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METs and Accelerometry of Walking in Older Adults: Standard versus Measured Energy Cost

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Abstract

Purpose—This study aimed to measure the metabolic cost (METs) of walking activities in older adults, to examine the relationship between accelerometer output and METs across walking activities, and to compare measured MET values in older adults with the MET values in the compendium.

Methods—Twenty older adults (mean age = 75, range = 60–90 yr) completed eight walking activities (five treadmill based, three free living) for 6 min each. Oxygen consumption ($\dot{V}O_2$) and resting metabolic rate (RMR) were measured using a portable metabolic system, and motion was recorded using a waist-mounted ActiGraph accelerometer (GT3X; ActiGraph, Pensacola, FL). Energy expenditure across activities was defined as kilocalories per minute and measured as METs ($\dot{V}O_2/\text{RMR}$) and standard METs ($\dot{V}O_2/3.5 \text{ mL} \cdot \text{kg}^{-1} \cdot \text{min}^{-1}$). Mixed modeling was used to assess differences in counts per minute and kilocalories per minute by weight status, sex, comorbidity status, and functional status. Linear regression analysis was applied to develop a prediction equation for kilocalories per minute. Energy costs of walking were subsequently compared with METs in the compendium of physical activities.

Results—Average measured RMR was $2.6 \text{ mL} \cdot \text{kg}^{-1} \cdot \text{min}^{-1}$, 31.6% less than the standard RMR of $3.5 \text{ mL} \cdot \text{kg}^{-1} \cdot \text{min}^{-1}$. On average, standard METs were 71% lower than the measured METs across all walking activities. Measured MET levels differed from previously reported values in the literature and values listed in the compendium, resulting in misclassification of activity intensities for 60% of the walking conditions. Average counts for the walking activities ranged from 809 (treadmill = 1.5 mph) to 4593 counts per minute (treadmill = 3.5 mph). Previous regression

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equations consistently overestimate all activities compared with the measured energy cost in this sample of older adults.

Conclusion—This study identifies the need for equations and cut points specific to older adults.

Keywords

VALIDATION; ENERGY EXPENDITURE; ACTIVITY MONITORS; CALIBRATION;
COMPENDIUM OF PHYSICAL ACTIVITIES; METABOLIC

Accurate and reliable measures of physical activity (PA) are required by behavioral researchers and epidemiologists alike who are interested in studying PA and characterizing PA patterns over time and across groups. Objective measures of PA such as accelerometers are now common in PA research. By providing information on the amount, frequency, duration, and intensity of PA, accelerometers are widely used as a means to overcome limitations in self-report measures. The literature suggests that self-report PA measures are less accurate in assessing light- to moderate-intensity activities (28). This is an important limitation in the context of PA research with older adults, a population that spends a larger percentage of their day engaging in light-intensity activities (30) compared with younger adults. Consequently, accelerometers appear particularly well suited to research in older adults.

Indeed, a recent review (18) calls for increased utilization of objective measures of PA in older adult populations. However, as with self-report measures of PA, objective measures of PA are only valid to the extent in which they accurately characterize the activity intensity of that particular population. The output generated from an accelerometer, activity “counts,” although in and of itself is not interpretable, is a reflection of intensity. Researchers have performed calibration studies exploring the relationship between accelerometer counts and measured energy expenditure to allow for estimates of PA-related energy expenditure and time spent in various absolute intensities of PA (4,15,26). The most commonly used approach has relied on regression equations to identify “cut points,” which delineate different absolute PA intensities (i.e., light < 3.0 METs, moderate = 3.0–5.9 METs, and vigorous ≥ 6.0 METs; 1 MET = 3.5 mL·kg⁻¹·min⁻¹ O₂).

The first study to establish regression formulas relating accelerometer counts to energy expenditure was reported by Freedson et al. (8) using a sample of young adults (mean age = 24.8 yr). The authors developed accelerometer count ranges for light, moderate, and vigorous PA intensity levels (<1952, 1952–5724, and ≥ 5725 counts per min, respectively). Similar results have been reported elsewhere (27). An important limitation of this literature, however, is the paucity of studies that have explored these relationships in older adults (18) and their reliance on treadmill-based activities for determining these point estimates (10). Epidemiologic and intervention studies are including accelerometers and applying these point estimates in older samples, with little evidence to support whether these point estimates are appropriate to use in older populations.

To our knowledge, only three studies have examined the evidence for the validity of estimating energy expenditure via accelerometry in older adults (5,17,21). In their study of

the relationship between activity counts and energy expenditure in treadmill walking in a sample of older adults (mean age = 69.7 yr), Copeland and Eslinger (5) demonstrated a moderate relationship between counts per min and oxygen consumption ($r = 0.60$, $SEE = 2.48 \text{ mL}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$). The authors identify a cut point of 1041 counts per minute to denote moderate/vigorous PA (MVPA). However, it is important to note that this cut point was based on the counts per minute associated with a single reference activity (walking at $3.2 \text{ km}\cdot\text{h}^{-1}$) and also upon the assumption that $1 \text{ MET} = 3.5 \text{ mL}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$ and was not based on any measured criterion of the intensity (energy cost) of this walking speed. Similar limitations are noted in studies by Miller et al. (17) and Pruitt et al. (21). Whether these and other cut points accurately reflect the energy cost of walking activities for older adult samples remains unclear. Finally, the previous literature is limited by its reliance on relatively healthy older adult samples (e.g., no prior cardiovascular or metabolic conditions) to examine energy costs of daily activities. Our knowledge of the energy cost of daily activities among individuals with physical and functional impairments remains limited.

