Validity and Comparability of a Wrist-Worn Accelerometer in Children

Orjan Ekblom, Gisela Nyberg, Elin Ekblom Bak, Ulf Ekelund, and Claude Marcus

Background: Wrist-worn accelerometers may provide an alternative to hip-worn monitors for assessing physical activity as they are easier to wear and may thus facilitate long-term recordings. The current study aimed at a) assessing the validity of the Actiwatch (wrist-worn) for estimating energy expenditure, b) determining cut-off values for light, moderate, and vigorous activities, c) studying the comparability between the Actiwatch and the Actigraph (hip-worn), and d) assessing reliability. Methods: For validity, indirect calorimetry was used as criterion measure. ROC-analyses were applied to identify cut-off values. Comparability was tested by simultaneously wearing of the 2 accelerometers during free-living condition. Reliability was tested in a mechanical shaker. Results: All-over correlation between accelerometer output and energy expenditure were found to be 0.80 (P < .001). Based on ROC-analysis, cut-off values for 1.5, 3, and 6 METs were found to be 80, 262, and 406 counts per 15 s, respectively. Energy expenditure estimates differed between the Actiwatch and the Actigraph (P < .05). The intra- and interinstrument coefficient of variation of the Actiwatch ranged between 0.72% and 8.4%. Conclusion: The wrist-worn Actiwatch appears to be valid and reliable for estimating energy expenditure and physical activity intensity in children aged 8 to 10 years.

Keywords: Actigraph, Actiwatch, cut-off values, energy expenditure, indirect calorimetry

Accelerometers are now commonly used to quantify physical activity in adults, adolescents, and children. The ability to quantify frequency, intensity, and duration makes it possible to estimate energy expenditure and to estimate the amount of time accumulated and frequency of bouts of activity in prespecified, absolute intensities in large cohorts. However, loss of data is a common problem in epidemiological research when accelerometers are used, not least in children. In many studies, individuals are usually instructed to wear a motion sensor between 4 and 8 days. In some studies, authors are forced to exclude a relatively large number of individuals due to loss of data (ie, too few days or too few hours per day). Wrist-worn motions sensors seem to be more feasible compared with hip worn monitors and thus facilitate long-term recordings in children.

There are several different models of accelerometers, and they may be worn on different positions on the body (ie, wrist, waist, and chest). The Actiwatch (AW) is a uniaxial accelerometer usually intended to be worn on the wrist of the nondominant arm. The placement on the wrist makes it possible to study low-intense physical activities such as arm movements during household work or when playing interactive games, as well as monitoring physical activity during sleep for sleep duration and quality assessment. Frequent movements of low intensity have been shown to be of great importance for weight control. Previous validation studies have examined the validity of the AW when the monitor was placed on the hip and have reported good validity (correlation coefficients between 0.66–0.89) and proposed cut-off values for different activity intensities. A previous study suggested that activity monitors placed on hip, ankle, or wrist may provide similar physical activity output (although different absolute counts) in adults. Results from another study in adult women suggested that the wrist-worn AW accurately estimated activity energy expenditure (r = .73). However, the validity of the wrist-worn monitor in children has not yet been established.

It is likely that estimated energy expenditure and cut-off values for light (1.5 METs), moderate (3 METs), and vigorous (6 METs) physical-activity intensity varies depending on the placement and age. The aims of the current study were, therefore, a) assessing validity of a wrist-worn AW for estimating energy expenditure using indirect calorimetry as reference method, b) determining cut-off values for light, moderate, and vigorous activities, c) examining the agreement between the AW
accelerometer (wrist-worn) and the more commonly used Actigraph accelerometer (hip-worn), and d) examining the intra- (test-retest) and interinstrument reliability of the AW.

