Convergent Validity of a Piezoelectric Pedometer and an Omnidirectional Accelerometer for Measuring Children’s Physical Activity

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The aim of this study was to assess the convergent validity of a new piezoelectric pedometer and an omnidirectional accelerometer for assessing children’s time spent in moderate to vigorous physical activity (MVPA). A total of 114 children (51 boys, 63 girls) aged 5–11 years wore a sealed NL-1000 piezoelectric pedometer (New Lifestyles Inc, Lee’s Summit, MO) and an Actical accelerometer (Mini Mitter, Bend, OR) over one school day. The NL-1000 pedometers were randomized to one of two manual intensity thresholds used to define MVPA (1): Level 3 = 2.9 metabolic equivalent test (MET) and (2) Level 4 = 3.6 MET. Compared with the Actical, the NL-1000 underestimated the time spent in MVPA by 37% and 45% at intensity levels 3 and 4, respectively. In addition, the 95% limits of agreement were wide at both intensity levels (level 3 = -144%, 70%; level 4 = -135%, 45%), indicating a low level of precision.

Physical activity during childhood offers numerous health advantages, including improvements to blood lipid profile, bone health and self-efficacy, and a reduction in the risk of developing cardiovascular disease, type 2 diabetes and obesity (3,18). As such, the promotion of physical activity in children is a key public health priority in many countries. National physical activity guidelines are typically expressed in units of time; the most common recommendation is that children accumulate at least 60 min of moderate to vigorous physical activity (MVPA) each day (10). Thus, the accurate measurement of time spent in MVPA is essential so that population trends and interventions can be monitored using a unit that has direct relevance to public health policy.

Accelerometers are advanced motion sensing devices that are generally considered to be the most effective way of estimating MVPA in large samples (16). They are particularly useful in pediatric populations, where they provide an objective and unobtrusive assessment of physical activity frequency, duration, and intensity that does not rely on subjective recall of behavior. Several studies have
established the validity and reliability of a variety of accelerometer models for measuring MVPA in children, including uniaxial (vertical plane of motion only), triaxial (three planes of motion), and omnidirectional (multiple planes of motion) variations (9). However, accelerometers are expensive instruments (USD300–600) that require expertise to configure and operate. They are therefore less useful for health practitioners undertaking large population studies. In addition, the requirement for data to be downloaded onto a computer before access means that they cannot be used to provide immediate feedback to the individual being monitored.

Pedometers, on the other hand, are inexpensive and technically uncomplicated devices that can provide ongoing feedback to study participants (data can be accessed directly from the digital display). Pedometers are principally designed to measure the number of steps taken each day. Most pedometers perform this function using a spring-mounted horizontal lever arm that detects vertical forces at the waist level greater than approximately 0.35 g. Expressing physical activity in terms of steps per day has several advantages: steps are an easy unit to understand for the general public, daily step counts include all physical activity (not just moderate to vigorous), and increasing steps is a sustainable approach for those who are less able to participate in more vigorous physical activities. Step-based guidelines have been developed for children based on a reduction in risk of negative health outcomes (5,19). However, given that ownership of a pedometer is required before an individual can self-monitor adherence to step-based guidelines, increasing minutes spent in MVPA remains the preferred message for most public health agencies.

The recently released NL-1000 pedometer (New Lifestyles Inc, Lee’s Summit, MO) bridges, at least in part, the gap between accelerometers and pedometers by including an ability to detect and record daily minutes of MVPA in addition to daily step counts. This feature is possible through the use of a piezoelectric strain gauge sensor that permits a graded response to vertical movement rather than the all-or-nothing response of spring-levered pedometers. It also features an internal memory that automatically stores daily step counts and minutes of MVPA for up to seven days, removing the need for researchers or participants to manually record each day’s data. The capability of the relatively inexpensive NL-1000 (USD50) to objectively measure minutes of MVPA has significantly reduced the financial outlay required to obtain MVPA estimates in large samples. In addition, all NL-1000 data (including minutes of MVPA) can be easily accessed straight from the digital display.

