Tracmor system for measuring walking energy expenditure

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ORIGINAL COMMUNICATION

Tracmor system for measuring walking energy expenditure

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Objective: Walking is an important mode of exercise and is likely to represent a major component of nonexercise activity thermogenesis. The question arises, how best to quantify walking-energy expenditure (EE) in free-living individuals. The *tri*axial *a*ccelerometer for *m*ovement *r*egistration (Tracmor) is a valid measure of body displacement and so we wanted to evaluate this tool for quantifying walking-EE.
Hypothesis: In this study, we test the hypothesis that walking-EE, measured in a Room Calorimeter, can be predicted from Tracmor output using a regression equation derived from a brief Tracmor/treadmill/Metabolic Cart protocol.
Design: First, 11 healthy subjects completed a 40-min procedure whereby they wore a Tracmor unit and walked on a treadmill at 0, 1, 2 and 3 mph while EE was measured using a Metabolic Cart. This allowed a regression equation to be defined for each subject to convert Tracmor output to EE. Each subject then entered a Room Calorimeter wearing the Tracmor Unit and walked at two self-selected velocities ('slow', 'fast') while EE was measured. 'Tracmor/regression equation' predictions of walking-EE were compared with Room Calorimeter measurements of walking-EE for the two velocities.
Results: The 'Tracmor/regression equation' prediction of EE for walking slowly was 6.36 ± 1.67 kJ/min, and for walking fast it was 11.0 ± 2.60 kJ/min. Room Calorimeter measurements were 6.43 ± 1.85 and 10.9 ± 3.03 kJ/min, respectively. The intraclass correlation coefficient for slow-paced walking was 0.93 ($P < 0.001$), and for fast-paced walking it was 0.82 ($P < 0.005$).
Conclusions: When combined with laboratory measures of EE, the Tracmor accelerometer provides useful data on walking-EE and is applicable to free-living individuals.
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Introduction

Walking is an important mode of purposeful exercise and, even at a slow pace, walking doubles energy expenditure (EE). Hence, because free-living individuals ambulate throughout the day, walking is likely to represent a major component of nonexercise activity thermogenesis (NEAT) (Levine *et al*, 1999b). One of the most precise and reproducible tools for quantifying body displacement/acceleration in free-living individuals is the *tri*axial *a*ccelerometer for *m*ovement *r*egistration (Tracmor) (Bouten *et al*, 1994, 1997a, b; Pannemans *et al*, 1995). In previous studies (Levine *et al*, 2001), Tracmor output has been shown to be highly reproducible, stable over 10 days and there are strong linear relations between Tracmor output and velocity regardless of whether subjects walk on ground or a treadmill. There are also strong linear relations between Tracmor output and EE for subjects walking at graded velocities on a treadmill (r^2 for all subjects that were studied >0.99). In a Room Calorimeter protocol (Bouten *et al*, 1994) that included a treadmill component, Tracmor output accounted for more than 90% of the variance of total energy expenditure−sleep energy expenditure (which is a good surrogate of activity thermogenesis). In another study performed in free-living individuals using doubly labeled water, Tracmor output correlated ($r = 0.73$) with activity thermogenesis (Bouten *et al*, 1996); here, it was not possible to distinguish how much of this activity was attributable to walking. Thus, evidence attests to the ability of the Tracmor to quantify walking and to its

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ability to estimate activity thermogenesis. What we do not know is whether Tracmor output can be used to predict walking-EE for free-living individuals detached from laboratory instruments.

In this study, we propose to address the hypothesis that walking-EE can be predicted from Tracmor output where Tracmor output is converted to EE using a regression equation derived from a brief Tracmor/treadmill/Metabolic Cart protocol.

Subjects and methods

Subjects

A total of 11 healthy, nonobese volunteers (5 M:6 F, 34 ± 5 y, 66 ± 9 kg, BMI 23 ± 3 kg/m^2) were recruited. Subjects had no chronic illnesses, were not on medications and reported weight stability (<2 kg fluctuation) for 3 months before the study. The University of Colorado and Mayo IRB have approved the protocol.

