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Physical activity related energy expenditure in children by doubly labeled water as compared with the Caltrac accelerometer

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OBJECTIVE: The objective of this study was to determine whether the Caltrac accelerometer was a meaningful predictor of physical activity related energy expenditure (AEE) in free-living, pre-adolescent children.
SUBJECTS: The sample consisted of 31 children (14 girls, 17 boys; 22 Caucasian, 9 Mohawk) with a mean age of 8.3 (±2.0) y.
MEASUREMENTS: AEE was measured by subtracting postprandial resting metabolic rate (RMR), measured *via* indirect calorimetry, from total daily energy expenditure (TDEE), derived from the doubly labeled water (DLW) method. Average daily activity counts (AC) were measured using a Caltrac accelerometer, which was worn for three days, two weekdays and one weekend day, within the DLW dosing period.
RESULTS: AEE was related to gender ($r = 0.42$, $P = 0.02$), fat mass (FM, $r = 0.32$; $P = 0.07$), and fat free mass (FFM, $r = 0.32$; $P = 0.07$), but not to AC ($r = -0.09$; $P = 0.63$). After adjusting for gender, race, FM and FFM using multiple correlation regression analysis ($R = 0.53$), AC did not significantly increase the amount of variation explained in AEE. An estimate of the calories expended in physical activity was derived from AC using a formula developed by Sallis *et al.* This estimate was significantly higher than AEE (956 kcal/d *vs* 469 kcal/d, respectively, $t = 5.9$, $P < 0.001$).
CONCLUSION: The Caltrac was not a meaningful predictor of AEE in our sample. The caloric estimates of energy expended in physical activity derived from the Caltrac AC, were significantly higher in comparison with measured AEE in these free-living children.

Keywords: children; physical activity; energy expenditure; Caltrac; doubly labeled water

Introduction

America's children are becoming increasingly overweight.[1] Based on NHANES III (1988–1991) data, 22% of school-aged children in 1988–1991 were overweight compared with 15% in 1963.[1] The etiology of this increase in the rate of overweight among children remains controversial. Research has linked total energy intake, as well as diet composition, to rates of overweight among children.[2–5] A growing number of studies also link rates of overweight among children to physical activity levels. Some researchers have found increased rates of television watching among overweight children compared to children of normal weight,[6–8] while others did not observe this relationship.[9,10] Researchers have also found an inverse relationship between physical activity levels and percent body fat and body mass index (BMI),[11–14] while others have found no such association.[15,16] Thus, the evidence is not unequivocal for the role of physical activity in the onset and development of childhood obesity. This may be partially due to methodological constraints in measuring energy expended in physical activity.

Current methods used to assess physical activity levels possess characteristics that negatively affect their reliability and validity when used with children. Physical activity diaries, recall surveys and quantitative history surveys, which have been used extensively to assess physical activity levels among adults, are unreliable in children, as children do not have the cognitive ability needed to record type, duration and intensity of physical activity.[17] Heart rate monitoring has also been used as a measure of physical activity among adults as well as children,[16–18] however, its validity is questionable as it overestimates physical activity levels among sedentary and obese subjects.[16,18]

Presently the doubly labeled water (DLW) method is considered the 'gold standard' for the determination of total daily energy expenditure (TDEE), however, its usefulness for large epidemiological studies is limited by excessive cost.[19] In conjunction with indirect calorimetry, the doubly labeled water method can be used to obtain a caloric value of activity related energy expenditure (AEE). Goran and Nagy[20]

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measured postprandial resting metabolic rate (RMR) in children which subsequently incorporates the thermic effect of food. An estimate of AEE can be determined by subtracting postprandial RMR, measured by indirect calorimetry, from TDEE. This methodology provides an estimate of AEE by which other practical, easily administered methods of measuring physical activity, can be compared.