Despite the potential of the NL-1000 pedometer for physical activity research, it is critical that the MVPA estimates recorded by the NL-1000 are comparable to accelerometer-based estimates. To our knowledge, only one study has investigated the performance of the NL-1000 for assessing MVPA in children. McMinn et al. (12) compared time spent in MVPA between the NL-1000 and a uniaxial accelerometer (Actigraph GT1M, Actigraph LLC, Pensacola, FL). Children aged 10–13 years wore the equipment under three different conditions (1): a cross-country run (N = 12) (2), physical education (N = 18), and (3) classroom activity breaks (N = 42). The authors concluded that the NL-1000 performed well when compared with the accelerometer-determined minutes of MVPA. An important caveat of this conclusion is that the NL-1000 only performed adequately when the threshold used to define MVPA in the criterion measure was higher than the commonly accepted thresholds of three metabolic equivalent of task (MET) levels or a physical activity...
ratio (PAR) of three. In addition, the sample size and age range were limited, and the testing conditions were not free-living but discrete high activity periods. Thus, the purpose of the current study was to assess the accuracy and precision of the NL-1000 pedometer for detecting MVPA in free-living children when compared with an omnidirectional accelerometer set to record activities greater than PAR 3.

**Methods**

**Participants**

A total of 126 children from Years 1–6 at a local primary school were recruited to participate in the study. Of this initial sample, 12 were excluded from analysis procedures due to incomplete data, resulting in a final sample size of 114 (51 boys, 63 girls). Written informed assent and consent were obtained from children and parents, respectively. The age and sex of participants were collected from the current school roll. Ethical approval to conduct the study was granted by the institutional ethics committee.

**Instruments**

Physical activity was recorded using two portable motion sensing devices (1): Actical accelerometers (Mini Mitter, Bend, OR) and (2) NL-1000 pedometers. The Actical is an omnidirectional accelerometer that has been established as one of the better and most widely used instruments for assessing physical activity duration in children with excellent validity and reliability (9,14). They are also able to detect steps with an acceptable level of accuracy (7). The shortest possible epoch time of 15 s was selected to minimize the MVPA misclassification that is possible at longer epochs (11). MVPA was calculated from Actical activity counts using a previously validated and commonly used prediction equation developed specifically for children (15). The NL-1000 is a piezoelectric pedometer that has the capability of logging minutes of MVPA in four-second epochs. The NL-1000 has nine intensity levels that correspond to various estimated MET levels. These levels can be adjusted to record the time spent at different intensities. The manufacturers recommend setting the activity level at 4—equivalent to a threshold of 3.6 MET—to measure MVPA. However, MVPA is usually defined as intensity at or above 3 MET (1). Therefore, setting the NL-1000 at activity level 3 (> 2.9 MET) may provide a more appropriate estimation of time spent in MVPA. The intensity level used for each participant was randomized between levels 3 and 4, such that 58 children were tested at level 3 and 56 at level 4.

**Procedures**

Participants were concurrently fitted with a sealed pedometer and accelerometer at the beginning of the school day (9.30am). One device was fitted above the iliac crest of the left hip with the other fitted on the right hip using an elasticized waistband with an adjustable belt. The order the devices were placed on the left or right hip was randomized. Pedometers were reset and sealed immediately before fitting them to each child. Researchers removed the equipment at the end of the school day.
day (2.30pm) and NL-1000 step counts and MVPA were recorded immediately from the digital display. To ensure accuracy, time of the day was recorded as soon as the equipment was placed on and removed from each child. In addition, children were asked if they had removed the pedometer or accelerometer during the day; those that had were excluded from data analysis (N = 12). Data collection took place daily over a 4-week period (approximately 6–7 children per day) using 10 NL-1000 pedometers and 10 Actical accelerometers.

Statistical Analysis

Descriptive statistics were generated for age and monitoring time in addition to the MVPA and step count data recorded by the Actical accelerometers. Sex differences were examined using independent-samples t tests. While accelerometers do not provide a gold standard estimate of MVPA, for the purposes of our analyses they were treated as the criterion measure. Bias (NL-1000 MVPA—Actical MVPA) was converted to a percentage of Actical MVPA to assess the relative under- or overestimation of the NL-1000. A negative value indicates underestimation whereas a positive value indicates overestimation. The 95% limits of agreement and loss of precision statistics were also calculated to provide an indication of reliability. The loss of precision, or the variance of prediction error divided by the variance of the criterion value, measures the theoretical increase in sample size required to offset the prediction error. The consistency of percent bias at the extremes of the observed MVPA distribution was clarified using correlation analysis. Bland-Altman plots were generated to demonstrate the effects of different NL-1000 intensity levels on mean percent bias and 95% limits of agreement. All data were analyzed using PASW Statistics 18.0 (SPSS Inc, Chicago, IL) and a P value of less than 0.05 to indicate statistical significance.

