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Ankle Accelerometry for Assessing Physical Activity among Adolescent Girls: Threshold Determination, Validity, Reliability, and Feasibility

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Abstract

Purpose—Ankle accelerometry allows for 24-hour data collection, improving data volume/ integrity versus hip accelerometry. Using Actical ankle accelerometry, the purpose was to (a) develop sensitive/specific thresholds; (b) examine validity/reliability; (c) compare new thresholds with manufacturer's; and (d) examine feasibility in a community sample (low-income, urban adolescent girls).

Methods—Two studies were conducted with 6th–7th grade girls (age 10–14 years): *Laboratory study* (n=24)- Two Actical accelerometers were placed on the ankle and worn while measuring energy expenditure (Cosmed K4b2, Metabolic Equivalents (METs)) during 10 prescribed activities. Analyses included device equivalence reliability (intraclass correlation (ICC): activity counts of 2 Acticals), criterion-related validity (correlation: activity counts and METs), and calculations of sensitivity, specificity, kappa and ROC curves for thresholds. *Free-Living study* (n=459)- an Actical was worn >7 days on the ankle (full 24-hour days retained). Analyses included feasibility (frequencies: missing data) and paired t-tests (new thresholds versus manufacturer's).

Results—*Laboratory study*- Actical demonstrated reliability (ICC=.92) and validity (r=.81). Thresholds demonstrated sensitivity (91%), specificity (84%), kappa=.73 (p=.043), area under curve range .81–.97. *Free-Living study*- 99.6% wore the accelerometer; 84.1% had complete/valid data (mean=5.7 days). Primary reasons for missing/invalid data: Improper programming/ documentation (5.2%), failure to return device (5.0%), wear-time ≤2 days (2.8%). The Moderate to Vigorous Physical Activity (MVPA) threshold (>3200 counts/minute) yielded 37.2 minutes/ day, 2–4.5 times lower than the manufacturer's software (effect size=.74–4.05).

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Conflict of Interest
The authors have no conflicts of interest to disclose.

Conclusions—Validity, reliability, and feasibility evidences support Actical ankle accelerometry to assess physical activity in community studies of adolescent girls. When comparing manufacturers' software versus new thresholds, a major difference was observed.

Keywords

Actical; community studies; moderate-vigorous physical activity; African American

National guidelines recommend that children and adolescents engage in at least 60 minutes of moderate to vigorous physical activity (MVPA) each day (USDHHS, 2008). Two recent articles synthesized the evidence supporting the beneficial effects of physical activity in youth. A meta-analysis of pooled accelerometry and health data from 14 independent studies (20,871 healthy children age 4–18 years), found that more time spent in MVPA was associated with reduced risk for cardiometabolic risk factors, independent of time spent in sedentary behaviors (Ekelund et al., 2012), and a systematic review of 86 observational and experimental studies identified numerous health benefits of physical activity in youth [including, but not limited to cholesterol/blood lipid levels, blood pressure, metabolic syndrome, overweight/obesity, and depression (Janssen & Leblanc, 2010)].

Accurate assessments of physical activity are necessary to determine level of physical activity (i.e., sedentary, light, moderate, and vigorous), to examine trends and correlates of activity, and to evaluate the effectiveness of physical activity promotion programs (Warren et al., 2010). Accelerometry provides a non-invasive method for objectively assessing physical activity that can be used to examine intensity, frequency, duration, and patterns of physical activity.

The majority of epidemiologic and intervention studies utilizing accelerometry focus on time spent in sedentary, light, moderate, and vigorous physical activity, based on METs [Metabolic Equivalent, the ratio of the working metabolic rate to the resting metabolic rate (Ainsworth et al., 2000)]. Because accelerometer output is in counts per unit of time, count thresholds are used to delineate the counts that correspond to each of the MET-based categories. The accelerometer count thresholds are determined through calibration studies specific to the monitor, placement, and population of interest (Welk, 2005). Calibration studies typically compare accelerometer output with energy expenditure (in kcals or METS) collected via indirect calorimetry. Applying thresholds generated from calibration studies to data collected from free-living populations can provide information on time spent in MVPA, a widely-used metric in the fields of public health and behavioral intervention research. A recent "best practices" guide for the measurement of physical activity using wearable monitors recommends that monitors be validated in both laboratory and free-living populations (Butte, Ekelund, & Westerterp, 2012).

