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Physical Activity Assessment with the ActiGraph GT3X and Doubly Labeled Water

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Abstract

Purpose—To compare the degree to which four accelerometer metrics—total activity counts per day (TAC/d), steps per day (steps/d), physical activity energy expenditure (PAEE, kcal/kg/day), and moderate- to vigorous-intensity physical activity (MVPA, min/d)— were correlated with PAEE measured by doubly-labeled water (DLW). Additionally, accelerometer metrics based on vertical axis counts and triaxial counts were compared.

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Methods—This analysis included 684 women and 611 men aged 43 – 83 years. Participants wore the Actigraph GT3X on the hip for seven days twice during the study and the average of the two measurements was used. Each participant also completed one DLW measurement, with a subset having a repeat. PAEE was estimated by subtracting resting metabolic rate and the thermic effect of food from total daily energy expenditure estimated by DLW. Partial Spearman correlations were used to estimate associations between PAEE and each accelerometer metric.

Results—Correlations between the accelerometer metrics and DLW-determined PAEE were higher for triaxial counts than vertical axis counts. After adjusting for weight, age, accelerometer wear time, and fat free mass, the correlation between TAC/d based on triaxial counts and DLW-determined PAEE was 0.44 in women and 0.41 in men. Correlations for steps/d and accelerometer-estimated PAEE with DLW-determined PAEE were similar. After adjustment for within-person variation in DLW-determined PAEE, the correlations for TAC/d increased to 0.61 and 0.49, respectively. Correlations between MVPA and DLW-determined PAEE were lower, particularly for modified bouts of ≥10 minutes.

Conclusion—Accelerometer measures that represent total activity volume, including TAC/d, steps/d, and PAEE, were more highly correlated with DLW-determined PAEE than MVPA using traditional thresholds and should be considered by researchers seeking to reduce accelerometer data to a single metric.

Keywords

accelerometer; energy expenditure; exercise; wearable monitors

INTRODUCTION

The use of accelerometers in physical activity research has grown dramatically in recent years (3). Due to declining costs, accelerometers are even feasible for use in large-scale, longitudinal epidemiological studies seeking to relate this objective measure of physical activity to development of clinical endpoints (15). While it has become common to use accelerometers in research, there is still debate on the best metrics to use to summarize the vast amount of data produced.

To assess physical activity level, data are typically obtained from the vertical axis of a waist-worn accelerometer and converted to number of minutes per day spent in various physical activity intensity categories with the goal of measuring minutes per day of moderate- to vigorous-intensity physical activity (MVPA) in 10-minute bouts (3). Moreover, sometimes a “modified” 10-minute bout is used that allows for 1–2 minutes of activity in a bout to drop below the defined threshold, reflecting events such as waiting to cross a street while jogging (33). Time spent in MVPA in 10-minute bouts has been the status quo for most physical activity and public health researchers in the United States when using accelerometers, perhaps because the national physical activity recommendations have been expressed in this way. These recommendations (e.g. the 1996 U.S. Surgeon General’s Report and the 2008 Physical Activity Guidelines for Americans) are primarily based on studies that used questionnaires to assess physical activity; questionnaires assess MVPA performed in bouts more accurately than light-intensity or lifestyle activity (25, 32, 37). In studies utilizing accelerometers, however, various investigator-defined cutpoints are currently being used to identify time spent in light, moderate, and vigorous intensity activity. This is problematic as estimates of time spent in MVPA can vary considerably, depending on the chosen cutpoint (18). Furthermore, MVPA accumulated in 10-minute bouts is only a small subset of all physical activity performed throughout a 24-hour day (33). Emerging evidence indicates that other types of activity, in particular light-intensity physical activity, have significant health consequences as well (10, 22).

Instead of focusing on a subset of physical activity, like MVPA, there may be situations where it is preferable to consider the total volume of physical activity performed. Physical activity is a complex behavior with multiple dimensions, including frequency, intensity, duration, and activity type (24). Nevertheless, for many applications, it is important to determine what single variable best accounts for all dimensions and represents total physical activity.

Total activity counts (TAC) per day provides an alternative to MVPA that represents total volume of physical activity performed (3). TAC accounts for minutes spent in sedentary, light, moderate, and vigorous physical activity and weights each minute according to intensity. Recently, TAC was found to have stronger associations to several cardiometabolic biomarkers when compared to MVPA accumulated in modified ≥ 10 minute bouts (40). Thus, TAC may be an important measure of total physical activity volume and should be considered when utilizing data collected with accelerometers.

Another metric that can be estimated from accelerometers and reflects the energy expended in physical activity is physical activity energy expenditure. Several prediction equations exist to estimate energy expenditure based on data from accelerometers (19). These equations were developed using indirect calorimetry for comparison so that accelerometer activity counts can be converted into energy expenditure (8, 19).

Finally, despite the robust information accelerometers can provide about intensity and duration of activity, steps per day is another measure of total activity volume that is simple, easy to interpret, and readily available through use of inexpensive devices like pedometers (36). In addition to recording body acceleration and deceleration, accelerometers can also capture step data.

As all physical activity results in energy expenditure, utilizing energy expenditure measured by the doubly-labeled water (DLW) method is a logical choice to validate an accelerometer measure of total volume of physical activity. Thus, the goal of this study was to answer the question: “Compared to considering MVPA alone, how much does accounting for total volume of physical activity improve the correlation between accelerometer-measured physical activity and physical activity energy expenditure measured by DLW?” To address this, we examined the degree to which four different accelerometer measures-- total activity counts per day, steps per day, physical activity energy expenditure (kcal/kg/day), and minutes of MVPA per day-- were correlated with physical activity energy expenditure measured by DLW. Additionally, we compared results using accelerometer activity counts from the vertical axis only to those obtained when using counts from all three axes (triaxial vector magnitude) since traditionally accelerometers were uniaxial, but now it is more common to measure acceleration along all three axes.

