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Wrist-based cut-points for moderate- and vigorous-intensity ambulatory physical activity for the Actical accelerometer in adults

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Abstract

Wrist-based accelerometers are increasingly used to assess physical activity (PA) in population-based studies; however, cut-points to translate wrist-based accelerometer counts into PA intensity categories are still needed. The purpose of this study was to determine wrist-based cut-points for moderate and vigorous intensity ambulatory PA in adults for the Actical accelerometer. Healthy adults (n=24) completed a four-phase treadmill exercise protocol (1.9, 3.0, 4.0, and 5.2 mph) while wearing an Actical accelerometer on their wrist. MET levels were assessed by indirect calorimetry. Receiver operating characteristics (ROC) curves were generated to determine accelerometer counts that maximized sensitivity and specificity for classification of moderate (< 3 METs) and vigorous (>6 METs) ambulatory activity. The area under the ROC curves to discriminate moderate and vigorous intensity ambulatory activity were 0.93 (95% CI: 0.90–0.97; p <0.001) and 0.96 (95% CI: 0.94–0.99; p<0.001), respectively. The identified cut-point for moderate intensity ambulatory activity was 1031 counts/minute, which had a corresponding sensitivity and specificity of 85.6% and 87.5%, respectively. The identified cut-point for vigorous intensity ambulatory

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activity was 3589 counts/minute, which had a corresponding sensitivity and specificity of 88.0% and 98.7%, respectively. This study established intensity-specific cut-points for wrist-based wear of the Actical accelerometer which are recommended for quantification of moderate and vigorous intensity ambulatory activity.

Keywords

physical activity; accelerometer; calibration; validation; adults

INTRODUCTION

As an abundance of evidence demonstrates that physical inactivity is a major risk factor for many chronic conditions including obesity, hypertension, diabetes, and cardiovascular disease,¹ the accurate measurement of physical activity has become increasingly important. Historically, researchers have relied on self-report questionnaires to assess physical activity levels, a method subject to substantial reporting bias.² Accelerometers, which are portable, unobtrusive devices that measure bodily changes in velocity, are now widely recognized as a valid and reliable tool for objectively assessing physical activity under free-living conditions that can overcome several limitations of self-report questionnaires.³

Both research-grade (e.g. Actigraph, Actical) and consumer-based accelerometers (or ‘fitness trackers’), such as those made by Fitbit, can be used to objectively measure physical activity. Although consumer-based accelerometers hold considerable potential for use in research settings (e.g. low cost, user-friendly, permits self-monitoring), evidence supporting their use is still limited relative to nearly two decades of evidence supporting use of research-grade accelerometers. As such, research-grade accelerometers are conventionally used in population-based or national surveillance studies.⁴ Research-grade accelerometers convert raw acceleration signals into dimensionless activity “counts” per user-specified period of time (e.g. epoch). As public health guidelines are expressed in terms of time spent in moderate or vigorous intensity physical activity (MVPA),⁵ translating counts into a quantitative estimate of MVPA minutes makes the raw accelerometer data from these devices more clinically meaningful and interpretable. Conventionally, thresholds (or cut-points) to define moderate or vigorous activity have been developed using a calibration study in which accelerometer counts are compared with measures of energy expenditure.⁶ Once established, time spent in MVPA can be quantified using raw data from a given research-grade accelerometer.

The hip has been the conventional attachment site for accelerometers because of its proximity to the human body’s center of mass (hence providing a more accurate measure of activity); nevertheless participant non-compliance has been recognized as a major issue with hip-based accelerometer wear due to the reported discomfort and/or inconvenience of wearing a device on the hip.^{4, 7} In addition, some evidence suggests that the wrist may be a more ideal attachment site for identification of physical activity as it is less influenced by atypical gait patterns and can capture the arm motions of non-ambulatory based activities (e.g. desk work, ironing, etc.).^{8–10} In an effort to improve participant compliance to

