Prediction of Energy Expenditure From Wrist Accelerometry in People With and Without Down Syndrome

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This study examined the relationship between energy expenditure and wrist accelerometer output during walking in persons with and without Down syndrome (DS). Energy expenditure in metabolic equivalent units (METs) and activity-count rate were respectively measured with portable spirometry and a uniaxial wrist accelerometer in 17 persons with DS (age: 24.7 ± 6.9 years; 9 women) and 21 persons without DS (age: 26.3 ± 5.2 years; 12 women) during six over-ground walking trials. Combined groups regression showed that the relationship between METs and activity-count rate differed between groups ($p < .001$). Separate models for each group included activity-count rate and squared activity-count rate as significant predictors of METs ($p \leq .005$). Prediction of METs appeared accurate based on Bland-Altman plots and the lack of between-group difference in mean absolute prediction error (DS: 17.07%; Non-DS: 18.74%). Although persons with DS show altered METs to activity-count rate relationship during walking, prediction of their energy expenditure from wrist accelerometry appears feasible.

Keywords: physical activity assessment, accelerometers, over-ground walking, Down syndrome
Persons with Down syndrome (DS) have high risks for mortality and morbidity (Day, Strauss, Shavelle, & Reynolds, 2005; Draheim, McCubbin, & Williams, 2002; Esbensen, Seltzer, & Greenberg, 2007; Rimmer & Yamaki, 2006), which may be partially related to their low levels of moderate-to-vigorous physical activity (Draheim, Williams, & McCubbin, 2002; Shields, Dodd, & Abblitt, 2009; Whitt-Glover, O’Neill, & Stettler, 2006). The relationship between physical activity and health in people with DS may be examined more accurately if it is based on objective physical activity assessment provided by accelerometry (Matthews, 2005). Accelerometer output, however, must be calibrated against measures of actual energy expenditure to provide accurate estimates of physical activity levels (Welk, 2005). Therefore, the validity of accelerometry for individuals with DS may be established only after the relationship between energy expenditure and accelerometer output in this population is known.

The relationship between energy expenditure and rate of activity counts provided by accelerometers may be altered in people with DS. This is particularly the case for walking, which appears to be the most common physical activity among people with intellectual disability including those with DS (Draheim, Williams et al., 2002) and should therefore be expected to greatly impact their overall physical activity levels. On average, people with DS show lesser body stability during walking (Agiovlasitis, McCubbin, Yun, Mpitsos, & Pavol, 2009; Kubo & Ulrich, 2006) thought to result from their inherent joint laxity, muscle hypotonia, reduced strength, and deficits of the cerebellum (American Academy of Pediatrics, 2001; Pinter, Eliez, Schmitt, Capone, & Reiss, 2001; Pitetti, Climstein, Mays, & Barrett, 1992). To improve balance during gait, people with DS seem to walk with higher step frequencies and step width variations (Agiovlasitis, McCubbin, Yun, Mpitsos, et al., 2009) and may employ greater cocontraction of antagonistic muscle groups than people without DS (Ulrich, Haehl, Buzzi, Kubo, & Holt, 2004). These gait behaviors, however, impart an energetic cost (Doke, Donelan, & Kuo, 2005; Donelan, Shipman, Kram, & Kuo, 2004; Kuo, 2007) and may partially explain why people with DS show higher energy expenditure during walking than people without DS (Agiovlasitis, McCubbin, Yun, Pavol, & Widrick, 2009). In addition, most persons with DS have very low aerobic fitness (Fernhall et al., 1996; Pitetti, Climstein, Campbell, Barrett, & Jackson, 1992), which may also contribute to higher energy expenditure during walking (Sawyer et al., 2010). These physiologic attributes may not be captured by accelerometer output, potentially altering the relationship between energy expenditure and activity-count rate in persons with DS.