METHODS

Study Population

The original Nurses' Health Study (NHS) cohort was established in 1976 and included 121,700 U.S. female registered nurses aged 30 to 55 years (4). The Nurses' Health Study II (NHS II) is a similar cohort of 116,671 female nurses 25 to 42 years of age at study initiation in 1989. The Health Professionals Follow-up Study is a cohort of 51,529 male U.S. health professionals aged 40 to 75 years at study initiation in 1986 (9). The participants in all three cohorts respond to biennial questionnaires that assess updated lifestyle characteristics and medical history.

In 2010 – 2013, two studies were conducted within the NHS, NHS II, and HPFS to assess the validity of the food frequency questionnaire and physical activity questionnaire used in these cohorts. A subset of women from NHS/NHS II participated in the Women's Lifestyle Validation Study (WLVS) in 2010 – 2012. Similarly, a subset of men from HPFS, along with additional men from the local community who were members of the Harvard Pilgrim Health Care insurance plan, participated in the Men's Lifestyle Validation Study (MLVS) in 2011 – 2013. WLVS and MLVS participants were a random sample of NHS/NHS II participants and HPFS participants who completed the 2006/2007 FFQ and had previously provided blood in these cohorts. The Harvard Pilgrim participants were recruited at random from among men who have been enrolled in the program for at least five years, to ensure stability for our study. We included men and women 40 to 85 years of age and the sample was stratified by age (5-year groups) to obtain a uniform distribution. Persons with a history of coronary heart disease, stroke, cancer, or major neurological disease were excluded. The availability of broad band internet was required as some of the study activities were to be completed online. Finally, no expected changes in habitual diet or physical activity patterns was also a requirement for eligibility. For the WLVS, n = 796 women consented to participate and were enrolled in the study. For the MLVS, n = 671 men consented to participate and were enrolled in the study. This study was approved by the Institutional Review Board of the Harvard T.H. Chan School of Public Health and Brigham and Women's Hospital.

Data Collection Procedures

The data collected for each participant within the WLVS and MLVS included one doubly-labeled water (DLW) measurement (with n = 86 women and n = 102 men having a repeat measurement to assess within-person variability) and two accelerometer measurements with approximately six months between each measurement. The data collection period for each participant spanned 12 to 15 months, depending on study group (Figure 1). The DLW measurement and one of the accelerometer measurements were designed to occur during the same 3-month time window (phase) during the study, but not during the same week to avoid artificially high correlations. For participants in study groups 1 and 2, the mean (± S.D.) number of days between DLW and accelerometer measurement #1 was 35.0 (± 28.2) [median: 29, IQR: 22] in women and 45.1 (± 43.2) [median: 41, IQR: 24] in men while the mean (± S.D.) number of days between DLW and accelerometer measurement #2 was 152.6 (± 21.5) [median: 154, IQR: 6] in women and 150.9 (± 23.1) [median: 154, IQR: 6] in men. For participants in study groups 3 and 4, the mean (± S.D.) number of days between DLW and accelerometer measurement #1 was 174.0 (± 26.9) [median: 175, IQR: 9] in women and 169.1 (± 41.0) [median: 175, IQR: 10] in men while the mean (± S.D.) number of days between DLW and accelerometer measurement #2 was 32.4 (± 20.5) [median: 25.5, IQR: 21] in women and 37.0 (± 30.0) [median: 34, IQR: 22] in men. For the current analysis, we used the first DLW measurement and the average of the two accelerometer measurements for each participant (or a single accelerometer measurement for n = 25 women and n = 99 men who only had one valid measure.) In addition, we used the repeat DLW measurements to adjust for random within-person variation in energy expenditure.

Accelerometer—The participants were mailed an accelerometer (ActiGraph GT3X, Actigraph Corporation, Pensacola, FL), detailed instructions, and a wear time diary. Participants were instructed to wear the monitor on the hip for seven days during all waking hours, except when bathing or swimming, and record the days the monitor was worn. Participants then shipped the accelerometer and completed wear time diary back to the study center where their data could be downloaded and reviewed.

The epoch was set to 1 s and the low frequency extension was enabled. Enabling the low frequency extension on the ActiGraph GT3X widens the bandpass filter that is applied to the raw acceleration signal after it has passed through a proprietary low-pass anti-aliasing filter (13). The low frequency extension is recommended to increase the device sensitivity in the low frequency range and make the device output (counts per minute) similar to an earlier model, the ActiGraph 7164 (38). Accelerometer data were screened for wear time using standard methods (33, 35). For data based on vertical axis counts, non-wear time was defined as ≥ 60 consecutive minutes with zero accelerometer counts, allowing up to two minutes with limited movement (< 100 counts/min). For triaxial vector magnitude data, the algorithm was modified to allow for up to two minutes of counts < 200 counts/min, which is the threshold for sedentary time when using triaxial counts (1). Daily wear time was determined by subtracting non-wear time from 24 hours. Wear days were identified using the wear time diary (to avoid counting spurious physical activity while monitors were moving in mail transit). Participants with at least 4 days with ≥ 10 hours of wear per day were included in the analysis.

Physical activity as measured by the accelerometer was examined in four ways: 1) total activity counts per day (TAC/d); 2) steps per day (steps/d); 3) physical activity energy expenditure (PAEE, kcal/kg/day) and 4) minutes per day (min/d) spent in MVPA. Data based on both vertical axis counts only and triaxial counts were utilized. Total activity counts are the accelerations captured by the device that were filtered, full-wave rectified, and integrated over time, representing the intensity of ambulatory activity. Vertical axis counts are activity counts measured in the vertical plane, whereas triaxial counts are a composite vector magnitude from three individual orthogonal planes (vertical, antero-posterior, and medio-lateral). TAC/d based on vertical axis and triaxial counts were determined by averaging the total activity counts per day across valid wear days. ActiGraph uses a proprietary algorithm to count steps and no information about the specifics of this process is

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publicly available. Step counts are based only on accelerometer data collected on the vertical axis. Steps/d was determined by averaging the steps taken per day across valid wear days.