Three sites–hip, wrist, and ankle, have commonly been used for accelerometer placement. These sites have been compared for validity and reliability. Most laboratory studies show that the hip placement provides a more valid and reliable estimate of activity energy expenditure compared to placement at the ankle, wrist, or knee (Choi, Chen, Acra, & Buchowski, 2010; Heil, 2006; Puyau, Adolph, Vohra, & Butte, 2002), and the hip placement has been used in the majority of accelerometer studies to date. In studies of free-living individuals, however, the hip placement has raised concerns about data volume and integrity. First, because participants are instructed to remove the elastic band at night and when showering, missing data is an inherent problem with hip accelerometry. As few as 8 hours of accelerometer data collected in a single day have been used, with missing values imputed, to approximate physical activity for a given day (Catellier et al., 2005; R. Colley, Gorber, & Tremblay, 2010; Staudenmayer, Zhu, & Catellier, 2012). Studies have shown biases in wear times for adults (Loprinzi et al., 2012) and biases in data validity among children (Loprinzi et al., 2013). Recent studies suggest a minimum wear time of greater than 12 hours/day (Herrmann, Barreira, Kang, & Ainsworth, 2013, 2014) is necessary for valid physical activity measurement, and a wear time of less than 10 hours/day may be missing 26.2% of moderate activity and 40.3% of vigorous activity (compared to 14 hours/day of wear time) (Herrmann et al., 2014). Second, the validity of hip accelerometry has been questioned among overweight/obese populations because of the monitor "tilt" that can occur with abdominal obesity (Feito, Bassett, Tyo, & Thompson, 2011). Finally, compliance for the hip placement is lower in children, compared to adults, suggesting that other placements might be more feasible (Troiano et al., 2008). Recent studies have begun to examine the wrist more closely as an alternative placement in children (Schaefer, Nace, & Browning, 2013), overcoming concerns with data volume/integrity through 24-hour continuous data collection, however a major limitation to the wrist placement is the inability to capture activities involving locomotion. Finally, the ankle placement has not been extensively studied, yet may overcome many of the limitations of the hip site, through the opportunity for continuous, 24-hour data collection, and the limitations of the wrist site, through the ability to capture locomotion, a common form of physical activity.

The Actical accelerometer (Philips Respironics, Minimitter, Bend, OR) is a small (28×27×10mm), light-weight (17g), waterproof omnidirectional accelerometer. For the Actical, the manufacturer's software uses equations developed through a calibration study with children, adolescents, and adults (Heil, 2006) to generate time spent in varying levels of activity. For the hip and wrist placements, these equations have been challenged and updated (Alhassan et al., 2012; R. C. Colley & Tremblay, 2011; Crouter et al., 2011; Hooker et al., 2012; Lyden, Kozey, Staudenmeyer, & Freedson, 2011; Rothney, Schaefer, Neumann, Choi, & Chen, 2008; Schaefer et al., 2013). The impetus for the current study was our laboratory's experience applying the Actical manufacturer's thresholds to ankle accelerometry data collected in free-living studies. The output for time spent in moderate activity for each dataset was substantially higher (i.e.: average of several hours) than reports from other investigators (Pate et al., 2009; Troiano et al., 2008). Therefore, a re-examination of thresholds for Actical ankle accelerometry is needed.

The purpose of this study was two-fold. First, in a laboratory study, we sought to establish activity count thresholds for sedentary, light, and MVPA for Actical ankle accelerometry among adolescent girls. This was accomplished by comparing Actical output with portable indirect calorimetry. From this laboratory study, Actical ankle accelerometry validity and reliability were also determined. Second, in a study of free-living adolescents, the thresholds developed in the laboratory study were applied to physical activity data collected from a community sample of adolescent girls who wore an Actical accelerometer on the ankle. Data from this study were used to estimate physical activity levels and to compare with thresholds generated from the manufacturer's software. This free-living study also allowed for the examination of the feasibility of ankle accelerometry to measure physical activity in community studies.

Methods

First Study: Laboratory

Adolescent girls (n=24) were recruited from local middle schools or through a "refer-a-friend" program to participate in a brief, one-day research study. Primary caregivers of potential participants completed eligibility and health screens by telephone. Eligibility criteria included female gender, enrolled in the 6^{th} or 7^{th} grade, able to read and understand English, and successful completion of a brief health screen (able to participate in activities similar to those done in physical education class). Participants were scheduled for a 2-hour appointment at a fitness center located on the campus of an urban medical center. All procedures were approved by the University Institutional Review Board. Participants arrived at the fitness center accompanied by a primary caregiver, dressed to exercise (sneakers, etc.), and having fasted for at least 2 hours. Upon arrival, the participants and their primary caregivers provided written informed assent and consent, respectively. Adolescent girls provided information on date of birth and race/ethnicity.

Anthropometrics—Height was measured to the nearest centimeter using a portable stadiometer (Shorr Productions, Olney, MD) and weight was measured in kilograms using the TANITA TBF-300 body composition scale (TANITA Corp., Tokyo, Japan), both measured in duplicate. Gender-specific BMI-for-age percentiles were generated to describe the sample using CDC 2000 growth indices. A BMI-for-age ≥ 85% was considered overweight/obese.

Accelerometry—Two Actical accelerometers were strung side-by-side on one hospital bracelet and fastened superior to the lateral malleolus of the adolescent girls' non-dominant ankle, per the manufacturer's instruction so that the arrow was pointed up. At placement, one Actical was randomly assigned as the primary prior to data collection. Accelerometer counts were collected in 15 second intervals.

Indirect calorimetry—A portable gas analyzer (K4b2, Cosmed; Rome, Italy) was used to measure oxygen consumption and carbon dioxide production breath by breath. Data were smoothed using Cosmed software to 15 second intervals. Variables included in the analysis were O_2 consumption, CO_2 production, respiratory quotient, and Metabolic Equivalents (METs, based on the standard resting value of 1 MET equivalent to 3.5 mL/kg/min, as has been used in prior pediatric accelerometer validation studies (Freedson, Pober, & Janz, 2005; Treuth et al., 2004)).