Current public health guidelines recommend 30 min or more of moderate-intensity aerobic activity on most, if not all, days of the week for older adults, although the guidelines do specifically state that if older adults “cannot do $150 \text{ min}\cdot\text{wk}^{-1}$ of MVPA due to chronic conditions, they should be as physically active as their condition allows” (20). Accurate measurement of PA is essential if we wish to examine and characterize activity patterns and determine the link between PA and several health-related outcomes (i.e., physical function, cardiovascular disease, obesity). Recent work by Evenson et al. (7) underscores the current limitations in the measurement of PA as applied to older adults. Using the accelerometer data from the National Health and Nutrition Examination Survey, they determined that the time spent in MVPA differed on the basis of the cut point chosen, and consequently, the prevalence of those meeting PA recommendations also differed. With these limitations in mind, the primary purpose of this study was to explore the relationship between accelerometer counts from the ActiGraph GT3X monitor and measured oxygen consumption among older adults with heterogeneous health and functional profiles. Comparisons with the existent regression equations and cut points are explored, as are potential new regression formulas for use in older adults. A secondary purpose was to compare MET values measured in this sample of older adults during treadmill and self-paced walking to the standard MET values from the compendium of PA.

METHODS

Participants

Twenty participants (5 women and 15 men; age range = 61–90 yr) volunteered in this study. Individuals were recruited through an outpatient exercise program (Gerofit) sponsored by the Durham Veterans Affairs Medical Center (VAMC). All participants read and signed an informed consent form approved by the institutional review board of the Veterans Affairs Medical Center before study participation. Individuals who were not physically able to walk unassisted were excluded from the study.

Biometric Measures

Anthropometric measurements—Before testing, individual height and weight were measured using a stadiometer and physician's scale, respectively. Body mass index (BMI) was calculated as body mass (kg) divided by height squared (m^2).

Comorbidities—The number of comorbidities was determined via self-report by asking participants to indicate which, if any, conditions they currently experienced. Conditions surveyed include cardiovascular disease, significant disorders of heart rhythm, peripheral vascular disease, central nervous system disorders or residuals, pulmonary disease, functional impairment of the musculoskeletal system, hypertension, hyperlipidemia, diabetes, anemia or bleeding disorder, phlebitis or emboli, cancer, emotional disorders, ulcers, edema, infectious disease, and hearing loss. Responses to the individual items were summed to arrive at a total number of chronic conditions.

Physical performance—Rapid gait speed was derived from a 30-m walk test. Participants were instructed to walk as fast as they were able. Time to complete the test was measured by two research assistants using handheld stopwatches. The final time is an average of the two recorded times.

Testing Protocol

Routine 1—During this visit, participants completed the informed consent form and a comorbidity checklist. Before participation, individuals were familiarized with the equipment and procedures for the study. Participants then completed a period of quiet sitting as a proxy for resting metabolic rate (RMR) followed by a series of walking tests. With newer technology, such as the MedGem metabolic analyzer, the RMR is measured from steady-state oxygen consumption in 5–11 min. This tool and technique, including the amount of sampling time, has been validated against the techniques used with the ParvoMedics. Because our values closely approximate and are not higher than those reported in other research (14), we are confident these values are valid. For the quiet sitting condition, participants were instructed to remain seated and refrain from talking during the 6-min testing period. After this baseline assessment was completed, the remaining tests were explained.

The first walking session consisted of walking on a motor-driven treadmill at five different speeds. The speeds were $2.4 \text{ km}\cdot\text{h}^{-1}$ ($1.5 \text{ miles}\cdot\text{h}^{-1}$), $3.2 \text{ km}\cdot\text{h}^{-1}$ ($2.0 \text{ miles}\cdot\text{h}^{-1}$), $4.0 \text{ km}\cdot\text{h}^{-1}$ ($2.5 \text{ miles}\cdot\text{h}^{-1}$), $4.8 \text{ km}\cdot\text{h}^{-1}$ ($3.0 \text{ miles}\cdot\text{h}^{-1}$), and $5.6 \text{ km}\cdot\text{h}^{-1}$ ($3.5 \text{ miles}\cdot\text{h}^{-1}$). Grade was held constant at 0% for the duration of the tests. Participants walked on the treadmill for 6-min bouts at each of the five walking speeds; the order of the walking speeds was randomized and counterbalanced across participants. At the end of each bout, the participant was asked to sit quietly for a minimum of 5 min or until their heart rate returned to within 4 beats per minute of their resting heart rate. Verbal encouragement was provided during each of these walking bouts. All five walking speeds were performed by all of the participants except the $5.6\text{-km}\cdot\text{h}^{-1}$ condition, which was performed by 19 of the 20 participants.