The Caltrac accelerometer (Muscle Dynamics Fitness, Madison, Wisconsin, USA) offers hope as a simple, easy-to-use method of assessing AEE. The Caltrac is the size of a personal pager, and measures the degree and intensity of movement in the vertical plane. From this measure, a caloric value of TDEE is estimated.[21] In order to negate the Caltrac's calculation of RMR and measure only activity counts (AC), Sallis *et al*[17] recommend the following values be entered into the Caltrac's internal computer: gender = 0, age = 99, weight = 25 and height = 36.

The Caltrac has been validated against doubly labeled water in adults,[22,23] and against heart rate monitoring[17] and direct observation[24] in controlled research settings in children. It is not clear, however, if the Caltrac can provide valid predictions of AEE in free-living children. The aim of this study was to compare the Caltrac accelerometer against AEE, estimated using the DLW method and postprandial RMR, in free-living children.

Methodology

Subjects

Study participants were recruited from a longitudinal study of 80 Caucasian children and 40 Mohawk children, tracking the development of obesity among young children. The Mohawk children lived in the Akwasasne community in upstate New York and the Caucasian children lived in Burlington, VT and the surrounding rural areas. Ethnicity was determined by whether or not parents and both sets of grandparents were of the same racial descent. Children were not eligible to participate in the study if they had suffered a major illness since birth. Data collection took place during the school year at the St Regis Mohawk Health Services on the St Regis Mohawk Indian Reservation and at the General Clinical Research Center (GCRC) of the University of Vermont, Burlington, VT. The protocol was approved by the Committee on Human Research at the University of Vermont and the Akwasasne community. Informed written consent was obtained from the parent or guardian of each child.

Study protocol

The Caucasian subjects were admitted to the GCRC for an overnight stay followed by a morning of data collection. In addition, the subjects visited the hospital 14–16 d later for a follow-up visit. The Mohawk children, along with a parent or guardian, visited the St Regis Health Services for two consecutive days without an overnight stay and again 14 d later for follow up.

Measurements

Activity counts. As suggested by Sallis *et al*,[17] each Caltrac was programmed prior to use, to read only 'Activity Counts' (AC) by entering the following values: gender = 0, age = 99, weight = 25, height = 36 in order to negate the computer's internal estimate of RMR.

AC were collected for three days, including one weekend day, during the 14 d DLW dosing period. Gretebeck and Montoye[25] found that among adult males, activity levels differed considerably between weekdays and weekend days, so each should be monitored. Prior to discharge on the morning of the first visit, the Caucasian subjects and care-givers were introduced to the Caltrac. The children were allowed to handle the instrument and become acquainted with its appearance. The care-giver and subject were instructed on proper use of the instrument and given an information sheet that outlined the protocol to take home. The subjects were instructed to begin wearing the Caltrac upon waking in the morning and continue until just before going to sleep at night. If at any time the Caltrac was taken off during the day, the subjects or care-givers were to note the time and Caltrac reading at time off and at time of replacement in the Caltrac reading worksheet. The subjects were instructed to only take the Caltrac off for activities involving water, such as swimming or bathing. Subjects were also instructed not to turn the Caltrac on or off, only to take readings each time the Caltrac was removed or each time it was placed on the subject. This request was made to ensure that opportunities to touch the buttons of the Caltrac were kept to a minimum. To further ensure that mishandling was kept to a minimum, the buttons of the Caltrac were covered with cardboard and taped prior to use. Each subject was fitted with a belted pouch in which to wear the Caltrac and told to keep the Caltrac in its pouch continuously, only removing it to take readings. The subjects were told to wear the Caltrac on either hip since Sallis *et al*[17] found a high reliability between left and right hip ($r = 0.96$). The Caucasian children were instructed to return the Caltrac with the recording sheet on the follow up visit.

In contrast, the Mohawk children and their care-giver were instructed by a research assistant, to wear the belted pouch containing the Caltrac without recording information from the Caltrac on a worksheet. When the instrument was not on the child's waist, the guardian was instructed that the Caltrac should be placed upright on a flat surface. The research assistant entered the appropriate data into the Caltrac during the first visit and the family was instructed not to tamper with the instrument while in their possession. Three days later, the Caltrac was returned to the St Regis Health Services and the research assistant recorded the total AC for the three-day period.

