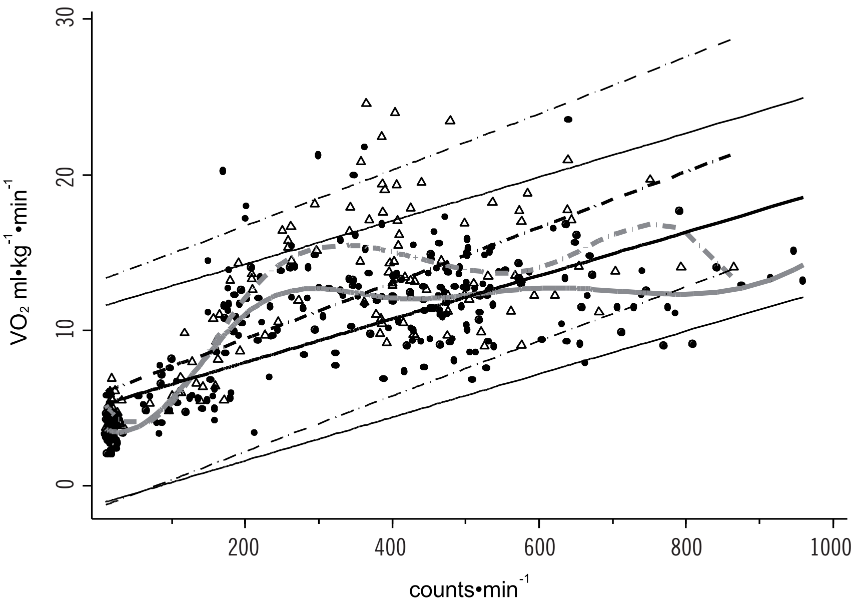

Figure 2: Scatter plot showing relationship between accelerometer counts and VO_2/kg for obese (solid circles) and normal weight adults (hollow triangles). Cubic spline regression lines are depicted as grey lines, linear regression lines with 95%-prediction intervals as black lines (obese: solid lines; normal weight adults: dash-dotted lines).

DISCUSSION

This study provides new insight into the relationship between accelerometer output and energy expenditure, expressed as VO_2/kg, in obese adults and normal weight controls. The assessed physical activities (Table 2) represented typical activities from the daily life of both obese and normal weight adults, and are characterized by dynamic concentric, dynamic-eccentric, and isometric muscle work.

Energy expenditure in obese compared to normal weight adults

For all activities including lying and sitting, obese adults exhibited higher absolute VO_2 but lower VO_2/kg values than adults with normal weight (Fig. 1a). The higher absolute VO_2 cannot only be explained by the absolute greater body mass but also by the greater effort of moving heavier legs contributing significantly to the oxy-gen cost as shown for cycling (17). The absolute VO_2/kg was 13% to 66% higher in obese than in normal weight adults, corresponding to a difference of 541 kJ per hour of activity (Fig. 1b).

Relationship between physical activity and energy expenditure

There exists a linear relationship between AC and VO_2/kg only at low AC (Fig. 2, Table 3a). Nevertheless, a significant linear relationship can be modelled over the whole AC range, but the fairly wide prediction intervals indicate that a prediction of energy expenditure from AC using this model equation is not appropriate. In the study of Treuth et al. (19), accelerometer and VO_2/kg measures showed a similar distribution as in our study, however, the authors only showed a 95%-CI.

When accounting for the type of activity, the association between AC and VO_2/kg diminished, and the extent of energy expenditure could mostly be explained by the type of activity. Therefore, recording the type of activity provided more information on the estimation of VO_2/kg than measuring the AC. The following example depicts the shortcomings of the AC: Vacuum cleaning and carrying grocery bags caused similar energy expenditure but obviously the pattern of movement was very different, which resulted in different AC.

