# Comparison of equations for predicting energy expenditure from accelerometer counts in children

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**Several prediction equations developed to convert body movement measured by accelerometry into energy expenditure have been published. The study aim was to examine the degree of agreement between three different prediction equations, when applied to data on physical activity in a large sample of children. We examined 1321 children (663 boys, 658 girls; mean age 9.6 ± 0.4 y.) from four different countries. Physical activity was measured by the MTI accelerometer (model 7164). One equation, derived from doubly-labelled water (DLW) measurements was compared to one treadmill-based and one room calorimeter-based equation (mixture of activities). Predicted physical activity energy expenditure (PAEE) was the main outcome variable. In comparison with DLW-predicted PAEE, the laboratory-significantly ($p < 0.001$) overestimated PAEE by 17% and 83% respectively when based on a 24-hour prediction, while significantly ($p < 0.001$) underestimated PAEE by 46% and 3% respectively, when based on awake time only. Predicted PAEE differ substantially between equations, also depending on time frame assumptions. These equations can not be used interchangeably and interpretations of average levels of PAEE in children from available equations should be made with caution. Further development of equations applicable to free-living scenarios is needed.**

The prevalence of overweight in children has been reported to have increased in many western countries (Lobstein et al., 2003; Troiano & Flegal, 1998; Willms et al., 2003), which has raised scientific interest in the potential relationship between components of total energy expenditure (TEE) and the development of overweight and obesity in childhood (DeLany, 1998; Salbe et al., 2002) and other features of the metabolic syndrome (Andersen et al, 2006). Physical activity energy expenditure (PAEE) is the most variable component of TEE and therefore key for the regulation of TEE and of specific interest to measure accurately in epidemiological studies. However, the direct assessment of daily PAEE is problematic since the methods with the highest degree of validity are either expensive (doubly labelled water) or impractical in field settings (respiratory gas analysis) (Schutz et al., 2002). Therefore, assessing physical activity with other objective methods, such as accelerometry, is an approach that has been successfully used in large-scale epidemiological studies in children (Riddoch et al., 2004; Ekelund et al., 2004).

The outcome from accelerometry (i.e. activity counts) can be transformed to predict PAEE by regression analysis. This relationship may also be used when interpreting children's physical activity behavior. For example, when analyzing time spent at different intensity levels of physical activity (e.g. low, moderate, high) or when examining proportions of children who reach recommended levels of physical activity, the relationship between activity counts and EE is used to establish intensity thresholds.

One of the most widely used accelerometers, the MTI accelerometer is valid for assessing the total amount of physical activity on a group level (Ekelund et al., 2001), and provides detailed information of activity at different levels of intensity (Nilsson et al., 2002; Trost et al., 2002; Puyau et al., 2002; Freedson et al., 1998; Hendelman et al., 2000; Swartz et al., 2000). However, activity counts from accelerometry do not provide direct information on TEE and its sub-components. A number of prediction equations have been developed to convert activity counts to components of TEE (Ekelund et al., 2001; Trost et al., 2002; Puyau et al., 2002; Freedson et al., 1998; Hendelman et al., 2000; Swartz et al., 2000). Almost all prediction equations have been developed during laboratory-restricted activities using respiratory gas analysis as the criterion measure (Trost et al., 2002; Puyau et al., 2002; Freedson et al., 1998; Swartz et al., 2000), and these equations can also be used to create specific cut-off limits using activity counts corresponding to certain intensity levels. To determine appropriate intensity levels from calorimetry measurements, the Metabolic Energy Turnover (MET) classification system is often used,

