Reliability and Accuracy of the AMP 331 for Activity Monitoring and Energy Expenditure Prediction in Young Adults

Benjamin J. Darter, Kathleen F. Janz, Michael L. Puthoff, Barbara Broffitt, and David H. Nielsen

Background: A new triaxial accelerometer (AMP 331) provides a novel approach to understanding free-living activity through its ability to measure real time speed, cadence, and step length. This study examined the reliability and accuracy of the AMP 331, along with construction of prediction equations for oxygen consumption and energy cost. Methods: Young adult volunteers (n = 41) wearing two AMP units walked and ran on a treadmill with energy cost data simultaneously collected through indirect calorimetry. Results: Statistically significant differences exist in inter-AMP unit reliability for speed and step length and in accuracy between the AMP units and criterion measures for speed, oxygen consumption, and energy cost. However, the differences in accuracy for speed were very small during walking (≤ 0.16 km/h) and not clinically relevant. Prediction equations constructed for walking oxygen uptake and energy expenditure demonstrated $R^2$ between 0.76 to 0.90 and between subject deviations were 1.53 mL O₂ · kg⁻¹ · min⁻¹ and 0.43 kcal/min. Conclusions: In young adults, the AMP 331 is acceptable for monitoring walking speeds and the output can be used in predicting energy cost during walking but not running.

Key Words: accelerometry, physical activity, ambulation monitoring, gait

Accurately assessing free-living physical activity levels, including common though hard to remember activities such as walking, is necessary to establish associations between physical activity and health outcomes, and in setting health-related physical activity guidelines. A variety of methods have been employed to assess free-living activity including doubly labeled water, direct observation, activity logs, questionnaires, accelerometry, and pedometry. All of these methods have limitations. Currently, accelerometry-based activity monitors are one of the more objective and increasingly common methods used to assess free-living physical activity. For example, the federal government surveillance of physical activity through the National Health and Nutrition Examination Survey (NHANES) as of 2003 uses...
accelerometry-based monitors. Accelerometry-based activity monitors generally measure changes in acceleration and tabulate the raw signal as movement counts for a given time period. They are typically small, worn at the waist or on an extremity, and include one to three accelerometers embedded within a small case.

The AMP 331 (Dynastream Innovations, Cochrane, AB) is a newly developed triaxial activity monitor with a unique accelerometer orientation (biaxial and one uniaxial) that allows the unit to track the position of the lower leg during individual steps and therefore assess speed, cadence, and stride length. Its accelerometer positioning and ability to record individual steps and individual step velocity are desirable features not currently available in other monitors. Unlike traditional accelerometry output (i.e., movement counts), the AMP outputs of speed, cadence, and stride length are easily interpretable variables. Given its design, the AMP should be particularly well suited for assessing ambulation. This might make the AMP attractive for use in exercise prescription and health promotion, especially since gait characteristics such as speed have been shown to be predictive of disability. Similar to other accelerometers, output from the AMP unit can be calibrated to estimate oxygen uptake and energy expenditure. Overall, the design of the AMP is novel and potentially offers an improvement over other accelerometry-based designs for specific assessment of quantity and quality of ambulatory movement.

The purpose of this study was to evaluate the reliability and validity of the AMP monitor for measuring ambulatory movement in young adults. Specifically we examined the AMP inter-unit reliability for measuring speeds (km/h), cadence (steps/min), and step length (meters) during treadmill walking and running. Also examined was AMP accuracy for speed, and the AMP manufacturer algorithms for estimating oxygen uptake (mLO2 kg-1 · min-1) and energy expenditure (kcal/min). A secondary purpose of our study was to use metabolic data collected during testing to develop and validate AMP unit specific prediction equations for oxygen uptake and energy expenditure determination.

Methods

Subjects
Forty-one young adult volunteers participated in the study (23.2 ± 3.4 y). All subjects were apparently healthy (as assessed by a brief questionnaire) and familiar with using a treadmill. Subject demographic data are presented in Table 1. Prior to enrollment in the study, subjects provided written informed consent for participation in accordance with the University of Iowa Institutional Review Board.