Material and Methods

Validity Testing

Validity was tested in a sample of 22 children, including 9 boys and 13 girls [mean age (SD) 8.8 (0.9) years, height 137.7 (7.1) cm, body mass 31.6 (5.4) kg, BMI SDS 0.36 (1.1), resting metabolic rate 1034 (200) kcal/dag] who volunteered to participate in this study. A full written, informed consent was given by parents or care-givers. Ethical approval was obtained from the local research ethical board for medicine in Stockholm (2001/336 and 2007/1025–31). The children participated were tested during 2 occasions. On the first occasion, they performed 8 different activities, including PC gaming, slow walking, school-like tasks, cleaning/swabbing, fast walking, horizontal jogging, jogging up-hill, and a paced step test. Activities were chosen to mimic a variety of commonly performed activities. On the second occasion, which took place in the morning after an overnight fast, resting metabolic rate (RMR) was assessed in the awake but resting state. On both occasions, expired air was collected by Douglas bags. Subjects wore a Hans-Rudolph mask, covering the nose and mouth. The mask was tightly fitted to ensure that any leakages were minimized if leakage occurred. During activities performed as over-ground activities (activities A, C, E, F), the Douglas bag was worn on a specially designed back-pack. The weight of this arrangement was approximately 2 kg. The content of the Douglas bags was analyzed for oxygen and carbon dioxide concentration using VacuMed analyzer model 17518A and model 17515A (VacuMed, Ventura, CA, USA), respectively. Gas volume was measured with a Tissot spirometer. Oxygen uptake was calculated from concentration of oxygen and carbon dioxide, gas temperature of the expired air, and ambient air pressure using conventional equations based on the Haldane transformation. Gas collection started 2 minutes after the start of the activity to allow the subject to reach a steady oxygen uptake. This delay was determined following initial pilot testing measuring time to steady state heart rate and oxygen consumption using an on-line metabolic cart (Oxycon Pro, Erich Jaeger GmbH, Hoechberg, Germany). To collect a sufficient amount of expired gases, time for each activity varied between activities because ventilation varied. In the PC gaming, where ventilation was the lowest, the collection time was typically between 9 and 12 minutes. In the more intense activities, collection times were typically 1 to 2 minutes. RMR was measured in supine position.

An AW motion sensor (Cambridge Neurotechnology Ltd, Cambridge, UK) was worn on the wrist of the non-dominant arm and was fitted using a nonflexible band and adjustable clip. For validity assessment, the epoch length was set to 15 s. Data were downloaded to a PC using software and interface as instructed by the manufacturer in the ActiWatch 6.0 software. Data were then transferred to the statistical software (Statistica 8.0, StatSoft Inc., Tulsa, OK, USA) for further statistical analysis.

Comparability Testing

Agreement between AW (wrist-worn) and Actigraph accelerometer model 7164 (hip-worn), (Manufacturing Technology Inc, Fort Walton Beach, FL, USA) was tested in a sample of 23 boys and 21 girls during free-living conditions [mean (SD) age 9.1 years (0.7), weight 33.9 (7.5), height 137.1 (7.5), BMI SDS 1.14 (1.72)]. Data were collected between 8 AM and 9 PM during 7 consecutive days and were subsequently used for agreement analysis. For agreement analyses (both between AW and Actigraph and for reliability analysis), the epoch length was set to 1 minute. Only data from the monitors including time matched pairs of AW and Actigraph were included in further analyses and the mean (SD) recorded time was 55 hours. Actigraph motion sensor data were analyzed using the Actilife software (Actigraph, Pensacola, FL, USA).

Reliability Testing

The intrainstrument (test-retest) and interinstrument reliability of the AW were examined in vitro using a mechanical shaker. Twenty instruments were randomly selected and tested in a mechanical shaker (Innova 4200, Incubator shaker, New Brunswick Scientific, Edison, NJ, USA) at 4 different intensities [180, 240, 280, and 320 revolutions per minute (rpm)] and each intensity level was repeated on 3 separate occasions.

Statistical Analyses

Validity Testing. Energy expenditure was calculated from the oxygen consumption and corrected for respiratory exchange ratio.15 Total energy expenditure (TEE) was calculated as the total amount of energy expended per minute and kilo body mass and expressed as TEE kcal·min⁻¹·kg⁻¹. Activity-related energy expenditure (AEE) was calculated as the total energy expenditure during an activity minus resting energy expenditure and expressed as AEE (kcal·min⁻¹·kg⁻¹) = TEE-REE. Physical activity intensity was expressed as the metabolic equivalents (METs) and calculated as TEE / measured REE.

Correlation between energy expenditure and accelerometer counts was assessed by resampling technique, using the Rundom Pro 3.14 Software (Jadwizsczak, P. 2009, available at www.pjadw.tripod.com). Limits of agreement17 were used to study prediction accuracy from AW counts only and from multiple regression.