Physical activity protocol—Activities appropriate for middle school girls were chosen for this protocol based on prior adolescent accelerometer validation studies (Puyau, Adolph, Vohra, Zakeri, & Butte, 2004; Treuth et al., 2004), structured focus groups with middle school girls conducted to inform an obesity prevention intervention, and three pilot sessions with the Cosmed unit. Activities also needed to be executed at a steady state of energy expenditure, while wearing the gas analyzer. For example, basketball drills were considered and piloted, but the face mask of the gas analyzer made it difficult to see the ball when dribbling. The final protocol can be found in Table 1. A shortened version of the protocol was administered to a subset of participants based on scheduling.

Data reduction and analysis—The gas analyzer data were reduced and aligned by participant and activity, removing times between activities when the mask may have been removed for the participant to rest. Data were further reduced to ensure that only time intervals representing a steady state of oxygen consumption (at least one minute) were included by truncating the first minute and last 30 seconds of each activity and additional intervals to ensure VO_2 was within 200 mL. Once the data were reduced, differences by age, weight status category (normal weight versus overweight/obese), and BMI-for-age percentile were examined for participants with valid data compared to those without valid data using chi-squared analyses and independent t-tests.

Statistical analyses were completed using SPSS version 20.0. Accelerometer reliability ("device equivalence reliability", consistency of the output of two devices used in the same way at the same time (Zhu & Lee, 2010)) was determined based on the Intraclass Correlation (ICC, one-way random model) between the activity counts produced from the two Acticals worn concurrently on the same ankle. Accelerometer validity ("criterion-related validity", comparing device output compared to the output of a criterion method (Trochim, 2000)) was determined based on the Spearman correlation between the activity counts from the primary Actical and the MET values produced at each of the 15-second intervals.

Means and standard deviations (SD) for the activity counts and MET values were compared for each activity, graphically, to identify data clusters for each activity level (sedentary was considered ≤1.5 METS, light activity was 1.5–3.0 METs, moderate was 3.1–6.0 METs, and vigorous was >6.0 METs), similar to previous studies (Treuth et al., 2004). A team of four researchers with accelerometry experience, agreed upon two sets of thresholds to be tested. Once thresholds were generated, they were applied to the dataset, and sensitivity and specificity were calculated for each intensity level, receiver operator curves (ROC) curves were plotted, and % agreement and kappa values (index agreement accounting for chance; Kappa .61–.80 is considered substantial agreement, >.80 is considered almost perfect (Landis & Koch, 1977)) were calculated.

Second Study: Free-Living

Adolescent girls (n=459) were recruited from 18 schools in an urban public school district serving predominantly low-income communities to participate in a health promotion study (*Challenge! in Schools*). Eligibility criteria were the same as above. Mean recruitment rate per school was 46% (range 22%–85%). Caregivers and their adolescent daughters provided written informed consent and assent, respectively. The protocol was approved by the Institutional Review Boards at both the University and the public school system where this study took place.

Anthropometrics—The same methods described above were applied in the Free-Living study.

Accelerometry—Using a computerized randomization scheme based on the number of girls attending an evaluation session and the number of accelerometers available for distribution, a subset of participants was selected to wear an accelerometer. If a participant refused the accelerometer, it was recorded and the device was then distributed to another participant using the randomization scheme. The Actical accelerometer was placed superior to the lateral malleolus of the non-dominant ankle using a hospital bracelet (once latched, the band cannot be removed unless cut off) and was worn for at least 7 consecutive days without removal. Because of the waterproof nature of the Actical, the device can be worn while bathing or swimming without damage. Also, because of the small dimensions and light weight, the device can be worn while sleeping or playing sports (under a sock) without interference. Activity counts were collected in 1-minute intervals.

Data reduction and analysis—Statistical analyses were completed using SPSS version 20.0. After removing the first and last days of data, a maximum of 7 full days of physical activity data (24 hour periods, maximum of 9 days of wear time) were analyzed for minutes per day in each level of activity. Because the thresholds generated in the Laboratory Study were based on 15-second intervals of data, these values were multiplied by 4 to be applied to data collected in 1-minute intervals. Reasons for not wearing an accelerometer or not having valid accelerometer data were recorded by data collection staff.

To compare the adolescent ankle thresholds from the Laboratory Study with the manufacturer's thresholds, a random subset (n=50) of participants was selected for further analysis. Minutes in MVPA were generated using the manufacturer's software, using both single and double regression MET-based thresholds given the adolescent's gender, age, height, and weight (Heil, 2006). For consistency with the Laboratory Study, settings for MVPA were changed in the Actical software from 2.7 METs (default) to 3.0 METs (used in Laboratory Study). However, results were also generated with the Actical default settings. The time spent in MVPA according to the Actical software was compared to time derived from thresholds generated through the Laboratory Study using paired t-tests. For all analyses, alpha <.05.