accelerometer wear, population-based studies including the National Health and Nutrition Examination Survey (NHANES), Dallas Heart Study, and the UK Biobank project have recently moved the accelerometer to a wrist-worn attachment site.^{4, 11, 12} To date, however, cut-points for moderate and vigorous intensity activity have not been identified in adults for wrist attachment of the Actical accelerometer, one of the most commonly used accelerometers in population-based physical activity research.^{12–15} The purpose of this study, therefore, was to determine wrist-based Actical cut-points for moderate and vigorous intensity ambulatory physical activity in apparently healthy adults. As a secondary objective, hip-based Actical cut-points for moderate and vigorous intensity ambulatory physical activity were determined. Test characteristics (e.g. sensitivity, specificity) of the wrist- and hip-based cut-points for identifying moderate and vigorous intensity physical activity during treadmill walking/running were then compared to evaluate differences in accuracy among wrist/hip attachment sites.

METHODS

Study Population

We recruited a convenience sample of 24 apparently healthy adult participants who were 18 years of age and able to walk without human assistance or walking aids. Participants with a mobility-limiting health condition, a history of any chronic medical condition, or 2 cardiovascular risk factors were excluded. The study adhered to the guidelines set forth by the Declaration of Helsinki and was approved by the institutional review board of Columbia University Medical Center. All participants provided informed consent.

Study Protocol

Participants completed a four-phase treadmill exercise protocol under laboratory conditions after having fasted for six hours and refrained from exercise, alcohol, and use of any stimulants (caffeine, tobacco, and medication) in the previous 24 hours. The protocol consisted of walking at slow (1.9 mph), moderate (3.0 mph), and brisk (4.0 mph) paces at 0% grade, and light running (5.2 mph) at 0% grade. Each phase was 6 minutes in duration. After each phase, the treadmill was stopped and the participant was instructed to stand motionless on the treadmill for a 3-minute rest period. The treadmill speeds are similar to previous studies examining Actical accelerometer cutpoints^{16, 17} and were selected to correspond to Metabolic Equivalent of Task (MET) levels within the range of light (1.9 mph; ~2.0 METS), moderate (3.0 and 4.0 mph; ~3.3 and 5.0 METS, respectively), and vigorous (5.2 mph; ~9.0 METS) physical activity.¹⁸

Actical Accelerometer

Participants were fitted with four Actical accelerometers (Philips Respironics, Bend, OR) in accordance with manufacturer specifications: two fitted to their wrist (one on left wrist and one on right wrist) using the manufacturer provided nylon wrist-band and positioned on the dorsal aspect of the wrist, just proximal to the radial and ulnar processes; and two fitted to their hip (one on left hip and one on right hip), positioned over the anterior iliac spine via attachment to an elastic belt. The Actical accelerometer is a small ($2.8 \times 2.7 \times 1.0$ cm³), light weight (17 g), omni-directional accelerometer that senses the acceleration of change in

bodily motion in all directions. It detects low frequency (0.5 to 3.2 Hz) G-forces (0.05 to 2.0 Hz) common to human movement and generates an analog voltage signal that is filtered and amplified before being digitized by an A-to-D converter at 32 Hz. Frequencies are filtered to exclude signals that are unlikely to be generated by human movement, such as vibrations and accelerations while travelling by automobile. The digitized values (counts) are then summed over a specified interval (epoch); in the present study, we used 1-minute recording epochs. Accelerometers were initialized approximately 10 minutes before each test using a serial port computer interface. Resulting data were downloaded using the serial port computer interface and Actical software (version 3.1) and were subsequently exported as text files.

Metabolic Measurement

MET levels were assessed by gas exchange indirect calorimetry (Ultima CPX, MedGraphics, St. Paul, Minnesota) using a nose-clip and mouthpiece attached to a pneumotach/gas-sampling port. The calorimeter was calibrated immediately before each test. This included volume calibration using a three liter syringe and gas calibration using known concentrations of O₂ (21%) and CO₂ (5%). The internal time of the metabolic system was synchronized to the desktop computer used to initialize the Actical accelerometers approximately 10 minutes before the start of each test. The metabolic system determines METs from O₂ uptake and CO₂ production on a breath-by-breath basis. Breath-by-breath MET values were aggregated to 1-minute epochs for the present study.