To compute total daily energy expenditure (TDEE) in kcal/kg/day from the accelerometer, we first used the Freedson and Sasaki MET prediction equations to determine energy expenditure in METs for each minute (8, 29). To predict METs from vertical axis counts, we used the equation METs = 1.439008 + (0.000795* counts/min) (8). To predict METs from triaxial counts, we used the equation METs = 0.000863* (VM3) + 0.668876 where VM3 is the composite vector magnitude of activity counts from all three axes (29). In both cases, for minutes where the vertical axis or triaxial counts were below the threshold for sedentary behavior (100 counts/min and 200 counts/min, respectively (1, 21)), a value of 1 MET was assigned. Each minute of non-wear time was also assigned a value of 1 MET. Additionally, for minutes where the vertical axis or triaxial counts were in the range for light-intensity activity (100 – 2020 counts/min and 200 - 2690 counts/min, respectively (1, 21)), two approaches were used: 1) Extrapolate the MET prediction equations to estimate METs in this range; and 2) Assign a constant 2.0 METs. Next, the computed METs were summed over all minutes to get TDEE in MET-min/day, which was then divided by 60 to get TDEE in MET-hr/day. TDEE in MET-hr/day is numerically equivalent to TDEE in kcal/kg/day based on the fact that 1.0 MET = 1.0 kcal/kg/hr (2). Finally, to get an estimate of PAEE in kcal/kg/day from the accelerometer, we multiplied TDEE by 0.90 (to correct for the thermic effect of food, which is assumed to be 10% of TDEE) and subtracted 24 kcal/kg/day to account for resting energy expenditure (1 MET * 24 hours) (5).

To determine estimates of time per day spent in different intensities of activity, we utilized two sets of thresholds. For data based on vertical axis counts only, we used thresholds described previously by Troiano et al. as primarily reflecting locomotor activity (33): moderate intensity (3 – 5.99 METs) = 2020-5999 counts/min; and vigorous intensity (≥ 6 METs) = ≥ 6000 counts/min. Light-intensity physical activity was defined as the total number of minutes between 100 and 2020 counts/min (21). We also examined associations for moderate-intensity activity when the threshold was lowered to the Matthews' cut point of 760 counts/min (MVPA-760), which may allow better capture of the full range of moderate-intensity activities encountered in daily living (20). For data based on triaxial counts, we used thresholds determined by Sasaki et al. for MVPA: moderate intensity (3 – 5.99 METs) = 2690-6166 counts/min; and vigorous intensity (≥ 6 METs) = ≥ 6167 counts/min (29). Light-intensity physical activity was defined as the total number of minutes between 200 and 2690 counts/min (1). As there is not yet a published threshold equivalent to the MVPA-760 based on triaxial counts, two of the authors (AKC and DRB) estimated a threshold of 1010 counts/min by graphing the vertical axis and triaxial thresholds against each other (see Figure, Supplemental Digital Content 1, Thresholds for vertical axis counts graphed against triaxial counts). A bout of sedentary behavior was defined as consecutive minutes in which the accelerometer registered less than 100 counts/min for vertical axis counts and less than 200 counts/min for triaxial counts (1, 21).

Time spent in activity of a defined intensity (sedentary, light, moderate, vigorous, or MVPA) was determined by summing minutes in a day where the count met the criterion for that intensity. Time spent in physical activity is presented for every minute that meets the specific criterion as well as for modified 10-min activity bouts, as described previously (33). Mean daily time in intensity-specific categories was calculated across all valid wear days.

Doubly-labeled water—The doubly-labeled water (DLW) method was used to assess total daily energy expenditure (TDEE). Bottled DLW was mailed to participants a few days before they underwent the protocol. Participants provided four urine samples, two directly before and two after the administration of the DLW dose (i.e. 4.5 and 6 hours post-dose). The 4.5 hour time point was not included, however, if the enrichment was less than the 6 hour time point. After 10 to 14 days, participants provided two more urine samples on the same day, but at least 30 minutes apart, following the same procedures. Participants recorded the date and time that all samples were collected. All samples were sent to Dr. Jennifer Rood at the Mass Spectrometry Core at Pennington Biomedical Research Center to determine energy expenditure via mass spectroscopic analysis of urine specimens for deuterium and oxygen-18 (30, 31). To estimate PAEE, we subtracted resting metabolic rate and the thermic effect of food from TDEE (5). Resting metabolic rate was calculated based on sex, weight, height, and age as described by Mifflin et al. (23) For thermic effect of food, we used a constant 10% of total energy (5).

For the analysis, TDEE and PAEE were expressed in kcal/kg/day to adjust for any differences in energy expenditure due to body mass. Additionally, multivariable models included self-reported body weight and fat free mass estimated from DLW.

Statistical Analysis

All analyses were performed using SAS statistical software, version 9.4 (SAS Institute Inc, Cary, North Carolina, United States). Analyses were run separately in WLVS and MLVS. Mean values and standard deviations (S.D.) were calculated for baseline characteristics, DLW measures, and accelerometer variables.

As the distributions of many accelerometer variables were skewed, they were log-transformed prior to analysis. Since DLW-measured PAEE in kcal/kg/day was not normally distributed despite transformation, Spearman correlation coefficients were calculated. Partial correlations adjusted for weight, age, accelerometer wear time, and fat free mass were calculated between TDEE and PAEE measured by DLW and TAC/d, steps/d, PAEE, min/d of MVPA, and min/d of MVPA using the lower threshold (MVPA-760/1010) measured by accelerometer. Additionally, correlations between TAC/d and the other accelerometer variables were examined. To adjust for random within-person variation in energy expenditure measured by DLW, we calculated deattenuated Spearman correlations using the methods of Rosner et al. for interclass correlations (27).