Results

First Study: Laboratory

Twenty-four adolescent girls (mean age: 12.9 ± .59, range 11.8–14.1 years, 100% African American) were recruited to participate. Nearly half of the girls (45.5%) were overweight or obese. The duration, intensity (based on mean MET value), MET values, and activity counts by activity are presented in Table 1. Eleven girls were unable to maintain a steady state of energy expenditure during "jumping rope" and "running", reducing the sample size to 13 for these activities. Girls who completed the jumping and running activities had a significantly lower BMI-for-age percentile (88.1 ± 15.3 versus 51.5 ± 30.2, t=3.6(14.8), p=.003; effect size=.68). There was no difference by age or weight status category by completion of the jumping and running activities (p>.05). Eight adolescent girls completed the shortened protocol, leading to a sample size of 16 for the “setting the table” and “step routine” activities. There was no difference in age, BMI-for-age percentile, or weight status category by having finished the entire protocol versus the shortened protocol (p>.05).

The device equivalence reliability analysis revealed an ICC between the activity counts of the two accelerometers worn concurrently on the ankle of .92, as derived from the long-form dataset. The criterion-related validity analysis revealed a correlation between the activity counts generated from the primary accelerometer and the smoothed MET values from the Cosmed unit of .81.

Based on the indirect calorimetry data, all activities fell within the intended intensity category as per the Compendium of Physical Activities (Ainsworth et al., 2000), sedentary to vigorous, with mean values ranging from 1.2 to 8.0 METs (Table 1). Activity counts generated from the accelerometer increased with increasing intensity as expected; however, the two walking activities elicited a higher activity count respective to the intensity/MET values (Table 1). The step routine activity resulted in large activity count standard deviation and was excluded from consideration when generating thresholds.

Based on the clustering of data by MET values, two sets of thresholds were generated and examined. The “first approach” considered walking activities (which elicited higher than expected activity counts), and led to thresholds of: Sedentary <10; Light 10–800; Moderate 800–1550, and Vigorous >1550 counts/minute. The “second approach” excluded walking and led to thresholds of: Sedentary <10; Light 10–500; Moderate 500–1100, and Vigorous >1100 counts/minute.

Both approaches for the thresholds resulted in a low sensitivity for moderate and vigorous physical activity (first approach: 51% and 52%, respectively; second approach: 42.0% and 41.7%, respectively), indicating that these cut-offs were accurately categorizing moderate and vigorous activity only ~40–50% of the time based on the true energy expenditure. Additionally, the Kappa value for these thresholds overall was .55 and .51, respectively. Based on these findings, the cut-offs for moderate and vigorous activity were combined to represent a threshold for MVPA >800 counts/minute (first approach) and >500 counts/minute (second approach). The >800 counts/min approach resulted in a sensitivity of 91%, indicating that the MVPA threshold accurately categorized MVPA 91% of the time, and a specificity of 84%, indicating that this threshold accurately categorized intervals that were not MVPA 84% of the time. The Kappa value with the MVPA threshold was .73 (p=.043). For the >500 counts/min approach, the sensitivity was 85% and the specificity was 93%. These thresholds would accurately categorize MVPA 85% of the time. The >800 counts/min thresholds was chosen as the preferred approach, prioritizing sensitivity over specificity for the measurement of MVPA.

The ROC analyses revealed an area under the curve of .97 (95% CI: .95, .99) for the Sedentary (<10 counts/minute) threshold, .81 (95% CI: .73, .88) for the Light threshold (10–800 counts/minute), and .87 (95% CI: .81, .92) for the MVPA threshold (>800 counts/minutes).

Second Study: Free-Living in a Community Sample

A total of 594 6th and 7th grade girls from 18 schools were evaluated. Of these, 459 (77.3%) were randomized to receive an accelerometer, 457 agreed to wear the accelerometer (99.6%), and complete/valid physical activity data were obtained from 386 adolescent girls (84.1%). Reasons for missing/invalid data (n=71) are presented in Table 2. Nearly half of the missing/invalid data was due to technical problems (35/71) related to improper programming/documentation or device malfunction. The additional missing data was due to participant compliance (36/71) mostly related to lost or never returned accelerometers. The mean number of days with accelerometry data was 5.7 (range 1–7, 86.3% with 5–7 days of data), with, by design, 24 hours of data each day.

The mean age of the girls in the Free-Living Study was 12.1 ± .73 years (range 10.1–14.7) and over half were in the 6th grade (54.9%). Most were African American (84.8%) and half were overweight or obese (50.0%). The thresholds generated in the Laboratory Study when applied to data collected in 1-minute intervals were: Sedentary <40; Light 40–3200; MVPA >3200. Based on these thresholds, this sample spent an average of 37.2 minutes per day in MVPA. Average minutes per day and % of the day spent in sedentary, light, and MVPA as determined by the adolescent ankle thresholds are also shown in Table 3. Of the 24-hour period, an average of 64.9% of the time was spent in sedentary time (15.6 hours), which includes sleep.

Accelerometry data from a randomly selected subset of 50 girls were used to compare the adolescent ankle thresholds from the Laboratory Study with the manufacturer's thresholds (Table 4). Based on the manufacturer's thresholds, this subset of girls engaged in an average of 84–186 minutes in MVPA per day compared to the Laboratory Study thresholds of 40 minutes in MVPA per day. A statistically significant difference between the Laboratory Study threshold and each of the 4 thresholds generated from the manufacturer was detected for time spent in MVPA ($p < .001$, effect size range .74–4.05, Table 4).