by dividing the energy cost of activity by either measured or estimated resting metabolic rate (RMR).
When calibrating activity counts against EE, walking or running are frequently used (Trost et al., 2002; Puyau et al., 2002; Freedson et al., 1998; Swartz et al., 2000). However, since children's habitual physical activity behavior is likely to be more complex, additional activities (e.g. household tasks, rope jump, martial arts) have sometimes been included (Puyau et al., 2002, Hendelman et al., 2000; Swartz et al., 2000). Two prediction equations developed for use in children and adolescents (Trost et al., 2002; Puyau et al., 2002) have been applied in several studies to examine the amount and proportion of time spent at different intensity levels derived from activity counts (Reilly et al., 2004; Montgomery et al., 2004; Pate et al., 2002). Since the cut-off limits from activity counts proposed to correspond to a certain intensity level differ substantially between these equations, the amount of time spent at different intensities of physical activity will differ, depending on the equation applied to the data. Prediction equations producing large differences may affect comparability between studies and it could be argued that a prediction equation applied to free-living conditions should be based on free-living measurements of activity by accelerometry, using the DLW method as the criterion measure. Furthermore, the comparability of different laboratory-derived equations for the prediction of TEE and PAEE during free-living conditions is unclear.
Therefore, the aim of this study was to examine the degree of agreement between three different EE prediction equations; two derived during laboratory conditions (Trost et al., 2002; Puyau et al., 2002) and one derived during free-living using DLW (Ekelund et al., 2001), when applied to a large, randomly selected population based sample of children.

## Research Methods and Procedures

### Subjects

Participants in this study were 9-10 year-old children participating in the European Youth Heart Study (EYHS). The study aims, design, sampling procedures, and methods have been described in detail previously (Riddoch et al., 2005). Briefly, the study population is based on a random selection of children from four European countries (Denmark, Portugal, Estonia and Norway). All children with complete data on objectively measured physical activity, height and weight were included in the current analyses. In total, 1321 children (663 boys, 658 girls) with mean age 9.6 ± 0.4 years were included. Mean height and weight for boys were 139 ± 6.6 cm and 33.2 ± 6.4 kg, and corresponding values for girls were 138 ± 6.7 cm and 32.9 ± 6.9 kg (height: $p$ = 0.08, weight: $p$ = 0.48). Mean body mass index was 17.2 ± 2.4 and 17.2 ± 2.7 $kg·m^{-2}$ for boys and girls, respectively ($p$ = 0.95).

### Assessment of physical activity

Physical activity was assessed using the MTI accelerometer, model 7164 (Manufacturing Technology Inc., Fort Walton Beach, FL). The MTI accelerometer is a lightweight electronic motion sensor, which measures the vertical accelerations of body movement. The validity and reliability of this instrument for measuring physical activity has been tested during a variety of conditions (Ekelund et al., 2001; Hendelman et al., 2000; Metcalf et al., 2002; Nichols et al., 2000). The children wore the accelerometer attached on the hip during all waking hours for four consecutive days, including two weekdays and two weekend-days. For the purpose of this study, the total sum of counts was divided by registered time ($cnts·min^{-1}$) and applied to the data using the different energy expenditure prediction equations (see below). Detailed descriptions of the physical activity measurement protocol and data reduction procedures have been described previously (Riddoch et al., 2004).

### Predictions of energy expenditure estimates

Based on the simultaneous measurement of accelerometer counts, expressed as $cnts·min^{-1}$, and PAEE ($kcal·day^{-1}$) by the DLW method a PAEE prediction equation has recently been developed (Ekelund et al., 2001). The original equation (Ekelund et al., 2001), was based on a random sample of 18 of 26 children 9-to-10 years of age, and subsequently cross-validated in the remaining eight children. For the current study, we used a slightly modified equation based on all 26 children, which essentially left the predictive power unchanged and with normally distributed residuals. Activity counts and gender explained 44% of the variation in PAEE with a standard error of 150 $kcal·day^{-1}$. This equation was then compared with two laboratory-based equations developed for use in children (Trost et al., 2002; Puyau et al., 2002). All three equations are shown in Table 1.
The equation by Trost et al. (2002) was developed during treadmill locomotion in 6-17 year old children and adolescents (n=80). Oxygen uptake and accelerometer counts were simultaneously measured during the test and data on oxygen uptake were subsequently transformed to MET values.
We predicted TEE from the Trost et al. (2002) equation by recalculating 1 MET defined as $3.5mlO_2·kg^{-1}·min^{-1}$ to EE ($kcal·day^{-1}$) by assuming a conversion factor of 4.825 kcal per litre of oxygen consumed, and a resting respiratory quotient equivalent to 0.82 (Weir, 1949). This value was then multiplied with the predicted MET value to express TEE. Predicted REE according to Schofield et al. (1985) was subtracted from TEE to predict PAEE.