RESULTS

Among the n = 796 women who were enrolled in the WLVS, n = 775 women had a least one accelerometer measurement with at least 4 days with ≥ 10 hours of wear per day. We excluded n = 31 women with negative values for accelerometer-estimated PAEE. We then excluded 23 women without a DLW measurement and 37 women with > 40,000 steps per day, resulting in 684 women included in this analysis. Among n = 671 men enrolled in the

MLVS, n = 667 men had a least one accelerometer measurement with at least 4 days with ≥ 10 hours of wear per day. We excluded n = 27 men with negative values for accelerometer-estimated PAEE. We then excluded 17 men without a DLW measurement and 12 men with > 40,000 steps per day, resulting in 611 men included in this analysis.

The mean (± S.D.) age of women included in this analysis was 62.8 (± 9.4) and the mean (± S.D.) age of men was 67.9 (± 7.7) (Table 1). Women had higher body mass index, and lower weight, than men. Men had higher mean TDEE (2778 kcal) and PAEE (916 kcal) than women (2198 kcal and 722 kcal, respectively) as measured by DLW. The intraclass correlations for TDEE and PAEE are provided in Supplemental Digital Content 2 [see Table, Supplemental Digital Content 2, Intraclass correlation coefficients (ICC) for doubly labeled water (DLW) and accelerometer variables].

Means and standard deviations for the accelerometer variables are presented in Table 2 and intraclass correlations in Supplemental Digital Content 2. Based on triaxial counts, women wore the accelerometer for a mean (± S.D.) of 15.1 (± 1.0) hrs/day over a mean (± S.D.) of 6.8 (± 0.4) days; wear time for men was similar. Mean (± S.D.) wear time was less when using vertical axis counts: 14.8 (± 1.1) hrs/day for women and 14.7 (± 1.1) hrs/day for men. For women and men, mean TAC/d was higher using triaxial counts (597,545 and 602,923, respectively) compared to vertical axis counts (249,380 and 290,024, respectively), but the difference between men and women was much less when using triaxial counts. Amount of time spent in light, moderate, and vigorous activity was higher for women and men when triaxial counts were used compared to vertical axis counts, while sedentary time was lower. Using the 2020 counts/min threshold and including every minute, women and men engaged in a mean (± S.D.) of 20.2 (± 16.9) and 31.8 (± 21.7) min/day of MVPA based on vertical axis counts. When using triaxial counts and the 2690 counts/min threshold, these means (± S.D.) nearly doubled to 41.6 (± 24.9) min/day for women and 51.6 (± 28.3) min/day for men.

Using results presented in Tables 1 and 2, we can quantitatively compare TDEE and PAEE measured by DLW to TDEE and PAEE estimated by accelerometer. In Table 1, TDEE determined by DLW was 31.7 kcal/kg/day for women and 34.5 kcal/kg/day for men. In women, TDEE estimated by accelerometer ranged from 29.7 kcal/kg/day to 32.6 kcal/kg/day, which was similar to TDEE measured by DLW (Table 2). In men, accelerometer-estimated TDEE ranged from 30.2 kcal/kg/day to 32.6 kcal/kg/day, which was slightly lower than TDEE measured by DLW (Table 2). In contrast to TDEE, PAEE estimated by accelerometer was quite a bit lower than PAEE measured by DLW. PAEE determined by DLW was 10.5 kcal/kg/day in women and 11.5 kcal/kg/day in men (Table 1). PAEE estimated by accelerometer ranged from 2.8 to 5.3 kcal/kg/day in women and 3.1 to 5.3 kcal/kg/day in men (Table 2). The difference between PAEE determined by DLW and PAEE estimated by accelerometer is also shown in Bland-Altman plots [see Figures, Supplemental Digital Content 3, Bland–Altman plots comparing physical activity energy expenditure (PAEE) estimated by doubly labeled water (DLW) to PAEE estimated by accelerometer]. Based on the plots, it appears that the error in the accelerometer estimate of PAEE is minimal at lower levels of PAEE but is greater at higher levels.

As the purpose of this paper is to validate a measure of physical activity, and correlations were similar when using TDEE or PAEE, we will focus on PAEE. In general, the Spearman correlations between accelerometer-assessed physical activity and PAEE measured by DLW were higher for triaxial counts than vertical axis counts for most of the accelerometer variables (Table 3). After adjusting for weight, age, wear time, and fat free mass, TAC/d, accelerometer-estimated PAEE (using a constant 2 METs for light-activity), and time spent in MVPA-1010 based on triaxial counts and including every minute had the highest correlations with DLW-determined PAEE (ρ = 0.44 for each) in women. In men, steps/d had the highest correlation with PAEE (ρ = 0.42), while correlations with MVPA-1010, TAC/d. and accelerometer-estimated PAEE (constant) using triaxial counts were similar. The correlations with DLW-determined PAEE were lowest for MVPA using the higher (i.e. 2690 or 2020 counts/min) threshold, particularly when only modified bouts of ≥ 10 minutes were included (ρ = 0.18 and 0.21 for women and men, respectively, using triaxial counts). After adjusting for random within-person error in DLW-determined PAEE, the Spearman correlations for time spent in MVPA-1010 including every minute, TAC/d, and accelerometer-estimated PAEE (constant) based on triaxial counts with DLW-determined PAEE increased to 0.64 (95% CI: 0.51, 0.74), 0.61 (95% CI: 0.47, 0.71), and 0.59 (95% CI: 0.46, 0.69), respectively, in women. The deattenuated correlations for steps/d and accelerometer-estimated PAEE (constant) with DLW-determined PAEE increased to 0.53 (95% CI: 0.44, 0.61) and 0.51 (95% CI: 0.41, 0.59), respectively, in men.

Table 4 presents the correlations between TAC/d and the other accelerometer metrics. TAC/d was highly correlated with steps/d, MVPA-760/1010, and accelerometer-estimated PAEE as well as MVPA when every minute is included with multivariable-adjusted correlations ranging from 0.77 – 0.99. Correlations between TAC/d and MVPA in modified bouts ≥ 10 min were lower, ranging from 0.56 – 0.73.