Routine 2—The second walking session was performed on a separate day from Routine 1 and consisted of walking at three self-selected speeds in an isolated, indoor corridor. Participants were instructed to walk at “leisurely” (bout 1), “brisk” (bout 2), and “fast” (bout 3) paces also for 6 min each, with a minimum of 5 min rest in between bouts (more if heart rate remained elevated above resting levels). For the leisurely pace, participants were instructed to “walk as if you were walking and talking with a friend”; for the brisk pace, instructions were to “walk as if you were hurrying across the street at a cross-walk”; for the fast pace, instructions were to “walk as fast as you can but not so fast that you feel unsafe.” The order of the walking bouts was randomized and counterbalanced across participants and verbal encouragement was provided during each of these walking bouts.

Instrumentation

Throughout both routines, participants wore two instruments that provided concurrent measures of the intensity of each of the eight walking trials: a triaxial accelerometer (ActiGraph GT3X) and a portable indirect calorimetry system (Cosmed K4b², Rome, Italy).

Portable indirect calorimeter—The Cosmed K4b² is a portable indirect calorimeter that measures oxygen uptake over a wide range of exercise intensities and has been shown to be both valid and reliable in the general population (16). The Cosmed K4b² comprises an analyzer unit and a battery pack, which are secured to the participant using a light-weight chest harness. The soft, flexible mask is held in place with a nylon mesh head harness and covers the individual’s nose and mouth to capture the expired air. The expired air is channeled through a bidirectional digital turbine that measures the volume of inspired and expired air. A sample line runs from the turbine to the analyzer unit where O₂ and CO₂ content of the expired air are measured.

The Cosmed K4b² was calibrated immediately before each test according to the manufacturer’s guidelines. After warming up the unit for 30 min, the CO₂ and the O₂ analyzers were calibrated against room air as well as a reference gas of known composition (5.2% CO₂, 16.0% O₂, and 78.8% N). A delay calibration was then performed to compensate for the lag time between when the expired air was sampled. Finally, the turbine was calibrated using a 3.0-L syringe (Hans-Rudolph, Shawnee, KS) to ensure accurate volume measurements.

After the completion of these calibration procedures, the ambient humidity and individual biometric characteristics (age, height, weight, and sex) were entered into the Cosmed K4b². To account for the extra weight of the Cosmed K4b², 1 kg was added to each individual’s body weight and entered into the unit. The Cosmed K4b² was synchronized to a reference digital clock.

ActiGraph accelerometer—Participants wore an ActiGraph accelerometer (GT3X) on the right hip for the duration of each routine. The ActiGraph is a triaxial accelerometer that measures vertical, anteroposterior, and mediolateral acceleration. Accelerations in the range of 0.05g–2.0g are recorded. The ActiGraph also filters the data to only detect movements that occur within a given frequency (0.25–2.5 Hz) so as to detect human body movement and reject other forms of motion (i.e., vibration). The acceleration data are integrated over a

user-specified time interval, called epochs, to give several “counts.” The more activity a person does, the greater the number of counts recorded by the ActiGraph.

Data Collection and Reduction

The ActiGraph initialization software was synchronized with a digital clock so the start time could be synchronized with the Cosmed K4b². The ActiGraph was initialized using 1-s epochs to begin collecting data 20 min before the start of the testing protocol. Upon arrival to the laboratory, participants were fitted with both the accelerometer and the Cosmed K4b². The ActiGraph was secured around the participant’s waist using a nylon belt and was positioned on the right hip along the axillary line.

At the start of each walking trial, the time on the reference clock was noted to the nearest second, and simultaneously, the Cosmed software was used to insert a time mark in the data file. This method of synchronization ensured that oxygen consumption for a given period of activity could be matched with activity counts for precisely the same period of activity. Electronic time marks were also inserted into the Cosmed data at the end of the initial rest period and at the start and end of each walking trial. Fifteen-second (manual) pulse was also taken at the beginning and end of each walking bout by the research staff.

Data Analysis

At the conclusion of each routine, data from the ActiGraph and the Cosmed were downloaded to a personal computer for analysis. The Cosmed K4b² provides breath-by-breath pulmonary data. Data were averaged for 1-min intervals, and $\dot{V}O_2$ values were averaged for each 6-min activity performed, discarding the first 2 min and last 10 s of each activity to eliminate the transitions between rest and PA. The ActiGraph provides a continuous record of second-by-second acceleration data along three axes. These data were downloaded from the ActiGraph, and the average counts per minute were determined for the same 3:50 min of each activity as the Cosmed data.