Results

Table 1 shows the descriptive statistics for the study sample. Based on data from the Actical accelerometers, participants accumulated approximately 30 min of MVPA and 6,000 steps over the duration of the monitoring period. MVPA was significantly lower for the NL-1000 when compared with the Actical estimates for all subgroups and intensity levels (p < .001 for all). There were no significant step count differences between devices for either girls or boys or across the whole sample. There were also no significant differences in age, total monitoring time, MVPA, or step count between boys and girls.

The utility of the NL-1000 pedometer for measuring minutes of MVPA was assessed using multiple indices related to accuracy and precision (Table 2). For all subgroups, the NL-1000 significantly underestimated MVPA when compared with the Actical accelerometer. The poor level of agreement was also reflected in the lack of association between the two measures. Underestimation was only slightly lower (approximately 2 min or 8%) when the NL-1000 was set to level 3 when compared with level 4. The negative bias was 24.6% greater in boys than in girls at level 3, but 5.2% lower at level 4. The negative association between MVPA (Actical) and percent bias shows that the underestimation was greatest for participants who accumulated the most amount of MVPA during the measurement
Table 1 Descriptive Statistics for the Study Sample

<table>
<thead>
<tr>
<th></th>
<th>Boys (N = 51)</th>
<th>Girls (N = 63)</th>
<th>All (N = 114)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age (years)</td>
<td>8.4 ± 1.9</td>
<td>8.4 ± 1.8</td>
<td>8.4 ± 1.8</td>
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<tr>
<td>Total monitoring time</td>
<td>310.5 ± 10.5</td>
<td>311.0 ± 11.0</td>
<td>310.7 ± 10.7</td>
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<tr>
<td>Actical MVPA (min)</td>
<td>31.8 ± 15.9</td>
<td>28.9 ± 13.7</td>
<td>30.2 ± 14.7</td>
</tr>
<tr>
<td>NL-1000 MVPA L3 (min)¹</td>
<td>13.0 ± 10.6</td>
<td>13.5 ± 6.7</td>
<td>13.3 ± 8.6</td>
</tr>
<tr>
<td>NL-1000 MVPA L4 (min)²</td>
<td>13.3 ± 8.3</td>
<td>12.1 ± 8.0</td>
<td>12.6 ± 8.1</td>
</tr>
<tr>
<td>Actical step count</td>
<td>6,312 ± 2,779</td>
<td>5,885 ± 2,457</td>
<td>6,076 ± 2,603</td>
</tr>
<tr>
<td>NL-1000 step count</td>
<td>6,367 ± 2,346</td>
<td>5,951 ± 1,997</td>
<td>6,150 ± 2,162</td>
</tr>
</tbody>
</table>

Mean ± SD; MVPA, moderate to vigorous physical activity.

¹L3 = Intensity level 3 (Boys, N = 26; Girls, N = 32)
²L4 = Intensity level 4 (Boys, N = 25; Girls, N = 31)

period. The 95% limits of agreement were wide for all subgroups, indicating that the low accuracy of the NL-1000 units for measuring MVPA is compounded by low precision. Indeed, the loss of precision ranged from 127% in boys (level 4) to as high as 163% in girls (level 4).

Figures 1 and 2 illustrate the percent bias and 95% limits of agreement associated with measuring MVPA with the NL-1000 pedometer at levels 3 and 4. The decreased accuracy when using level 4 rather than level 3 was accompanied by an increase in precision. Nonetheless, the overall performance at both levels was poor. The tendency for underestimation to increase with the total minutes of MVPA can also be clearly observed. For both intensity levels, percent bias decreased in a relatively linear fashion between approximately five and 30 min before stabilizing at MVPA levels greater than 30 min.