Statistical Analyses

In accordance with accelerometer protocols utilized in NHANES and other population-based studies,^{4, 11, 12} only data from the non-dominant wrist/hip were analyzed. To ensure steady state exercise and exclude periods involving treadmill start/stop, only the 4th and 5th minutes of each 6-minute exercise phase were included in analyses. For each phase, descriptive statistics were calculated for METs and accelerometer counts. Receiver operating characteristics (ROC) curves were generated to determine wrist and hip accelerometer count cutoff values at various levels of sensitivity and specificity for the intensity categories of moderate (3 METs) and vigorous (>6 METs) ambulatory physical activity. ROC curve analysis was chosen to determine the ambulatory physical activity intensity cut-points as it is superior to previous accelerometer calibration methods that used linear regression approaches.¹⁹ We modeled accelerometer counts from minutes 4 and 5 of each phase as the independent variable, and the dependent variable was calculated by creating an indicator variable for moderate and vigorous ambulatory activity as either 0 or 1. For the moderate intensity ROC curve, MET values <3 were assigned a 0 while MET values ≥3 were assigned a 1. For the vigorous intensity ROC curve, MET values ≤6 were assigned a 0 while MET values >6 were assigned a 1. Area under the ROC curve was calculated for moderate and vigorous intensity ambulatory activity. Similar to the methods of Evenson et al., the accelerometer count that maximized sensitivity and specificity (e.g. sum of sensitivity and specificity; same as the cut-point that maximizes Youden's index²⁰) was identified.²¹ The accelerometer counts that yielded 99%, 95%, 90%, 85%, 80% and 75% sensitivity were also identified. We compared wrist and hip area under the ROC curves for each intensity level

using the non-parametric approach described by Delong et al.²² Data analyses were conducted using SAS version 9.3 (SAS Institute, Cary, NC, USA).

RESULTS

Participant Characteristics

Among the 24 participants who completed the study, the mean age was 30.5 ± 7.8 years (range: 20 to 54 years), 10 (41.7%) were male, 14 (58.3%) self-identified their race as white, and 8 (33.3%) were of Hispanic ethnicity. Participants' body mass index (BMI) ranged from 19.6 to 29.9 kg/m², with a mean of 24.9 ± 3.0 kg/m².

MET Levels and Accelerometer Counts

The mean METs and corresponding accelerometer counts are provided in Table 1 for each of the walking/running phases. Slow walking, moderate walking, brisk walking, and running yielded mean MET values of 2.8, 3.8, 5.7, and 8.9, respectively.

ROC Curve Analysis

Plots of the ROC curves for moderate and vigorous ambulatory activity are presented in Figure 1 for both the wrist (Panels A and B) and hip (Panels C and D) attachment sites. The discrimination of moderate and vigorous ambulatory activity was high for all ROC curves. Overall, the area under the ROC curve to discriminate moderate and, separately, vigorous intensity ambulatory activity for the wrist attachment site was 0.93 (95% CI: 0.90–0.97; $p < 0.001$) and 0.96 (95% CI: 0.94–0.99; $p < 0.001$), respectively. The area under the ROC curve to discriminate moderate and, separately, vigorous intensity ambulatory activity for the hip attachment site was 0.97 (95% CI: 0.95–0.99; $p < 0.001$) and 0.98 (95% CI: 0.96–0.99; $p < 0.001$), respectively. Compared to the wrist attachment site, the hip attachment site was significantly better at discriminating moderate intensity ambulatory activity ($p = 0.029$), but not vigorous intensity ambulatory activity ($p = 0.660$).

Moderate and Vigorous Intensity Cut-Points

The identified wrist cut-point that maximized the sum of sensitivity and specificity for moderate intensity ambulatory activity was 1031 counts per minute, which had a corresponding sensitivity and specificity of 85.6% and 87.5%, respectively. This moderate intensity wrist cut-point had a positive predictive value of 94.9% and negative predictive value of 69.0%. Sensitivity, specificity, positive predictive value, and negative predictive value for the optimal moderate intensity hip cut-point (1775 counts per minute) were 90.2%, 100%, 100%, and 79.2%, respectively.