PA levels and energy cost were calculated (mean $\pm$ SD) for all activities combined and then by weight status, sex, comorbidity status, and functional status. Recognizing the lack of independence in the data (i.e., repeated measures are made of each study participant across activities), mixed modeling was used to assess differences in counts per minute from the ActiGraph and energy cost ($\text{kcal}\cdot\text{min}^{-1}$) from the Cosmed K4b². Consistent with analytic guidelines put forth for accelerometer calibration studies (29), a prediction equation was developed on the entire data set using a linear regression model between the vertical axis (counts per minute) and the total energy expenditure ($\text{kcal}\cdot\text{min}^{-1}$). Using the leave-one-out methodology, the accuracy of this new prediction equation was tested by creating a new regression equation from the data for all but one subject and then testing the accuracy on the omitted subject (6,22). This process was repeated, eliminating all data from a different subject from the regression analysis each time. The accuracy was reported as the average root-mean-square error (RMSE). Differences between measured energy expenditure and predicted values from the new and published prediction equations (8,25) were examined. All data were analyzed using SAS statistical software (version 9.2; SAS Institute Inc., Cary, NC) and significance was set at $P < 0.05$.

RESULTS

Participant characteristics

Table 1 shows the demographic and biometric characteristics of the sample. Twenty older adults (5 women and 15 men) completed the study. The average age was 75 (range = 60–90 yr), the average BMI was $29.1 \text{ kg}\cdot\text{m}^{-2}$ with 65% of the sample meeting criteria for overweight/obesity, and the average rapid gait speed was $1.50 \text{ m}\cdot\text{s}^{-1}$. Participants reported an average of three comorbid conditions, with the most prevalent being functional impairment of the musculoskeletal system (40%), hypertension (65%), hyperlipidemia (35%), and diabetes (15%). Three participants (15%) reported using a walking device (cane). Average resting heart rate was 70.2 ± 12.7 beats per minute. RMR measured at $2.66 \pm 0.6 \text{ mL}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$. Men were significantly taller than women ($P < 0.05$); however, there were no significant differences in age, weight, BMI, gait speed, or number of chronic conditions across sexes (data not shown).

Accelerometer counts and energy expenditure

All of the participants completed the free-living hallway walking speeds (slow, brisk, and fast), whereas all but one participant completed all of the treadmill walking speeds. This resulted in a total of 156 observations (persons $\times$ activity). Results from the walking sessions (both treadmill and self-selected) are shown in Table 2, including the walking speed, mean counts per minute values from the accelerometer (vertical axis only), oxygen consumption, metabolic cost in METs (adjusted for equipment mass), and average energy expenditure in kilocalories per minute. Average counts per minute ranged from 809 for the least intensive walking condition (1.5 mph) to 4593 for the most intensive walking condition (3.5 mph). Measured energy expenditure increased with increasing treadmill speed. This was also true of the hallway walking bouts, indicating that the instructions used were understood and able to be carried out by the participants.

Repeated-measures ANOVA results revealed significant differences by sex in activity counts per minute during the treadmill and hallway walking sessions, such that men recorded significantly fewer counts per minute across the treadmill walking speeds and consistently more counts per minute across the hallway walking speeds compared with women ($P < 0.05$). Using criteria for gait speed established by Studenski et al. (24) of $1.4 \text{ m}\cdot\text{s}^{-1}$, participants with slower gait speed acquired significantly fewer counts per minute (2436 ± 192 , $n = 6$) compared with those with faster gait speed (2988 ± 138 , $n = 14$). There were no significant differences in the energy cost of any walking activity (treadmill or hallway) across sex, BMI classification, or gait speed ($P > 0.05$). However, those with one or more chronic conditions ($n = 12$) demonstrated a significantly greater work rate in terms of measured METs (5.6 vs 4.7 METs) compared with those individuals with one or no chronic conditions ($n = 8$). Group characteristics are shown in Table 3. *Post hoc* analyses comparing those who self-reported using a cane ($n = 3$) versus those who reported no use of a walking aide revealed no significant differences in any of the outcome variables ($P > 0.05$).

Once again referencing Table 2, the energy cost of the activities obtained from indirect calorimetry ranged from $4.1 \text{ kcal}\cdot\text{min}^{-1}$ during the 1.5-mph walking to $7.7 \text{ kcal}\cdot\text{min}^{-1}$

during the 3.5-mph walking. Measured METs (total energy cost of the activity divided by the measured RMR) was used as an indicator of intensity across the walking speeds. Measured MET values indicated that walking speeds of 1.5–3.0 mph were moderate intensity (3.0–5.9 METs), and speeds >3.0 mph were vigorous intensity (6.0 METs) in this sample of older adults. Of note, standard METs (total energy cost of the activity divided by the reference $3.5 \text{ mL} \cdot \text{kg}^{-1} \cdot \text{min}^{-1}$) were significantly lower than measured METs across all activities ($P < 0.05$). Differences between measured and standard METs ranged from -1.0 to -1.7 METs across all observations.

Table 4 shows the measured METs, the standard METs reported in previous studies, and the values reported in the compendium of PA (1,2) for treadmill walking speeds. The measured MET values for each of the treadmill walking activities in the current study were higher than the standard MET values reported in previous studies of middle-age and older adults (10,17) and notably were much higher than the MET values listed in the compendium (3).

