Validity of heart rate, pedometry, and accelerometry for predicting the energy cost of children's activities

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Eston, Roger G., Ann V. Rowlands, and David K. Ingle dew. Validity of heart rate, pedometry, and accelerometry for predicting the energy cost of children's activities. J. Appl. Physiol. 84(1): 362–371, 1998.—Heart rate telemetry is frequently used to estimate daily activity in children and to validate other methods. This study compared the accuracy of heart rate monitoring, pedometry, triaxial accelerometry, and uniaxial accelerometry for estimating oxygen consumption during typical children's activities. Thirty Welsh children (mean age 9.2 ± 0.8 yr) walked (4 and 6 km/h) and ran (8 and 10 km/h) on a treadmill, played catch, played hopscotch, and sat and crayoned. Heart rate, body accelerations in three axes, pedometry counts, and oxygen uptake were measured continuously during each 4-min activity. Oxygen uptake was expressed as a ratio of body mass raised to the power of 0.75 [scaled oxygen uptake (sV˙O2)]. All measures correlated significantly (P < 0.001) with sV˙O2. A multiple-regression equation that included triaxial accelerometry counts and heart rate predicted sV˙O2 better than any measure alone (R² = 0.85, standard error of the estimate = 9.7 ml·kg⁻⁰·⁷⁵ ·min⁻¹). The best of the single measures was triaxial accelerometry (R² = 0.83, standard error of the estimate = 10.3 ml·kg⁻⁰·⁷⁵ ·min⁻¹). It is concluded that a triaxial accelerometer provides the best assessment of activity. Pedometry offers potential for large population studies.

physical activity; oxygen consumption; triaxial accelerometry; uniaxial accelerometer; heart rate monitoring

To overcome the problem of unreliable self-report in children (3, 31), heart rate is commonly employed as an objective method of assessing children's physical activity. Heart rate does not measure physical activity directly but is based on the linear relationship between oxygen uptake and heart rate. The widespread use of heart rate monitoring is due to its ease of measurement, its ability to record values over time, and its reflection of the relative stress placed on the cardiopulmonary system due to physical activity (34). However, heart rate can also be elevated by emotional stress, which is independent of any change in oxygen uptake. The return of heart rate to baseline may also lag behind the return of oxygen uptake to baseline (24). Additionally, the heart rate-oxygen uptake relationship is moderated by the proportion of active muscle mass and whether the activity is continuous or intermittent (17).

Children's physical activity is highly transitory (2, 24). The relative delay in heart rate response to changes in movement suggests that heart rate monitors may mask potential information. The physical fitness levels of children are also a limiting factor when heart rate monitoring is used to assess physical activity. A fitter child has a higher stroke volume and, hence, a lower heart rate for any given activity (27). Mean daily heart rates may therefore be more representative of children's fitness than their activity level (27).

Despite these weaknesses, heart rate monitoring is commonly used to validate commercial accelerometers (14, 33). This is due to the lack of an adequate alternative criterion measure. Doubly labeled water is considered the gold standard for the assessment of energy expenditure in the field (21), but it is often inappropriate because of its high cost. In addition, information is limited to total energy expenditure, with no frequency, intensity, or duration information.

Conceptually, the use of activity monitors offers the ideal solution, particularly the new generation of uniaxial and triaxial accelerometers that facilitate temporal tracking of the frequency, intensity, and duration of activity. Studies of uniaxial and triaxial accelerometry have elicited encouraging results. However, the majority of studies have used indirect criterion measures, such as heart rate (14, 18, 33), or have restricted the activities to regulated walking and running on a treadmill (20). Few studies have validated accelerometry during a range of activities against the criterion of energy expenditure, and those studies have used adults as subjects (7, 19).

Laboratory studies elicit higher validity coefficients than field studies. This observation is also true for studies using adults compared with children (14). Children engage in a greater variety of movement than adults. Hence, whereas typical adult activities and laboratory activities (walking/running) may be adequately assessed by a uniaxial accelerometer (15), a triaxial accelerometer may be more sensitive to the increased range of movement in children. Some support for this concept is provided by Welk and Corbin (33), who obtained correlations of r = 0.46–0.74 (mean r = 0.60) between average vector magnitude from a triaxial accelerometer and average heart rate (corrected for resting values) compared with correlations of r = 0.51–0.69 (mean r = 0.57) obtained by J anz (14) with a uniaxial accelerometer. Both studies utilized 3 days of monitoring, but Welk and Corbin spread the days over an 8-mo period, whereas J anz assessed activity over 3 consecutive days. Although sample size was similar in the two studies, there was a much greater age range in the study by J anz (7–15 yr) than in the study by Welk and Corbin (9–11 yr), which limits the comparability between the studies.