Accelerometers
The AMP 331 (Figure 1) is a small, lightweight monitor (size: 86.4 × 38.1 × 33 mm; weight: 56 g) with a triaxial accelerometer design (biaxial and one uniaxial). The biaxial accelerometer at one end of the pod is sensitive to the anterior-posterior (horizontal) and proximal-distal (vertical) motions while the uniaxial accelerometer at the other end of the pod is sensitive to only anterior-posterior motion. The AMP is worn in a small mesh pouch at the ankle and monitors the angle and angular velocity of the shank during the gait cycle. Cadence and step length are directly
determined using stride detection algorithms and the raw accelerometry data. Speed is calculated using the sum of all the stride lengths and direct measures of movement time. Oxygen consumption and energy expenditure are predicted using proprietary equations. The monitor can be powered for approximately 7 to 10 d by a single AAA battery. Data can be collected in 1, 2, 3, 4, 5, 6, 10, 12, 15, 20, 30, or 60 min epochs and can be downloaded via a radio frequency link and displayed in a Microsoft Excel spreadsheet.6

**Table 1  Characteristics of Participants**

<table>
<thead>
<tr>
<th></th>
<th>Whole group</th>
<th>Experimental group</th>
<th>Validation group</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age (y)</td>
<td>23.2 (3.4)</td>
<td>23.1 (3.0)</td>
<td>23.8 (4.4)</td>
</tr>
<tr>
<td>Height (cm)</td>
<td>168.7 (8.9)</td>
<td>169.2 (8.2)</td>
<td>167.1 (10.9)</td>
</tr>
<tr>
<td>Weight (kg)</td>
<td>65.4 (11.3)</td>
<td>65.6 (11.4)</td>
<td>64.8 (11.0)</td>
</tr>
<tr>
<td>Right leg length (cm)</td>
<td>224.6 (14.7)</td>
<td>225.7 (15.2)</td>
<td>221.1 (13.7)</td>
</tr>
<tr>
<td>Left leg length (cm)</td>
<td>224.7 (14.5)</td>
<td>225.8 (15.1)</td>
<td>221.5 (13.0)</td>
</tr>
<tr>
<td>BMI</td>
<td>22.9 (2.1)</td>
<td>22.7 (2.2)</td>
<td>23 (1.7)</td>
</tr>
</tbody>
</table>

*Note: Values are means with standard deviation in parentheses; experimental group, n = 31; validation group, n = 10; BMI, body-mass index.*

**Figure 1**—AMP unit.

A pre-calibrated motorized Trackmaster treadmill (JAS Fitness Systems, Newton, KS) was used for the treadmill tests. Agreement between belt speed and the treadmill
display speedometer (0.16 km/h increments) was verified with a custom-designed speedometer device which had a measurement accuracy of ± 0.036 km/h.8

**Metabolic Cart**

Oxygen uptake and energy expenditure were determined by the open circuit method with breath by breath measurements taken with a computer interfaced Medical Graphics2 metabolic cart (Medical Graphics Corp., St. Paul, MN). Prior to testing of each subject, the system was calibrated for flow and volume measurements using a 3 L syringe and for gas analysis using manufacturer-specified calibration and references gases.

**Data Collection Protocol**

Prior to the treadmill test, the weight and height of each subject were measured using a calibrated balance beam scale and stadiometer (Detecto Scales, Inc., Brooklyn, NY). Testing consisted of a single 45 min multi-speed level (0 %) grade walking/running treadmill test, involving bilateral physical activity monitoring with concurrent energy cost measurements. The same individually numbered monitors were placed in a standardized position on the posterior ankle for all subjects (AMP1 at the right ankle, AMP2 at the left). The AMP monitors were initialized in adherence with manufacturer’s operation procedure, and time synchronized to a metabolic cart using a desktop computer. Minute epochs were used during data collection. Each subject was asked to complete 4 min stages at each of the five walking and three running stages (3.22 km/h, 4.02 km/h, 4.83 km/h, 5.63 km/h, 6.44 km/h, 8.05 km/h, 9.65 km/h, and 11.27 km/h, respectively). A 5 to 10 min cool-down period was provided at the completion of the test.