Figure 1 depicts the relationship between total measured energy expenditure ($\text{kcal} \cdot \text{min}^{-1}$) and accelerometer counts per minute with the resultant equation:

$$\text{EE} (\text{kcal} \cdot \text{min}^{-1}) = 3.28 + (0.0009 \times \text{counts per minute})$$

$$R^2 = 0.41, \text{ SEE} = 0.27 \text{ kcal} \cdot \text{min}^{-1}$$

This regression equation is compared with the predicted energy expenditure using the published regression equations of Freedson et al. (8) and Swartz et al. (25). The equations of both Freedson et al. and Swartz et al. consistently overestimate all activities compared with the current prediction equation. The accuracy of the newly developed regression equation was tested using the leave-one-out procedure. The leave-one-out analysis demonstrated no difference in the outcome when testing on the one participant left out each time compared with the outcome from the regression model developed on the entire group. The average RMSE was 1.51 ± 0.3 with a range of 1.39–1.55. The intraclass correlation coefficient for the accelerometer counts was 0.82.

DISCUSSION

Efforts to better understand the frequency, intensity, and duration of PA in older adults have intensified during the past decade. Increasingly, such studies have relied on objective assessments, such as accelerometers, to quantify these activity domains. The literature exploring the relationship between accelerometer output and physiological variables is vast and continues to grow. From this literature, studies have generated numerous regression equations that can be used to predict the intensity of activity. However, such studies have largely been conducted in small, homogeneous samples of younger and middle-age adult populations. There remains a great deal of uncertainty among behavioral researchers as to which equation and/or cut points should be adopted and applied to various population groups. This is particularly problematic in studies of older adults, a group that to date has

received far less attention in these initial calibration studies. Despite this limitation, the general practice, with few exceptions, has been to apply these established regression equations and cut points to characterize PA behavior in older adults (7). With these limitations in mind, this study was designed to explore the relationship between accelerometer output (counts per minute) and energy expenditure in a heterogeneous sample of older adults. It was our hope that we would derive a regression equation that could be used to predict the intensity of activity and identify age-appropriate cut points for activities of varying intensity, information which could be used in future studies to more accurately characterize older adults' activity patterns.

Consistent with our expectations and previous literature, we saw a moderate relationship between accelerometer output (counts per minute) and walking speed ($r = 0.41$). Of greater public health importance, however, was the relationship between activity counts per minute and energy expenditure. Typically, regression equations are used to define activity intensity in METs; however, given that our measure of RMR in this study was not consistent with typical resting protocols, we selected total kilocalories per minute as the primary indicator of energy expenditure. The linear regression model generated in this study predicting kilocalories per minute from activity counts per minute accounted for 41% of the variation in our sample, which is consistent with previous reports in other samples. When compared with two other frequently cited regression equations by Freedson et al. (8) and Swartz et al. (25), we found that these regression models consistently overestimated the intensity of all walking activities. Our ability to include activities of varying intensities in our calibration protocol is a strength as it allowed us to develop a conservative regression model that could be applied across multiple intensities. Previous studies of older adults have not included vigorous activities in their calibration protocols, resulting in regression models that may overestimate time spent in moderate activity (15).

This study provides behavioral researchers with the range of activity counts per minute associated with various walking speeds intensities for older adults. Although certainly not definitive, the activity counts per minute observed here along with the regression equation comparison suggest that cut points to quantify light, moderate, and vigorous activity in older adults may need to be lower than those seen in other samples (5,8,17,21,25). Contrary to our expectation, however, even our slowest treadmill walking speed (1.5 mph) was associated with moderate-intensity energy expenditure in this sample. As such, we are unable to determine a lower bound for moderate intensity activity (and by default, an upper bound for light-intensity activity). Irrespective of this limitation, our data suggest that previously adopted cut points for moderate-intensity activity in younger adults (1952 counts per minute) (8) and well-functioning older adults (1000) (5,25) may be too high. Preliminary data in older adults with mobility limitations indicate a moderate-intensity threshold 1452 (21), substantially higher than what was measured here. In the present study, an average of 809 counts per minute was associated with moderate-intensity PA (1.5 mph, 10.0 mL·kg⁻¹·min⁻¹, 3.9 METs). Considering the lower bound of moderate-intensity activity is 3.0 METs, our data suggest that the lower accelerometer cut point for moderate-intensity activity in older adults is 809 counts per minute.

Although the accelerometer output is not readily interpretable to many outside the realm of research, of interest to general practitioners and public health professionals is the description of the kilocalories per minute across the range of walking speeds. Indeed, these data can be used to estimate caloric expenditure associated with various walking speeds, information that is particularly important in discussions of energy intake/energy balance. The caloric cost of walking ranged from 4.1 to 7.7 kcal·min⁻¹ in this sample. Importantly, our inclusion of self-paced walking bouts alongside treadmill walking broadens the applicability of our results to free-living activities. For example, an older adult can expect to use ~ 120 kcal to walk for 30 min at a pace of 1.5 mph. Our data suggest that similar caloric expenditure can be expected from walking at a self-described “leisurely” pace in the natural environment. Conversely, walking for 30 min at the highest speed tested here (3.5 mph) would result in ~240 calories expended by an older adult. Similar results could be expected if you instructed an older adult to simply “walk fast” (if they were able to sustain this intensity for the entire 30 min).