Triaxial accelerometry appears to be more accurate for predicting energy expenditure (oxygen uptake) in adults undertaking a variety of activities than any dimension on its own (7). Bouten et al. (7) observed that the dominant dimension for predicting energy expenditure changed according to the activity being performed.
For example, walking was predicted within 4% accuracy using only the anteroposterior component, but this dimension underestimated sedentary activities, on average, by >60% (7). When the vector magnitude of the three dimensions was used as the predictor, the energy expenditure of sedentary activities and walking was predicted with an accuracy of ~15%. Triaxial accelerometry has been reported to predict energy expenditure during low-level activities with greater accuracy than heart rate (19) and is highly associated with energy intake (r = 0.99, P < 0.025) during 1 wk under free-living conditions in adults (19). However, in the latter study, heart rate monitoring and triaxial accelerometry predicted free-living energy expenditure as 30% higher than energy intake, although higher individual differences were present when heart rate measurement was used.

Studies on mechanical pedometers have generally concluded that they are inaccurate at counting steps or measuring distance walked (10, 16, 25, 32). However, the newer, commercially available electronic pedometers provide a reasonably accurate estimate of distance walked and number of steps taken (4). Bassett et al. (4) observed that the Yamax DW-500 pedometer was the most accurate, recording 100.7 and 100.6% of steps taken on the left and right foot, respectively.

Pedometers, therefore, show great potential for assessing daily activity. Sequeira et al. (29) demonstrated that the pedometer could differentiate between various levels of occupational activity in adults (sitting, standing, and moderate-effort occupational categories). However, heavy work did not differ from moderate work. The heavy work category contained a high proportion of static work, such as lifting heavy objects. Pedometers are unable to measure physical activity of this type and, hence, underestimated the energy cost of individuals in this occupational category. The contribution of static work to total daily energy expenditure was observed to be trivial in adults (19). In children, the contribution of static work to a day’s energy expenditure is likely to be less than in adults, so the inability of the pedometer to measure this type of work is not a cause for concern. Pedometer readings from 4- to 6-yr-old children correlated highly with observation (26). The pedometer differentiated between the most and the least active children as predetermined by supervisor’s questionnaire (P < 0.001) and confirmed by observation (P < 0.01). The validity of the pedometer as a measure of habitual activity needs to be tested using more stringent criteria. If validity is confirmed, the pedometer would be particularly suited to population studies, inasmuch as it is inexpensive, reusable, and objective.

The purpose of this study was to compare the accuracy of heart rate monitoring, triaxial accelerometry, uniaxial accelerometry, and pedometry to estimate oxygen uptake (energy expenditure) during a number of representative childhood activities (walking, running, hopping, catching, and sitting and crayoning), when used in isolation and in combination with one another.

### METHODS

#### Subjects

The subjects were 30 Welsh children (15 boys and 15 girls) aged 8.2–10.8 yr [9.3 ± 0.8 (SD) yr, mass = 29.8 ± 5.9 kg, height = 133.7 ± 8.1 cm] from a local primary school in the Bangor, North Wales, area. Written informed consent was obtained from the parents or guardians.

#### Procedure

The relationship between pedometry, uniaxial accelerometry, triaxial accelerometry, heart rate, and oxygen uptake was assessed during two walking speeds (4 and 6 km/h) and two running speeds (8 and 10 km/h) on an electronically driven treadmill. In addition, three nonregulated play activities were also performed: playing catch, hopscotch, and sitting and crayoning.

Each child was habituated to the Powerjog treadmill for 5 min. The child then walked at 4 and 6 km/h and ran at 8 and 10 km/h for 4 min at each speed. After a rest period to allow heart rate to return to resting levels, the subject played hopscotch for 4 min. Hopscotch involved alternately hopping and jumping on a hopscotch grid at the subject’s preferred pace (knowing they would be required to continue for 4 min). The subject rested again to allow heart rate to return to baseline, then played catch with an assistant. A soccer ball was thrown between the assistant and the child (~3 m). The child selected the pace, and the rhythm was maintained for the 4 min. The order of the catch and hopscotch activities was interchanged between subjects. The subject rested again to allow heart rate to return to baseline. After resting heart rate was reached, the child sat and crayoned for 10 min. Before each activity started the three electronic pedometers were reset to zero, and at the end of each activity the total number of counts was recorded for each activity. Counts per minute were then calculated.

#### Instrumentation

**Pedometry.** A commercially available electronic pedometer (Digiwalker DW-200, Yamax, Tokyo, Japan) was used. This unit measures vertical oscillations, providing a total count of the accumulated movements. Units were firmly secured to the ankle and wrist using Velcro strips. A third unit was attached to a belt worn by the subject, with the pedometer positioned on the left side of the body.