An accelerometer worn at the wrist may offer some advantages for physical activity assessment. First, a wrist accelerometer may assess upper-body movements that are not captured by an accelerometer worn at the hip. Second, accelerometers worn at the wrist or arm have been used successfully for estimating energy expenditure in people without disabilities (Chen et al., 2003; Heil, 2006; Johannsen et al., 2010; Melanson & Freedson, 1995; Swartz et al., 2000) and these devices are used widely in physical activity research. Finally, a wrist accelerometer may potentially achieve higher participant compliance because it could be secured more effectively, reducing the chances of removal by participants compared with
a hip accelerometer; this might be particularly important for individuals with DS who often have some degree of intellectual disability. Notably, previous research has employed wrist accelerometers to measure physical activity in persons with intellectual disability (Foley & McCubbin, 2009; Kim & Yun, 2009). Therefore, an examination of the relationship between actual energy expenditure and wrist accelerometer output in people with DS may benefit physical activity assessment in these individuals.

We examined whether the relationship between activity-count rate provided by wrist accelerometry and energy expenditure during over-ground walking is different between individuals with and without DS. We also explored whether wrist accelerometer output would offer accurate prediction of energy expenditure. We hypothesized that individuals with DS would show altered relationship between accelerometer output and energy expenditure—greater increases in energy expenditure with increases in activity-count rate.

**Method**

**Participants**

Seventeen individuals with DS (9 women, 8 men) and 21 individuals without DS or any other disability (12 women, 9 men) participated in this study. The groups of participants with and without DS were recruited by convenience from the local community. Recruitment of those with DS was facilitated by community-based programs for persons with developmental disabilities. We recruited participants without DS who had similar age and physical activity profiles to those without DS. All participants with and without DS were healthy, nonsmokers, and without any orthopedic problems or mobility limitations. None of the persons with DS had severe form of intellectual disability that could interfere with verbal communication. Two women and one man with DS had undergone corrective heart surgery in childhood but had no medical restrictions on physical activity. We did not directly measure physical activity in this study; however, all participants engaged at least three times per week in moderate levels of activity (i.e., activity equivalent to a brisk walk that can increase significantly breathing and heart rate). This information was reported by participants without DS and for those with DS by their parents/guardians and the participants themselves. All persons with DS participated in community-based physical activity programs and 14 of them were part-time workers. Five participants with DS lived in group-homes and 12 lived with their parents. Mean body mass (DS: 76.9 ± 16.8 kg; Non-DS: 73.4 ± 22.6 kg) and age (DS: 24.7 ± 6.9 years; Non-DS: 26.3 ± 5.2 years) was not significantly different between groups (p > .05). Participants with DS, however, had shorter height (DS: 154.0 ± 7.9 cm; Non-DS: 171.1 ± 8.2 cm) and greater body mass index (BMI; DS: 32.6 ± 7.7 kg/m²; Non-DS: 24.9 ± 7.4 kg/m²) than participants without DS (p < .05). The Institutional Review Board approved the study protocol. Written informed consent was obtained from participants with and without DS. The legal guardians of participants with DS also provided written informed consent.
Procedures

Participants attended 2 sessions conducted over a period of 1–2 weeks. During the first session, participants were familiarized with the testing procedures. Specifically, participants practiced breathing through the mask as needed. Then they were connected to the portable spirometer for 6 min of sitting, 6 min of standing, 6 min of walking at the preferred speed, 6 min of walking at the slowest speed (0.50 m/s) and 6 min of walking at the fastest speed (1.50 m/s). Data collection occurred during the second session and all participants were able to complete the experimental protocol.