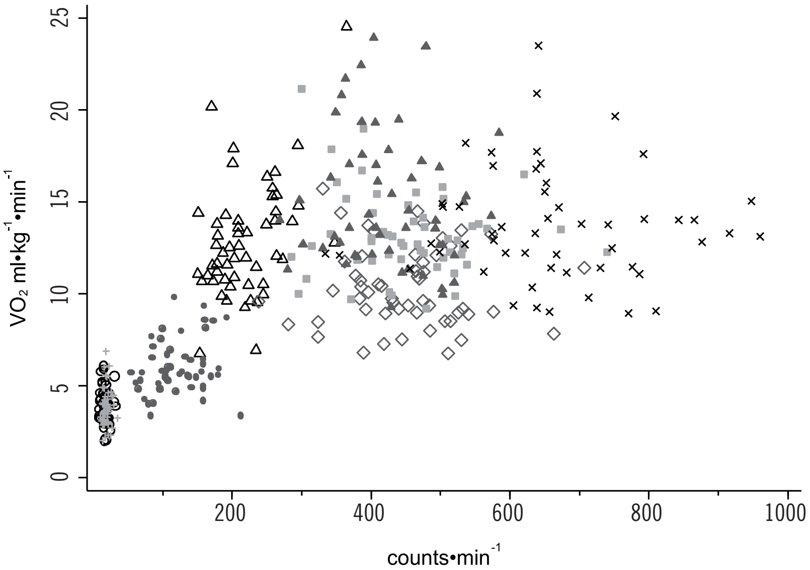

Figure 3: Scatter plot showing associations of the various types of activities with accelerometer counts and VO_2/kg. Activities: lying: hollow circle, watching TV: +, vacuum cleaning: hollow triangle, slow walking: hollow diamond, walking at slope: solid square, cycling: solid triangle, carrying grocery bags: x, push-ups on wall: solid circles.

The limited association between AC and VO_2/kg seems to be explained by two issues: the different types of muscle work generated by different modes of physical activity (i.e. dynamic-concentric and/or isotonic; dynamic-eccentric; isometric muscle work), and the location of the accelerometer. In normal weight adults, a closer correlation of AC and VO_2/kg was reported with rhythmic-dynamic activities such as walking and running (5,8,10,16) than with complex activities (12,21), which are characterized by multiple and non-axial movements of the body or limbs, and by complex types of muscle work (11,12). The more isometric muscle work is involved in physical activities, the less AC is measured for a similar VO_2/kg, and energy expenditure will thus be underestimated by AC. This seems to be independent of whether an accelerometer measures uniaxial or triaxial (14,21). Two triaxial accelerometers that were worn by obese adults over two weeks in everyday life and were simultaneously evaluated by a doubly labelled water method did not provide accurate estimates of activity-related energy expenditure at individual levels (14). In normal weight adults, the more varying physical activities and body movements are considered, the more inaccurate is the regression equation describing the relation between AC and VO_2/kg (15). In this context the location of wearing the accelerometer is relevant. The closer the accelerometer is located to the centre of gravity of the body, the less accurate physical activity can be measured by accelerometers. If the device is fixed at the hip, even small variations of location (e.g. the medial axillar line versus the Spina iliaca anterior) resulted in different AC for the same physical activity (18). The most frequent location of carrying a mobile phone is the front trouser pocket (13). In our study, participants wore the accelerometer attached to a belt, which is close to the trouser pocket. However, the two locations might still lead to differences in the movement pattern.

The aim of obtaining dependencies between metrical physical parameters and VO_2/kg as a measure of energy expenditure needs precise transformation of the given parameters for each individual and the current class of activity. Because of the sensor noise, the accuracy of the acceleration data is not sufficient to use kinematic relations, e.g. velocity or distance (1). Bouten et al. (4) are identifying a set of parameters; hereby the sum of the integral of the acceleration of each axis is a promising parameter for the correlation between physical activity and energy expenditure.

Recently, more sophisticated methods to predict energy expenditure from accelerometer data were published that also account for different types of activity (3,7,9). These studies suggest that in the future an artificial neural network algorithm as recently proposed by Freedson et al. (9) probably could help to improve estimation of accelerometer-based physical activity metrics across a range of activity types and intensities.

In conclusion, we found a linear relation between AC and VO_2/kg only for low AC in both obese and normal weight adults. We suggest that further developments in multidimensional accelerometer technologies should focus on recognizing patterns of physical activity (i.e. body movement including gravity aspects) and the characteristics of muscle work itself in order to differentiate between activities. A combination of hip placed sensors and new generation, smart wrist watches with integrated sensors might lead to a significant improvement in the estimation of VO_2/kg as measure of energy expenditure during everyday life activities.

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Conflict of interest

None of the authors have conflicts of interest.

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