**Uniaxial accelerometer.** The WAM accelerometer (model 7164, Computer Science Applications, Shalimar, FL) is a very small (5 × 4 × 1.5 cm), lightweight (43 g) unit with a time-sampling mechanism that allows it to provide a chronological measure of frequency, intensity, and duration of movement. It allows data to be analyzed over user-defined intervals (ranging from 1 s to several minutes). In this study, epoch duration was set at 1 min. This epoch was selected, as this was the epoch duration that would most likely be used in field-based studies, allowing data to be collected for up to 22 days with no download. The unit was stored in the pouch supplied, which allowed it to be threaded onto the belt worn by the subject. The WAM was positioned above the left hip.

**Triaxial accelerometer.** The Tritrac-R3D accelerometer (model T303, version 6.0, Professional Products, Reining, Madison, WI) has the same time-sampling ability as the WAM but, in addition, assesses activity in three dimensions, giving output measures in mediolateral (x), anteroposterior (y), and vertical (z) dimensions, as well as the vector magnitude. The Tritrac is bulkier than the WAM (11.1 × 6.7 × 3.2 cm).
The sampling intervals for the Tritrac are 1–15 min, with a maximum of 14 days of data collection when the epoch interval is set at 1 min. The unit was programmed with the subject's age, height, mass, and gender and set to collect data every minute. This would ensure that the WAM and Tritrac were directly comparable. It was necessary to tape the unit securely to the belt worn by the subject to prevent any extraneous movement. The Tritrac was positioned above the right hip.

Heart rate telemetry. The heart rate monitor (BHL 6000 Medical, Fleurier, Belgium) was attached with small adhesive electrodes to minimize the discomfort to the child and improve accuracy of the recording. It was necessary to add adhesive tape to ensure that the electrodes did not slip. The heart rate monitor was programmed to record the average of every eight heartbeats.

Gas analysis. Oxygen uptake was measured by on-line gas analysis every 30 s during each activity (Biokinetics, Bangor, UK). This system involves a very lightweight, low-resistance heart rate monitor was programmed to record the average of extraneous movement. The Tritrac was positioned above the subject's age, height, mass, and gender and set to collect data every minute. This would ensure that the WAM and Tritrac were directly comparable. It was necessary to tape the unit securely to the belt worn by the subject to prevent any extraneous movement. The Tritrac was positioned above the right hip.

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Results

Values for Tritrac vector magnitude (Tritrac<sub>xz</sub>), Tritrac<sub>x</sub>, Tritrac<sub>y</sub>, Tritrac<sub>z</sub>, WAM, heart rate, hip pedometer, ankle pedometer, wrist pedometer, and sV<sub>O</sub><sub>2</sub> during each of the activities are given in Table 1.

Each activity measure correlated significantly (P < 0.001) with sV<sub>O</sub><sub>2</sub> and heart rate (Table 2), with the exception of the wrist pedometer when sV<sub>O</sub><sub>2</sub> was predicted for treadmill activities alone. Correlations with sV<sub>O</sub><sub>2</sub> were consistently higher than corresponding correlations with heart rate. In addition, when heart rate was used as the criterion, a different trend in scores emerged, with Tritrac, showing the best relationship. This was the weakest of the Tritrac variables when sV<sub>O</sub><sub>2</sub> was the criterion measure. There was no significant relationship between sV<sub>O</sub><sub>2</sub> and body mass (r = 0.024). This confirmed that the effects of mass had been factored out by the scaling.

Planned comparisons of the correlations with sV<sub>O</sub><sub>2</sub> were carried out comparing Tritrac<sub>xz</sub> and heart rate, WAM and heart rate, hip pedometer and heart rate, Tritrac<sub>xz</sub> and WAM, and Tritrac<sub>xz</sub> and hip pedometer. In addition, the correlations between sV<sub>O</sub><sub>2</sub> and Tri-
and the best uniaxial predictor (Tritech) were compared to assess whether the three-dimensional assessment was better than any one uniaxial assessment. These were carried out using an adapted t-test that takes into account the correlation between the two coefficients of correlation (12). To control for type I error, the Bonferroni correction was used (13); α (0.05) was divided by the number of tests to give \( P = 0.008 \). s\( \dot{VO}_2 \) correlated significantly better with Tritechxyz than with heart rate, WAM, hip pedometer, or Tritechz (\( P < 0.001 \)). The correlation between heart rate and s\( \dot{VO}_2 \) was not significantly different from that between WAM or hip pedometer and s\( \dot{VO}_2 \).