The identified wrist cut-point that maximized the sum of sensitivity and specificity for vigorous intensity ambulatory activity was 3589 counts per minute, which had a corresponding sensitivity and specificity of 88.0% and 98.7%, respectively. This vigorous intensity wrist cut-point yielded a positive predictive value of 95.6% and negative predictive value of 96.3%. Sensitivity, specificity, positive predictive value, and negative predictive value for the optimal vigorous intensity hip cut-point (5428 counts per minute) were 90.0%, 96.9%, 90.0%, and 96.9%, respectively. Accelerometer counts that corresponded with

approximately 99%, 95%, 90%, 85%, 80% and 75% sensitivity for moderate and vigorous activity are presented in Table 2 for the wrist attachment site and in Supplemental Table 1 for the hip attachment site.

DISCUSSION

In this study of apparently healthy adults who performed treadmill walking and running, we identified intensity-specific cut-points for wrist-based wear of the Actical accelerometer. The high area under the ROC curve demonstrates that wrist-based Actical accelerometer counts provide excellent discrimination of moderate and vigorous intensity ambulatory activities, with the highest discrimination observed for vigorous intensity ambulatory activity. Our results indicate that cut-points of 1031 and 3589 counts per minute yielded the greatest classification accuracy (e.g. maximized sensitivity and specificity) for moderate and vigorous intensity ambulatory activity, respectively.

Because of participant compliance issues related to hip-based accelerometer wear, including reported discomfort and/or inconvenience of wearing a device on the hip and forgetting to put the monitor back on after taking it off at night, several population-based studies have moved the accelerometer to a wrist-worn attachment site.^{4, 11, 12} Notably, the 2011–2012 and 2013–2014 cycles of NHANES moved to a wrist attachment site for the Actigraph GT3X+ (early cycles used hip attachment). Preliminary data from the 2011–2012 cycle of NHANES show that 70–80% of participants provided at least 6 days of data with at least 18 hours of wear. In contrast, only 40–70% of participants provided at least 6 days of data with at least 10 hours of wear in the 2003–2004 cycle of NHANES that relied upon a hip-based attachment site.⁴ Promising compliance results with wrist wear have also been reported in the Dallas Heart Study, which conducted a 7-day accelerometer protocol in 2008–2009 using a wrist-worn Actical accelerometer. Among 2755 participants, 2628 (95%) had at least 4 days of valid wear.¹² Given the high compliance of wrist attachment reported in these and other studies and considering that wrist attachment is less influenced by gait abnormalities and captures the arm motions of non-ambulatory activities, it has been suggested that the wrist may be the ideal location for accelerometer placement.^{7, 23–25} As such, the findings from the present study are important to existing and future population-based studies by providing the first available cut-points to translate wrist worn Actical accelerometer counts into quantitative estimates of moderate and vigorous ambulatory physical activity.

ROC curve analyses permit the determination of cut-points based on the desired sensitivity and specificity. Similar to other calibration studies,^{21, 25–28} the 1031 and 3589 cut-points for moderate and vigorous activity were selected based on the accelerometer counts that maximized the combined sensitivity and specificity. Nonetheless, investigators adopting such cut-points to quantify ambulatory-based MVPA from wrist worn Actical accelerometers should consider whether greater sensitivity or specificity is desired. As the quantification of current MVPA levels and the determination of persons meeting physical activity guidelines is a primary interest for many population-based studies, it may be important to select cut-points that maximize specificity, thereby minimizing the misclassification of non-moderate or vigorous ambulatory activity. Relative to the 1031 cut-point for moderate activity which yielded sensitivity and specificity of 85% and 87%,

respectively, a higher cut-point would yield better specificity. For example, a cut-point of 1342 counts per minute yielded better specificity (96%); albeit with lower sensitivity (75%). Thus, the trade-off between sensitivity and specificity is an important consideration when selecting Actical cut-points during data processing.