Discussion

This paper describes two separate studies that together create (Laboratory) and apply (Free-Living) thresholds for ankle accelerometry, while also demonstrating the validity, reliability, and feasibility of ankle accelerometry among adolescent girls. In the Laboratory Study, there were two primary findings. First, the Actical accelerometer placed on the ankle is a valid method for measuring variations in energy expenditure compared to indirect calorimetry and can reliably record movement. This finding supports a prior study of a mixed-age and mixed-gender sample (Heil, 2006). Second, thresholds for sedentary, light, and MVPA were created. These adolescent ankle thresholds were sensitive, specific, and were in agreement with measured energy expenditure. Demonstrating the validity and reliability of ankle accelerometry and providing sensitive and specific thresholds for sedentary, light, and MVPA for adolescent girls provides researchers with an additional approach for measuring physical activity by accelerometry.

In the Free-Living Study, ankle accelerometry was used to measure physical activity in a community sample of low-income, urban, predominantly African American adolescent girls.

Nearly all participants agreed to wear the accelerometer and the majority had valid data, supporting the feasibility of ankle accelerometry. One-third of the missing data resulted from technical problems related to staff training which can be remedied with additional training, leading to greater volume of valid data. Another third of the missing data resulted from lost or never returned accelerometers. Accelerometer losses raise financial concerns. Over half of the accelerometer losses occurred in just three of the eighteen schools, suggesting that with additional staff training and unique school-specific strategies, losses could be reduced. Such strategies may include incentives for retuning the device (prizes or a lottery), decorating the band to increase attractiveness, involving parents or teachers to encourage longer wear-time or device return, a phone call on the 2nd or 3rd day to ensure the device is still attached/in the participant's possession, or individual or group reminders through text messaging. Only two participants refused the ankle accelerometer, which does not support a common view that participants would not wear an accelerometer on the ankle due to fear that it looks like a house arrest bracelet.

To obtain 24 hour periods of data, first and last days were truncated. The wear time protocol prescribed 7 or more days wearing the accelerometer in an effort to obtain 5 days of valid data. The mean number of days of valid data exceeded the goal, again supporting feasibility. There was no need for imputation methods with ankle accelerometry, as is necessary when using hip accelerometry, as ankle accelerometry produces 24 hours of continuous data collection.

Using the thresholds from the Laboratory Study, the sample of low-income, urban, predominantly African American adolescent girls were engaging in an average of 37 minutes of MVPA per day. This result is slightly higher than, but comparable to other studies of adolescent girls, with one study reporting 24.3 minutes in MVPA per day (defining MVPA as >4.6 METS) among 6th grade girls (Pate et al., 2009) and a national study reporting 75.2 minutes/day for female children 6–11 years and 24.6 minutes/day for female adolescents 12–15 years (Troiano et al., 2008). Because methods were not standardized across these studies and the populations differ, it is difficult to compare findings across studies but all studies demonstrate that, in general, adolescent girls engage in relatively low rates of MVPA.

Compared to minutes in MVPA generated from the Laboratory Study thresholds, the manufacturer's software overestimated time spent in MVPA by 2–4.5 times. A recent evaluation of the hip accelerometry thresholds used in the Actical manufacture's software found that, among adults, the manufacturer's thresholds underestimated energy expenditure across a range of activities, leading to a misclassification of 10–15% of moderate activities and nearly 50% of vigorous activities (Lyden et al., 2011). The manufacturer's equations for energy expenditure and thresholds for activity intensity have been closely scrutinized for the hip placement, with updated and refined models publicly available (Crouter & Bassett, 2008; Crouter et al., 2011). To date, the manufacturer's equations for the ankle placement have not been examined. This study uniquely adds to the literature by presenting output from the manufacture's software for free-living adolescents. The findings suggest that researchers should use caution when relying on the manufacture's software for ankle placement among adolescents. Given the promising sensitivity and specificity of the adolescent ankle thresholds, researchers studying adolescent physical activity patterns can utilize these thresholds.

There are several strengths to this study. First, although many validation/calibration studies of hip accelerometry have been conducted, few studies have focused on ankle accelerometry. This study of ankle accelerometry provides researchers with a valid, reliable, and feasible approach for collecting larger volumes of activity data, without imputation. Second, this study had two components: laboratory and free-living, consistent with recommendations from a recent “best practices” guide for assessing physical activity using wearable monitors (Butte et al., 2012). The activities chosen for the Laboratory Study were typical of activities done by low-income, urban adolescent girls and included a range of activities from sedentary to vigorous, which helps in the translation of these laboratory-generated thresholds to free-living samples.