Indirect calorimeter, 'Metabolic Cart'

The Metabolic Cart was a SensorMedics 229N (Yorba Linda, CA, USA) flow-over, indirect calorimeter (Levine *et al*, 2000). The calorimeter was calibrated for flow daily using a 3 l calibrated syringe and before each measurement with two primary standard span gases (4% CO_2, 16% O_2 and 26% O_2; balance N_2). Data were integrated every 30 s and stored on a PC. The system was tested by burning a measured mass high-purity ethanol (AAPER Alcohol and Chemical Company, Shelbyville, KN, USA) within the system using a specialized apparatus (SensorMedics, Yorba Linda, CA, USA). Expired air was collected using a full-face transparent mask (Scott Aviation, Lancaster, NY, USA). The face mask was connected to the calorimeter by 6 m of 22 mm diameter leak-proof tubing (Hans Rudolph Inc., Kansas, MO, USA). This system permits almost complete mobility with minimal agitation. The response time for the system is $\sim$20 s.

Indirect calorimeter: Room Calorimeter

Total EE was measured in the whole-Room Calorimeter at the Center for Human Nutrition, University of Colorado Health Sciences Center (Sun *et al*, 1994). A treadmill (Landice 8700, Randolph, NJ, USA) was placed inside the Room Calorimeter so that subjects could walk unrestrained inside the chamber. The subject's O_2 consumption and CO_2 production were determined from the measured flow rate and the differences in O_2 and CO_2 concentrations between entering and exiting air. Values were corrected for temperature, barometric pressure and humidity. Total EE was calculated using published equations (Jequier *et al*, 1987). Values for all measured variables were collected each minute and stored on a PC.

Tracmor Unit

The triaxial accelerometer (Bouten *et al*, 1996, 1997a, b) comprised three uniaxial piezoresistive accelerometers (ICSensors 3031-010) mounted orthogonally in a resin block ($50 \times 30 \times 8$ mm, 16 g) whereby each axis is independently sensed. The accelerometer was worn on the lower back attached using a 70×85 mm piece of adhesive plastic (Tegaderm, 3 M, MN, USA). A cable connected the accelerometer to a portable data logger (Tattletale 5F, Onset Computer, 512 kB, 16-bit, $10 \times 70 \times 35$ mm, 250 g). Data for each axis were amplified and filtered (0.11 Hz high pass, 20 Hz low pass) to attenuate the DC responses, and the sum of the rectified and integrated acceleration curves for the three axes was measured. Data were recorded continuously and downloaded, via a serial connection, to a PC.

Experimental protocol

Subjects provided informed, written consent. Overnight fasted, rested subjects were admitted into a standard room on the GCRC at UCHSC, Colorado at 07:00. A Tracmor Unit was attached to the back. Using the Metabolic Cart, basal metabolic rate (BMR) was measured for 30 min while subjects lay supine with a single pillow for head support, motionless.

Subjects entered the Room Calorimeter and were instructed regarding how to operate the treadmill. The calorimeter door was sealed and total EE was measured. Subjects rested for an hour for calorimeter and subject acclimatization. Resting EE was then measured for 30 min while subjects lay flat with a single pillow for head support, motionless. Subjects were subsequently asked to walk for two 20-min periods. For the first 20-min period, subjects were instructed to select a velocity compatible with ambling at home or work. For the second 20-min period, subjects were instructed to walk at a self-selected pace compatible to purposeful locomotion (eg walking to an appointment).

After exiting the Room Calorimeter, EE was measured while standing motionless (0 mph) and walking at 1, 2 and 3 mph on a treadmill. This part of the protocol was performed after the Room Calorimeter measurements because we did not want the EE of walking to impact the Resting EE measurement conducted during the Room Calorimeter protocol. After the treadmill walking, the Tracmor Unit was removed from the subject and the data downloaded to a PC. All measurements were made at 22°C.

Data analysis

The term Walking-EE$^{\text{Predicted}}$ refers to the prediction of Walking-EE made using the Tracmor/Treadmill/Metabolic Cart approach and the term Walking-EE$^{\text{Room Calorimeter}}$ refers to the Walking-EE measured in the Room Calorimeter.

Walking-EE$^{\text{Predicted}}$: Metabolic Cart measurements were used to calculate the EE of walking at 1, 2 and 3 mph above BMR. Mean Tracmor output above resting for walking at the three velocities was calculated. For each subject, a regression equation was derived to convert Tracmor output to walking-EE. This regression equation was used to convert Tracmor output to Walking-EE$^{\text{Predicted}}$ for each of the two 20-min walks that were completed while subjects were inside the chamber.

