Human Kinetics

Accuracy of Thresholds Based on Cadence and Lifestyle Counts per Minute to Detect Outdoor Walking in Older Adults With Mobility Limitations

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Objective: To determine the optimal threshold, based on cadence and lifestyle counts per minute, to detect outdoor walking in mobility-limited older adults. *Methods*: Older adults ($N = 25$, median age: 77.0 years, interquartile range: 10.5) wore activity monitors during 80 outdoor walks. Walking bouts were identified manually (reference standard) and compared with identification using cadence thresholds (≥ 30, ≥ 35, ≥ 40, ≥ 45, and ≥ 50 steps/min) and >760 counts per minute using low frequency extension analysis. *Results*: Median walking bout duration was 10.5 min (interquartile range 4.8) and median outdoor walking speed was 0.70 m/s (interquartile range 0.20). Cadence thresholds of ≥ 30, ≥ 35, and ≥ 40 steps/min demonstrated high sensitivity (1.0, 95% confidence intervals [0.95, 1.0]) to detect walking bouts; estimates for specificity and positive predictive value were highest for ≥ 40 steps/min. *Conclusion*: A cadence threshold of ≥ 40 steps/min is recommended for detecting sustained outdoor walking in this population.

Keywords: accelerometer, low frequency extension, sensitivity, specificity

Mobility in older adults is important for maintaining independence and participation in daily activities. It is often evaluated in clinical and research environments using measures of capacity such as the 10-m walk test (10mWT; Rydwik, Bergland, Forsen, & Frandin, 2012) and the 6-min walk test (6MWT; Harada, Chiu, & Stewart, 1999), but results of these tests are not necessarily related to performance in everyday life (Giannouli, Bock, Mellone, & Zijlstra, 2016). Because walking is the most common form of physical activity in older adults (Valenti, Bonomi, & Westerterp, 2016), it is important to accurately measure ambulation in daily life in order to characterize mobility behavior.

Activity monitors that include accelerometers are frequently used to quantify physical activity and walking (Schrack et al., 2016). Often, physical activity is described by the amount of time spent in sedentary, light, and moderate to vigorous intensity aerobic activity based on counts per minute (cpm) thresholds (ActiGraph, 2008; Tryon & Williams, 1996). Thresholds of >760 cpm (Gennuso, Gangnon, Matthews, Thraen-Borowski, & Colbert, 2013; Matthew, 2005) or >809 cpm (Hall, Howe, Rana, Martin, & Morey, 2013) have been suggested to represent moderate activity in older adults.

Other researchers have used step data to specifically describe walking, regardless of activity intensity, in adults during free-living behavior (Granat, Clarke, Holdsworth, Stansfield, & Dall, 2015; Orendurff, Schoen, Bernatz, Segal, & Klute, 2008). These studies have shown that most episodes of walking last <30–60 s and involve <40 continuous steps. When longer, continuous walking events occur, they tend to be associated with higher cadence (steps per minute) values (Granat et al., 2015; Tudor-Locke & Rowe, 2012).

Nevertheless, few studies have attempted to identify episodes of sustained walking in free-living data collected in older adults, and there is no consensus on appropriate methods for analyzing such data.

Tudor-Locke, Camhi, et al. (2011) and Tudor-Locke and Rowe (2012) suggested that cadences between 40 and 59 represent purposeful walking and cadences between 60 and 79 indicate slow walking in adults and older adults. Gardner, Montgomery, Scott, Afaq, and Blevins (2007) collected accelerometer data over 7 days and found that the average cadence of the best 5 min (i.e., the maximum number of steps taken over a sliding window of 5 min) was 68 steps/min in their sample of 129 healthy older adults (mean 64 years of age, mean 6MWT distance 416 m). Cadences approximating 100 steps/min are achieved during free-living walking in healthy older adults (Paraschiv-Ionescu et al., 2018; Tudor-Locke, Barreira, Brouillette, Foil, & Keller, 2013; Urbanek et al., 2018), but these levels are rarely sustained (Tudor-Locke et al., 2013). Maximum sustained cadences achieved by people with mobility limitations have not been examined.

The purpose of this evaluation was to determine the optimal threshold for identifying outdoor walking bouts in mobility-limited older adults. Five cadence thresholds (≥ 30, ≥ 35, ≥ 40, ≥ 45, and ≥ 50 steps/min) and a lifestyle cpm threshold (>760 cpm) were evaluated. Identification of the optimal method of detecting walking bouts may have practical implications for detecting walking in free-living accelerometer data collected in similar samples of older adults.