Table 1. The three equations used for predicting TEE and its components from accelerometer measurement.

| | Prediction Equation |
|---|---|
| Ekelund et al. (2001) | PAEE (kcal/day) = 66.847 + (cnts/min · 0.953) – (176.91· Gender) |
| Puyau et al. (2002) | PAEE (kcal/kg/min) = 0.0183 + (cnts/min· 0.00001) |
| Trost et al. (2002) | METs = 2.757+(cnts/min · 0.0015) – (0.08957·Age) – (0.000038 · cnts/min·Age) |

Gender: boys = 0, girls = 1. Age in years.

The equation by Puyau et al. (2002) is based on 26 children with an age range of 6-16 years. PAEE was measured by indirect calorimetry during different structured activities (e.g. treadmill walking, tossing ball, rope jump) in a metabolic chamber. TEE was calculated from this equation by summing PAEE and predicted REE estimated according to Schofield et al. (1985).

When calculating TEE from PAEE and REE (or vice versa), the diet induced thermogenesis was assumed to account for 10% of TEE (Maffeis et al., 1993). We calculated mean EE estimates per day in two ways from the laboratory-derived equations (Trost et al., 2002; Puyau et al., 2002).

The first approach was calculated by multiplying the predicted outcome per minute by 1440 (24 hours). The second approach was calculated by multiplying the predicted outcome per minute by measured accelerometer time, assumed to correspond to awake time. The remaining time of the day was assumed as sleep, and EE was defined as REE according to Schofield et al. (1985).

**Statistics**

Mean and standard deviation (± SD) were used to describe physical characteristics, energy expenditure estimates (TEE, PAEE, and REE) and the physical activity level (PAL = TEE / REE). The degrees of agreement between EE variables derived from the three different equations are presented as Bland and Altman plots (mean difference ± 2 SD) (Bland & Altman, 1986). Estimation differences were tested by paired t-test. Systematic differences were calculated as the correlation coefficients between the difference of the methods and the mean of the methods in the Bland-Altman plots. One-way analysis of variance (ANOVA) was used to test for gender differences between anthropometric variables and the different components of EE. All assumptions for normal distribution among tested variables were fulfilled. All data were analysed by SPSS (Statistical Package for the Social Sciences for Windows, 11.0, 2001, SPSS Inc., Chicago. IL) and alpha was set at 0.05.

## Results

The total time of physical activity measurements averaged 3066 ± 788 min, which corresponds to an average of 12.8 ± 3.3 hours per day. The average intensity of physical activity (cnts·min$^{-1}$) was 784 ± 271 cnts·min$^{-1}$ for boys compared to 652 ± 204 cnts·min$^{-1}$ for girls ($p < 0.001$). Predicted REE averaged 1208 ± 129 kcal·day$^{-1}$ and 1153 ± 124 kcal·day$^{-1}$ for boys and girls, respectively ($p < 0.001$). No significant differences between genders were observed for any of the anthropometric variables.

Predicted TEE, PAEE, and PAL from the three different prediction equations are shown in Table 2. Two sets of daily EE estimates are shown for the laboratory-derived equations. The first is based on 24 hours and the second is based on measured time. Regardless of the time factor used, gender differences were observed for all variables of EE ($p < 0.05$), except when PAL was predicted from the equation by Puyau et al. (2002) and the time factor was based on measured time.

The equation by Trost et al. (2002) overestimated PAEE by 17% ($p < 0.001$) when based on 24 hours compared with DLW-predicted PAEE. In contrast, when based on measured time it underestimated PAEE by 46% ($p < 0.001$). Similarly, the equation by Puyau et al. (2002) overestimated PAEE by 83% ($p < 0.001$) when based on 24 hours, and underestimated PAEE by 3% ($p < 0.05$) when based on measured time, compared with free-living predicted PAEE.

Agreement between predicted PAEE from the equation by Trost et al. (2002) and the DLW-based equation (Ekelund et al., 2001) is shown in Figure 1A-B. When predicted PAEE was based on 24 hours, a significant inverse correlation was observed between the difference of the methods and the mean of the methods (Figure 1A; $r = -0.17$; $p < 0.001$). When predicted PAEE was based on measured time, a significant and positive correlation was observed (Figure 1B; $r = 0.26$; $p < 0.001$), indicating a systematic bias for this equation regardless of the time factor used. Agreement between predicted PAEE from the equation by Puyau et al. (2002) and the DLW-based equation (Ekelund et al., 2001) is shown in Figure 2A-B. When predicted PAEE was based on 24 hours, the observed error variance in PAEE was randomly distributed (Figure 2A;$r = 0.04$; $p = 0.12$). In contrast, a systematic bias was indicated when PAEE was based on measured time (Figure 2B;$r = 0.20$; $p = 0.001$).