Triaxial accelerometry revealed that the major acceleration component varied in some subjects according to activity. Generally, the vertical plane, Tritechz, had the largest acceleration component followed by the anteroposterior plane, Tritechy, (Fig. 1). However, mean values (Table 1) show that, during crayoning and catching, the anteroposterior plane had the greatest influence followed by the mediolateral (Tritechx) plane for crayoning and the vertical plane for catching.

Because of the strong relationships, linear regression equations were computed to predict s\( \dot{VO}_2 \) from each of the measures (Table 3, Fig. 2). The best single measure was Tritechxyz, which accounted for 82.5% of the variance. Irrespective of the Tritech measure used, the variance accounted for by the Tritech was greater than any of the other measures (Table 3). The weakest of the Tritech predictors (Tritracey) was still superior to the best of the rest, i.e., the pedometer worn at the hip (71.8% compared with 64.8%). It is surprising that the simple pedometer had less error associated with its predictions than did either the WAM or the heart rate monitor. The WAM data from one subject had to be rejected, because the counts seemed “jammed” at a high level. A small number of unusually high WAM counts were recorded during hopscotch and running at 10 km/h. However, these scores could not be eliminated, because counts before and after appeared normal. This

Table 2. Correlations of the various measures of energy expenditure with heart rate and s\( \dot{VO}_2 \) for all activities combined, treadmill activities, and unregulated play activities

<table>
<thead>
<tr>
<th></th>
<th>Tritechxyz</th>
<th>Tritechx</th>
<th>Tritechy</th>
<th>Tritechz</th>
<th>WAM</th>
<th>Pedometer</th>
</tr>
</thead>
<tbody>
<tr>
<td>All activities</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>s( \dot{VO}_2 )</td>
<td>0.908</td>
<td>0.847</td>
<td>0.876</td>
<td>0.891</td>
<td>0.780</td>
<td>0.806</td>
</tr>
<tr>
<td>HR</td>
<td>0.791</td>
<td>0.816</td>
<td>0.764</td>
<td>0.756</td>
<td>0.684</td>
<td>0.622</td>
</tr>
<tr>
<td>Treadmill activities</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>s( \dot{VO}_2 )</td>
<td>0.883</td>
<td>0.765</td>
<td>0.740</td>
<td>0.863</td>
<td>0.692</td>
<td>0.782</td>
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<tr>
<td>HR</td>
<td>0.855</td>
<td>0.835</td>
<td>0.760</td>
<td>0.805</td>
<td>0.614</td>
<td>0.816</td>
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<tr>
<td>Unregulated play activities</td>
<td></td>
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<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>s( \dot{VO}_2 )</td>
<td>0.926</td>
<td>0.865</td>
<td>0.928</td>
<td>0.925</td>
<td>0.852</td>
<td>0.921</td>
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<tr>
<td>HR</td>
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<td>0.864</td>
<td>0.875</td>
<td>0.867</td>
<td>0.734</td>
<td>0.883</td>
</tr>
</tbody>
</table>

Unregulated play activities consist of hopping, catching, and crayoning. HR, heart rate. *Not significant; all others are significant (\( P < 0.001 \)).
contributed to the relatively poor relationship between WAM and s\(\text{VO}_2\). Additional pedometers worn at the wrist and ankle did not improve the estimate of s\(\text{VO}_2\) from the hip pedometer alone.

Multiple regression analysis was used to establish the efficacy of using two measures simultaneously (Table 3). Each possible pair of measures was forced into the regression equation. The order of entry was alternated to illustrate the amount of variance accounted for by the second measure, over and above that already accounted for by the first measure. To reduce the possibility of type I error, \(\alpha\) was adjusted to 0.01. The best model contained Tritrac\(_{xyz}\) and heart rate \((R^2 = 0.849)\). Heart rate added 2\% \((P < 0.01)\) of variance to that already explained by Tritrac\(_{xyz}\), whereas Tritrac\(_{xyz}\) was responsible for an extra 21.1\% \((P < 0.01)\) in addition to the variance accounted for by heart rate. The pedometer caused a similar increase in \(R^2\) when added to heart rate, as heart rate did when used in addition to the pedometer (16.4 and 15.3\%, respectively).

The relationships between s\(\text{VO}_2\) and Tritrac\(_{xyz}\), WAM, heart rate, and hip pedometer are presented in Fig. 2. The reduced scatter can be seen in the Tritrac\(_{xyz}\) scattergram compared with the WAM and heart rate scattergrams. However, the pedometer data appear to deviate from the assumption of homogeneity of variance. This was confirmed by a graph of the residuals, which also showed the WAM data to deviate slightly from normal distribution.