TDEE. TDEE was measured over 13–16 d under free-living conditions, using the DLW technique. Baseline urine samples were taken before oral dosing with 0.15 g $H_2{}^{18}O$ and 0.12 g ^2H_2O per kg body mass. The following morning, subjects provided two timed urine samples and another two urine samples were collected 13–16 d later. Samples were analyzed in triplicate for $H_2{}^{18}O$ and ^2H_2O by isotope ratio mass spectrometry at the Energy Metabolism Research Unit in the Department of Nutritional Sciences at The University of Alabama at Birmingham. CO_2 production rate was determined using Equation R2 of Speakman *et al*[26] and was converted to energy expenditure using equation 12 of de Weir.[27]

RMR. RMR was measured using a portable DeltaTrac Metabolic Monitor (Datex/Instrumentarium, Helsinki, Finland). One hour after a standard breakfast, a postprandial RMR was taken while the subject lay in bed with their head elevated by a pillow. The children were allowed to watch video cartoons while under the DeltaTrac hood. The measure was taken at one-minute intervals, for 20 min. A second postprandial RMR was taken 13–16 d later in the Caucasian subjects. An average of the two RMRs was used in statistical analysis. The postprandial RMR incorporated the average energy cost associated with meal induced thermogenesis. Goran and Nagy[20] established that resting energy expenditure is 11% higher using the postprandial condition, compared to the fasting state.

One postprandial RMR was collected from each Mohawk subject. The morning after the initial visit, each child returned and underwent testing using a portable DeltaTrac metabolic monitor (Datex/Instrumentarium, Helsinki, Finland). Only one RMR was available on the Mohawk subjects.

AEE. AEE was assessed by subtracting postprandial RMR as measured by indirect calorimetry from TDEE derived by the DLW technique.

Other variables. Subject characteristics expected to influence body composition and activity energy expenditure were measured. These included age, gender and ethnicity (Caucasian or Mohawk). In addition, the height of each subject was measured using a wall-mounted measurement board (Novel Products Inc., Addison, IL) to the nearest 0.1 centimeter. Subjects were weighted with an electronic scale (Scale Tronix ST, Wheaton, IL) to the nearest 0.1 kg.

Total body water (TBW) was measured by ^{18}O ($H_2{}^{18}O$) dilution as described by Schoeller *et al*.[28] Fat mass (FM) fat-free mass (FFM) were derived from TBW with the assumption that FFM is 73.2% hydrated.[29]

Statistical analysis

Subject characteristics were described using frequencies, means and standard deviations. In all statistical analyses for gender, female = 0, male = 1; and for race, Caucasian = 0, Mohawk = 1. Independent *t* tests were used to determine differences in physical characteristics and metabolic measures between girls and boys.

Bivariate analysis. Correlation coefficients were used to determine the linear relationship between the independent variable, AC and the dependent variable, AEE derived from DLW. Bivariate correlations were also performed to determine the relationships between AEE and the subjects' physiological characteristics.

Sallis *et al*[17] developed the following equation to determine average calories in AEE as estimated from the Caltrac AC reading:

Caltrac average calories = 0.101 kcal/kg body weight/AC

Paired *t*-tests were performed to compare the mean of AEE to Caltrac average calories. Agreement between AEE as derived from DLW and Caltrac average calories was assessed using the method of Bland and Altman.[30] With this method, a pair-wise comparison is used to show the relative bias (mean difference) and the limits of agreement (mean difference ±2 s.d. of the difference) between the two measurements by plotting their mean difference against the mean of the two methods.

Multivariate analysis. Multiple correlation regression analysis was used to determine the best predictors of AEE in the sample using the study variables. All statistics were performed using SPSS (Statistical Package for the Social Sciences for Windows, version 7.0, 1995, SPSS Inc., Chicago, IL) and the level for significance for all analyses was specified at $P < 0.05$.