Table 2. Mean values (± SD) of PAEE, TEE and PAL based upon different prediction equations when applied on accelerometer data.

| | Boys n = 663 | Girls n = 658 | All n = 1321 |
|---|---|---|---|
| PAEE ($kcal \cdot d^{-1}$) | | | |
| Ekelund et al. (2001) | 814 ± 258* | 511 ± 194 | 663 ± 274 |
| [a]Trost et al. (2002) | 376 ± 216† | 339 ± 215 | 357 ± 216§ |
| [b]Trost et al. (2002) | 805 ± 330* | 740 ± 302 | 773 ± 318§ |
| [a]Puyau et al. (2002) | 669 ± 221* | 623 ± 230 | 646 ± 227†† |
| [b]Puyau et al. (2002) | 1247 ± 266* | 1175 ± 257 | 1211 ± 264§ |
| TEE ($kcal \cdot d^{-1}$) | | | |
| Ekelund et al. (2001) | 2247 ± 317* | 1849 ± 251 | 2049 ± 348 |
| [a]Trost et al. (2002) | 1760 ± 341* | 1657 ± 345 | 1709 ± 347§ |
| [b]Trost et al. (2002) | 2237 ± 480* | 2103 ± 457 | 2170 ± 473§ |
| [a]Puyau et al. (2002) | 2085 ± 419* | 1972 ± 366 | 2029 ± 356†† |
| [b]Puyau et al. (2002) | 2728 ± 426* | 2586 ± 417 | 2657 ± 427§ |
| PAL (TEE/REE) | | | |
| Ekelund et al. (2001) | 1.87 ± 0.25* | 1.61 ± 0.20 | 1.74 ± 0.26 |
| [a]Trost et al. (2002) | 1.45 ± 0.18‡ | 1.43 ± 0.17 | 1.44 ± 0.17§ |
| [b]Trost et al. (2002) | 1.84 ± 0.24‡ | 1.80 ± 0.22 | 1.82 ± 0.23§ |
| [a]Puyau et al. (2002) | 1.72 ± 0.17 | 1.70 ± 0.18 | 1.71 ± 0.17** |
| [b]Puyau et al. (2002) | 2.25 ± 0.15‡ | 2.23 ± 0.14 | 2.24 ± 0.14§ |

[a]Based on assumption that average counts per registered minute reflect measured time only, whereas remaining time is assumed to be sleep.
[b]Based on assumption that average counts per registered minute reflect all minutes of the day (24 hours).
* gender difference ($p < 0.001$)
† gender difference ($p < 0.01$)
‡ gender difference ($p < 0.05$)
§ significantly different from Ekelund et al. (2001) equation estimate ($p < 0.001$)
** significantly different from Ekelund et al. (2001) equation estimate ($p < 0.01$)
††significantly different from Ekelund et al. (2001) equation estimate ($p < 0.05$)

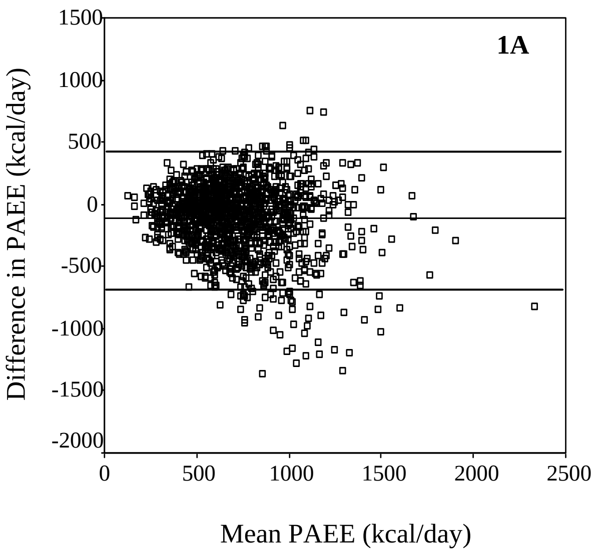
The observed differences in predicted PAEE between equations remained similar when the equations were used to estimate TEE and PAL (Table 2). In comparison to the DLW-based equation, both laboratory-derived equations significantly overestimated TEE and PAL when based on 24-hour measurement, and significantly underestimated TEE and PAL when based on measured time.