**Data Analysis**

AMP unit output and steady state oxygen consumption from the third minute of each stage were used for the statistical analyses.9 Two-factor (AMP unit x treadmill speed) repeated measures analyses of variance (ANOVAs) with follow-up pairwise speed-specific contrasts were used to assess the inter-AMP unit reliability between AMP1 and AMP2 for estimating speed, cadence, and step length. To further analyze AMP unit reliability, one-factor (AMP unit) repeated measures ANOVA data were used to estimate generalizability (G). The techniques as described by Morrow10 partition out the variance for the factor and interaction terms (with error-free measures all variance would be attributed to the differences between subjects). G-coefficients can be interpreted as 0.0 representing no reliability (generalizability) and 1.0 equal to perfect reliability. G-coefficients can provide an assessment of the reliability for a single monitor under normal conditions of expected use.11 Accuracy for the AMP units against criterion measures for speed, oxygen uptake, and energy expenditure was assessed using one-factor (speed) ANOVAs with repeated measures. Tukey follow-up speed-specific comparisons between the AMP1 and AMP2 units, and comparisons for each AMP unit versus the criterion measure were made to further clarify any possible trends in performance for the activity monitor-determined measures. Residuals from the ANOVA were used to further
examine AMP unit accuracy. Separate analyses were performed for the treadmill walking and running speeds.

Energy expenditure and oxygen consumption estimates were calculated from generalized estimating equations structured using an autoregressive correlation structure for successive speeds within subjects. Ten subjects were withheld from the regression model to provide unbiased estimates of prediction accuracy and variation. Statistical significance for all testing was set at $P < 0.05$. Statistical analyses were performed using SPSS version 13.0 (SPSS, Inc., Chicago, IL) and SAS version 8.1 (SAS Institute, Inc., Cary, NC).

Results

Descriptive Data

Ambulation data were collected by the AMP units on all 41 subjects for the five walking and three running speeds. Metabolic data were also collected on all subjects for all walking and running speeds. When subjects did not demonstrate a steady state of oxygen uptake the data were removed from the metabolic analysis. This resulted in eliminating data for one subject at the middle running speed (9.65 km/h) and five subjects at the high running speed (11.27 km/h).

Inter-AMP Reliability

Means for both AMP units at each treadmill speed for walking and running speed, cadence, and step length are presented in Figures 2 through 4. G-study results for the variance components and G-coefficients at each of the walking and running speeds are presented in Tables 2 and 3. At walking speeds the two-factor ANOVA for cadence revealed no significant differences. G-coefficients for the five speeds ranged between 0.93 to 0.98, with between-subject differences accounting for roughly 97% of the variance. In contrast, the two-factor ANOVAs for speed and step length data revealed significant differences between AMP1 and AMP2 ($P < 0.01$) with significantly lower values measured by AMP1 at each treadmill speed. Furthermore, the AMP units accounted for much of the variance with step length (47.4% to 59.6%) and speed (73.0% to 77.0%). Large sources of variance were also found in the subject × AMP unit (S × U) interactions with step length (8.7% to 13.6%) and speed (14.0% to 16.9%). G-coefficients for step length were greater than 0.80 only for the higher walking speeds (4.83, 5.63, and 6.44 km/h), while all G-coefficients for speed were 0.40 or lower.

For running speeds, the same pattern was found with non-significant differences for measures of cadence, but significant differences for measuring speed and step length between AMP1 and AMP2 at all three running speeds ($P < 0.01$). The G-study results for cadence showed that the subjects again accounted for the overwhelming majority of the variance (83.7% to 97.3%) while the AMP unit was the source for no more than 1.1%. G-coefficients for cadence were greater than 0.85 for all three speeds. Unlike walking speeds, G-study results showed subjects comprised the largest amount of the total percent of variance for step length (53.6% to 62.8%) and speed (35.1% to 66.5%). Large values were also found with step length and
Figure 2—Inter-unit reliability and accuracy for speed.

speed for the AMP unit term and the \((S \times U)\). G-coefficients at the running speeds for step length ranged between 0.67 to 0.76 and for speed between 0.51 to 0.76.

**AMP Unit Accuracy**

Comparison of AMP1 and AMP2 data versus the criterion value for speed is presented in Figure 2. One-factor ANOVAs on the walking data showed AMP2-calculated speeds were significantly higher than the criterion values at 3.22
km/h and significantly lower at 5.63 km/h and 6.44 km/h ($P < 0.05$) while AMP1 underpredicted for all speeds ($P < 0.01$). For walking speeds the standard deviation for the residuals was at most 0.16 km/h. At all running speeds, both AMP1 and AMP2-calculated speed were significantly lower ($P < 0.01$) than the criterion values. For running speeds standard deviations for the residuals were values as high as 1.06 km/h.