Discussion

The release of the NL-1000 pedometer has provided researchers and health practitioners with a practical and affordable means to obtain estimates of MVPA duration in large samples; however, the accuracy and precision of the estimates must be established before they can be confidently used in the field. Our results show that, on average, the NL-1000 underestimates MVPA by 37–45% in children aged 5–11 years when compared with Actical accelerometers. Given that the latter device provides accurate and reliable estimates of MVPA (9,14), these findings suggest that the NL-1000 misses a substantial proportion of children’s MVPA. Furthermore, the associations between percent bias and MVPA suggest that the underestimation increases with the total amount of MVPA. Curiously, however, this negative trend was apparent in children who accumulated between five and 30 min of MVPA but not in their more active counterparts. It is possible that there
<table>
<thead>
<tr>
<th>Difference in MVPA (min) (^a)</th>
<th>(r_Y, %\text{bias}) (^e)</th>
<th>Mean percent bias (%) (^c)</th>
<th>(p^d)</th>
<th>Proportion of under- and over-estimation (%)</th>
<th>(r_Y, %\text{bias}) (^e)</th>
<th>95% limits of agreement (%) (^f)</th>
<th>Loss of precision (%) (^g)</th>
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<tr>
<td><strong>Male</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Level 3</td>
<td>-19.3</td>
<td>18.1</td>
<td>0.093</td>
<td>-50.6</td>
<td>-0.512 ((p = .008))</td>
<td>-125.7, 24.5</td>
<td>134.6</td>
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<td>Level 4</td>
<td>-18.0</td>
<td>18.6</td>
<td>-0.021</td>
<td>-42.0</td>
<td>-0.722 ((p &lt; .001))</td>
<td>-125.5, 40.9</td>
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<tr>
<td><strong>Female</strong></td>
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<td>Level 3</td>
<td>-14.1</td>
<td>16.8</td>
<td>-0.175</td>
<td>-26.0</td>
<td>-0.788 ((p &lt; .001))</td>
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<td>-18.3</td>
<td>16.7</td>
<td>-0.206</td>
<td>-47.2</td>
<td>-0.634 ((p &lt; .001))</td>
<td>-143.6, 49.2</td>
<td>162.5</td>
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<tr>
<td><strong>All</strong></td>
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<tr>
<td>Level 3</td>
<td>-16.4</td>
<td>17.4</td>
<td>-0.022</td>
<td>-37.0</td>
<td>-0.676 ((p &lt; .001))</td>
<td>-143.8, 69.8</td>
<td>134.6</td>
</tr>
<tr>
<td>Level 4</td>
<td>-18.2</td>
<td>17.4</td>
<td>-0.108</td>
<td>-44.9</td>
<td>-0.660 ((p &lt; .001))</td>
<td>-135.1, 45.3</td>
<td>142.0</td>
</tr>
</tbody>
</table>

\(^a\) Difference in MVPA = NL-1000 MVPA—Actical MVPA.
\(^b\) Correlation coefficient between Actical MVPA and NL-1000 MVPA.
\(^c\) Percent bias = ((NL1000 MVPA—Actical MVPA)/Actical MVPA) x 100.
\(^d\) Probability that mean percent bias = 0.
\(^e\) Correlation coefficient between Actical MVPA and the percent bias.
\(^f\) 95\% limits of agreement = mean percent bias ± 1.96 x percent bias SD.
\(^g\) Loss of precision = ((variance of NL-1000 MVPA—Actical MVPA)/variance of Actical MVPA) x 100.
\(^h\) Underestimation/overestimation.
are particular types of activities performed by more active children and not by less active children, and that these activities are somehow less likely to be detected by the NL-1000. The biphasic trend observed in our data could be explained if the prevalence of these hypothetical activities gradually increased from a minimum in inactive children to a maximum in children who were at least moderately active (£30 min MVPA during the school day). In fact, it could be that the ability of the NL-1000 to detect activity reaches a maximum point beyond which any additional vigorous activity is not recorded. If more active children accumulate more vigorous activity, then it is likely the NL-1000 will perform better in inactive children. A recent study investigating the accuracy of step counts in a pedometer that uses the same internal mechanism as the NL-1000 (NL-800) supported the notion that

Figure 1 — Bland-Altman plot showing percent bias of the NL-1000 pedometer (Level 3) for measuring minutes of moderate to vigorous physical activity (MVPA) in children aged 5–11 years. The solid line is the mean percent bias and the dashed lines are the 95% limits of agreement.
the mode of activity is an important determinant of pedometer accuracy (17). The latter authors observed significant underestimation of step counts (compared with a hand counter) when children were skipping, galloping, and sliding, with acceptable performance during walking and hopping. Such findings highlight the variable nature of the NL-1000 motion sensor.