Participants refrained from food, caffeine, and exercise for at least 3 hr before data collection. The testing session commenced with the measurement of body mass and height, allowing for calculation of BMI. The body mass of participants was also measured while carrying the equipment described below; this value was used in the calculation of energy expenditure during walking. Thereafter, participants sat for 10 min to bring physiologic functions to resting levels. Energy expenditure was then measured as the rate of oxygen uptake (VO$_2$) during 6 min of sitting and during six over-ground walking trials, each lasting 6 min. The rate of activity counts was also measured during the walking trials. These trials were conducted in a quiet rectangular hallway 90 m in perimeter. For the first trial, participants were instructed to walk at their most comfortable walking speed and they were quietly followed by 2 researchers; one researcher maintained a distance of ~1 m from the participant and rolled a distance-measuring wheel (MP301DM, Keson, Aurora, IL) equipped with a cycle computer (Velo 8, Cateye, Osaka, Japan) that displayed instantaneous speed, while the other researcher timed the trial with a stopwatch. For the remaining trials, participants walked at target speeds of 0.50, 0.75, 1.00, 1.25, and 1.50 m/s. The order of these trials was from slowest to fastest. The speed was set by the researcher rolling the distance-measuring wheel. This researcher walked at the target speed about 1 m in front of the participant. The second researcher who followed the participant timed the trial and encouraged as needed the participant to maintain the same distance from the pacing researcher. Participants sat for 6 min after each walking trial allowing VO$_2$ to approach resting values before starting the next trial.

A portable open-circuit spirometer (K4b$^2$, Cosmed, Italy) was used for determination of VO$_2$ (ml/kg/min). This spirometer uses a breathing mask to collect breath-by-breath expired air. Calibration of the spirometer took place before each data collection session in accordance with manufacturer specifications. VO$_2$ was determined as the average over the last 3 min of the sitting trial and each walking trial. VO$_2$ during each walking trial was then divided by each participant’s own resting VO$_2$ during sitting to derive Metabolic Equivalent units (METs). Activity counts were measured with a uni-axial accelerometer (Actigraph, model 7164) secured at the right wrist. Activity counts were collected in 30 s epochs over the 6 min of each walking trial, providing the rate of activity counts (counts/min). We calibrated the accelerometer before, during, and after the research. Specifically, we had a person walk on a treadmill for 15 min at 3 mph while wearing several accelerometers. All accelerometers were within 5% of the average value across units. The accelerometer had also been calibrated by the manufacturer before the initiation of the study.
Statistical Analyses

The relationship between METs and activity-count rate was analyzed with multilevel modeling, accounting for the nesting of observations within participants. The dependent variable was the METs achieved during the walking trials. Fixed effects included group (1 = DS vs. 0 = Non-DS), activity-count rate, the interaction between group and activity-count rate, and the squared activity-count rate. In addition, we examined whether BMI or height, both of which differed between groups, significantly contributed to the prediction equation. Potential random effects included the intercepts and slopes of the METs to activity-count rate relationship across participants. Parameters were included in the model based on the difference in the \(-2\) log-likelihood between models against a \(\chi^2\) distribution with 1 degree of freedom. Follow-up multilevel models for each group were run if the group by activity-count rate interaction was significant. These models were the same as the main model, but excluded the effect of group and the interaction between group and activity-count rate. The equations developed from these separate-groups models were used to predict METs during the walking trials for each participant with or without DS. Before these analyses, we confirmed that there were no outliers using a previously suggested procedure (Tabachnick & Fidell, 2001). Agreement between actual and estimated METs was examined with Bland-Altman plots (Bland & Altman, 1999) and with the absolute percent error calculated for each participant as the absolute value of \([\text{actual METs — estimated METs}] / \text{actual METs} \times 100\). The difference between groups in absolute percent error was analyzed with an independent \(t\) test.

We also examined differences between groups in rate of activity counts and METs across walking speeds. These were analyzed with \(2 \times 6\) (group by speed) mixed-model analyses of variance. The Greenhouse-Geisser correction was applied as warranted. When the interaction was significant, follow-up independent-samples \(t\) tests with Bonferroni-adjusted alpha \((0.008)\) were conducted at each speed. The alpha level was 0.05 except when adjusted. Statistical analyses were conducted using PASW Statistics 17.0 (SPSS Inc., Chicago, IL, USA).