Figures 5 and 6 present comparisons of AMP1 and AMP2 data versus the oxygen consumption and energy expenditure data provided by indirect calorimetry (criterion measure). Analyses revealed significant under-predictions by both AMP units at all walking and running speeds ($P < 0.01$). At running speeds the magnitude of the under-predictions were much greater (9.1 to 17.6 mL $O_2 \cdot kg^{-1} \cdot min^{-1}$, 2.9 to 5.8 kcal/min) than for walking (0.3 to 2.9 mL $O_2 \cdot kg^{-1} \cdot min^{-1}$, 0.1 to 0.9 kcal/min).

Validation of Oxygen Consumption and Energy Expenditure Equations

Following the data collection, the AMP units were returned to the manufacturer and AMP1 was found to be outside of the manufacturer’s error specifications with the total distance error $> \pm 3\%$. Therefore, only data from AMP2 were used for the oxygen uptake and energy expenditure prediction equations. Thirty-one subjects (prediction group) were randomly selected and used to develop the oxygen consumption and energy expenditure prediction equations. Ten “hold-out” subjects (validation group) were used to validate the equations. Gender, age, height, weight, step cadence, and step length were considered in these models though only variables significant at $P < 0.05$ were retained in the final models. Oxygen uptake and energy
Table 2 (Part 1) Variance Components (percent of total) and Generalizability Coefficients for Each Walking Speed

<table>
<thead>
<tr>
<th>AMP output:</th>
<th>Cad</th>
<th>SL</th>
<th>Speed</th>
<th>Cad</th>
<th>SL</th>
<th>Speed</th>
<th>Cad</th>
<th>SL</th>
<th>Speed</th>
</tr>
</thead>
<tbody>
<tr>
<td>Subjects (S)</td>
<td>97.4</td>
<td>26.9</td>
<td>7.6</td>
<td>93.4</td>
<td>36.0</td>
<td>8.5</td>
<td>97.3</td>
<td>40.1</td>
<td>8.7</td>
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<tr>
<td>AMP unit (U)</td>
<td>0.0</td>
<td>59.6</td>
<td>75.5</td>
<td>0.0</td>
<td>53.3</td>
<td>75.3</td>
<td>0.0</td>
<td>51.1</td>
<td>77.0</td>
</tr>
<tr>
<td>S × AMP unit</td>
<td>2.6</td>
<td>13.6</td>
<td>16.9</td>
<td>6.6</td>
<td>10.8</td>
<td>16.2</td>
<td>2.7</td>
<td>8.8</td>
<td>14.3</td>
</tr>
<tr>
<td>Total</td>
<td>100.0</td>
<td>100.0</td>
<td>100.0</td>
<td>100.0</td>
<td>100.0</td>
<td>100.0</td>
<td>100.0</td>
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</tr>
<tr>
<td>Generalizability</td>
<td>0.97</td>
<td>0.66</td>
<td>0.31</td>
<td>0.93</td>
<td>0.77</td>
<td>0.35</td>
<td>0.97</td>
<td>0.82</td>
<td>0.38</td>
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Table 2 (Part 2)

<table>
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<tr>
<th>AMP output:</th>
<th>Cad</th>
<th>SL</th>
<th>Speed</th>
<th>Cad</th>
<th>SL</th>
<th>Speed</th>
</tr>
</thead>
<tbody>
<tr>
<td>Subjects (S)</td>
<td>97.3</td>
<td>41.5</td>
<td>10.8</td>
<td>97.7</td>
<td>43.9</td>
<td>9.4</td>
</tr>
<tr>
<td>AMP unit (U)</td>
<td>0.0</td>
<td>48.4</td>
<td>73.0</td>
<td>0.0</td>
<td>47.4</td>
<td>76.7</td>
</tr>
<tr>
<td>S × AMP unit</td>
<td>2.7</td>
<td>10.1</td>
<td>16.3</td>
<td>2.3</td>
<td>8.7</td>
<td>14.0</td>
</tr>
<tr>
<td>Total</td>
<td>100.0</td>
<td>100.0</td>
<td>100.0</td>
<td>100.0</td>
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<tr>
<td>Generalizability</td>
<td>0.97</td>
<td>0.80</td>
<td>0.40</td>
<td>0.98</td>
<td>0.84</td>
<td>0.40</td>
</tr>
</tbody>
</table>