In the present study, comparisons between wrist and hip attachment sites of the Actical accelerometer show that the identified hip-based cut-points had better sensitivity and specificity for distinguishing moderate intensity ambulatory activity compared to wrist-based cut-points (hip: 90% sensitivity and 100% specificity vs. wrist: 85% sensitivity and 87% specificity). There was relatively little difference between attachment sites for classification of vigorous ambulatory activity (hip: 90% sensitivity and 96% specificity vs. wrist: 88% sensitivity and 98% specificity). These findings are consistent with previous studies that have similarly demonstrated that hip-based accelerometer wear outperforms wrist-based wear for estimating energy expenditure, step counts, and METs during most locomotive activities;^{29–32} which some have attributed to the smaller amounts of upper body motion during locomotive activities compared to the lower body.³³ The higher hip-based cut-points (1771 and 5438) for moderate and vigorous ambulatory activity classification relative to the wrist-based cut-points (1031 and 3589) in the present study generally support this hypothesis and suggest that caution is warranted when translating cut-points across attachment sites. Our findings furthermore confirm the superiority of the hip attachment site for the determination of ambulatory-based MVPA. It should however be acknowledged that the wrist-based cut-points still performed reasonably well at discriminating moderate and vigorous ambulatory physical activity. Given the greater wear compliance that has been demonstrated for the wrist attachment site and considering the relatively small gap in ambulatory-based MVPA classification accuracy of the wrist and hip attachment sites, the wrist may be a suitable location for accelerometer wear.

To date, only one study has examined wrist placement of the Actical accelerometer in adults. The primary aim of this study by Heil et al. was to derive equations (which are currently used by the manufacturer) to estimate energy expenditure from accelerometer counts rather than cut-points of MVPA.³⁴ Extrapolation of the regression equations yields accelerometer counts that range from 840–971 and 4874–4926 for moderate and vigorous activity, respectively. However, caution is warranted when interpreting cut-points derived using linear regression methods in light of several limitations of such methods including the non-linear relationship between aerobic energy expenditure and activity levels at the upper level of intensity (due to the contribution of anaerobic energy sources), the high susceptibility to outliers, and the assumption that the error in prediction of energy expenditure is constant across all intensity levels.^{19, 21}

To our knowledge, two previous studies identified cut-points for the Actical accelerometer at the hip attachment site using a multi-stage treadmill protocol. In a study of 26 young adults by Colley et al. that involved treadmill walking/running at 1.9, 3.1, and 5.0 mph, cut-points of 1535 and 3960 counts per minute were identified for moderate and vigorous intensity ambulatory activity, respectively.¹⁶ Cut-points ranging from 1726–1923 for moderate intensity ambulatory activity and 4032–4117 for vigorous intensity ambulatory activity were identified in normal weight and overweight adults based on a multi-stage treadmill protocol

that included three stages: 2.0, 3.0, and 4.0 mph.¹⁷ The hip-based cut-point for moderate intensity ambulatory activity identified in the present study (1775 counts per minute) falls within the range of cut-points identified in previous studies. However, the vigorous intensity cut-point (5428 counts per minute) of this study is much higher than previous studies. This difference may, in part, be attributed to the direct measurement of METs via indirect calorimetry in the present study (vs. the estimation of METs based off of treadmill speed by Colley et al.¹⁶) and the use of two treadmill speeds of higher intensity: one near the demarcation point between moderate and vigorous activity (4.0 mph; mean METs: 5.8) and the other well above it (5.2 mph; mean METs: 8.9); as compared to a single treadmill speed of higher intensity by Colley et al. (5.0 mph)¹⁶ and Giffuni et al. (4.0 mph).¹⁷