We finally reanalysed all data by normalising PAEE by body weight (i.e. expressing the outcome from all equations as PAEE per kg). After normalising for body weight, the equation by Trost et al. (2002) overestimated PAEE by 19% ($p < 0.001$) (no systematic bias: $r = -0.05$; $p = 0.087$) and underestimated by 45% ($p < 0.001$) (systematic bias: $r = 0.48$; $p < 0.001$) when based on 24 hours and awake time, respectively. The equation by Puyau et al. (2002) overestimated by 86% ($p < 0.001$) (systematic bias: $r = 0.29$; $p < 0.001$) when based on 24 hours. In contrast, no significant difference was observed between predictions when based on awake time (mean error 0.6%; $p = 0.61$), although a systematic bias was evident ($r = 0.39$; $p < 0.001$).

## Discussion

Our results suggest that estimated EE values from accelerometer counts differ substantially depending on the equation used and which integration period is chosen for laboratory-based equations, designed to predict instantaneous intensity. Overall, individual differences were quite substantial, with standard deviations around ± 290 kcal·day$^{-1}$, when comparing the laboratory-based equations with the DLW derived equation. Moreover, systematic differences were also indicated when estimating PAEE from the laboratory based equations.

The choice of activities when calibrating activity counts against EE likely affects the ability of a prediction equation to accurately estimate PAEE during free-living conditions. The equation by Trost et al. (2002) is based on the relationship between EE and accelerometer counts during walking and running on a treadmill. In comparison, the equation developed by Puyau et al. (2002) included a more extensive calibration, where EE during a scheduled set of activities was measured in a room calorimeter simultaneously with measurements of body movement by accelerometry. Activities such skipping and jumping are likely to be overestimated while high intensity running, biking, climbing stairs and crawling are likely to be underestimated. The chosen mixture of activities during calibration will affect the slope and intercept of the regression line for the relationship between activity counts and energy expenditure. It is therefore unlikely



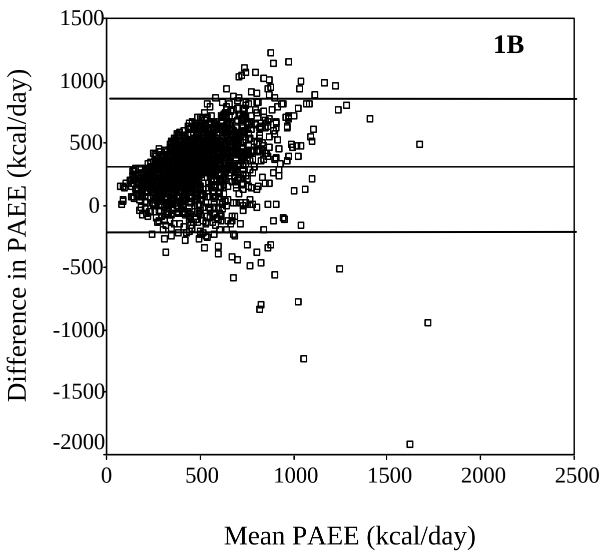




**Figure 1A-B**. Limits of agreement (± 2 SD) of predicted PAEE (kcal·day$^{-1}$) where the mean from equations by Trost et al. (2002) and Ekelund et al. (2001) is plotted against the difference between them. The solid lines represent mean difference ± 2 SD (**A**): Predicted PAEE based on 24 hours. Mean difference was –109 kcal·day$^{-1}$ (limits of agreement: -683 – 465), $p < 0.001$. Correlation between the mean of methods and the difference of methods was $r = -0.17$; $p < 0.001$. (**B**): Predicted PAEE based on measured time only. Mean difference was +306 kcal·day$^{-1}$ (limits of agreement: -234 – 846), $p < 0.001$. Correlation between the mean of methods and the difference of methods was $r = 0.26$; $p < 0.001$.