DISCUSSION

This study showed that total activity counts per day, steps per day, accelerometer-estimated PAEE, and minutes per day of MVPA based on the lower threshold (760 counts/min for vertical axis or 1010 counts/min for triaxial) had similar associations with PAEE determined by DLW. Incorporating accelerometer counts from all three axes by using triaxial vector magnitude resulted in stronger associations between each of the accelerometer variables and DLW-determined PAEE compared to only using counts from the vertical axis. Additionally, associations between the accelerometer measures and PAEE were stronger when every minute of activity was included versus only including minutes of activity that were accumulated in modified bouts of ≥ 10 minutes. Notably, minutes per day of MVPA based on the threshold of 2020 counts/min (vertical axis counts) or 2690 counts/min (triaxial counts) and accumulated in modified bouts of ≥ 10 minutes showed the weakest association with PAEE in the current study, which is not surprising as MVPA accumulated in 10-minute bouts is only a small subset of all physical activity performed.

Previous studies have validated accelerometers against DLW. Recently, Plasqui and colleagues systematically reviewed all accelerometer validation studies (2007–2011) using DLW as the reference (26). Although several studies included in the review validated the

Actigraph, they were limited to the 7164 and GT1M models, both of which are uniaxial accelerometers, and the majority of the studies were done in children. Additionally, only three studies reported a partial correlation or *R* increase which is necessary for interpreting correlations between TAC and DLW-determined PAEE because body weight, age, and FFM are determinants of PAEE, even when expressed as kcal/kg/day (26). For the uniaxial Actigraph accelerometer, unadjusted correlations between TAC and DLW-determined PAEE ranged from 0.37 – 0.56 in studies that included adult men and women (5, 26). For the triaxial accelerometers, unadjusted correlations ranged from 0.32 – 0.79 in adults (26). Partial correlations between TAC and PAEE adjusted for body mass or fat mass/fat free mass using triaxial accelerometers in men and women ranged from 0.27 – 0.55, which is comparable to the current study (26).

We found that values of PAEE estimated by accelerometer were 50 – 73% lower than PAEE determined by DLW. This was true whether vertical axis counts or triaxial counts were used in the MET prediction equations, although utilizing triaxial counts produced estimates closer to DLW. These results were similar to those reported by Leenders et al. who found that estimates of PAEE from the triaxial Tritrac accelerometer and uniaxial CSA (predecessor to Actigraph) accelerometer were 35% and 59% lower, respectively, than PAEE determined by DLW (17). A possible reason for this discrepancy is that waist-worn accelerometry underestimates energy expenditure because it does not register some types of activity, for example arm movements, walking uphill (versus on a flat surface), or additional work performed when carrying objects. In contrast, when we quantitatively compared DLW-determined TDEE and accelerometer-estimated TDEE, the values were much closer, with differences ranging from only −13% to +3%. Another study conducted by Leenders and colleagues also found accelerometer-estimated TDEE to be closer to DLW than accelerometer-estimated PAEE. In their study, estimates of TDEE from published regression equations using data from both a uniaxial and triaxial accelerometer under- and overestimated DLW-determined TDEE, with percent differences ranging from −32% to +16% (with an additional equation overestimating TDEE by 101%) (16). It makes sense that estimates of TDEE from the accelerometer and DLW are in closer agreement than estimates of PAEE because resting metabolic rate, which has fairly low day-to-day variability, accounts for 65–70% of TDEE (23).

The current study provides evidence that utilizing accelerometer data from all three axes provides a better measure of physical activity volume than only using data from the vertical axis. Prior research comparing uniaxial and triaxial accelerometers has yielded conflicting results. Some previous studies suggest that triaxial accelerometers provide a more accurate estimate of DLW-determined PAEE than uniaxial devices (11, 28). Hendelman et al. reported stronger correlations between energy cost and activity counts from the triaxial Tritrac accelerometer compared to the uniaxial CSA accelerometer (11). A study by Howe et al., however, used the RT3 triaxial accelerometer in 212 individuals and found triaxial counts did not significantly improve the relationship between TAC and AEE compared to vertical axis counts (12). The study by Howe et al. compared vertical axis and triaxial counts from the same device, whereas the other studies compared counts from two different devices which can be complicated by different monitor technology and data processing (3). Nevertheless, in the current study, we compared metrics measured with the same monitor

(Actigraph GT3X) and found metrics utilizing triaxial counts had a higher correlation with PAEE measured by DLW compared to metrics using vertical counts. This indicates that movements that result in horizontal accelerations in the anterior-posterior and medial-lateral directions expend energy; thus, accounting for this by utilizing triaxial counts increases the correlation between accelerometer metrics and energy expenditure measured by DLW.

This study further demonstrates the effects of using different investigator-defined cutpoints for MVPA. The estimates of time spent in MVPA varied greatly when the threshold of 2020 counts/min was used compared to the threshold of 760 counts/min. Additional factors that affected the estimates of time spent in MVPA were: (a) whether vertical axis or triaxial counts were used, and (b) whether every minute of activity was included or only modified bouts of ≥ 10 minutes. In the current analysis, correlations with DLW-estimated PAEE were highest for MVPA when triaxial counts and the lower threshold (1010 counts/min) were used and every minute of activity was included.

The current study is important because we directly compared various summary accelerometer metrics against DLW, the accepted gold standard for energy expenditure. Previous studies examining TAC/d versus minutes per day of MVPA have utilized an indirect validation approach in that they considered correlations between the accelerometer summary variables and biomarkers known to be correlated with physical activity, HDL cholesterol and triglycerides (40). Strengths of the current study include the fact that it included a much larger sample of men and women than previous studies that compared accelerometers to DLW. In addition, the study sample included middle-aged and older adults with a wide age range. As we measured DLW twice in a subset of study participants, we were also able to adjust for the within-person variation in energy expenditure measured by DLW.