Several limitations should be noted when interpreting our findings. First, it is important to acknowledge that the translation of cut-points developed from treadmill walking/running under controlled laboratory conditions to the broad range of movement that will occur under free-living conditions should be done cautiously. Although our findings provide the first available data to translate raw accelerometer data from wrist-based Actical accelerometers into a quantitative estimate (e.g. minutes of moderate or vigorous physical activity) that is meaningful and interpretable, cross-validation of the cut-points proposed herein for non-stepping activities and under free-living conditions is needed. Second, the wrist and hip attachment sites were compared only for locomotor activities. As the hip attachment site may not capture the arm motions of many non-locomotor activities, the observed superiority of the hip relative to the wrist during treadmill walking/running should not be generalized to other activities. Third, speed of movement affects the raw acceleration signal.³⁵ Thus, slower and faster walking/running speeds could yield differing cut-points. Fourth, our study sample was comprised of healthy volunteers who were young to middle-aged adults and normal-to-overweight. Differences in gait mechanics and body composition have been reported to affect the raw acceleration signal.^{35, 36} Thus, our findings may not be generalizable to older adult, obese, or musculoskeletal-/neuromuscular-impaired populations. Finally, although our sample size was similar to several previous Actical validation studies,^{16, 25, 34, 37–40} it was nonetheless small and thus precluded sub-group analyses (e.g. young vs. middle-aged adults; normal weight vs. overweight, etc.). As age and body weight have been reported to influence Actical accelerometer cut-points,^{17, 41} future studies with sample sizes adequate to conduct sub-group analyses may be warranted.

In conclusion, the results of the present study provide moderate and vigorous intensity ambulatory physical activity cut-points for wrist-based wear of the Actical accelerometer in adults. Cut-points of 1031 and 3589 maximized sensitivity and specificity for classifying moderate and vigorous intensity ambulatory physical activity, respectively, and may be used for the determination of ambulatory-based MVPA levels. Future studies, however, are still needed to cross-validate these cut-points across other physical activities besides walking/running.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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Figure 1. ROC curve for moderate intensity (A) and vigorous intensity (B) ambulatory physical activity for wrist (solid blue) and hip (dashed red) attachment sites.

Table 1
Descriptive statistics for MET levels and accelerometer counts across each exercise phase.

Exercise Phase	METs			Wrist Accelerometer Counts			Hip Accelerometer Counts		
	Mean $\pm$ SD	Range		Mean $\pm$ SD	Range		Mean $\pm$ SD	Range	
Slow Walking (1.9 mph)	2.8 $\pm$ 0.2	2.5–3.4		871.6 $\pm$ 374.2	210–1782		984.3 $\pm$ 303.4	379–1638	
Moderate Walking (3.0 mph)	3.8 $\pm$ 0.3	3.4–4.7		1573.0 $\pm$ 625.0	580–2831		2509.2 $\pm$ 345.2	1772–3234	
Brisk Walking (4.0 mph)	5.7 $\pm$ 0.5	5.0–7.2		2427.5 $\pm$ 917.8	583–4336		4651.1 $\pm$ 629.7	3528–5747	
Jogging (5.2 mph)	8.9 $\pm$ 0.6	8.1–10.7		8467.3 $\pm$ 2090.0	5995–13478		11056.5 $\pm$ 1476.0	7652–14282	

Table 2

Wrist Actical accelerometer counts that correspond with approximately 99%, 95%, 90%, 85%, 80%, and 75% sensitivity for moderate and vigorous intensity ambulatory physical activity.

Moderate Intensity Physical Activity (3 METs)				
<i>Accelerometer Counts</i>	<i>Sensitivity (%)</i>	<i>Specificity (%)</i>	<i>Positive Predictive Value (%)</i>	<i>Negative Predictive Value (%)</i>
866	99.3	44.6	84.0	96.4
917	95.4	48.2	85.3	81.6
969	90.2	69.6	89.0	72.2
1018	85.6	87.5	92.2	67.2
1056	80.3	89.3	95.3	61.7
1073	75.2	94.6	97.4	57.6
Vigorous Intensity Physical Activity (>6 METs)				
<i>Accelerometer Counts</i>	<i>Sensitivity (%)</i>	<i>Specificity (%)</i>	<i>Positive Predictive Value (%)</i>	<i>Negative Predictive Value (%)</i>
4051	98.0	67.9	52.7	98.3
4062	94.0	75.4	57.5	96.9
4212	90.0	96.2	88.0	96.2
4368	84.0	98.7	97.6	95.2
4657	78.0	100	100	93.5
4660	74.0	100	100	91.9