When compared with the Actical, the NL-1000 also showed a low level of precision when measuring MVPA in our sample. The wide 95% limits of agreement at intensity level 3 imply that the accelerometer-determined value of MVPA could be as much as 107% higher or lower than that recorded by a NL-1000 pedometer. For a child averaging 60 min of MVPA each day, the limits of agreement correspond to a potential error of ± 64 min. While these limits narrow slightly to ± 54 min when

![Figure 2 — Bland-Altman plot showing percent bias of the NL-1000 pedometer (Level 4) for measuring minutes of moderate to vigorous physical activity (MVPA) in children aged 5–11 years. The solid line is the mean percent bias and the dashed lines are the 95% limits of agreement.](image-url)
intensity level 4 is used, both levels remain well beyond what would normally be considered a worthwhile detectable difference. It should be noted, however, that a larger sample would likely have resulted in narrower limits of agreement. It could be argued that the loss of precision statistic holds more relevance for population research, given that it defines the theoretical increase in sample size that would be required to offset the random error associated with the NL-1000 pedometer. Our data suggest that the sample size must be increased by 135% and 142% at levels 3 and 4 (respectively) to compensate for the use of NL-1000 pedometers instead of Actical accelerometers. Naturally, this estimate relates to precision only and does not offset the underestimation of MVPA by the NL-1000.

If we assume that the Actical accelerometer provides an accurate estimate of MVPA, our results suggest that the NL-1000 is an unsuitable measure of MVPA in children when using intensity levels 3 or 4. It is likely, however, that lowering the threshold used to define MVPA in the NL-1000 would reduce the degree of underestimation. The manufacturer states that the intensity levels of 1 and 2 correspond to MET values of 1.8 and 2.3, respectively, placing them below the most commonly used definition of MVPA (≥ 3 MET). Our data suggest that, in reality, levels 1 and 2 may be nearer to 3 MET than levels 3 and 4 (estimated as 2.9 and 3.6 MET, respectively). Nonetheless, the relatively minor improvement in percent bias we observed when comparing level 4 with level 3 (1.8%) suggests that even level 1 would continue to underestimate MVPA by a substantial margin (approximately 13.6% assuming a linear relationship exists between estimated MET and percent bias). We also observed distinct sex differences in the relationship between intensity level and percent bias, such that level 3 performed better than level 4 in girls and vice versa in boys. This provides further support for the hypothesis that specific (in this case sex-related) activities are detected differently between the two devices, and raises the possibility that a threshold reduction in boys may not be worthwhile. Regardless, lowering the intensity threshold would not improve the low precision or negate the difference in percent bias at opposite ends of the MVPA distribution.

We found it interesting that the NL-1000 pedometer was much better at detecting step counts than minutes of MVPA. Supplementary analysis (not shown) revealed that the number of steps collected by the NL-1000 was positively correlated with both step count and minutes of MVPA recorded by the Actical. Counting steps is clearly the primary purpose of the NL-1000, and we have previously established the accuracy of this function in children using a New Lifestyles pedometer with the same internal mechanism (6). The positive correlation between NL-1000 and Actical step counts—and indeed between NL-1000 step counts and Actical MVPA—rules out the possibility that variation in wear time or researcher error contributed to the differences in MVPA between devices. It appears that the piezoelectric strain gauge and/or proprietary algorithm used to detect and define movement in the NL-1000 pedometer is effective at classifying steps but not minutes of MVPA. It is possible this may be resolved by updates to the hardware or firmware of the NL-1000.