Results

The relationship between METs and rate of activity counts varied significantly across participants in intercepts \((p < .01)\), but not in slopes. Group, activity-count rate, their interaction, and the squared activity-count rate were significant predictors of METs \((p < .001; \text{level-1 } R^2 = 0.61; \text{Table 1})\). BMI and height did not predict METs significantly. Follow-up multilevel models for each group included activity-count rate and the squared of activity-count rate as significant predictors of METs \((p \leq .005; R^2 = 0.61 \text{ and } 0.37 \text{ for DS and Non-DS groups, respectively; Table 2 and Figure 1})\). The Bland-Altman plots showed that the difference between actual and predicted METs demonstrated somewhat greater variability among participants with DS (Figure 2). Mean absolute error did not differ significantly between groups (DS: 17.07%; Non-DS: 18.74%).

METs and rate of activity counts demonstrated significant group by speed interactions \((p \leq .001; \text{Table 3})\). Follow-up \(t\) tests between groups showed that METs were higher at all speeds \((p \leq .002)\) except at the preferred walking speed. The rate of activity counts, however, was higher only at 1.25 and 1.50 m/s \((p \leq .007)\) and did not differ statistically between groups at other speeds \((p > .05)\).
Table 1  Estimates of Fixed Effects in Combined-Groups Multilevel Model Predicting METs for Participants With and Without Down Syndrome

<table>
<thead>
<tr>
<th></th>
<th>b</th>
<th>SE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intercept *</td>
<td>1.641749</td>
<td>0.201020</td>
</tr>
<tr>
<td>Activity-count rate [counts/min] *</td>
<td>0.001013</td>
<td>0.000095</td>
</tr>
<tr>
<td>Group [1 = DS; 0 = Non-DS]</td>
<td>–0.060141</td>
<td>0.284308</td>
</tr>
<tr>
<td>Activity-count rate × Group *</td>
<td>0.000323</td>
<td>0.000077</td>
</tr>
<tr>
<td>Activity-count rate² [(counts/min)²] *</td>
<td>–7.957058×10⁻⁸</td>
<td>1.401220×10⁻⁸</td>
</tr>
</tbody>
</table>

Note. * = p < 0.001; b = unstandardized coefficient; SE = standard error

Table 2  Estimates of Fixed Effects in Separate-Group Multilevel Models Predicting Metabolic Equivalent Units (METs) for Participants With Down Syndrome (DS) and Participants Without Down Syndrome (Non-DS)

<table>
<thead>
<tr>
<th></th>
<th>DS</th>
<th>SE</th>
<th>Non-DS</th>
<th>SE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intercept *</td>
<td>1.580524</td>
<td>0.296684</td>
<td>1.636848</td>
<td>0.224327</td>
</tr>
<tr>
<td>Activity-count rate [counts/min] *</td>
<td>0.001340</td>
<td>0.000150</td>
<td>0.001014</td>
<td>0.000158</td>
</tr>
<tr>
<td>Activity-count rate² [(counts/min)²] *</td>
<td>–8.019771×10⁻⁸</td>
<td>1.793185×10⁻⁸</td>
<td>–7.906516×10⁻⁸</td>
<td>2.733322×10⁻⁸</td>
</tr>
</tbody>
</table>

Note. * = p ≤ 0.005 for each group; b = unstandardized coefficient; SE = standard error

Figure 1 — Metabolic equivalent units (METs) as a function of activity-count rate in (A) participants with Down syndrome and (B) participants without Down syndrome. The lines show the mean regressions using the model coefficients shown in Table 2. The relationship between METs and activity-count rate is different between groups.
Figure 2 — Bland-Altman plots of the difference between actual and estimated metabolic equivalent units (METs) as a function of actual METs in (A) participants with Down syndrome and (B) participants without Down syndrome. Solid and dotted lines show mean and 95% limits of agreement, respectively. The difference between actual and estimated METs shows somewhat greater variability in participants with Down syndrome than participants without Down syndrome, but this difference appears small.