that prediction equations developed using specific activities in a laboratory are valid throughout the range of free-living activities, which will affect predicted daily PAEE from these equations. The equation by Trost et al. (2002) was developed to predict MET values. In order to convert MET values to PAEE information on REE is necessary. MET values should be multiples of REE and 1 MET (i.e. the EE during rest) has been defined as 3.5ml $O_2 \cdot kg^{-1} \cdot min^{-1}$ (Ainsworth et al., 1993). However, defining 1 MET as 3.5ml $O_2 \cdot kg^{-1} \cdot min^{-1}$ in children may be biased. Harrell et al. (2005) recently presented data on energy costs during different activities in children and compared measured MET values based on measured REE against MET values based on estimated REE, (i.e. equivalent to the adult value of 3.5ml $O_2 \cdot kg^{-1} \cdot min^{-1}$). These authors showed that estimated MET values were significantly higher than the measured MET values, due to the significantly higher REE in children when expressed in relation to body weight (ml $O_2 \cdot kg^{-1} \cdot min^{-1}$) and concluded that the difference in energy expenditure during rest must be adjusted for when converting MET values into caloric cost in children. We chose not to present data on PAEE based on age-adjusted REE when using the equation by Trost et al. (2002) since we believe that the METs predicted by the equation reflect oxygen uptake in relation to 3.5ml $O_2 \cdot kg^{-1} \cdot min^{-1}$. It should be emphasized that, if adjustment for children's higher metabolic rate when expressed per body mass are made, the equation would substantially overestimate PAEE compared to the DLW-based equation. This is likely explained by the assumption that 1 MET was defined as 3.5ml $O_2 \cdot kg^{-1} \cdot min^{-1}$ (i.e. the adult value) when the equation was developed. Since data on measured TEE and its derivatives are not available in this population it is important to compare the estimated energy expenditures predicted from the three equations to those previously published. Hoos et al. (2003) recently published data on TEE and its derivatives using the DLW method. These data are based on a compilation of studies conducted in different settings and including varying numbers of children. Nonetheless, average gender-combined values on TEE and PAEE were approximately 2000 $kcal \cdot d^{-1}$ and 650 $kcal \cdot d^{-1}$, respectively, in 9-10 year-old children. In comparison, predicted TEE and PAEE from the DLW-derived equation (Ekelund et al., 2001), were 2049 $kcal \cdot d^{-1}$ and 663 $kcal \cdot d^{-1}$, respectively. Theoretically, predicted PAEE based on awake is likely to provide the best prediction, since no PAEE per definition occurs during sleep. If this assumption holds true, predicted PAEE from the equation by Puyau et al. (2002) were similar to the DLW-derived equation (Ekelund et al., 2001) and also in good agreement with measured PAEE reported elsewhere (Hoos et al., 2003). However, even if this equation produces a similar mean value of PAEE as the DLW-based equation, a systematic trend of the differences was evident which may still