Cut-off Value Identification. Receiver operating characteristic (ROC) analyses were applied to identify cut-off values for sedentary (1.5 METs), moderate (3 METs), and vigorous (6 METs) activities. Multiple linear
regression analyses were performed to study predictors for AEE, TEE, and METs from accelerometer counts and other potential predictors (ie, gender, age, height, and body mass). Level of significance was set to 5%.

**Comparability Analyses.** The association between AW and Actigraph energy expenditure estimates was examined by linear regression analysis. Actigraph energy expenditure was estimated according to the method proposed by Puyau et al.9 Bias between the monitors (ie, the difference between the mean energy expenditure) was examined using t test for dependent samples. Systematic error was analyzed by examining the correlation coefficient between the difference of AW and Actigraph energy expenditure estimates and the mean of estimated EE from the monitors.

**Reliability Analyses.** Intra- and interinstrument reliability for the AW monitor during the in vitro experiment was examined by calculating the coefficient of variation.

**Results**

**Validity Testing**
The correlation between TEE and AW counts for all 8 activities was studied and was found to be 0.80 ($P < .001$). Cut-off values corresponding to light (1.5 METs), moderate (3 METs), and vigorous (6 METs) activity were determined by applying ROC-analyses, and are presented in Table 1.

To examine the relative contribution of predictor variables explaining the variances of energy expenditure estimations, accelerometer counts, age, gender, height, and body mass were used as independent variables in a multiple regression model, with AEE, TEE, and METs, respectively, as dependent variables. The adjusted $R^2$ from these models are shown in Table 2. Adjusted $R^2$ ranged from 0.693 to 0.746 and were generally higher in prediction of METs, compared with AEE and TEE. Adding REE to the models increased the explained variance by 1 to 3% (data not shown). Only a minor effect on prediction accuracy was found when adding these other potential predictors (see Table 3).

**Comparability Testing**
TEE estimate from AW counts was correlated with that from Actigraph counts according to the method proposed by Puyau et al.9 ($r = .67$, $P < .001$), but with a significantly higher estimated TEE from the AW monitor compared with that of the Actigraph ($P < .001$). A significant negative correlation ($r = –0.58$, $P < .001$) was observed between the difference of AW and Actigraph energy estimates and the mean of the methods. This resulted in lower AW levels in highly active children and consequently higher AW levels in low-active children compared with Actigraph, suggesting the output from the 2 different instruments is not comparable on individual level.

**Reliability Testing**
The coefficient of variation (CV) for the intrument repeatability of the AW devices was 1.72% on 180 rpm, 0.94% on 240 rpm, 1.17% on 280 rpm, and 0.72% on 320 rpm. The CV for the interinstrument reliability on the 4 intensities ranged between 6.6 to 8.4%.

<table>
<thead>
<tr>
<th>Table 1</th>
<th>Proposed Cut-off Values for 1.5, 3, and 6 METs*</th>
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<tbody>
<tr>
<td>Intensity</td>
<td>Cut-off value (counts/15 s)</td>
</tr>
<tr>
<td>1.5 METs</td>
<td>80</td>
</tr>
<tr>
<td>3 METs</td>
<td>262</td>
</tr>
<tr>
<td>6 METs</td>
<td>406</td>
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* Specificity and sensitivity values were obtained from ROC-curve analyses.

<table>
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<tr>
<th>Table 2</th>
<th>Adjusted $R^2$ From Multiple Linear Regressions for Predicting Different Measures of Energy Expenditure</th>
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<tbody>
<tr>
<td>Predictors</td>
<td>$R^2$ for TEE</td>
</tr>
<tr>
<td>AW (counts·15s⁻¹)</td>
<td>0.694</td>
</tr>
<tr>
<td>AW + gender</td>
<td>0.693</td>
</tr>
<tr>
<td>AW + gender + age</td>
<td>0.701</td>
</tr>
<tr>
<td>AW + gender + age + body mass</td>
<td>0.705</td>
</tr>
<tr>
<td>AW + gender + age + body mass + height</td>
<td>0.703</td>
</tr>
</tbody>
</table>

* Specificity and sensitivity values were obtained from ROC-curve analyses.
Discussion

The correlation between accelerometer counts and TEE was 0.80, indicating acceptable validity for measuring physical activity in children between 8 and 10 yrs. The current study presents proposed cut-off values for a wrist-worn ActiWatch accelerometer corresponding to light (1.5 METs), moderate (3 METs), and vigorous (6 METs) physical activity.