It can be seen from Fig. 3 that the accuracy with which each individual activity was measured depended on which activity monitor was being used. This is highlighted when hopscotch is studied. WAM and heart rate assessed hopscotch more accurately than any other activity. Conversely, this activity was the least accurately assessed by Tritrac\(_{xyz}\) and the hip pedometer. Overall, the tendency to underestimate s\(\text{VO}_2\) as the exercise intensity increases is clearly shown, particularly as hopscotch had a higher oxygen cost than running at 8 km/h (Table 1).

<table>
<thead>
<tr>
<th>Predictor Variables</th>
<th>Increment in (R^2) When Predictor Variable Entered</th>
<th>(\text{Final Equation}^{\text{a}})</th>
<th>(\text{UNSTANDARDIZED REGRESSION COEFFICIENT}^{\text{b}})</th>
<th>(\text{STANDARDIZED REGRESSION COEFFICIENT}^{\text{b}})</th>
<th>SEE</th>
<th>SEE as percentage of mean s(\text{VO}_2)</th>
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<td>Single predictor variable</td>
<td></td>
<td></td>
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<td></td>
<td></td>
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<tr>
<td>Tritrac(_{xyz})</td>
<td>0.825</td>
<td>25.640</td>
<td>0.012</td>
<td>0.908</td>
<td>10.31</td>
<td>18.23</td>
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<td>Tritrac(_y)</td>
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<td>28.237</td>
<td>0.015</td>
<td>0.891</td>
<td>11.19</td>
<td>19.79</td>
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<td>0.876</td>
<td>11.92</td>
<td>21.08</td>
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<td>29.616</td>
<td>0.031</td>
<td>0.847</td>
<td>13.11</td>
<td>23.18</td>
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<td>WAM</td>
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<td>36.917</td>
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<td>0.780</td>
<td>15.71</td>
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<td>0.254</td>
<td>0.806</td>
<td>16.00</td>
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<td>Ankle pedometer</td>
<td>0.623</td>
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<td>0.246</td>
<td>0.789</td>
<td>15.15</td>
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<td>Wrist pedometer</td>
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<td>29.951</td>
<td>0.274</td>
<td>0.665</td>
<td>18.43</td>
<td>32.59</td>
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<td>Two predictor variables (in order of forced entry)</td>
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<td>Tritrac(_{xyz})</td>
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<td>6.209</td>
<td>0.010</td>
<td>0.735</td>
<td>9.66</td>
<td>17.08</td>
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<td>Heart rate</td>
<td>0.020</td>
<td>6.209</td>
<td>0.016</td>
<td>0.735</td>
<td>9.66</td>
<td>17.08</td>
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<td>Heart rate</td>
<td>0.638</td>
<td>6.209</td>
<td>0.010</td>
<td>0.735</td>
<td>9.66</td>
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<td>0.755</td>
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<td>Heart rate</td>
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<td>0.518</td>
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<td>19.53</td>
</tr>
<tr>
<td>Heart rate</td>
<td>0.153</td>
<td>17.376</td>
<td>0.385</td>
<td>0.491</td>
<td>11.05</td>
<td>19.53</td>
</tr>
<tr>
<td>Heart rate</td>
<td>0.649</td>
<td>17.376</td>
<td>0.385</td>
<td>0.491</td>
<td>11.05</td>
<td>19.53</td>
</tr>
<tr>
<td>Hip pedometer</td>
<td>0.053</td>
<td>25.651</td>
<td>0.168</td>
<td>0.525</td>
<td>11.96</td>
<td>21.14</td>
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<tr>
<td>Hip pedometer</td>
<td>0.053</td>
<td>25.651</td>
<td>0.168</td>
<td>0.525</td>
<td>11.96</td>
<td>21.14</td>
</tr>
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</table>

\(s\text{VO}_2\) was measured in ml \(\cdot\) kg\(^{-0.75}\) \(\cdot\) min\(^{-1}\). SEE, standard error of estimate. \(N\) varies from 159 to 177 because of listwise deletion for missing values. Italics indicate significance at 0.01 level.
DISCUSSION

Prediction of sV\textsubscript{O}_2

All activity measures studied showed a strong linear relationship with the criterion measure of sV\textsubscript{O}_2. The Tritrac vector magnitude was the best single predictor of sV\textsubscript{O}_2. The 82.5% of variance accounted for by the Tritrac vector magnitude measure is less than the 90.25% accounted for by the vector magnitude in the study of Bouten et al. (7). However, the activities in the

Fig. 2. Relationship between O\textsubscript{2} uptake scaled for body mass (sV\textsubscript{O}_2) and Tritrac total magnitude counts (A), WAM counts (B), heart rate (C), and hip pedometer counts (D) during regulated treadmill and unregulated play activities in 30 boys and girls aged 8-10 yr. bpm, Beats/min.