Our study also has several important limitations that should be mentioned. First, the study population, consisting of predominantly white women and men of higher socioeconomic status, is not representative of the general population. Another limitation is that TDEE and PAEE may have been underestimated as the study participants included older adults for whom urinary retention can be a substantial problem. If the bladder is not completely voided prior to consuming the DLW dose, the post-dose measurements are diluted and the peak isotopic enrichments are underestimated. Additionally, neither of the two accelerometer measurements occurred at the same time as the DLW measurement; the DLW and accelerometer measurement that were done in the same 3-month time window were measured on average 32 – 45 days apart. Thus, the true correlations between short term energy expenditure measured by DLW and the accelerometer measures of physical activity are almost certainly higher than those reported in the current study (14). However, collecting both measures concurrently overestimates the true long term correlation between these methods, which is usually the focus of epidemiologic studies with disease outcomes (39). Furthermore, resting energy expenditure was not measured, but was estimated using the Mifflin-St. Jeor equation for the DLW data and 1 kcal/kg/hour for the accelerometer data. These additional sources of error may have attenuated the correlations between the accelerometer metrics and PAEE estimated by DLW.

Another limitation was that we chose to enable the low frequency extension on the ActiGraph GT3X accelerometer. While this has the benefit of making the ActiGraph GT3X counts per minute values resemble the previous Actigraph 7164, it nearly doubles the steps/d compared to use of the default filter (34), and it vastly overestimates steps/d compared to a criterion device, the ankle-worn StepWatch. In contrast, the default filter produces 24-hour step counts that are much more reasonable (7). Unfortunately, it was not possible for us to reanalyze the data with the extension turned off because we no longer have the raw .gt3x files. Additionally, we elected not to use "censored steps", a method in which any steps taken during minutes where the Actigraph counts per minute were < 500 are not counted, in the current analysis (36). This approach can potentially eliminate a lot of light-intensity physical activity and intermittent MVPA. Furthermore, previous work has shown in free-living adults that the Actigraph 7164 steps per day (uncensored) corresponded well with the StepWatch (6).

In conclusion, we found that measures of total activity volume assessed by an accelerometer were reasonably correlated with PAEE measured by DLW after accounting for within-person variation in the DLW. This study is the first to compare the triaxial Actigraph GT3X accelerometer with physical activity energy expenditure measured by DLW and indicates that metrics using triaxial counts are more highly correlated with PAEE compared to metrics using vertical axis counts. TAC/d had higher correlations with DLW-determined PAEE than min/d of MVPA using the 2020 counts/min threshold, consistent with prior research showing stronger associations between TAC/d and cardiometabolic biomarkers compared to MVPA (40). Additionally, steps/d, min/d of MVPA based on the lower threshold (760 counts/min for vertical axis or 1010 counts/min for triaxial), and accelerometer-estimated PAEE had similar correlations with DLW-measured PAEE and were highly correlated with TAC/d. One of the major advantages of accelerometers over physical activity questionnaires is that accelerometers can capture ubiquitous, light intensity activity performed throughout the day. As total activity counts or other measures of total activity volume account for time spent in activities of all intensity levels, it may be preferable over min/day of MVPA for researchers seeking to reduce accelerometer data down to a single metric. Nonetheless, it is important to note that TAC/d is not a perfect measure of physical activity energy expenditure, but with the development of more advanced pattern recognition methods there is potential for improved approaches to capture all movement that contributes to energy expended in physical activity. Finally, we recognize that physical activity has multiple dimensions and researchers will continue to be interested in questions related to frequency, intensity, and duration of activity bouts. Thus, measures of total activity volume should complement, not replace, other physical activity metrics.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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Months	1	2	3	4	5	6	7	8	9	10	11	12
Group 1 N = 178 women N = 135 men	Accelerometer #1 DLW #1						Accelerometer #2			DLW #2 (in subset)		
Group 2 N = 175 women N = 165 men				Accelerometer #1 DLW #1						Accelerometer #2		
Group 3 N = 168 women N = 154 men	Accelerometer #1						Accelerometer #2 DLW #1					
Group 4 N = 163 women N = 157 men				Accelerometer #1						Accelerometer #2 DLW #1		

Figure 1.
Women’s and Men’s Lifestyle Validation Study Timeline according to Study Group

Table 1

Baseline characteristics of participants in Women's and Men's Lifestyle Validation Studies.

	Women (n = 684) Mean (SD)	Men (n = 611) Mean (SD)
Age	62.8 (9.4)	67.9 (7.7)
Weight, kg	70.7 (14.9)	81.4 (12.0)
Body Mass Index, kg/m^2	26.3 (5.2)	26.0 (3.5)
DLW Measures		
Total daily energy expenditure, kcal	2198 (367)	2778 (426)
Physical activity energy expenditure, kcal *	722 (245)	916 (333)
Total daily energy expenditure, kcal/kg/day	31.7 (5.2)	34.5 (5.6)
Physical activity energy expenditure, kcal/kg/day	10.5 (3.9)	11.5 (4.4)

DLW: Doubly-labeled water

* Physical activity energy expenditure was calculated by subtracting resting metabolic rate, as estimated by the Mifflin-St. Jeor equation, and the thermic effect of food from total daily energy expenditure.

Table 2

Means (SD) for accelerometer variables using triaxial (3 axes) vs. vertical axis only.