Methods

Protocol

This analysis was conducted as part of a larger trial for community-dwelling older adults with self-reported outdoor mobility limitations. The protocol for the larger randomized controlled trial (Salbach et al., 2019) and our pilot work (Barclay et al., 2018)

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have been published. Participants in the study self-identified as having difficulty walking outdoors because of physical impairments, low confidence, and/or low motivation. Older adults were ineligible for the trial if they engaged in ≥150 min of physical activity per week. In brief, the purpose of the larger study was to determine if there was a difference in outdoor walking activity in older adults assigned to a 1-day educational workshop and a supervised outdoor walking program compared with those assigned to the 1-day educational workshop and weekly walking reminders. Baseline measurements included basic demographics and capacity-based measures such as the 10mWT and the 6MWT (and others detailed in our protocol [Salbach et al., 2019]). For the 10mWT, participants were asked to walk at a comfortable pace and were measured over the middle 10 m of a 14-m course. Instructions provided for the 6MWT were to walk as far as possible in 6 min. Physical activity was measured for 8 days using ActiGraph GT3X+ activity monitors (ActiGraph LLC, Pensacola, FL) and Qstarz BT-Q1000XT A-GPS travel recorder global positioning system (GPS) devices (Qstarz International Co., Ltd., Taipei, Taiwan). Ethical approval for this study was obtained from research ethics boards at the University of Toronto, University of Manitoba, University of Alberta, and McGill University. All participants provided informed written consent prior to data collection.

This analysis is based on data from 25 older adults who took part in the supervised outdoor walking program in the summer and fall of 2018. The walking program consisted of supervised walking sessions in outdoor parks, held twice each week for 1 hr over 10 weeks. The sessions consisted of a 10-min warm-up, a continuous distance walk, time to practice specific outdoor walking skills (e.g., stopping suddenly, speeding up, walking on different surfaces), a second continuous distance walk, and a 10-min cooldown. Each week, the outdoor walking skills addressed two or more of the eight dimensions of outdoor mobility described by Patla and Shumway-Cook (1999). Target distances for the continuous walks ranged between 225 and 600 m for participants, and they were asked to try to complete the target distance for the walk if they were safely able to do so. For one walking session during Week 3 and one session during Week 9, participants wore ActiGraph GT3X+ monitors and Q-Starz BT-Q1000XT A-GPS devices on a belt over the right hip. The GT3X+ monitors were initialized using ActiLife6 software (version 6.13.3; ActiGraph LLC) to collect data at 100 Hz. Qstarz QTravel software (Qstarz International Co., Ltd.) was used to set the GPS devices to log data every 1 s. The supervisors of the walking sessions kept notes indicating when the activities started and ended and whether all participants engaged in all components of the session.

Data Analysis

Manual identification of walking bouts. GT3X+ activity monitor data were downloaded to obtain 5-s epoch files used to manually determine the start and end times of the continuous walking bouts. For this analysis, walking bouts ≥5 min in duration were tracked, because they represent a level of walking necessary for sustained function in the community (e.g., to walk to a corner store or a bus stop; Clarke, Holdsworth, Ryan, & Granat, 2013; Gardner et al., 2007). The start time of each bout was the time associated with the first instance of a step count ≥2 (per 5-s epoch) that was followed by at least 60 epochs with step counts ≥2 (allowing not more than 15 discontinuous epochs with step counts <2). When steps counts were <2 for >8 continuous epochs or >15 discontinuous epochs, the bout end time was recorded.

The low frequency extension (LFE) ActiGraph file was used to manually identify the bouts rather than the default file, because the total steps and, therefore, the step lengths recorded for the distances covered were more plausible with LFE. That is, the median step length (distance covered divided by number of steps) during the outdoor walks was 54 cm (interquartile range [IQR] = 11 cm) with the LFE analysis and 85 cm (IQR = 38 cm) with the default analysis. Studies have demonstrated that step lengths typically range from 52 to 57 cm in older women and from 57 to 66 cm in older men (Hollman, McDade, & Petersen, 2011; Shimada et al., 2010).

The global positioning system data were downloaded and the start and end times of each bout were marked as determined from the GT3X+ data. The Haversine formula was used to calculate the distance walked from latitude and longitude data (BlueMM, 2007). The accuracy of this technique was evaluated prior to the study over three walks ranging from 312 to 344 m in which distance was also measured with a 4-in. (10.16-cm) diameter metric measuring wheel. Absolute percentage error for the GPS device distances ranged from 1% to 4%. The average walking speed for each bout was determined as distance walked (in meters) divided by time (in seconds).