Results

Physical characteristics

The study sample consisted of nine Mohawk (four girls, five boys) and 22 Caucasian (10 girls, 12 boys) children. The subjects' physical characteristics are outlined in Table 1. The girls and boys did not

Table 1 Comparison of physical characteristics and Caltrac measurements of sample children by gender (mean ± standard deviation)

	Boys (n = 17)	*Girls (n = 14)*
Age (y)	8.2 ± 1.9	8.5 ± 2.0
Height (m)	1.3 ± 0.1	1.3 ± 0.2
Weight (kg)	32.9 ± 12.3	33.1 ± 13.5
BMI (kg/m^2)	19.5 ± 4.2	19.6 ± 4.3
Fat free mass (kg)[a]	24.9 ± 7.8	24.6 ± 8.6
Fat mass (kg)[a]	8.1 ± 4.9	8.5 ± 5.4
Percent body fat	25 ± 6.7	26 ± 6.8
TDEE (kcal/d)	1922 ± 501	1554 ± 319*
RMR (post-prandial kcal/d)	1324 ± 248	1242 ± 188
AEE (kcal/d)	598 ± 353	313 ± 275*
AC (3 d mean)	318 ± 111	298 ± 187
Caltrac calories (3 d mean)[b]	1006 ± 371	895 ± 401

*$P < 0.05$ by independent *t*-test
[a]measured by total body water estimated from ^{18}O dilution; [b]caloric estimate of energy expended in physical activity based on Caltrac AC using the formula .101 cal/kg body weight/AC as suggested by Sallis *et al.*[17]
BMI = body mass index; TDEE = total daily energy expenditure (measured by doubly labeled water), RMR = resting metabolic rate; AEE = activity energy expenditure (measured as TDEE − RMR); AC = Caltrac activity counts.

Table 2 Bivariate correlation coefficients between activity energy expenditure (AEE) and physiological characteristics and Caltrac measurements

	Boys (n = 17)	*Girls (n = 14)*	*Both (n = 31)*
Height (m)	0.42	0.02	0.21
Weight (kg)	0.52*	0.16	0.33
BMI (kg/m^2)	0.45	0.29	0.38*
Fat mass (kg)[a]	0.51*	0.14	0.32
Fat free mass (kg)[a]	0.50*	0.16	0.32
Percent body fat	0.45	0.00	0.25
AC	− 0.38	0.09	− 0.09
Caltrac calories[b]	0.16	0.21	0.22

*$P < 0.05$
[a]measured by total body water estimated from ^{18}O dilution; [b]caloric estimate of energy expended in physical activity based on Caltrac activity counts (AC) using the formula .101 cal/kg body weight/AC as suggested by Sallis *et al.*[17] BMI = body mass index; AC = activity counts.

differ significantly in height, weight, BMI, FFM, FM or percent body fat ($P > 0.05$). The Mohawk children were significantly younger than the Caucasian children (5.7 *vs* 9.3, $P < 0.001$) and thus had a lower mean FM (4.3 *vs* 8.9 kg, $P = 0.003$), mean FFM (17.3 *vs* 28.7 kg, $P < 0.001$) and mean total body weight (21.5 *vs* 37.5 kg, $P < 0.001$).

Components of energy expenditure

The boys had a significantly higher TDEE and AEE in comparison with the girls (Table 1). AEE accounted for 29% of TDEE in the boys and 18% of TDEE in the girls.

Bivariate associations between physical characteristics and AEE

There were no significant correlations between AEE and physical characteristics among the girls ($P > 0.05$). Significant associations were present between AEE and weight, FM and FFM among the boys ($P < 0.05$).

Bivariate associations between AEE and Caltrac measures

The three-day average of AC, measured by the Caltrac accelerometer, was not significantly correlated with AEE (***r*** = − 0.09, $P = 0.63$) (Table 2). In addition, per day and mean hourly AC were not significantly related to AEE.