Walking-EE$^{\text{Room Calorimeter}}$: Total EE for each of the 20-min walks was calculated from the Room Calorimeter data stream; data from the first 5 min of each measurement period were disregarded for steady state to be achieved. Walking-EE$^{\text{Room Calorimeter}}$ was calculated for each of the two, 20-min walks from total EE for that period minus resting EE.

To address our primary hypothesis, that Walking-EE$^{\text{Predicted}}$ compared favorably with Walking-EE$^{\text{Room Calorimeter}}$, a direct numerical comparison was made and intraclass correlation coefficients (ICC) calculated. To compare two independent variables, linear correlation analysis was used where appropriate. Data are expressed as mean $\pm$s.d. and statistical significance is defined as $P<0.05$.

Results

For the Metabolic Cart, repeated alcohol burn experiments yielded CO_2 and O_2 recoveries ~98%. The s.d. of the RQ for the last 15 min of these measurements was <1% of the mean. Test–retest differences for duplicate measurements of BMR, standing and walking-EE were <3%. For the Room Calorimeter, butane burn experiments showed recoveries of >97%.

Mean values for walking-EE and Tracmor output for the study are shown in Table 1. For each subject, there were excellent relations between changes in EE and Tracmor output ($r>0.99$ for all subjects).

For the slow-paced walk, subjects consistently selected velocities of 1–2 mph (1.2$\pm$0.4 mph). For the fast-paced walk, subjects self-selected velocities ranging from 2 to 3 mph (2.6$\pm$0.4 mph, $P<0.001$). Mean predicted walking-EE derived from the Tracmor unit for the slow walk was 6.4$\pm$1.7 kJ/min and for the fast walk it was, 11.0$\pm$2.6 kJ/min. This compared favorably with the measurements from the Room Calorimeter, 6.4$\pm$1.9 kJ/min for the slow walk and 10.9$\pm$3.0 kJ/min for the fast walk (Table 2). Walking-EE$^{\text{Predicted}}$ was not significantly different compared to Walking-EE$^{\text{Room Calorimeter}}$ at either speed. The slope for the relations was 1.0 for the slow walk and 0.97 for the fast walk with intercepts of 0.0 and 0.1, respectively. The mean deviations from the lines of identity were 0.8$\pm$11% for the slow walk and 1.4$\pm$15% for the fast walk.

When data from the two 20-min walks were combined, Walking-EE$^{\text{Predicted}}$ again compared well Walking-EE$^{\text{Room Calorimeter}}$, 17.3$\pm$3.9 *vs* 17.4$\pm$4.6 kJ/min with a slope of 1.0 and intercept of −0.1.

The ICC for the two methods were calculated for the slow walk, fast walk and the slow and fast walks combined. For the slow walk, the ICC was 0.93 with 95% confidence intervals of 0.77 and 0.98. This was significantly different from 0 ($P<0.0001$). This suggests that 93% of the variance is attributable to between-subject variance, and 100−93 = 7% to between-method disagreement. For the fast walk, the ICC was 0.82 (0.47–0.95; $P<0.0005$) and for the combined slow-and-fast walks, it was 0.87 (0.59–0.96; $P<0.0001$).

Table 1 Mean ($\pm$s.d.) values for energy expenditure and Tracmor output

	Energy expenditure (kJ/min)	*Tracmor output (TU/min)*
Metabolic Cart		
BMR	4.3$\pm$0.5	1492$\pm$42
1 mph	10.0$\pm$1.3	2221$\pm$302
2 mph	12.9$\pm$1.9	3578$\pm$404
3 mph	17.1$\pm$2.60	5455$\pm$488
Room Calorimeter		
RMR	4.8$\pm$0.7	1446$\pm$11
Slow-paced walk	11.2$\pm$2.0	2543$\pm$654
Fast-paced walk	15.7$\pm$3.2	4586$\pm$916

Throughout the study, Tracmor output was recorded. Energy expenditure was first measured using a Metabolic Cart while subjects were in a basal state and while walking at the stated velocities. The subject then entered the Room Calorimeter where total energy expenditure was recorded at rest and while walking at two, self-selected velocities, 'slow-paced' and fast-paced' BMR, basal metabolic rate; RMR, resting metabolic rate.