Fig. 3. Difference between actual and predicted sV\textsubscript{O}_2 for each activity measured by Tritrac\textsubscript{xyz}, WAM, heart rate, and hip pedometer.
latter study were more restrained, with set paces for all activities and no running included in the protocol. In addition, all 11 subjects were men. Perhaps most importantly, sleeping metabolic rate was accounted for in each subject, so accelerometry values were correlated with energy expenditure due to activity rather than total energy expenditure.

Although the heart rate monitor and WAM did significantly add to the variance accounted for by the Tritracxyz ($P < 0.01$), the increase was very small: 2.0 and 1.7% for heart rate and WAM, respectively. The justification of the cost of equipping a subject with two measures to effect this increase would be very questionable. It was expected that the heart rate would account for rather more variance, over and above that explained by the Tritracxyz, as a different construct was being measured (heart rate as opposed to movement). Conversely, the ability of heart rate to explain sV˙O2 was greatly enhanced when Tritracxyz was added as a second predictor (21.1% increase in explained variance). It is interesting to note the significant increase in variance accounted for by the WAM, as this indicates that some of the uniaxial WAM output is independent of the Tritracxyz output.

The variance in sV˙O2 accounted for by the measures used to assess separate unregulated play activities was low, ranging from 3.5 to 26.1%, 2.2 to 3.7%, 0.1 to 8.4%, and 3.8 to 12.7% for Tritracxyz, heart rate, WAM, and hip pedometer, respectively. However, when all unregulated play activities were considered together, the accounted variance increased to 85.8% (Tritracxyz), 73.6% (heart rate), 72.6% (WAM), and 84.8% (hip pedometer). The Tritrac vector magnitude results compared favorably with the study of Bouten et al. (7), in which only 3–32% of the variance in energy expenditure during individual sedentary activities and 67% for all sedentary activities together were accounted for by a triaxial accelerometer. This highlights the low sensitivity of accelerometry when energy expenditure is predicted for short-term individual activities. The extremely low variance accounted for by heart rate was not surprising here, as all but one of the unregulated activities was of low intensity. The inability of heart rate to predict oxygen uptake at low activity levels is well documented (11).

In the present study, only raw heart rate data were used to predict sV˙O2. It is possible that an improved relationship would have been found had resting heart rate been accounted for. However, this was not found to be the case in a similar study with adults (19), in which a simple linear regression technique was found most appropriate. In addition, development of an individual heart rate-sV˙O2 regression line for each subject would not be feasible for a large population study.

**Pedometer**

The pedometer was consistently worn on the left hip. It has been shown that it does not matter on which side of the body electronic pedometers are worn (4).

The hip pedometer results were very encouraging. An inexpensive, “low-tech” measure appears to be as valid as the frequently used measure of heart rate and “high-tech” uniaxial accelerometer (WAM). In addition, the pedometer accounted for more variance when added to either of these two measures (16.4 and 16.6% for heart rate and WAM, respectively) than they did when added to the pedometer (15.3 and 12.2% for heart rate and WAM, respectively; Table 3). This offers potential for objective population studies on activity levels. When only unregulated play activities were assessed, supposedly where the pedometer would be least suited, the correlation with sV˙O2 was 0.921, which was significantly higher than the corresponding correlations for the WAM and heart rate ($P < 0.005$). The pedometer worn on the wrist was least suited to the assessment of physical activity. It was thought that three pedometers, one worn on the ankle, one on the wrist, and one on the hip, would provide a more accurate prediction of sV˙O2 than the hip pedometer alone. However, the extra pedometers did not significantly improve the prediction.

The high correlation for the hip pedometer may be misleading. The data points were not distributed uniformly, consisting of one clump of low values and another clump of high values. This may be due to the nature of the activities performed. Catching and crayoning both led to very few counts on the relatively insensitive pedometer, followed by a large increase when the subject began walking. It is possible that an activity that fitted between those that involved minimal movement and regular movement categories would have improved the fit of the data. When treadmill activities alone were studied, which would effectively eliminate the first clump of data points, the correlation remained high [$r = 0.782$: level with heart rate (0.784) and higher than WAM (0.692)]. The ensuing scatter plot and residuals graph revealed normality and equality of variance. However, treating the WAM data in the same way did not resolve the problem.