Although one needs to be mindful of the limitations inherent in our assessment of RMR, this study also provides researchers the range of MET values (both measured and standard) for a variety of walking speeds. As mentioned previously, the average RMR for this sample was 2.6 mL·kg⁻¹·min⁻¹, 31.6% less than the standard RMR of 3.5 mL·kg⁻¹·min⁻¹. No significant differences in RMR were seen across sexes; however, healthy weight older adults had a significantly ($P < 0.05$) higher RMR than overweight individuals. Although our RMR value in this sample of older adults is consistent with other reports in older adults of (9,14), it is important to recognize that most calibration studies have not assessed RMR and have instead applied the referent value of 3.5 mL·kg⁻¹·min⁻¹ to estimate energy expenditure regardless of sample characteristics. We compared our measured MET values with the standard MET values published in previous reports to examine the magnitude of differences between the two approaches. Using the measured RMR, we saw MET values ranging from 3.9 to 6.8 across walking bouts. Compared with measured METs from this and other studies, the use of the standard 3.5 mL·kg⁻¹·min⁻¹ to define METs lead to an underestimation of average MET values on the order of 1 MET or greater. Differences in MET values were smallest when comparing samples of older adults (17) versus other samples that consisted of younger adults (8,10). The magnitude of these differences is consistent with other studies of older adults and energy cost assessments across common daily activities (11,17).

Perhaps more important than the consistent underestimation, however, is the misclassification of activity intensity that was observed in some cases. For example, the measured MET values indicate that walking at 1.5 mph is a moderate-intensity activity for these older adults (3–5.9 METs). However, if one were to use the standard MET value, this would be classified as a light-intensity activity. Similarly, when one considers walking at 3.5 mph, the measured MET values classify this as a vigorous activity whereas the standard METs reflect only moderate intensity. These findings speak directly to the work by Evenson et al. (7) and clearly have implications for public health guidelines, exercise prescription for older adults, and ultimately adherence. Furthermore, within a randomized controlled exercise trial, this systematic underestimation and misclassification may result in small or nonsignificant pre- and postbehavior change when assessing behavioral intensity. Thus, total

activity counts may be a more sensitive outcome to change in the absence of validated intensity cut points for older adults.

These results must also be considered in the context of current ActiGraph accelerometer data analysis software, which uses as the default option the Freedson et al. (8) energy expenditure equation. Clearly, our results and others (7,12,13,21) call into question the appropriateness of applying this often-cited regression equation to samples of older adults. Age-specific validation studies are needed in older adults to examine whether previous cut points provide accurate assessments in older adults or whether population-specific (i.e., age-specific, functional ability-specific) cut points are needed (29). Indeed, similar to previous reports (11), our results indicate that functional status (measured here via gait speed) differentially affects the energy cost of mobility, resulting in greater discrepancies between measured and standard MET values. However, these and other group differences (e.g., BMI, number of comorbidities) did not significantly affect the regression equation derived in this study.

In addition to comparing our energy expenditure results with previously published regression equations, we also compared our measured MET values with those of the compendium of PA. As many self-report PA measures, including those measures designed specifically for use in older adults (i.e., CHAMPS [23]), use the MET values listed in the compendium to standardize activity estimates, this comparison was performed to further explore the evidence for the validity of such measures in older adults. As expected, given the results of our previous comparisons, the measured METs in our sample were significantly different from the compendium METs across all levels of walking, with the measured MET values in this study being higher than the compendium values. It appears that the compendium and by default many self-report assessments of PA are likely underestimating the energy cost of walking activities in older adults.

Kozey et al. (12,13) recently explored this very question in a large, heterogeneous sample of adults (20–60 yr) and demonstrated sizeable and significant differences between the metabolic data collected on a wide range of activities and the MET values from the compendium. These authors recommended that additional changes to the compendium be made, specifically highlighting the use of a correction factor or, alternatively, devising a new compendium based on measured METs. Our data, although preliminary, support the revisions recommended by Kozey et al. to the extent they apply to the older adult population.

Recent work by Knaggs et al. (11) examines the energy cost and related accelerometry-derived output across a host of daily activities in older adults, creating a compendium of daily activities of sorts for older adults. However, these results suffer the same limitations as previous work, as they rely on the standard $3.5 \text{ mL} \cdot \text{kg}^{-1} \cdot \text{min}^{-1}$ to calculate METs. Clearly, more studies are needed that explore energy output and accelerometry in older adults. Such studies would do well to consider a variety of activities (e.g., daily, self-care, and exercise related) and a variety of subpopulations within the older age cohort.