Note: Cad, cadence; SL, step length.
<table>
<thead>
<tr>
<th>AMP output:</th>
<th>Treadmill speed (km/h)</th>
<th></th>
<th></th>
<th></th>
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<tbody>
<tr>
<td></td>
<td></td>
<td>8.05</td>
<td>9.66</td>
<td>11.27</td>
</tr>
<tr>
<td>Subjects (S)</td>
<td>Cad</td>
<td>SL</td>
<td>Speed</td>
<td>Cad</td>
</tr>
<tr>
<td>97.3</td>
<td>53.6</td>
<td>35.1</td>
<td>93.8</td>
<td>55.5</td>
</tr>
<tr>
<td>AMP unit (U)</td>
<td>0.3</td>
<td>22.4</td>
<td>31.8</td>
<td>0.0</td>
</tr>
<tr>
<td>S × AMP unit</td>
<td>2.4</td>
<td>24.0</td>
<td>33.1</td>
<td>6.2</td>
</tr>
<tr>
<td>Total</td>
<td>100.0</td>
<td>100.0</td>
<td>100.0</td>
<td>100.0</td>
</tr>
<tr>
<td>Generalizability coefficient</td>
<td>0.98</td>
<td>0.69</td>
<td>0.51</td>
<td>0.94</td>
</tr>
</tbody>
</table>

Note: Cad, cadence; SL, step length
expenditure equations are presented for walking speeds only since estimates for running were unacceptable (i.e., high error rates and poor agreement with criterion). The equations are as follows:

\[
(1) \text{mL O}_2 \cdot \text{kg}^{-1} \cdot \text{min}^{-1} = 2.05 \text{ (gender)} - 0.25 \text{ (height)} - 0.44 \text{ (cadence)} - 73.53 \text{ (step length)} + 0.81 \text{ (cadence x step length)} + 66.83
\]
(2) kcal × min = 0.58 (gender) + 0.03 (weight) – 0.10 (height) – 0.15 (cadence) – 24.69 (step length) + 0.27 (cadence × step length) + 18.53

Key for gender: male = 1, female = 0

The regression model for predicting oxygen consumption (mL O₂ · kg⁻¹ · min⁻¹) yielded R² values of 0.90 for the prediction group and 0.76 for the validation group. The residual oxygen uptake values for the validation group showed a mean of 0.10
mL O₂ · kg⁻¹ · min⁻¹, a within subject standard deviation of 0.69 mL O₂ · kg⁻¹ · min⁻¹, and a between subject standard deviation of 1.53 mL O₂ · kg⁻¹ · min⁻¹. Residual plots for the prediction and validation samples are presented in Figure 7.

The regression models for predicting energy expenditure (kcal × min) yielded $R^2$ values of 0.89 for the prediction group and 0.84 for the validation group. The residual energy expenditure values for the validation group showed a mean of –0.11 kcal/min, a within-subject standard deviation of 0.27 kcal/min, and a between-subject standard deviation of 0.43 kcal/min. Residual plots for the prediction and validation samples are presented in Figure 8.

**Discussion**

This study investigated the inter-unit reliability and accuracy of the AMP 331 physical activity monitor during treadmill walking and running. At a basic level, accurately monitoring ambulatory movement is important since it is the main physical activity people perform.¹²

The results indicate the reliability and accuracy of the AMP monitors varies depending on the output measure of interest. The two monitors used were new at the start of the study. Upon completion of the study, the monitors were returned to the manufacturer and one was found to be outside of specifications. The magnitude of the error for the “outside-of-specifications” monitor (AMP1) was similar for all subjects and was likely the source for the significant differences obtained with the ANOVA testing for AMP inter-unit reliability, and the sizable amounts of variance attributed to the units factor for step length and speed measures. This raises a concern over possibly inadequate quality control by the manufacturer. However, since only two units were tested, we are unable to fully evaluate any problems that may exist with inter-unit reliability. Future research is needed to investigate this concern. The remainder of this section will focus on results for the “within-specifications” monitor (AMP2).