	Triaxial* Mean (SD)	Vertical Axis** Mean (SD)
WOMEN		
Number of valid days	6.8 (0.4)	6.8 (0.5)
Wear time, hr/day	15.1 (1.0)	14.8 (1.1)
Total activity counts per day	597,545 (163,159)	249,380 (93,909)
Steps per day		14,560 (3624)
TDEE, kcal/kg/day	29.9 (2.0)	29.7 (1.7)
PAEE, kcal/kg/day	2.9 (1.8)	2.8 (1.5)
TDEE (constant), kcal/kg/day	32.6 (2.0)	30.5 (1.6)
PAEE (constant), kcal/kg/day	5.3 (1.8)	3.5 (1.4)
Vigorous physical activity, min/day		
Modified bouts of ≥ 10 min	1.7 (4.9)	0.8 (3.2)
Including every minute	2.2 (5.3)	1.0 (3.5)
Moderate physical activity, min/day		
Modified bouts of ≥ 10 min	13.8 (15.1)	10.2 (13.1)
Including every minute	39.4 (22.8)	19.2 (15.6)
Light physical activity, min/day		
Modified bouts of ≥ 10 min	128.2 (51.0)	132.5 (52.1)
Including every minute	393.7 (73.9)	328.8 (66.0)
Sedentary time, min/day		
Modified bouts of ≥ 30 min	108.8 (55.3)	138.1 (53.1)
Modified bouts of ≥ 15 min	216.5 (76.7)	263.4 (71.5)
Modified bouts of ≥ 5 min	367.3 (83.0)	424.3 (73.8)
Including every minute	470.4 (77.2)	537.0 (66.7)
MVPA-2690/2020, min/day		
Modified bouts of ≥ 10 min	16.5 (17.5)	11.4 (14.4)
Including every minute	41.6 (24.9)	20.2 (16.9)
MVPA-1010/760, min/day		
Modified bouts of ≥ 10 min	130.9 (62.9)	33.1 (26.7)
Including every minute	227.1 (60.3)	96.4 (39.8)
MEN		
Number of valid days	6.5 (0.7)	6.4 (0.7)
Wear time, hr/day	15.1 (1.1)	14.7 (1.1)
Total activity counts per day	602,923 (177,199)	290,024 (111,218)
Steps per day		15,030 (3685)
TDEE, kcal/kg/day	30.2 (2.2)	30.2 (1.8)
PAEE, kcal/kg/day	3.2 (2.0)	3.1 (1.7)
TDEE (constant), kcal/kg/day	32.6 (2.3)	30.7 (1.8)
PAEE (constant), kcal/kg/day	5.3 (2.0)	3.6 (1.6)
Vigorous physical activity, min/day		

	Triaxial[*] Mean (SD)	**Vertical Axis[**] Mean (SD)**
Modified bouts of ≥ 10 min	3.2 (7.8)	1.7 (4.7)
Including every minute	4.5 (8.5)	2.3 (5.2)
Moderate physical activity, min/day		
Modified bouts of ≥ 10 min	19.5 (17.4)	15.0 (16.1)
Including every minute	47.0 (25.1)	29.6 (19.9)
Light physical activity, min/day		
Modified bouts of ≥ 10 min	110.4 (50.1)	103.0 (45.4)
Including every minute	349.6 (73.7)	297.5 (63.9)
Sedentary time, min/day		
Modified bouts of ≥ 30 min	141.7 (66.2)	165.6 (60.7)
Modified bouts of ≥ 15 min	268.6 (88.6)	303.8 (77.0)
Modified bouts of ≥ 5 min	417.8 (91.4)	457.1 (76.3)
Including every minute	506.7 (84.1)	554.0 (70.4)
MVPA-2690/2020, min/day		
Modified bouts of ≥ 10 min	24.8 (21.0)	17.6 (18.0)
Including every minute	51.6 (28.3)	31.8 (21.7)
MVPA-1010/760, min/day		
Modified bouts of ≥ 10 min	131.6 (63.0)	51.3 (33.9)
Including every minute	216.4 (60.7)	110.8 (42.0)

TDEE: total daily energy expenditure from the Sasaki (triaxial) and Freedson (vertical axis) prediction equations using extrapolation to estimate METs for light-intensity activity; PAEE: physical activity energy expenditure from the Sasaki and Freedson prediction equations using extrapolation to estimate METs for light-intensity activity; TDEE (constant): total daily energy expenditure from the Sasaki and Freedson MET prediction equations using a constant 2.0 METs for light-intensity activity; PAEE (constant): physical activity energy expenditure from the Sasaki and Freedson MET prediction equations using a constant 2.0 METs for light-intensity activity; MVPA-2690/2020: moderate-to-vigorous physical activity using traditional thresholds; MVPA-1010/760: MVPA using thresholds of 1010 counts/min (triaxial) or Matthews' cut point of 760 counts/min (vertical axis).

[*]Triaxial thresholds: Light PA = 200 – 2659 counts/min; Moderate PA = 2690 – 6166 counts/min; Vigorous PA = ≥ 6167 counts/min

[*]Vertical axis thresholds: Light PA = 100 – 2019 counts/min; Moderate PA = 2020 – 5999 counts/min; Vigorous PA = ≥ 6000 counts/min

Table 3

Spearman Correlation Coefficients between physical activity measured by accelerometer and energy expenditure measured by doubly-labeled water.