This study represents the second investigation of the accuracy of the NL-1000 pedometer for measuring minutes of MVPA in children. The first such study compared the performance of the NL-1000 with a uniaxial accelerometer (Actigraph GT1M) for detecting older children’s MVPA during a cross-country run, physical education, and classroom-based physical activities (12). The authors concluded that the MVPA data recorded by the NL-1000 at intensity level 3 (≥ 2.6 MET)
were not meaningfully different from Actigraph estimates when using a 4 MET threshold (1,769–2,393 counts/minute, depending on age). These findings are clearly contrary to the results of the current study, which found the NL-1000 consistently underestimated MVPA when compared with Actical estimates. It is important to note, however, that McMinn et al. (12) reported significant underestimation when the NL-1000 was compared with the Actigraph at a 3 MET threshold (906–1,399 counts/min), the level generally used to define MVPA in children and adults. Thus, it is probable that differences in the thresholds used to define MVPA in the Actigraph and Actical accelerometers contributed to the substantial variation between studies. The equation used to define MVPA in our study was not based on a particular MET threshold but on a physical activity ratio (PAR) of three or greater, which corresponds to 1,500 counts per minute (15). The PAR index—calculated as energy expenditure divided by basal metabolic rate—is preferable to MET values in children given that the latter do not account for children’s age-related decline in resting metabolic rate. A PAR of three is generally considered to represent the boundary between light and moderate physical activity in children (15). In any case, it is likely that our Actical threshold of PAR £ 3 corresponds to the MET £ 3 threshold used by McMinn et al. (12), both of which resulted in significant NL-1000 underestimation. Clearly, any judgment of the utility of the NL-1000 for detecting MVPA duration in children depends heavily on the threshold used to define MVPA in the comparison measure. We contend that a PAR £ 3 currently represents the most appropriate definition of MVPA in children.

Disparity between the aforementioned studies may also have arisen from differences in the technical specifications of Actical and Actigraph accelerometers. The Actical has an omnidirectional sensor that can detect movement in multiple planes, whereas the Actigraph has a uniaxial sensor that measures movement in the vertical plane only. Furthermore, the Actical is sensitive to movements in the 0.5–3.0 Hz frequency range, while the Actigraph is sensitive to movements in the 0.25–2.5 Hz range. Previous studies have concluded that the physical activity data recorded by the two devices are not comparable (8,13). In fact, there is evidence that Actigraph counts attenuate at high intensity activities whereas Actical counts continue to increase (4,8). This observation is the another likely explanation of the differences between McMinn et al. (12) and the current study, which demonstrated a higher level of NL-1000 underestimation in the most active children. Put another way, if both the Actigraph and the NL-1000 underestimate MVPA at high intensities, then they will appear to be congruent and the NL-1000 underestimation may be missed. This is especially relevant given that McMinn et al. (12) tested children under ‘high intensity’ conditions such as cross-country running and physical education. Comparing MVPA data collected from all three units (NL-1000, Actical, Actigraph) simultaneously may be the only way to test this hypothesis.

The final notable source of difference between the current study and that described in McMinn et al. (12) are the epoch times selected for the Actical and Actigraph, respectively. The epoch refers to the duration of time over which the activity counts detected by the accelerometer are summed. This summed value is then entered into an equation to estimate the average physical activity intensity for the given epoch. In general, it is recommended to use an epoch as short as possible to reduce misclassification of intensity levels. This is particularly applicable to children, whose movement patterns are characterized by short, intermittent bursts
of activity (2). We chose the shortest possible Actical epoch of 15 s; McMinn et al. (12) were able to select one-second epochs for the Actigraph accelerometer. While the latter epoch is clearly preferable, it would not necessarily lead to the substantial differences in results observed between studies. As longer epochs tend to produce lower estimates of MVPA when compared with shorter epochs (11), it follows that the NL-1000 underestimation observed in our results would have been even greater had we been able to select one-second epochs for the Actical accelerometers. Similarly, it is probable that the four-second epoch featured in the NL-1000 pedometer at least partially counteracted the underestimation of MVPA when compared with Actical estimates based on a 15-s epoch. For these reasons it is unlikely that inconsistent epoch times are an important contributor to the observed differences between studies.

In summary, the development of the NL-1000 pedometer has provided researchers and health practitioners with an inexpensive means to measure physical activity in a unit that aligns with current time-based physical activity recommendations. Compared with a validated omnidirectional accelerometer, however, the NL-1000 significantly underestimates the total minutes of MVPA accumulated by 5–11-year-old children during a normal school day. In addition, the NL-1000 displayed a low level of precision overall and a nonlinear association between percent bias and MVPA. We therefore conclude that the NL-1000 pedometer does not provide a satisfactory estimate of MVPA duration in children.

References