The results showed significant statistical differences for comparisons between the AMP2 determined speed and the treadmill criterion measure at several speeds. However, the standard deviation for the ANOVA residuals for speed during walking were at worst 0.16 km/h. Considering the error in treadmill belt speed (calibration accuracy of 0.14 km/h) would not have been accounted for in the constant values used as the speed criterion measures, and because the belt speed error is comparable to the standard deviation for the ANOVA residuals, the walking speed differences are felt to be negligible. However, larger differences (up to 1.06 km/h) for the AMP2-measured speeds during running indicates unacceptable measurement error.

In this study, the AMP inter-unit cadence measures for the range of walking and running speed were not significantly different and the total variance for the units was no more than approximately 1%. This supports the conclusion that the AMP units are able to make reliable cadence counts. In general, accelerometry-based physical activity monitors have demonstrated acceptable accuracy for measuring the number of steps taken.¹³⁻¹⁵ Therefore, we speculate that the AMP units can measure cadence accurately. Based on the assumption that cadence measures are then correct, we then suspect the cause of inaccuracy with AMP unit speed determination lies in the measures of step length. If the cadence and speed values from the study were used...
to calculate a step length, the differences between the AMP monitor and calculated step length at walking speeds would amount to no more than approximately 2 cm. However, using this approach, the AMP-measured step length compared to the calculated values resulted in differences of up to 13.5 cm at running speeds. For running speeds, a lack of accuracy in the AMP-measured step length could have potentially caused the large errors in the AMP-determined speed.

To compensate for any potential inaccuracies in the AMP, a method is needed for users to check the calibration of the AMP measures, particularly step length. A potential solution could be to have a person walk or run a known distance (such as at a track) while recording the time to allow calculation of the walking or running speed. A step length could then be computed using the speed value and an assumption that cadence measures are accurate (cadence could be verified through a manual count). This would allow a comparison of a computed step length with the AMP monitor value. Testing at multiple speeds would be necessary since the error in the AMP unit step length was not uniform across the speeds. In a practical sense, the inaccuracies found with running speeds might be inconsequential if the population using the monitor spends little or no time at speeds greater than those found with walking.

Previous studies to develop equations for energy expenditure prediction using triaxial accelerometry-based activity monitors report $R^2$ values (0.69 to 0.90) similar to those found in this study (0.76 to 0.90). Close agreement to the criterion for the validation sample (95% CI of 2.99 mL O$_2$ · kg$^{-1}$ · min$^{-1}$ and 0.84 kcal × min) suggests the equations developed in this study are acceptable for use with the AMP monitor in young adults. We must keep in mind that equations based on laboratory testing might result in an underestimation of energy expenditure during field use and that any underestimation would become compounded if the tasks include movements that an ankle-mounted monitor cannot be expected to capture.

Some caution should be used when interpreting the conclusions of this study for several reasons. Our inability to include criterion measures for cadence and step length in the study design is problematic. Testing was also performed on a laboratory treadmill and only over level grades, which may affect the AMP unit’s application to free-living conditions. Furthermore, our sample consisted of young adults, and it is unknown how changes in gait characteristics with aging would affect AMP unit reliability and accuracy. Also, sizable amounts for variance associated with the (S × U) interaction term for step length and speed suggests that the AMP units functioned differently across subjects. Although small differences in orientation and positioning for the subjects may have caused the errors, it might be expected that these errors would increase with use in free-living conditions where it is more difficult to ensure wearing guidelines are being observed. Additional research which addresses these limitations is needed.

**Summary**

By presenting speed measures, the AMP provides a novel and potentially advantageous method for monitoring ambulatory movement. Assessing general activity levels or quantification of gait characteristics (walking speed, total steps taken, or distance covered) known to be associated with quality of life indicators are among
its potential uses. Inter-unit reliability differences warrant further research though it may be possible in the short term to use a simple test matching a known speed with the AMP output to assess the accuracy of the individual units. Negligible differences for speed measures when the AMP is within manufacturer specifications suggest the AMP provides an adequate assessment of overall gait speed during walking. Running speeds, however, are not accurately measured by the AMP. Furthermore, even though the accuracy of cadence and step length could not be confirmed due to limitations in the study design, the AMP unit output for cadence and step length can be used with the equations developed in this study to predict oxygen consumption and energy expenditure during walking with acceptable accuracy.

Acknowledgments

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References