There are important study limitations to be noted. First, as previously described, our RMR protocol was not consistent with typical methods, and as a result, caution is warranted when interpreting the MET values reported for the walking activities. However, because our RMR

values closely approximate and are not above those reported in other empirical studies with other older adults ($2.7\text{--}2.8\text{ mL}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$ (14)), we are confident that these values are valid. Future calibration studies are advised to follow either the ParvoMedics or the MedGem RMR protocols. Our finding that older adults have an RMR less than $3.5\text{ mL}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$ remains relevant and underscores the inadequacy of applying the referent $3.5\text{ mL}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$ in samples of older adults. A second limitation is that because of the limitations inherent in our RMR measurement procedures, we are unable to develop absolute cut points for light, moderate, and vigorous PA in older adults from our results. A third limitation is that the study sample is relatively small and is a convenience sample. This pilot study provides important preliminary data relative to the energy costs of walking activities in older adults and points to the need for equations and cut points specific to older adults. Although our sample did present with several physical and functional comorbidities, it is likely that our study sample is more physically active than the general population given their regular participation in the Durham VA's Gerofit exercise program. However, our decision to recruit among those participating in the Gerofit program and already familiar with exercise equipment enabled us to include a bout of vigorous walking in our testing protocol. Previous studies of older adults have not included vigorous-intensity activities (5). Finally, our failure to assess distance covered during the hallway walking bouts precludes us from quantifying individual gait speed over the course of the three self-paced trials. Such information is necessary to inform public health recommendations for caloric expenditure/energy balance in older adults through free-living activities.

This study has several important strengths. First, the study sample included elderly adults, with a wide range of chronic conditions, functional profiles, and BMI. Second, in addition to including a range of treadmill-based walking bouts, this study also included free-living/self-paced walking activities, which broadens the reach of our study findings. A previous study by Pruitt et al. (21) also examined activity count thresholds relative to self-paced walking activity in older adults. In this study, a 400-m walk test was used as a proxy for "meaningful activity," and associated activity counts (1452 counts per minute) were then used as a floor threshold to differentiate free-living activity. This study provided important preliminary data on the individualized activity count threshold for older adults. However, the lack of important objective markers of intensity such as oxygen consumption (METs) limits our ability to determine the intensity of specific activities and walking speeds and the corresponding energy costs in older adults.

This study provides information of value to behavioral researchers, practitioners, and the public. Although intuitive, our results suggest that there is considerable variation in terms of energy expenditure across a range of activities with age, such that older adults are working harder at a given walking speed compared with younger samples. Consequently, our results caution against the application of previously published cut points to older adults. These preliminary results also point to the need for additional research on the energy cost of daily activities and exercise in older adults and the implications for population-specific compendium tables. The results of our study also have public health implications. When considered alongside public health guidelines, which stipulate that an activity intensity of 4 METs is necessary for decreasing risk of morbidity/mortality (19), it would appear that even slow walking (2.0 mph) is sufficient to meet this guideline for older adults. Future research

should consider the role of fitness level, health status, and functional status (and relatedly economy of movement) on accelerometer-derived PA outcomes across a wide variety of daily activities.

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FIGURE 1.

The graph depicts the linear relationship between accelerometer counts per minute and measured energy expenditure from indirect calorimetry ($\text{kcal} \cdot \text{min}^{-1}$). The solid line represents predicted energy expenditure using the regression equation developed here (R^2 value for line of best fit = 0.41), and the grayed area represents the RMSE (± 1.51) of the regression. This regression is compared with the predicted energy expenditure using the equations of Freedson et al. (—) and Swartz et al. (.....). The equations of Freedson et al. ($R^2 = 0.45$) and Swartz et al. ($R^2 = 0.68$) consistently and similarly overestimate all activities compared with the measured energy cost.

TABLE 1

Descriptive statistics of study participants.

Variable	Mean $\pm$ SD or <i>n</i> (%)	Range
Age (yr)	75.0 $\pm$ 8.9	61–90
Sex (male)	15 (75)	N/A
Height (cm)	171.8 $\pm$ 8.4	157.5–188.0
Weight (kg)	86.2 $\pm$ 14.4	62.7–125.5
BMI (kg·m ⁻²)	29.1 $\pm$ 3.9	22.5–36.1
Overweight (≥ 25.0)	13 (65)	N/A
Healthy weight (<24.9)	7(35)	N/A
RMR (mL·kg ⁻¹ ·min ⁻¹)	2.66 $\pm$ 0.6	1.79–3.88
Resting heart rate (beats per min)	70.2 $\pm$ 12.7	52–100
Rapid gait speed (m·s ⁻¹)	1.50 $\pm$ 0.25	1.03–1.88
No. chronic conditions	2.6 $\pm$ 1.4	1–5

TABLE 2

PA and energy cost of treadmill and free-living walking.