The equation used to derive average calories based on Caltrac AC overestimated AEE. Caltrac average calories (956 ± 383 kcal/d) was significantly higher ($t = -5.94$, $P < 0.001$) than the mean AEE (469 ± 346 kcal/d). The mean difference between

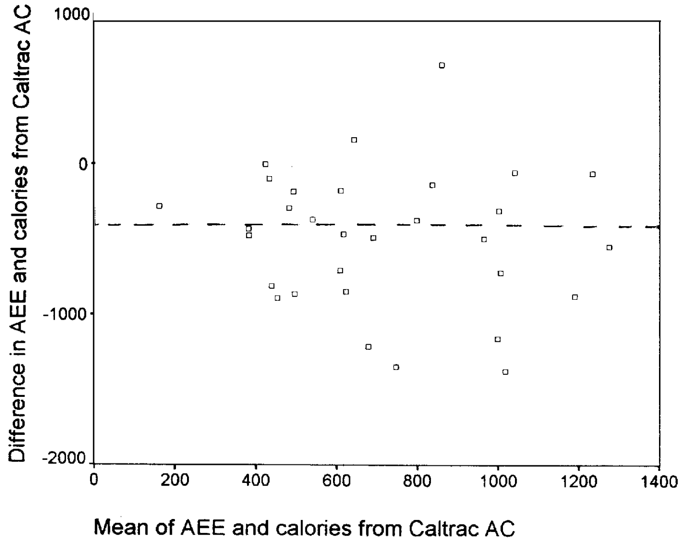

Figure 1 Difference between activity energy expenditure (AEE) derived from total daily energy expenditure (TDEE) − resting metabolic rate (RMR) and Caltrac activity counts (AC) using the formula .101 cal/kg body weight/AC plotted against the mean of the measurements ($n = 31$).

AEE derived from DLW and Caltrac average calories was − 487.4 kcal, indicating that Caltrac average calories was biased toward overestimating AEE. The limits of agreement were very wide, ranging from − 944.3 to − 30.53 (Figure 1).

Multivariate analysis explaining the variation in AEE
Multiple correlation regression analysis was used to determine the strongest predictors of AEE in the sample using the study variables. Gender, race, FM and FFM were the best predictors of AEE generating the equation:

$$AEE = 63.97 + (284.962 \times \text{gender}) - (17.671 \times \text{race}) + (12.876 \times FM) - (6.18 \times FFM)$$
$$R = 0.533,\ P = 0.06,\ SSE \pm 315$$

Gender was coded 0 = female and 1 = male; race was coded 0 = Caucasian and 1 = Mohawk; FM in kg; FFM in kg. FM and FFM were measured from TBW estimated from ^{18}O dilution. Only 28% of the variation in AEE was explained by this model. When the three-day mean AC was forced into the model, the amount of variation in AEE which was explained, did not increase significantly $R = 0.534$, $P = 0.12$, SSE ± 321).

Differences in methodology used for each ethnic group substantiated separate analyses of the Mohawk and Caucasian data. However, when separate analyses (based on ethnicity) were used, there was still no significant correlation between AEE and AC in either group. In addition, Caltrac average calories remained significantly higher than AEE. In separate multivariate analysis, AC or Caltrac average calories did not increase the amount of variation explained in AEE.

Discussion

This study compared the Caltrac accelerometer against AEE as measured using the DLW method and postprandial RMR in free-living children. The major finding was that the Caltrac accelerometer was not a useful predictor of AEE in the sample.

Other researchers have measured AEE in children using the DLW method. Fonteville *et al*[24] reported measures of AEE among 28, five-year-old Caucasian children. AEE was 231 ± 131 kcal/d, which explained 16% ± 7% of TDEE[24] compared to this study where AEE was 24% ± 14% of TDEE. Goran *et al* reported AEE to be 343 ± 239 kcal/d which explained 22% of TDEE among 232 Guatemalan, African-American, Mohawk and Caucasian children.[31] In this sample the AEE of the boys was almost twice that of the girls (Table 1). This finding may be important in explaining the greater fat gain seen in girls in comparison with boys as they approach puberty.[32]