This study also had limitations. First, these thresholds were created for a specific population: adolescent girls. Researchers targeting different population groups may want to replicate this Laboratory Study. Second, because of the ankle placement, walking elicited a higher activity count than other activities of a similar intensity. Walking was included in the generation of thresholds, however all activities were used to determine the sensitivity and specificity of the thresholds. Additionally, a resting metabolic rate (RMR) of 3.5mL/kg/min was used to define 1 MET in this study. RMR has been shown to be higher in children and adolescents (Harrell et al., 2005), which has led to the suggestion to use a higher resting VO_2 for pediatric populations (Crouter, Horton, & Bassett, 2012). Because 3.5mL/kg/min has been used in prior accelerometer calibration/validation studies (Freedson et al., 2005; Treuth et al., 2004), and the increment in RMR relative to adults is much smaller in adolescents than in younger children (Harrell et al., 2005), we chose to use 3.5mL/kg/min.

Conclusions

In conclusion, ankle accelerometry is an alternative, valid placement that reduces participant burden while improving the integrity and volume of the data collected. Future studies can incorporate these adolescent ankle thresholds when using ankle accelerometry to objectively measure physical activity in community studies of adolescents.

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References

Ainsworth BE, Haskell WL, Whitt MC, Irwin ML, Swartz AM, Strath SJ. Compendium of physical activities: an update of activity codes and MET intensities. Medicine and Science in Sports and Exercise. 2000; 32(9 Suppl):S498–504. [PubMed: 10993420]

Alhassan S, Lyden K, Howe C, Kozey Keadle S, Nwaokelemeh O, Freedson PS. Accuracy of Accelerometer Regression Models in Predicting Energy Expenditure and METs in Children and Youth. Pediatric Exercise Science. 2012; 24(4):519–536. [PubMed: 23196761]

Butte NF, Ekelund U, Westerterp KR. Assessing physical activity using wearable monitors: measures of physical activity. Medicine and Science in Sports and Exercise. 2012; 44(1 Suppl 1):S5–12.10.1249/MSS.0b013e3182399c0e [PubMed: 22157774]

Catellier DJ, Hannan PJ, Murray DM, Addy CL, Conway TL, Yang S. Imputation of missing data when measuring physical activity by accelerometry. Medicine and Science in Sports and Exercise. 2005; 37(11 Suppl):S555–562. [PubMed: 16294118]

Choi L, Chen KY, Acra SA, Buchowski MS. Distributed lag and spline modeling for predicting energy expenditure from accelerometry in youth. Journal of Applied Physiology. 2010; 108(2):314–327.10.1152/japplphysiol.00374.2009 [PubMed: 19959770]

Colley R, Gorber SC, Tremblay MS. Quality control and data reduction procedures for accelerometry-derived measures of physical activity. Health Reports. 2010; 21(1):63–69. [PubMed: 20426228]

Colley RC, Tremblay MS. Moderate and vigorous physical activity intensity cut-points for the Actical accelerometer. Journal of Sports Sciences. 2011; 29(8):783–789.10.1080/02640414.2011.557744 [PubMed: 21424979]

Crouter SE, Bassett DR Jr. A new 2-regression model for the Actical accelerometer. British Journal of Sports Medicine. 2008; 42(3):217–224. [PubMed: 17761786]

Crouter SE, Dellavalle DM, Horton M, Haas JD, Frongillo EA, Bassett DR Jr. Validity of the Actical for estimating free-living physical activity. European Journal of Applied Physiology. 2011; 111(7): 1381–1389.10.1007/s00421-010-1758-2 [PubMed: 21153659]

Crouter SE, Horton M, Bassett DR Jr. Use of a two-regression model for estimating energy expenditure in children. Medicine and Science in Sports and Exercise. 2012; 44(6):1177–1185.10.1249/MSS.0b013e3182447825 [PubMed: 22143114]

Ekelund U, Luan J, Sherar LB, Esliger DW, Griew P, Cooper A. Moderate to vigorous physical activity and sedentary time and cardiometabolic risk factors in children and adolescents. Journal of the American Medical Association. 2012; 307(7):704–712.10.1001/jama.2012.156 [PubMed: 22337681]

Feito Y, Bassett DR, Tyo B, Thompson DL. Effects of body mass index and tilt angle on output of two wearable activity monitors. Medicine and Science in Sports and Exercise. 2011; 43(5):861–866.10.1249/MSS.0b013e3181fefd40 [PubMed: 20962689]

Freedson P, Pober D, Janz KF. Calibration of accelerometer output for children. Medicine and Science in Sports and Exercise. 2005; 37(11 Suppl):S523–530. [PubMed: 16294115]

Harrell JS, McMurray RG, Baggett CD, Pennell ML, Pearce PF, Bangdiwala SI. Energy costs of physical activities in children and adolescents. Medicine and Science in Sports and Exercise. 2005; 37(2):329–336. [PubMed: 15692331]

Heil DP. Predicting activity energy expenditure using the Actical activity monitor. Research Quarterly for Exercise and Sport. 2006; 77(1):64–80. [PubMed: 16646354]

Herrmann SD, Barreira TV, Kang M, Ainsworth BE. How many hours are enough? Accelerometer wear time may provide bias in daily activity estimates. Journal of Physical Activity and Health. 2013; 10(5):742–749. [PubMed: 23036822]

Herrmann SD, Barreira TV, Kang M, Ainsworth BE. Impact of accelerometer wear time on physical activity data: a NHANES semisimulation data approach. British Journal of Sports Medicine. 2014; 48(3):278–282.10.1136/bjsports-2012-091410 [PubMed: 22936409]