Discussion

Walking is an important mode of purposeful exercise and walking-EE has the potential to impact substantively NEAT and total EE. Walking even at 1 mph doubles EE (Bouten *et al*, 1994; Haymes & Byrnes, 1993; Levine *et al*, 2000), and so the cumulative energetic cost of walking each day might be important. We therefore felt it important to validate carefully and independently our tools for measuring walking-EE in free-living subjects. From previous studies (Levine *et al*, 2001) we know that Tracmor output increases with progressive velocity (r^2 for all subjects $\geqslant$0.99) and that Tracmor output correlates well with EE as velocity increases (r^2 for all subjects $\geqslant$0.98). In this study, we test the hypothesis that freely selected walking-EE can be predicted from Tracmor output, using a regression equation that converts Tracmor output to EE. We tested this hypothesis by comparing walking-EE predicted from the 'Tracmor output-regression equation' approach with walking-EE measured in a Room Calorimeter. The results demonstrated that precise

Table 2 Mean ($\pm$s.d.) values for energy expenditure above resting for the slow-paced and fast-paced walks measured using the Room Calorimeter and predicted using the Tracmor

	Room Calorimeter energy expenditure above resting (kJ/min)	*Tracmor predicted energy expenditure above resting (kJ/min)*
Slow-paced walk	6.4$\pm$1.9	6.4$\pm$1.7
Fast-paced walk	10.9$\pm$3.0	11.0$\pm$2.6

predictions of walking-EE can be achieved using the 'Tracmor output-regression equation' approach.

There are several approaches used to measure physical activity and walking-EE in the field. Activity recall and time and motion studies provide nonspecific information about habitual activity. Predictably, substantial errors are introduced through inaccurate recall and inadequate data recording. These approaches can be used, however, for following trends in certain activities particularly with relation to occupational practices (United Nations University, 1989). Activity logs and the factoral method are frequently used for estimating activity EE in free-living individuals. First, a subject's physical activities, including walking, are logged over the time period of interest (eg 1 week). The energy equivalent of each of these activities is measured or estimated using a calorimeter or tables, respectively (Banerjee *et al*, 1971). The time spent in each activity is then multiplied by the energy equivalent for that activity. These values are then summed to derive an estimate of activity EE. Errors may result from an inaccurate recording of activities and from inaccurate determinations of the energy costs of the activities. To log activity, subjects are often asked to record in diary the nature and amount of time spent performing each of their activities throughout the day (Ferro-Luzzi *et al*, 1990). This has several limitations, subjects may be illiterate or enumerate, they may report their activities inaccurately or incompletely and/or may alter their normal activity patterns during periods of assessment. To limit these sources of error; one approach is to have trained enumerators follow subjects and objectively record the subject's activities (United Nations University, 1989). This approach is time consuming and expensive but potentially a valuable source of accurate and objective data. To determine the energy costs of physical activities, standard tables are often used. However, these may introduce substantial (albeit systematic) errors. First, the tables may not include the precise activity the subject performed. Second, the energy cost for a given activity is highly variable between subjects even independent of gender. Third, calorimeter methods for measuring the energy costs of activities have not been standardized between investigators so that precision and accuracy of data in the activity tables cannot always be assured. To limit these errors, the energy costs of each or most of the activities that the subjects of interest perform can be measured using calorimeters. At best, the energy costs for each subject's activities would be measured, but clearly this is rarely practical except for small studies.