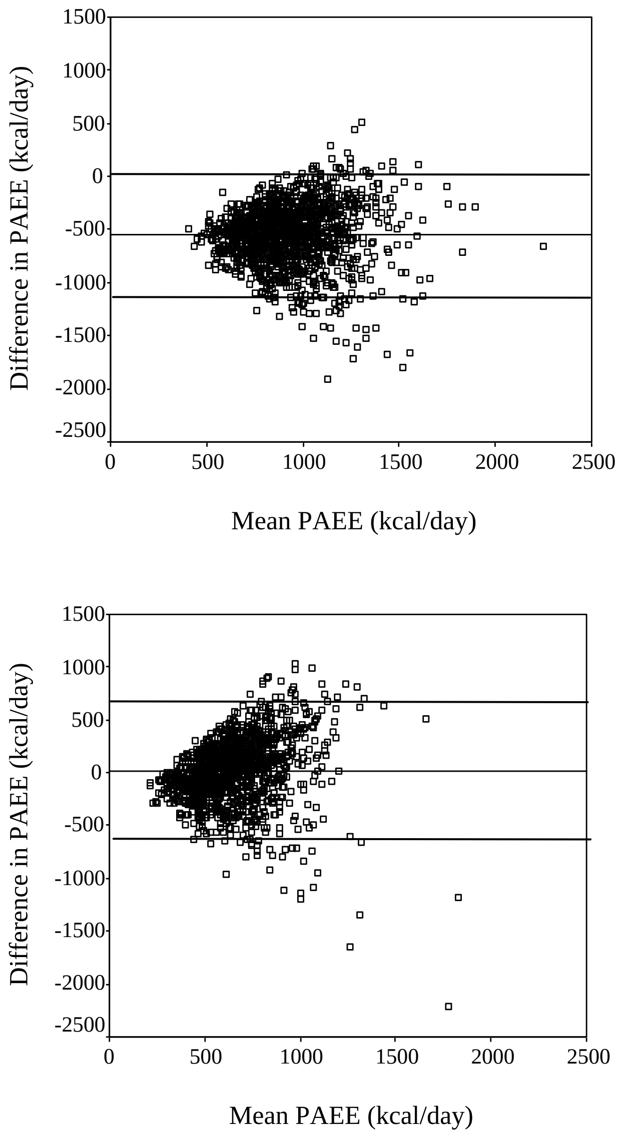



**Figure 2A-B**. Limits of agreement (± 2 SD) of predicted PAEE ($kcal \cdot day^{-1}$) where the mean from equations by Puyau et al. (2002) and Ekelund et al. (2001) is plotted against the difference between them. The solid lines represent mean difference ± 2 SD (**A**): Predicted PAEE based on 24 hours. Mean difference was –548 $kcal \cdot day^{-1}$ (limits of agreement: -1134 – 38), $p < 0.001$. Correlation between the mean of methods and the difference of methods was $r$ = 0.04; p = 0.12. (**B**): Predicted PAEE based on measured time only. Mean difference was +17 $kcal \cdot day^{-1}$ (limits of agreement: -603 – 637), $p < 0.05$. Correlation between the mean of methods and the difference of methods was $r$ = 0.20; $p < 0.001$.

limit to the comparability between equations to predict PAEE in free-living children.

The equation by Trost et al. (2002) clearly underestimated PAEE when based on awake time. The underestimation in predicted PAEE is also reflected in the predicted PAL value of 1.44 from this equation, which is considerably lower than previously reported (Hoos et al., 2003). The equation by Trost et al. (2002) estimated EE within the normal range when based on 24 hour time factor. However, these values were estimated assuming that 1 MET is equal to 3.5 ml $O_2 \cdot kg^{-1} \cdot min^{-1}$, which do not reflect multiples of true REE in children.

The equation by Ekelund et al. (2001), based on DLW measurements over several days, is likely to more accurately estimate daily PAEE compared to laboratory-based equations which are limited to a few specific activities. It showed no mean bias against measured PAEE and seems to reflect average daily PAEE with reasonable validity on group level. However, the equation cannot be expected to be valid on an individual level. More important, no systematic bias was indicated against measured PAEE, which clearly indicate the unbiased ability of the equation to predict average values on PAEE in 9 to 10 year old children. We believe this to be more important when comparing group mean values than any large individual variation per se. It can also be noted that this equation was derived from a relatively small sample of children which is likely to limit its external validity. Therefore, future work aimed at developing prediction equations based on more heterogeneous samples of children is needed. Finally, it should be emphazised that free-living derived equations based on daily PAEE can not be used to define cut off thresholds for specific intensity levels of physical activity. For this purpose, prediction equations based on specific activities in the laboratory are still needed.

In conclusion, laboratory-derived prediction equations based on the relationship between energy expenditure and accelerometry counts produced significantly different predictions of PAEE compared to a DLW derived equation. These equations can not be used interchangeably and interpretations of average levels of PAEE in children from available equations should be made with caution. Further development of equations applicable to free-living scenarios is needed.

## Perspectives

The outcome from accelerometry (i.e. activity counts) can be transformed to predict physical activity energy expenditure (PAEE) by regression analysis. Accurate predictions of PAEE may contribute to our understanding about the associations between PAEE and health outcomes such as the development of obesity in childhood. Further, the ability to accurately predict components of energy expenditure from accelerometer output is of interest when analyzing time spent at different intensity levels of physical activity or when examining proportions of children who reach recommended levels of physical activity. Currently, the accuracy of different equations for the prediction of energy expenditure is unclear. Our results show that laboratory-derived equations evaluated in this study produced significantly different predictions of PAEE compared to the doubly labelled water derived equation. Since predicted values on PAEE vary substantially between equations, interpretations of average levels of daily PAEE in children from currently available prediction equations should be made with caution. Further development of EE equations is needed. Such work should be based on larger and more heterogeneous samples and assessed during diverse activity scenarios, including free-living.

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