Hooker SP, Feeney A, Hutto B, Pfeiffer KA, McIver K, Heil DP. Validation of the actical activity monitor in middle-aged and older adults. Journal of Physical Activity and Health. 2012; 8(3):372–381. [PubMed: 21487136]

Janssen I, Leblanc AG. Systematic review of the health benefits of physical activity and fitness in school-aged children and youth. International Journal of Behavior Nutrition and Physical Activity. 2010; 7:40.10.1186/1479-5868-7-40

Landis JR, Koch GG. The Measurement of Observer Agreement for Categorical Data. Biometrics. 1977; 33(1):159–174. [PubMed: 843571]

Loprinzi PD, Cardinal B, Crespo CJ, Brodowicz GR, Andersen RE, Smit E. Differences in Demographic, Behavioral, and Biological Variables Between those with Valid and Invalid Accelerometry Data: Implications for Generalizability. Journal of Physical Activity and Health. 2012; 10(1):79–84. [PubMed: 22398390]

Loprinzi PD, Smit E, Cardinal BJ, Crespo C, Brodowicz G, Andersen R. Valid and Invalid Accelerometry Data Among Children and Adolescents: Comparison Across Demographic, Behavioral, and Biological Variables. American Journal of Health Promotion. 2013; 28(3):155–8.10.4278/ajhp.121116-ARB-563 [PubMed: 23875988]

Lyden K, Kozey SL, Staudenmeyer JW, Freedson PS. A comprehensive evaluation of commonly used accelerometer energy expenditure and MET prediction equations. European Journal of Applied Physiology. 2011; 111(2):187–201.10.1007/s00421-010-1639-8 [PubMed: 20842375]

Pate RR, Stevens J, Webber LS, Dowda M, Murray DM, Young DR. Age-related change in physical activity in adolescent girls. Journal of Adolescent Health. 2009; 44(3):275–282.10.1016/j.jadohealth.2008.07.003 [PubMed: 19237114]

Puyau MR, Adolph AL, Vohra FA, Butte NF. Validation and calibration of physical activity monitors in children. Obesity Research. 2002; 10(3):150–157. [PubMed: 11886937]

Puyau MR, Adolph AL, Vohra FA, Zakeri I, Butte NF. Prediction of activity energy expenditure using accelerometers in children. Medicine and Science in Sports and Exercise. 2004; 36(9):1625–1631. [PubMed: 15354047]

Rothney MP, Schaefer EV, Neumann MM, Choi L, Chen KY. Validity of physical activity intensity predictions by ActiGraph, Actical, and RT3 accelerometers. Obesity (Silver Spring). 2008; 16(8): 1946–1952.10.1038/oby.2008.279 [PubMed: 18535553]

Schaefer CA, Nace H, Browning R. Establishing Wrist-Based Cutpoints for the Actical Accelerometer in Elementary School Aged Children. Journal of Physical Activity and Health. 2013; 11(3):604–13.10.1123/jpah.2011-0411 [PubMed: 23493290]

Staudenmayer J, Zhu W, Catellier DJ. Statistical considerations in the analysis of accelerometry-based activity monitor data. Medicine and Science in Sports and Exercise. 2012; 44(1 Suppl 1):S61–67.10.1249/MSS.0b013e3182399e0f [PubMed: 22157776]

Treuth MS, Schmitz K, Catellier DJ, McMurray RG, Murray DM, Almeida MJ. Defining accelerometer thresholds for activity intensities in adolescent girls. Medicine and Science in Sports and Exercise. 2004; 36(7):1259–1266. [PubMed: 15235335]

Trochim, W. The Research Methods Knowledge Base. 2. Cincinnati, OH: Atomic Dog Publishing; 2000.

Troiano RP, Berrigan D, Dodd KW, Masse LC, Tilert T, McDowell M. Physical activity in the United States measured by accelerometer. Medicine and Science in Sports and Exercise. 2008; 40(1):181–188. [PubMed: 18091006]

USDHHS. 2008 Physical Activity Guidelines for Americans. Washington, DC: U.S. Department of Health and Human Services; 2008.

Warren JM, Ekelund U, Besson H, Mezzani A, Geladas N, Vanhees L. Assessment of physical activity - a review of methodologies with reference to epidemiological research: a report of the exercise physiology section of the European Association of Cardiovascular Prevention and Rehabilitation. European Journal of Cardiovascular Prevention and Rehabilitation. 2010; 17(2):127–139.10.1097/HJR.0b013e32832ed875 [PubMed: 20215971]

Welk GJ. Principles of design and analyses for the calibration of accelerometry-based activity monitors. Medicine and Science in Sports and Exercise. 2005; 37(11 Suppl):S501–511. [PubMed: 16294113]

Zhu W, Lee M. Invariance of wearing location of Omron-BI pedometers: a validation study. Journal of Physical Activity and Health. 2010; 7(6):706–717. [PubMed: 21088300]

What does this article add?

This study generated activity count thresholds and examined the validity, reliability and feasibility of Actical ankle accelerometry among low-income, urban, adolescent girls, a population at increased risk for physical inactivity. The study design followed best practices recommendations for accelerometer validation studies in that it had both laboratory and free-living components, using activities chosen for the laboratory component were typical of low-income, urban adolescent girls.