Identification of bouts using cadence thresholds and cpm threshold. The 5-s epoch files were reintegrated into 60-s files time synchronized with the GPS data using ActiLife6 software (version 6.13.3; ActiGraph LLC). A custom R program (https://www.r-project.org/) was used to detect start and end times of walking bouts in which cadence was ≥30 steps/min for a minimum of 5 min, allowing a maximum of 1 min below threshold (Figure 1). Analyses were also conducted to find start and end times of bouts using cadence thresholds ≥35, ≥40, ≥45, and ≥50 steps/min. ActiLife6 software (ActiGraph LLC) was used to detect 5-min lifestyle bouts (Axis 1 counts >760 cpm for a minimum of 5 min, allowing a maximum of 1 min below threshold). All threshold analyses were conducted on both default and LFE files.

Statistical Analysis

Descriptive statistical analysis was conducted using SigmaPlot (version 11.0; Systat Software Inc., San Jose, CA). Sensitivity, specificity, Youden's index, positive predictive value (PPV), and
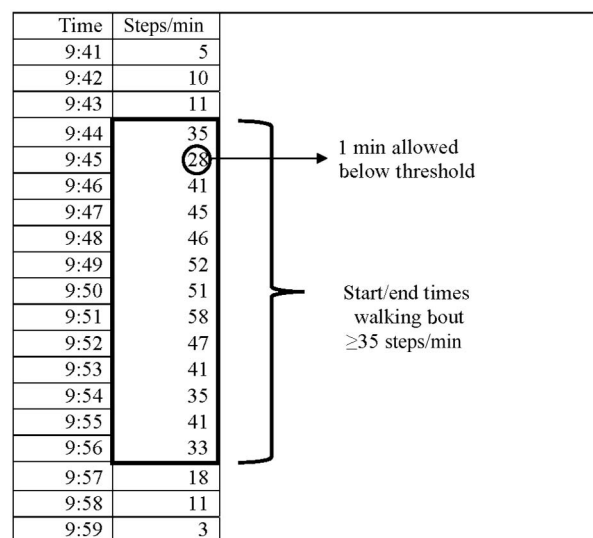
Figure 1 — Identification of start and end times of one walking bout using ≥35 steps/min as the cadence threshold.

negative predictive value results were estimated using SAS software (version 9.4; SAS Inc., Cary, NC). Sensitivity (Trevethan, 2017) of each analysis technique was estimated as the number of true positives (i.e., bouts that were identified manually in the 5-s epoch files that were also identified using the threshold analysis in the 60-s epoch files) divided by the sum of the number of true positives and the number of false negatives (i.e., bouts that were identified manually but were not identified using the threshold analysis). Specificity was estimated as the number of true negative walks (warm-up, cooldown, and intermittent walking skill practice times during the sessions when continuous walking did not occur) divided by the sum of true negative walks and false positive walks (which occurred when the threshold analysis detected a walk when none was identified manually). Youden's index (sensitivity + specificity − 1), PPV, and negative predictive value were also estimated. We calculated exact 95% confidence intervals (CIs) assuming a binominal distribution. The theoretical distribution of Youden's index is not defined; therefore, 95% CIs were not produced.

Results

Twenty-five older adults (19 women and six men) attended one or two supervised outdoor walking sessions. In those sessions, 15 participants completed a total of four continuous walks, three participants completed three walks, four participants completed two walks, and three participants completed one walk ($n = 80$ walks, median duration 10.5 min, IQR = 4.8 min; median outdoor walking speed = 0.70 m/s, IQR = 0.20). When walking outdoors, seven participants used a straight cane, four used a wheeled walker, and the remainder did not use a walking aid. Characteristics of participants and their walking capabilities are presented in Table 1.

Accuracy estimates for the different cadence and lifestyle cpm thresholds are presented in Table 2. Sensitivity estimates (0.83–1.0) were higher when cadence thresholds were used to analyze LFE files compared with default files (range = 0.40–0.74). Similarly, estimates of Youden's index were higher when analyses were conducted using the LFE files compared with the default files. Within the analyses conducted on LFE files, cadence thresholds of ≥30, ≥35, and ≥40 steps/min (LFE files) demonstrated the greatest sensitivity in detecting walking bouts and produced high specificity estimates (0.95–0.97). While sensitivity and negative predictive value were the same for these three thresholds (all having values of 1.0), ≥40 steps/min was associated with slightly greater estimates of specificity, Youden's index, and PPV. Using the lifestyle cpm threshold, sensitivity and specificity estimates for the LFE and default files were very similar. Sensitivity estimates associated with the lifestyle cpm threshold were substantially lower than those