**Error of Prediction for the Tritracxyz and the WAM**

The standard errors of the estimate (SEE) were 10.3 (18.23%) and 15.7 ml·kg$^{-0.75}$·min$^{-1}$ (27.78%) for the Tritracxyz and the WAM, respectively. To compare this result with previous studies, it is necessary to convert the values to kilojoules per minute. For a 30-kg subject (average mass of children in this study) this equates to an error of 2.66 kJ/min (Tritrac vector magnitude) and 4.06 kJ/min (WAM). Adjusting this to a typical adult subject of 70 kg would result in errors of 6.20 and 9.47 kJ/min for the Tritracxyz and WAM, respectively. However, this type of extrapolation outside the subject range is not valid, as energy cost does not increase linearly with increasing size (28), but does give an approximation for comparison. On the basis of a typical 70-kg subject, smaller errors of 5.5 (19) and 9.1 kJ/min (22) have been obtained for triaxial and uniaxial accelerometers, respectively. Although the error was larger in the study by Montoye et al. (22), which used the Caltrac accelerometer, it produced a lower SEE than the uniaxial accelerometer in the present study. This is surprising, since they included walking and running on
a gradient. It is recognized that accelerometry and pedometry cannot account for increased energy cost due to inclines (20) or isometric work (29). Activities in the study of Montoye et al. were less varied: walking and running at different speeds, bench stepping, knee bending, and floor touching, all activities where the major acceleration component was in the vertical direction and, hence, should be adequately measured by a uniaxial accelerometer. Using a triaxial accelerometer, Bouten et al. (7) also obtained smaller errors of prediction (15%) than in the current study. However, adults were used in these studies, and the activities were more controlled. For example, they included a set rate of sitting and standing, sitting relaxed, standing relaxed, walking a few paces every 30 s, and walking and running.

Dominant Axis

Neither the crayoning nor catching activities in the present study had movement primarily in the vertical direction (Table 1). In fact, TritracR (anteroposterior) had a slightly higher correlation with sV˙O2 than did either Tritrac vector magnitude or TritracR (vertical) during unregulated play activities (r = 0.928 vs. 0.926 and 0.925, respectively), although the difference in correlations was not significant (P > 0.1). The best uniaxial measure of overall activity was provided by TritracR, showing that the vertical direction is the most important to measure. However, it is important to note that the correlation between sV˙O2 and Tritrac vector magnitude was significantly higher than that for TritracR (P < 0.001). This illustrates the superiority of a three-dimensional measure of movement for predicting energy expenditure. However, the results from this study also indicated that the Tritrac provides uniaxial assessments of activity in children superior to those provided by the WAM.

Measurement of Subgroups of Activities

When treadmill activities alone were considered, a correlation between a WAM worn on the hip and oxygen uptake expressed relative to body mass (ml·kg−1·min−1) in 28 subjects was 0.82 (P < 0.01) (20). This exceeds our correlation of 0.780 for all activities or 0.692 for treadmill activities alone (both P < 0.001). The correlation in the study of Melanson and Freedson (20) was obtained from level treadmill walking and running only, as accelerometry did not differentiate between grades. Melanson and Freedson observed that a WAM worn on the wrist was the best predictor (r = 0.89, P < 0.01). They (20) also found the WAM correlated better with oxygen uptake than with heart rate (correlations with heart rate were 0.66 and 0.73 for WAM monitors worn on the hip and wrist, respectively, both significant at P < 0.01). This compares favorably with the correlation between the WAM (worn on hip) and heart rate monitor in the current study (r = 0.684, P < 0.001).

During the unregulated play activities (hopping, catching, and crayoning), correlations between all measures were higher than when treadmill activities or when all activities were considered. The explanation is most likely that when walking or running on the treadmill the activity levels of the children were relatively homogenous, which would elicit lower correlations (9). During the unregulated play activities the range of movement and heart rate scores were more heterogenous and, hence, resulted in higher correlations. Children’s habitual activity levels vary considerably between and within subjects. It is therefore important that each measure be validated across a whole range of activities and, hence, across a whole range of scores.

Different activities with similar sV˙O2 and heart rate responses did not always elicit similar counts from the activity monitors. When catching and walking at 4 km/h or hopscotch and running at 8 km/h were compared, the counts per minute were very different, whereas sV˙O2 and heart rate remained fairly constant (Table 1). We believe that the nature of the activities causes these discrepancies. Catching predominantly involves the arms with little torso movement; hopscotch is a jumping activity and, hence, uses more energy per movement than walking or running. It was our intention to deliberately select activities that would reflect normal “free-living” activities typical of children’s behavior. This would ensure a stringent test for the accelerometers and pedometers and enable us to make ecologically valid observations. Despite these activities being included, when all activities were considered together, the activity monitors still provided a very good prediction of sV˙O2. This gives us confidence that, when daily activity is assessed as a whole, the presence of these activities at times during the day should not throw out the overall estimation of the day’s activity. This again emphasizes the importance of validating the monitors over a range of activities and assessing how the monitors perform overall as opposed to during individual activities.