**Table 3** Mean ± SD of Rate of Activity Counts and Metabolic Equivalent Units (METs) Across Walking Speeds in Participants With Down Syndrome (DS) and Participants Without Down Syndrome (Non-DS)

<table>
<thead>
<tr>
<th>Walking Speed (m/s)</th>
<th>Activity-count Rate (counts/min)</th>
<th>METs</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>DS</td>
<td>Non-DS</td>
</tr>
<tr>
<td>PWS</td>
<td>2888 ± 1468</td>
<td>2758 ± 1373</td>
</tr>
<tr>
<td>0.50</td>
<td>862 ± 443</td>
<td>714 ± 279</td>
</tr>
<tr>
<td>0.75</td>
<td>1712 ± 747</td>
<td>1036 ± 420</td>
</tr>
<tr>
<td>1.00</td>
<td>2708 ± 1013</td>
<td>1992 ± 669</td>
</tr>
<tr>
<td>1.25</td>
<td>4052 ± 1864*</td>
<td>2743 ± 1140</td>
</tr>
<tr>
<td>1.50</td>
<td>5768 ± 2808*</td>
<td>3185 ± 1568</td>
</tr>
</tbody>
</table>

Note. * = p < 0.008 between groups; PWS = preferred walking speed; PWS was slower in persons with DS than persons without DS (1.09 ± 0.26 vs. 1.39 ± 0.17 m/s, respectively; p < 0.001 in independent-samples t test).

**Discussion**

The purpose of the current study was to examine whether the relationship between METs and activity-count rate as determined from an accelerometer worn at the wrist differs between individuals with and without DS. This relationship was different between the present samples of individuals with and without DS.
Explanations

As activity-count rate increased, participants with DS showed greater increases in METs compared with participants without DS. This effect may result from the gait characteristics of individuals with DS that increase their energy expenditure during walking (Agiovlasitis, McCubbin, Yun, Pavol, et al., 2009). Individuals with DS appear to have lesser stability during walking, especially in the mediolateral direction (Agiovlasitis, McCubbin, Yun, Mpitsos, et al., 2009; Kubo & Ulrich, 2006). This is accompanied by higher step frequencies and step width variations (Agiovlasitis, McCubbin, Yun, Mpitsos, et al., 2009) and likely greater antagonist muscle cocontraction (Ulrich et al., 2004), all of which may reflect compensations to lesser stability. These factors are known to increase the energetic cost (Doke et al., 2005; Donelan et al., 2004; Kuo, 2007). Arguably, higher step frequencies during walking in people with DS may be reflected in corresponding arm swing and may thus be indirectly captured by a wrist-worn accelerometer. Greater step width variations and cocontraction, however, may represent contributors to energetic cost that are not accounted for by accelerometer output, potentially explaining the present altered relationship between METs and activity-count rate in participants with DS.

Notably, METs increased in curvilinear fashion with increases in activity-count rate and showed a plateau at high levels of accelerometer output in participants with and without DS. Although both activity-count rate and METs increased with increases in walking speed, their responses to speed seem different. It appears that, for both groups, as walking speed increases, activity-count rate increases to a greater extent than the corresponding change in METs, causing the curvature in the relationship between METs and activity-count rate. This response may be explained by past research findings, indicating that greater arm swing contributes to gait stability while also reducing the energetic cost of stabilizing the body (Bruijn, Meijer, Beek, & van Dieen, 2010; Ortega, Fehlman, & Farley, 2008). Such a strategy, however, may not be adequate for individuals with DS who seem to have greater need for stabilization than individuals without DS (Agiovlasitis, McCubbin, Yun, Mpitsos et al., 2009; Kubo & Ulrich, 2006), as indicated by the observation that their METs increased at faster rates and showed a plateau at a higher level of activity-count rate. As stated, individuals with DS may use additional stabilization strategies that increase the energetic cost.