Table 1   Characteristics of Participants (N = 25)

Characteristic	Median (IQR)
Age (years)	77.0 (10.5)
Height (m)	1.59 (0.16)
Weight (kg)	70.5 (38.8)
Body mass index (kg/m^2)	28.6 (12.4)
10-m comfortable gait speed (m/s)	0.97 (0.25)
6MWT distance (m)	299.6 (108.6)
6MWT speed (m/s)	0.83 (0.30)

Note. IQR = interquartile range; 6MWT = 6-min walk test.

demonstrated using the ≥40 steps/min (LFE) cadence threshold (0.86 vs. 1.0, respectively).

Discussion

The purpose of this study was to determine the optimal analysis technique for identifying sustained outdoor walking in mobility-limited older adults, comparing different cadence thresholds and a lifestyle cpm threshold. Thresholds of ≥30, ≥35, and ≥40 steps/min (LFE files) all demonstrated high sensitivity (1.0, 95% CI [0.95, 1.00]) in detecting known continuous outdoor walking that lasted at least 5 min in our sample. The threshold of ≥40 steps/min demonstrated slightly greater specificity and PPV compared with ≥30 and ≥35 steps/min. Cadence thresholds of ≥45 and ≥50 steps/min were less sensitive, as were all thresholds evaluated using the default ActiGraph files. The cpm threshold demonstrated moderate sensitivity and high specificity in detecting walking bouts, with no substantial difference when used on the LFE or default files. These findings have practical significance for measuring sustained walking from accelerometer data collected during free-living activity in mobility-limited older adults.

Cadence is a measure that is relatively easily understood by older adults and clinicians (Tudor-Locke, Craig, et al., 2011; Tudor-Locke & Rowe, 2012). Median cadence values achieved during continuous walking in daily life have been shown to be associated with some mobility-related outcome measures such as gait speed and 400-m walk time (Urbanek et al., 2018). However, people demonstrate a wide range of cadence values throughout their daily routines (Tudor-Locke, Camhi, et al., 2011) and actually spend little time walking continuously for a number of minutes each day (Orendurff et al., 2008). For research purposes, it may be necessary to define a threshold that can be used to identify walking bouts that are relatively sustained, as opposed to sporadic stepping, in order to characterize free-living activity in older adults.

Tudor-Locke and Rowe (2012) suggested that cadences < 40 steps/min represent incidental and sporadic movements, cadences of 40–59 steps/min indicate purposeful steps, and rhythmic slow walking occurs at ≥60 steps/min. Our study is the first to measure cadences actually achieved by mobility-limited older adults during supervised outdoor walking sessions. During the continuous distance walks in each session, participants were encouraged to walk without stopping for a target distance, although they were permitted to take short breaks as needed. Our findings support Tudor-Locke's idea that cadences ≥40 steps/min that are sustained for a number of minutes likely represent purposeful stepping and rhythmic slow walking for the majority of adults and some older adults. In addition, our results showed that for older adults who self-report outdoor mobility limitations, cadences as low as ≥30 steps/min also occur during periods of relatively sustained walking.

Although sensitivity in detecting sustained walking was high using thresholds of ≥30, ≥35, and ≥40 steps/min, some episodes of sporadic walking (which occurred during warm-up/cooldown and walking skills activities) were incorrectly identified as continuous walking bouts at these lower thresholds. This is why specificity and PPV estimates were slightly lower for ≥30, ≥35, and ≥40 steps/min compared to the ≥45 and ≥50 steps/min thresholds. Researchers need to be aware that selecting a lower cadence for identifying sustained walking may result in mistakenly categorizing sporadic activities that occur repetitively as continuous walking bouts, whereas selecting a higher threshold may cause some continuous bouts of walking to go undetected (sensitivity decreases) if they do