All monitors underestimated sV˙O2 at 10 km/h, particularly the WAM (Fig. 3). A likely explanation for this is the much greater increase in stride length in relation to stride frequency. It is well documented that stride length increases in greater proportion than stride frequency in adults (6) and children (30). Accelerometry or pedometry methods will not account adequately for stride length changes, which leads to underestimation at higher speeds. Accelerometers have been found to underestimate energy expenditure during high-intensity activities (19). However, the Tritrac vector magnitude score was superior to the heart rate monitor (an underestimation of 1.93 ± 9.4042 ml·kg−0.75·min−1 compared with an underestimate of 7.26 ± 14.2071 ml·kg−0.75·min−1, respectively, during 10 km/h). Conversely, the sedentary crayoning activity was overestimated by all monitors. The accuracy of the WAM was more closely related to the accuracy of the heart rate monitor than were the other movement counters. WAM and heart rate had less absolute error (Fig. 3) when predicting sV˙O2 for hopscotch and the most error when predicting sV˙O2 for crayoning. Conversely, the Tritrac vector magnitude and the hip pedometer provided their worst estimates when the activity was hopscotch. The
examination of the accuracy of monitors to assess isolated activities is largely academic. As a measure of habitual physical activity, it is important that the monitor provide an accurate picture of varied activity over long periods of time.

Studies that have examined activity levels throughout a whole day have obtained lower correlations for the WAM and Tritrac with heart rate compared with those observed in the present study. In this study, correlations of the Tritrac vector magnitude and the WAM with heart rate were 0.791 and 0.684, respectively (P<0.001). Using the Tritrac activity monitor on 30 schoolchildren, aged 9–11 yr, Welk and Corbin (33) obtained correlations with heart rate of 0.34–0.50 over 3 days (mean = 0.44). When resting heart rate was accounted for, the correlation increased slightly to 0.46–0.74 (mean = 0.60). Janz (14), who also accounted for resting heart rate, obtained correlations of 0.51–0.70 (mean 0.57, P<0.05) over 3 days between the WAM and heart rate for 31 schoolchildren, aged 7–15 yr.

A stringent test concerning the validity of triaxial accelerometry in adults was carried out by Bouten et al. (8) on the Tracmor unit. Average daily metabolic rate was assessed over 7 days using the field study gold standard of doubly labeled water. Sleeping metabolic rate was measured during 2 nights in a respiration chamber. Physical activity level (defined as the ratio of the very activity levels that are maintained for the long periods of time, and does not interfere with normal activity. Results indicate potential for the hip pedometer as a measure of habitual physical activity in large samples.

Heart Rate vs. Triaxial Accelerometry

The higher correlation of s\(\dot{V}O_2\) with the triaxial movement measure than with heart rate highlights the unsuitability of heart rate as a criterion measure for the validation of Tritrac. The reverse situation would perhaps be more appropriate. The measurement of movement itself has face validity, and it has been shown that it is a good indication of energy expenditure over a variety of activities. Heart rate is an indirect measure, which is known to have weaknesses within the very activity levels that are maintained for the majority of the day by the majority of people. It is frequently used as the criterion, as it has minimal interference with the child's activity and does reflect moderate-to-vigorous activity. However, it has only recently been realized that three-dimensional accelerometry provides a better criterion measure. Welk and Corbin (33) correlated various methods of expressing heart rate with Tritrac. The heart rate measure that had the highest correlation with the Tritrac was then used as the criterion for the Tritrac. It is unclear which method provided the criterion measure in their study.

Summary

The best single predictor of s\(\dot{V}O_2\) in this study for a variety of children's typical activities was the three-dimensional accelerometry method provided by the Tritrac activity monitor. When two measures were used simultaneously, the Tritrac\(_{xyz}\) and heart rate provided the best estimate. However, the increase in known variance attributable to heart rate, as a second predictor, would not justify the additional cost and labor. A more realistic pair of measures would be heart rate and hip pedometer, accounting for 80.2% of the variance between them, only slightly lower than the 82.5% explained by the more expensive Tritrac.

The regression equations developed in this study should be cross validated on a different sample of children, if possible undertaking different activities. If the cross validation of the Tritrac confirms the results of this study, the Tritrac will provide the ideal criterion measure for use in finding less expensive, field-based assessments of activity levels, such as the pedometer. The Tritrac appears to have greater accuracy than the heart rate monitor, is capable of collecting data for a longer period of time, and does not interfere with normal activity. Results indicate potential for the hip pedometer as a measure of habitual physical activity in large samples.

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REFERENCES