Wrist accelerometry appears to offer adequate prediction of METs in individuals with DS. This was suggested by the lack of between-group difference in absolute percent error in prediction of METs. These results are in agreement with past research that has demonstrated the value of accelerometers worn at the wrist or arm for estimating energy expenditure either alone (Chen et al., 2003; Heil, 2006; Johannsen et al., 2010; Melanson & Freedson, 1995) or in combination with hip-accelerometry (Swartz et al., 2000) in individuals without DS. The Bland-Altman plots showed that the 95% limits of agreement were somewhat wider in participants with DS than those without DS. This effect is expected given the greater variability in physiologic function and movement patterns of individuals with DS (Agiovlasitis, McCubbin, Yun, Mpitsos et al., 2009; Ulrich et al., 2004), but the difference was small. The degree of accuracy demonstrated in the Bland-Altman plots is comparable to that provided by hip-accelerometry (Croeter, Churilla, & Bassett, 2006). Visual inspection of the plots also shows that the developed equations may
potentially be somewhat over-predictive at low MET levels and under-predictive at high MET levels for both groups of participants. This potential for error cannot be explained by the present results, but it has been previously reported across physical activities for other accelerometers worn at the wrist or upper arm (Chen et al., 2003; Johannsen et al., 2010). In addition, it has been demonstrated that equations developed using only walking tend to under-estimate the amount of vigorous-intensity physical activity (Crouter et al., 2006), but whether this applies to people with DS is not known. Nevertheless, the Bland-Altman plots suggest that the potential for systematic error in the prediction of METs from wrist accelerometer output in the present participants with and without DS may be small. Collectively, the present findings demonstrate that wrist accelerometry may be a suitable and practical way of assessing physical activity in people with DS, but the validity of this technique must be further evaluated.

Implications

These results may be important for the study of physical activity and health in people with DS. They specifically suggest that physical activity intensity should not be estimated with accelerometry-determined cut-offs established for people without DS. Using the equations for each group, we could calculate the activity-count rates that correspond to 3 and 6 METs, the cut-offs for moderate- and vigorous-intensity physical activity, respectively. For participants with DS, these are 1,137 and 4,525 counts/min, respectively, and are the first values for wrist accelerometry ever reported. For participants without DS, the moderate-intensity cut off appears to occur at 1,526 counts/min; however, their vigorous-intensity cut off cannot be presently calculated. This is because participants without DS showed only a few observations above 6 METs and their mean curvi-linear relationship between activity-count rate and METs leveled off below the 6 METs threshold. This difficulty suggests that the presently calculated cut offs should be viewed with caution and underscores the importance of studying the relationship between METs and wrist accelerometer output across different activities (Matthews, 2005; Welk, 2005) and at higher MET levels. Nevertheless, the present results suggest that physical activity assessment from wrist accelerometry in people with DS is feasible, but their altered relationship between METs and activity-count rate should be considered; this altered response likely creates different cut offs for moderate- and vigorous-intensity activity for persons with DS. Accurate physical activity assessment may improve our understanding of the relationship between physical activity and health in persons with DS.

Limitations

A set of limitations warrant consideration. First, the protocol employed a uni-axial accelerometer, which may not account for the greater mediolateral body motion of individuals with DS. Second, the samples used in this study were not selected randomly and had relatively small size; these factors limit the generalizability of the models presented herein. In this respect, it should be considered that we did not directly measure the levels of physical activity and intellectual disability of participants. Third, the demonstrated relationship between METs and wrist accelerometer
output may only be valid for walking and may not apply across different physical activities. Finally, the presented cut-offs for moderate- and vigorous-intensity physical activity should be used with caution in light of the small sample size and the wide variability of cut-offs reported in the literature (Matthews, 2005).

Suggestions for Future Research

Future research would benefit by cross-validating the present prediction equations in different samples of individuals with and without DS. It is also important to determine the causes of the altered relationship between METs and wrist accelerometer output. Additional research is needed to address whether prediction of METs might improve by the use of triaxial accelerometers. Furthermore, it is important to identify the cut offs for moderate- and vigorous-intensity physical activity in people with DS by examining the relationship between METs and wrist accelerometer output across different habitual, recreational, and occupational activities.

Conclusions

Participants with DS showed an altered relationship between METs and activity-count rate as determined by a uni-axial accelerometer worn at the wrist. Prediction of energy expenditure from a wrist-accelerometer in participants with DS appeared feasible and comparable to that of participants without DS. This knowledge may improve physical activity assessment in people with DS and may contribute to a better understanding of their physical activity patterns.

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References