Table 2   Accuracy of Cadence and Lifestyle cpm Thresholds

Analysis	≥30 steps/min	≥35 steps/min	≥40 steps/min	≥45 steps/min	≥50 steps/min	≥760 cpm
ActiLife LFE analysis						
Sensitivity (95% CI)	1.00 [0.95, 1.00]	1.00 [0.95, 1.00]	1.00 [0.95, 1.00]	0.89 [0.80, 0.95]	0.83 [0.72, 0.90]	0.86 [0.77, 0.93]
Specificity (95% CI)	0.95 [0.90, 0.98]	0.96 [0.91, 0.99]	0.97 [0.92, 0.99]	1.0 [0.98, 1.0]	1.0 [0.97, 1.0]	0.98 [0.95, 1.0]
Youden's index	0.95	0.96	0.97	0.89	0.83	0.85
PPV (95% CI)	0.93 [0.85, 0.97]	0.94 [0.87, 0.98]	0.95 [0.88, 0.99]	1.0 [0.95, 1.0]	1.0 [0.95, 1.0]	0.97 [0.90, 1.0]
NPV (95% CI)	1.0 [0.97, 1.0]	1.0 [0.97, 1.0]	1.0 [0.97, 1.0]	0.93 [0.88, 0.97]	0.90 [0.84, 0.95]	0.92 [0.86, 0.96]
ActiLife default analysis						
Sensitivity (95% CI)	0.74 [0.63, 0.83]	0.69 [0.57, 0.79]	0.73 [0.62, 0.81]	0.50 [0.39, 0.61]	0.40 [0.29, 0.52]	0.84 [0.74, 0.91]
Specificity (95% CI)	0.99 [0.96, 1.0]	1.0 [0.97, 1.0]	1.0 [0.97, 1.0]	1.0 [0.97, 1.0]	1.0 [0.97, 1.0]	1.0 [0.97, 1.0]
Youden's index	0.73	0.69	0.73	0.48	0.40	0.84
PPV (95% CI)	0.98 [0.91, 1.0]	1.0 [0.94, 1.0]	1.0 [0.94, 1.0]	1.0 [0.91, 1.0]	1.0 [0.89, 1.0]	1.0 [0.95, 1.0]
NPV (95% CI)	0.86 [0.79, 0.91]	0.84 [0.77, 0.89]	0.85 [0.79, 0.91]	0.76 [0.69, 0.83]	0.73 [0.66, 0.79]	0.91 [0.85, 0.95]

Note. cpm = counts per minute; LFE = low frequency extension; CI = confidence interval; PPV = positive predictive value; NPV = negative predictive value.

not meet the threshold for the required number of minutes. Our analyses demonstrated that ≥40 steps/min represents the optimal threshold for detecting continuous outdoor walking in mobility-limited older adults, because its sensitivity and specificity estimates were very high.

With the LFE files, the sensitivities associated with the lifestyle (<760) cpm threshold (0.86, 95% CI [0.77, 0.93]) and the cadence threshold of ≥45 steps/min (0.89, 95% CI [0.80, 0.95]) were similar. This suggests that the intensity of activity during these walking bouts was similar to that achieved using a cpm threshold of >760 cpm, which is thought to represent moderate-intensity free-living activity in older adults.

There were some limitations associated with our study, in which data from 80 walks recorded in 25 participants were analyzed. Our sample consisted of older adults who self-reported having difficulty in walking outdoors. Gait speeds in our study were typical of those recorded in people with mobility limitations (Barclay et al., 2018; Peel, Kuys, & Klein, 2013), but the sensitivity and specificity estimates associated with using cadence and cpm thresholds to detect walking may vary in older adults with different walking abilities and in different seasons. Similar analysis techniques could be used to determine appropriate thresholds for identifying sustained free-living walking in different samples. The 5-s epoch step data were analyzed to manually identify the start and end times of the walking bouts. Using this technique, it is possible that sporadic activity (e.g., in the last minutes of the warm-up or the first minutes of the cooldown) may have been mistakenly counted as part of the continuous walking time. Steps were not directly observed during the supervised walking sessions. While ActiLife's LFE filter has been shown to be accurate for use in individuals with gait speeds <1.0 m/s (Bertapelli et al., 2019; Korpan, Schafer, Wilson, & Webber, 2015; Webber & St. John, 2016), the absolute percentage error may be as high as 7% in individuals who walk slowly and use a walking aid (Korpan et al., 2015).

It is important to recognize that steps and steps per min represent variables that are inherently understood by older adults and clinicians (Tudor-Locke, Craig, et al., 2011; Tudor-Locke & Rowe, 2012). Therefore, using steps and cadence as outcomes may make findings of physical activity research more relevant to a broader audience of individuals from different disciplines. The threshold of ≥40 steps/min (LFE files) demonstrated the highest sensitivity and specificity estimates for detecting continuous

walking bouts in our sample of community ambulators who reported difficulties with outdoor mobility. Future studies should continue to evaluate typical cadence levels achieved during sustained walking in people of different ages and abilities during free-living activity.

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