Our results also suggest a good correlation between AW counts and Actigraph counts. However, a systematic error was observed, suggesting that the output from the 2 instruments rank individuals similarly but cannot be used interchangeably for assessing absolute levels of activity in children.

For quality control constant calibration should always be performed as a part of the laboratory practice, but the low coefficients of variation found indicate a good intra- and intermonitor reliability in AW.

Puyau and colleagues observed lower cut-off values for 3 and 6 METs, respectively. (To perform this comparison, cut-off values from the current study were multiplied by the factor 4, since they were obtained as counts per 15 seconds, whereas the values by Puyau were in counts per 60 seconds). This is likely explained by different placements of the monitor (waist vs. wrist) and the more homogeneous sample of children in the current study. The association between activity counts and energy expenditure estimates (as indicated by correlation coefficients) seems to be lower when the accelerometer was placed on the hip compared with the wrist placement in the current study; however, the association was similar in magnitude when comparing other studies using an ankle placement. Thus, wrist-worn accelerometers provide at least equally valid data as when obtained from other sites. In contrast, the AW output (ankle placement) was not significantly correlated with total energy expenditure (doubly labeled water) and body composition in 31 children (4–6 years) under free-living conditions. Table 3 shows the limits of agreement for predicting TEE (kcal·min	extsuperscript{-1}) using AW counts only or using multiple regression with AW, gender, height, body mass, and RMR as independent predictors.

Table 3 Limits of Agreement for Predicting TEE (kcal·min	extsuperscript{-1}) Using AW Counts Only or Using Multiple Regression With AW, Gender, Height, Body Mass, and RMR as Independent Predictors

<table>
<thead>
<tr>
<th>Intensity</th>
<th>Limits of agreement</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>AW counts only</td>
<td>Multiple adjusted</td>
<td></td>
</tr>
<tr>
<td>Below 1.5 METs</td>
<td>-0.87; -0.25</td>
<td>-1.16; 0.10</td>
<td></td>
</tr>
<tr>
<td>Between 1.5 and 3 METs</td>
<td>-1.53; 0.83</td>
<td>-1.39; 0.55</td>
<td></td>
</tr>
<tr>
<td>Between 3 and 6 METs</td>
<td>-1.38; 1.70</td>
<td>-1.26; 1.50</td>
<td></td>
</tr>
<tr>
<td>Above 6 METs</td>
<td>-1.44; 3.18</td>
<td>-1.56; 2.98</td>
<td></td>
</tr>
</tbody>
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Abbreviations: AW, Actiwatch; METs, Metabolic equivalents; RMR, resting metabolic rate.

Multiple regression analyses was slightly higher for METs than for AEE or EE, which may indicate that AW is a more valid instrument when assessing intensity then energy expenditure.

Similar to previous studies, we used a variety of different activities, not only restricted to treadmill locomotion, when establishing the association between activity counts and EE estimates. This approach is likely to be more similar to free-living assessment conditions when performed in a laboratory setting. Further, even active children (and adults) spend most of their time in sedentary or light-intensity activities. Therefore, inclusion of these types of activities when establishing the relationship between activity counts and EE estimates is a strength of the current protocol.

A weakness in the current study is the homogenous nature of the sample. Generalization of these results to other age groups or adults should be avoided. The study was performed using indoor activities only, although including locomotor activities and activities including upper-body work. The choice of activities in any protocol will likely influence the association between activity counts and energy expenditure estimates; including other activities may have altered the cut-off values to some extent. In addition, the fact that subjects wore a back-pack during 4 of the activities may have affected the cut-off values. However, this effect was considered minor and no attempt was made to correct for this.

The AW accelerometer placed on the waist seems to be a valid instrument for assessing physical activity and may be used to estimate energy expenditure in 8-to 10-year-old boys and girls. The use of wrist-worn AW monitors may be an alternative to hip-worn monitors for physical activity assessment in children between 8 and 10 years. The wrist placement is likely more feasible compared with a waist placement and will potentially reduce loss of data since the monitor can be worn overnight. The proposed cut-off values may be considered when categorizing activities based on intensity. Although the output from the AW appears to rank individuals in agreement with the more commonly used Actigraph, the absolute output from the 2 monitors cannot be interchangeably used. The AW monitor showed low coefficient of variation, indicating good reliability.
Acknowledgments

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References