This study failed to find a significant correlation between either AC and AEE or Caltrac average calories with AEE. Sallis *et al*[17] found a significant correlation between AC and heart rate monitoring among children of comparable age to the participants of this study. While the findings of Sallis *et al*[17] offered promise that the Caltrac could serve to monitor physical activity, methodological issues need to be considered. The Caltrac was validated against heart rate monitoring which is biased against less active and obese subjects, while this study validated the Caltrac against DLW, presently considered the ‘gold standard’ for determining TDEE.[16,18] In addition, Sallis *et al*[17] confined subjects to a clinical setting while wearing the Caltrac. In contrast, the aim of the present study was to validate the use of the Caltrac to measure physical activity in free-living children. The published equation used in this study to estimate calories expended in physical activity from Caltrac AC was generated from Sallis *et al*[17] data. The equation consistently overestimated AEE and had wide limits of agreement, making it unacceptable as an estimate of energy expended in physical activity for this sample.

Klesges and Klesges[33] found a significant correlation between AC and direct observation of physical activity among children older than 32.5 months. However, the study failed to determine whether the Caltrac was a valid physical activity monitor among children in a true, free-living state. Since the children were continuously observed, they were not able to mishandle the Caltrac at any point during the day. In a free-living environment, researchers do not have the assurance that some degree of Caltrac manipulation will not take place. Like Sallis *et al*[17], Bray *et al*[34] studied children within a confined clinical setting.

Research validating the Caltrac accelerometer against the DLW method in adults, suggests that the Caltrac estimates are valid indicators of TDEE. Gretebeck and colleagues[22,23] found no significant difference between the accelerometer estimate of TDEE and that derived from DLW among older women and young men. Again, the present study aimed to estimate AEE in free-living children, not TDEE. The Caltrac might be a more valid tool if subjects are able to wear the instrument for extended periods of time, as in the Gretebeck studies. However, in our experience, it is unrealistic to expect healthy, free-living children to comply with the proper wearing of the Caltrac for extended periods of time.

Variables specific to this study may have contributed to the lack of significant associations between the Caltrac AC and AEE. The only contact the subjects had with the research assistant was prior to wearing the Caltrac and when the Caltrac was returned, therefore, the children were left unobserved to wear the instrument for three days. In a free-living situation, children may be overtaken by curiosity and handle the Caltrac when it should be around the waist, consequently misrepresenting activity levels. Since the Caucasian children and guardians were left unassisted to use the Caltrac, it was their responsibility to record daily Caltrac readings. Caltrac readings may have been recorded improperly by either the child or care-giver. As the Mohawk children did not take daily recordings of the Caltrac readings upon placement in the morning and removal in the evenings, the accelerometer may have accumulated AC without actually being on the child.

Controversy surrounding the methodology used in this study to determine AEE may call into question its use as a 'gold standard.' AEE was determined by subtracting postprandial RMR, measured by indirect calorimetry, from TDEE, as measured by DLW. DLW measurements of TDEE have been shown to have a precision of 4–7%.[19] Although RMR measures were obtained under ideal conditions, described earlier by Goran and Nagy[20] several participants of this study had difficulty relaxing and remaining immobile throughout the RMR measurement. This could falsely lower the AEE value among these children. Goran *et al*[14] suggest the use of true values to derive AEE in order to minimize the error associated with using two variables (TDEE and RMR) with known error independent of each other. However, when true values of AEE were used in the statistical analysis for this study, the findings did not differ from these reported here.

Conclusion

The Caltrac had limited usefulness as a physical activity monitor in a group of free-living, school-aged children. The Caltrac may be useful, however, in supervised settings in which researchers want to assess the children's levels of physical activity.[17] Other products have emerged that also claim to objectively monitor physical activity. The Tri-trac accelerometer (Hemokinetics, Madison, Wisconsin, USA) measures on three planes rather than two and possesses the ability to store extensive data within its internal computer for retrieval at a later time. Future research may show that the Tri-trac is a valid indicator of AEE among children. Until an objective measure of AEE is found, physical activity assessment is limited to either expensive or potentially invalid methodologies, including the DLW method, direct observation and physical activity question-naires.

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