		Metabolic Data				
		PA	METs			
<i>N</i> ^a	Accelerometer (counts per minute)	$\dot{V}O_2$ (mL · kg ⁻¹ · min ⁻¹)	EE (kcal·min ⁻¹)	Measured ^b	Standard ^c	
All subjects	156	2822 ± 114	13.6 ± 3.7	5.8 ± 0.16	5.3 ± 0.1	3.9 ± 0.1
Treadmill walking (mph)						
1.5	20	809 ± 50 [*]	10.0 ± 0.5 [*]	4.1 ± 0.28 [*]	3.9 ± 0.2 [*]	2.9 ± 0.2
2.0	20	1617 ± 84 [*]	11.6 ± 0.6 [*]	4.9 ± 0.33 [*]	4.5 ± 0.2 [*]	3.3 ± 0.2
2.5	20	2582 ± 102 [*]	13.0 ± 0.5 [*]	5.5 ± 0.32 [*]	5.1 ± 0.3 [*]	3.7 ± 0.1
3.0	20	3551 ± 144 [*]	15.3 ± 0.6 [*]	6.5 ± 0.40 [*]	5.9 ± 0.3 [*]	4.4 ± 0.2
3.5	19	4593 ± 203 [*]	17.9 ± 0.8 [*]	7.7 ± 0.40 [*]	6.8 ± 0.3 [*]	5.1 ± 0.2
Self-paced hallway walking						
Leisurely	19	2269 ± 213 [*]	10.6 ± 0.6 [*]	4.5 ± 0.32 [*]	4.1 ± 0.2 [*]	3.0 ± 0.2
Brisk	19	3396 ± 264 [*]	14.2 ± 0.6 [*]	6.0 ± 0.38 [*]	5.5 ± 0.3 [*]	4.1 ± 0.2
Fast	19	3902 ± 297 [*]	16.5 ± 0.8 [*]	7.2 ± 0.42 [*]	6.4 ± 0.4 [*]	4.7 ± 0.2

Values are presented as mean ± SEE.

* Significant difference between groups or activities ($P < 0.05$).

^a There were 20 study participants with a total of 156 observations, accounted for by the repeated-measures design of the analysis.

^b Measured METs = $\dot{V}O_2$ /RMR.

^c Standard METs = $\dot{V}O_2$ /3.5 mL · kg⁻¹ · min⁻¹.

$\dot{V}O_2$, volume oxygen consumption; EE, total energy expenditure.

TABLE 3

PA and energy cost of walking across groups.

Sex	Participants (n)	Observation (n) ^a	PA		Metabolic Data		
			Accelerometer (counts per minute)	$\dot{V}O_2$ (mL · kg ⁻¹ · min ⁻¹)	EE (kcal·min ⁻¹)	METs	
						Measured ^b	Standard ^c
Men	15	116	2853 ± 136 [*]	13.7 ± 0.4	5.9 ± 0.18	5.2 ± 0.1	3.9 ± 0.1
Women	5	40	2731 ± 209 [*]	13.4 ± 0.5	5.5 ± 0.31	5.4 ± 0.3	3.8 ± 0.2
BMI classification							
HW	8	55	2731 ± 226	13.5 ± 0.6	4.9 ± 0.22	5.2 ± 0.2	3.7 ± 0.1
OW	12	101	2853 ± 133	13.7 ± 0.3	6.1 ± 0.19	5.3 ± 0.1	4.0 ± 0.1
No. comorbidities							
1	8	64	2669 ± 165	14.3 ± 0.5	5.8 ± 0.25	4.7 ± 0.2 [*]	4.1 ± 0.1
> 1	12	92	2928 ± 156	13.1 ± 0.4	5.8 ± 0.2	5.6 ± 0.2 [*]	3.7 ± 0.1
Rapid gait speed							
>1.4 m·s ⁻¹	14	109	2988 ± 138 [*]	14.2 ± 0.4	6.2 ± 0.2	5.3 ± 0.1	4.1 ± 0.1
1.4 m·s ⁻¹	6	47	2436 ± 192 [*]	12.3 ± 0.4	4.7 ± 0.2	5.1 ± 0.2	3.5 ± 0.1

Values are presented as mean ± SEE.

^{*} Significant difference between groups or activities ($P < 0.05$).^a There were 20 study participants with a total of 156 observations, accounted for by the repeated-measures design of the analysis.^b Measured METs = $\dot{V}O_2$ /RMR.^c Standard METs = $\dot{V}O_2$ /3.5 mL · kg⁻¹ · min⁻¹. $\dot{V}O_2$, volume oxygen consumption; EE, total energy expenditure; BMI, body mass index; HW, healthy weight (BMI < 27 kg·m⁻²); OW, overweight (BMI > 27 kg·m⁻²).

TABLE 4

Comparison of measured and standard PA intensity in METs across studies for treadmill walking.

Speed (mph)	Measured METs		Standard METs		
	Current Study (60–90 yr), <i>N</i> = 20	Miller et al. (17) (60–69 yr), <i>N</i> = 30	Hendelman et al. (10) (30–50 yr), <i>N</i> = 25	Freedson et al. (8) (mean age = 23 yr), <i>N</i> = 50	Ainsworth et al. (2,3)
1.5	3.9 ± 0.2	3.0 ± 0.34	N/A	N/A	2.0
2.0	4.5 ± 0.2	3.8 ± 0.42	N/A	2.4 ± 0.46	2.8
2.5	5.1 ± 0.3	N/A	2.78 ± 0.61	N/A	3.0
3.0	5.9 ± 0.3	N/A	3.33 ± 0.76	4.1 ± 0.74	3.3
3.5	6.8 ± 0.3	N/A	4.09 ± 0.85	N/A	4.3
4.0	N/A	5.7 ± 0.55	5.59 ± 0.33	5.8 ± 1.0	5.0

Values are presented as mean ± SEE. Grade was held constant at 0% for all walking activities. N/A = not assessed.