Kinematic techniques are those whereby body movement is sensed and quantified. The Tracmor, used in this study, falls under this category. Some kinematic techniques are only applicable for confined spaces (eg radar tracking, floor pressure sensing and cine photography (Schutz *et al*, 1982)). These tools have been used in room calorimeters. In free-living individuals, other approaches are necessary. These focus predominantly on pedometers and accelerometers. Pedometers typically count the number of steps a person takes. They tend to lack sensitivity for quantifying activity EE because neither stride length nor total body displacement is sensed. Accelerometers detect body displacement electronically with varying degrees of sensitivity; uniaxial accelerometers in one axis and triaxial accelerometers in three axes. Portable uniaxial accelerometers (eg Caltrac accelerometer) have been widely used to detect walking (Haymes & Byrnes, 1993). However, these instruments are not sufficiently sensitive to quantify walking in a given free-living individual, but rather are more valuable for comparing activity levels between groups of subjects (Bassett *et al*, 2000; Johnson *et al*, 1998; Pambianco *et al*, 1990; Swan *et al*, 1997). Triaxial accelerometers provide greater precision for quantifying walking. Of these, the Tracmor Unit has been most widely validated (Bouten *et al*, 1994, 1996, 1997a, b; Pannemans *et al*, 1995; Westerterp & Bouten, 1997; Westerterp *et al*, 1996). Against a motor-driven rotating arm, the Tracmor Unit shows test-to-test repeatability of 0.5% and when applied acceleration is plotted against Tracmor output, $r \approx 0.99$ (Bouten *et al*, 1997a). A second advantage of these units is that the conditions for optimum usage have been defined (eg site of attachment of accelerometer unit) (Bouten *et al*, 1997b). Third, Tracmor output correlates well with EE ($r = 0.95$) when subjects walk on a treadmill (Bouten *et al*, 1994). Finally, with respect to detecting total body motion, Tracmor output correlates well with activity EE (total daily EE, measured using doubly labeled water, divided by BMR) in free-living subjects; $r = 0.73$ ($P < 0.001$) (Bouten *et al*,1996; Westerterp & Bouten, 1997). We used the exact instruments in the above citations for our studies.

Kinematic approaches have drawbacks. For example, movements such as cycling and swimming are not detected. Car or bus locomotion can be mis-sensed by some kinematic instruments. Other approaches have also been attempted to capture activity EE. These include heart rate monitoring, integrated EMG, pulmonary ventilation volume and thermal imaging (Jequier *et al*, 1987). These approaches are associated with substantial error invariably because the measured variable(s) correlate poorly with the quantities and/or costs of NEAT and/or its components.

The study reported here has limitations. First, the periods for walking were short in duration. However, the precision of the Walking-EE$^{\text{Predicted}}$ estimates for each of the 20-min walk was similar and the precision was unaltered when the data from the two walks were combined. This argues against prolongation of the measurement periods improving the precision of the estimates. We deliberately performed these studies in a Room Calorimeter with rapid response ($\sim$2 min) (Sun *et al*, 1994). Second, the laboratory protocol used to define the Tracmor regression equation was conducted using a treadmill. It might be argued that treadmill walking is not representative of free-living ground-based walking. However, in our previous studies Tracmor outputs for walking on level ground were found to be identical to walking on a treadmill at the same velocities (Haymes & Byrnes, 1993). This suggests that a treadmill-based protocol for deriving the regression equation is likely to be valid. Third, resting EE measurements in the Room Calorimeter were 10% above the BMR measurements. This most likely reflects the time course of the experiment and is compatible with results from other investigators (Shetty *et al*, 1996). Fourth, the study was conducted on a seemingly small sample size. This was because the studies were complex to perform and required the dedicated use of a Room Calorimeter. Since we accounted for ⩾80% of the variance between the methods, it seems highly unlikely that a greater sample size would have improved our estimates. Fifth, we propose to use the Tracmor units/regression equation approach for measuring walking-EE in free-living subjects. However, the experiment we performed utilized a Room Calorimeter that limits physical activity; we were obliged to place a treadmill inside the Room Calorimeter to allow subjects to emulate free-living walking. We accept that this is a limitation; however, we would argue that this is the only viable approach that would allow us to define a gold standard measurement of walking-EE with which to compare our estimate.

In summary, the results from these experiments allow us to define the utility Tracmor system for quantifying the energy cost of walking in unrestricted subjects. By its nature, free-living physical activity cannot be represented by measurements undertaken using a Room Calorimeter that restricts normal daily activities such as walking to work or cooking a meal. It is proposed to use the 'Tracmor/regression equation approach' to measure walking-EE in free-living subjects. Subjects would undergo a short initial treadmill/Metabolic Cart protocol much like in this study to derive the Tracmor-to-EE regression equation. Tracmor output could then be readily converted to EE to determine walking-EE. To delimit periods of ambulation, additional sensors would be needed that define body position and this technology we propose to develop in future studies.

In conclusion, the Tracmor accelerometer can provide information on walking-EE by defining the Tracmor/walking-EE relation for each subject. By carefully defining tools to measure walking-EE in free-living subjects, the importance of walking in human energy balance may become more clearly determined.

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