There are three unique contributions related to physical activity assessment. First, findings from the laboratory component support criterion-related validity and device equivalence reliability of Actical ankle accelerometry and provide sensitive and specific thresholds for sedentary, light, and MVPA for use in future studies. The ankle placement provides an alternative to the hip and may overcome common criticisms of hip accelerometry (short wear-time, data volume biases). Second, the free-living component demonstrates feasibility of ankle accelerometry among a community sample of low-income, urban adolescent girls, with 99.6% of participants agreeing to wear the accelerometer on the ankle, debunking a common view of researchers that participants will not wear an ankle accelerometer due to fear that it looks like a house arrest bracelet. Third, the findings challenge the Actical manufacturer's software for the ankle placement, consistent with challenges to the software for the hip placement that has been challenged/updated in multiple studies.

In future studies, community researchers should consider ankle accelerometry when assessing physical activity among adolescent girls. Ankle accelerometry validation studies should be conducted among other populations and using other available devices.

Table 1

Validation Study: Protocol and Calorimetry (MET values)/Accelerometry (activity counts) Results.

	Protocol		Results				
Activity	**Duration *(minutes)*[a]**	**Intensity**	**Duration *(minutes)* [b]**	**Intensity**	**Heart Rate *(Mean ± SD)***	**METS *(Mean ± SD)***	**Activity Counts *(Mean ± SD)***
Rest	10–15	Sedentary	11.9	Sedentary	71.0 ± 12.9	1.2 ± 0.2	0.59 ± 2
Video Game	5–10	Sedentary	7.7	Sedentary	79.8 ± 11.1	1.1 ± 0.2	0.84 ± 2
Chores: Sweeping	5	Light	4.1	Light	92.6 ± 12.8	2.1 ± 0.5	81.1 ± 128
Chores: Setting the Table[c]	0–5	Light	4.2	Light	92.3 ± 17.4	2.5 ± 0.5	80.8 ± 84
Walking (2mph[d])	5–10	Light	7.2	Light	103.1 ± 26.6	2.8 ± 0.3	783 ± 277
Step Routine[c]	0–5	Moderate	4.5	Moderate	106.7 ± 22.3	3.6 ± 0.9	734 ± 527
Walking (4mph[d])	10	Moderate	7.6	Moderate	123.3 ± 28.1	4.8 ± 0.5	1472 ± 375
Stairs	5	Moderate	3.5	Moderate	113.7 ± 32.2	6.1 ± 0.6	826 ± 209
Running (6mph[d])[e]	5	Vigorous	3.2	Vigorous	147.0 ± 22.8	8.2 ± 0.9	1559 ± 464
Jumping Rope [e]	5	Vigorous	2.2	Vigorous	158.3 ± 14.7	8.0 ± 1.1	1584 ± 486

[a] range shows duration for shortened protocol-full protocol

[b] duration in a steady-state of energy expenditure

[c] sample size reduced due to shortened protocol (n=16)

[d] walking/running activities took place on an indoor track with a pacer

[e] sample size reduced due to inability to maintain a steady state of energy expenditure for ≥ one minute (n=13)

Table 2

Reasons for Missing Ankle Accelerometer Data (n=459)

Category	Specific Reasons	N (%)
Had valid data	--	386 (84.1%)
Refusal	Refused to wear the accelerometer	2 (0.4%)
Participant Compliance	Lost or did not return the accelerometer	23 (5.0%)
	Wore accelerometer for less than two days*	13 (2.8%)
Technical Problems	Staff training (i.e.: improper programming and documentation)	24 (5.2%)
	Device malfunction	11 (2.4%)

*because the first and last days are truncated, if the participant wore the accelerometer for 2 or fewer days the data cannot be used

Table 3

Adolescent Ankle Thresholds Applied to Daily Accelerometry Data from a Community Sample.

	Minutes/Day ***Mean ± SD***	**% of 24-Hour Day** ***Mean ± SD***
Sedentary (<40 counts/minute)	934 ± 102	64.9 ± 7.1
Light (40–3200 counts/minute)	466 ± 92	32.4 ± 6.4
Moderate-Vigorous (>3200 counts/minute)	37 ± 22	2.6 ± 1.5

Table 4

Subset (N=50) from Community Sample Comparing the Validation Study Thresholds with Manufacturer's Thresholds Using Paired T-Tests.

	Minutes per Day in MVPA *(Mean ± SD)*	**t (p)**	**Effect Size**
Validation Study			
Adolescent Ankle Thresholds[a]	40.1 ± 20.1	*reference*	
Manufacturer's Thresholds			
Single Regression, MET [a]	83.9 ± 61.0	5.2 (<.001)	0.74
Double Regression, MET [a]	146.9 ± 53.8	15.0 (<.001)	2.12
Single Regression, MET [b]	125.4 ± 38.9	25.5 (<.001)	3.61
Double Regression, MET [b]	185.8 ± 47.6	28.3 (<.001)	4.05

[a] MET threshold for moderate activity=3.0

[b] MET threshold for moderate activity=2.7 (manufacturer's default)