	DLW MEASURES				DLW MEASURES			
	TDEE	PAEE	TDEE	PAEE	TDEE	PAEE	TDEE	PAEE
	Women		*Men*		*Women*		*Men*	
Accelerometer Variables	**Triaxial**				**Vertical Axis**			
Total activity counts per day								
Crude	0.59	0.57	0.58	0.56	0.55	0.51	0.54	0.51
Adj. for weight	0.57	0.52	0.54	0.52	0.55	0.49	0.51	0.47
Multivariable-adjusted *	0.44	0.44	0.42	0.41	0.38	0.38	0.35	0.33
Deattenuated ρ and 95% CI	0.62 (0.47, 0.73)	0.61 (0.47, 0.71)	0.5 (0.40, 0.58)	0.49 (0.40, 0.57)	0.49 (0.36, 0.60)	0.47 (0.36, 0.58)	0.37 (0.28, 0.45)	0.36 (0.27, 0.44)
Steps per day								
Crude					0.58	0.55	0.56	0.56
Adj. for weight					0.56	0.51	0.53	0.52
Multivariable-adjusted **					0.42	0.42	0.42	0.42
Deattenuated ρ and 95% CI					0.55 (0.41, 0.67)	0.56 (0.42, 0.66)	0.52 (0.43, 0.60)	0.53 (0.44, 0.61)
MVPA (Modified bouts of ≥ 10 min)								
Crude	0.39	0.36	0.37	0.34	0.33	0.29	0.29	0.25
Adj. for weight	0.33	0.29	0.35	0.31	0.25	0.22	0.24	0.21
Multivariable-adjusted *	0.18	0.18	0.24	0.21	0.12	0.11	0.13	0.1
Deattenuated ρ and 95% CI	0.18 (0.08, 0.29)	0.19 (0.09, 0.29)	0.21 (0.11, 0.31)	0.2 (0.11, 0.29)	0.08 (−0.02, 0.18)	0.09 (−0.01, 0.19)	0.13 (0.04, 0.22)	0.12 (0.02, 0.21)
MVPA (Including every minute)								
Crude	0.48	0.44	0.47	0.45	0.45	0.39	0.41	0.37
Adj. for weight	0.49	0.42	0.46	0.42	0.39	0.32	0.37	0.33
Multivariable-adjusted *	0.31	0.31	0.32	0.3	0.19	0.18	0.22	0.19
Deattenuated ρ and 95% CI	0.4 (0.28, 0.50)	0.39 (0.28, 0.49)	0.34 (0.25, 0.43)	0.34 (0.25, 0.42)	0.19 (0.09, 0.30)	0.18 (0.08, 0.29)	0.17 (0.08, 0.26)	0.16 (0.07, 0.25)
MVPA-1010/760 (Modified bouts of ≥ 10 min)								
Crude	0.51	0.51	0.5	0.49	0.48	0.46	0.45	0.43
Adj. for weight	0.48	0.46	0.46	0.46	0.44	0.41	0.42	0.4

	DLW MEASURES				DLW MEASURES			
	TDEE	PAEE	TDEE	PAEE	TDEE	PAEE	TDEE	PAEE
	Women		*Men*		*Women*		*Men*	
Accelerometer Variables	**Triaxial**				**Vertical Axis**			
Multivariable-adjusted*	0.43	0.42	0.4	0.39	0.31	0.31	0.32	0.3
Deattenuated ρ and 95% CI	0.61 (0.47, 0.72)	0.6 (0.47, 0.70)	0.48 (0.38, 0.56)	0.47 (0.38, 0.55)	0.36 (0.24, 0.46)	0.36 (0.25, 0.46)	0.35 (0.26, 0.44)	0.35 (0.26, 0.43)
MVPA-1010/760 (Including every minute)								
Crude	0.55	0.54	0.52	0.52	0.51	0.49	0.52	0.51
Adj. for weight	0.52	0.5	0.49	0.49	0.54	0.48	0.5	0.48
Multivariable-adjusted*	0.45	0.44	0.42	0.41	0.39	0.39	0.38	0.36
Deattenuated ρ and 95% CI	0.66 (0.51, 0.77)	0.64 (0.51, 0.74)	0.5 (0.41, 0.58)	0.5 (0.41, 0.58)	0.55 (0.41, 0.66)	0.54 (0.41, 0.64)	0.38 (0.29, 0.46)	0.38 (0.29, 0.46)
Accelerometer-estimated PAEE**								
Crude	0.57	0.54	0.55	0.53	0.56	0.54	0.57	0.55
Adj. for weight	0.56	0.5	0.52	0.5	0.57	0.52	0.54	0.51
Multivariable-adjusted*	0.42	0.41	0.4	0.38	0.42	0.43	0.39	0.38
Deattenuated ρ and 95% CI	0.59 (0.45, 0.70)	0.58 (0.45, 0.68)	0.46 (0.37, 0.55)	0.46 (0.37, 0.54)	0.59 (0.45, 0.70)	0.58 (0.45, 0.68)	0.43 (0.35, 0.52)	0.43 (0.34, 0.51)
Accelerometer-estimated PAEE (constant)**								
Crude	0.6	0.58	0.6	0.58	0.56	0.55	0.58	0.56
Adj. for weight	0.57	0.53	0.55	0.54	0.57	0.52	0.54	0.52
Multivariable-adjusted*	0.44	0.44	0.42	0.41	0.43	0.43	0.4	0.39
Deattenuated ρ and 95% CI	0.6 (0.45, 0.71)	0.59 (0.46, 0.69)	0.51 (0.42, 0.59)	0.51 (0.41, 0.59)	0.6 (0.46, 0.70)	0.59 (0.46, 0.69)	0.45 (0.36, 0.53)	0.45 (0.36, 0.53)

TDEE: total daily energy expenditure (kcal/kg/day); PAEE: physical activity energy expenditure (kcal/kg/day); MVPA: Min/day of moderate-to-vigorous physical activity; MVPA-1010/760: Min/day of MVPA using thresholds of 1010 counts/min (triaxial) or Matthews' cut point of 760 counts/min (vertical axis).

*Adjusted for weight, age, wear time, and fat free mass

**PAEE: physical activity energy expenditure (kcal/kg/day) from the Sasaki (triaxial) and Freedson (vertical axis) prediction equations using extrapolation to estimate METs for light-intensity activity; PAEE (constant): physical activity energy expenditure (kcal/kg/day) from the Sasaki (triaxial) and Freedson (vertical axis) MET prediction equations using a constant 2.0 METs for light-intensity activity.

Table 4

Spearman Correlation Coefficients between total activity counts and other accelerometer measures

	Triaxial Activity Counts		Vertical AxisActivity Counts	
	Women	Men	Women	Men
Steps per day				
Crude	0.89	0.86	0.86	0.82
Multivariable-adjusted *	0.83	0.82	0.79	0.77
MVPA (Modified bouts of ≥ 10 min)				
Crude	0.63	0.69	0.63	0.73
Multivariable-adjusted *	0.56	0.67	0.6	0.71
MVPA (Including every minute)				
Crude	0.86	0.88	0.84	0.9
Multivariable-adjusted *	0.83	0.87	0.79	0.89
MVPA-1010/760 (Modified bouts of ≥ 10 min)				
Crude	0.91	0.9	0.87	0.88
Multivariable-adjusted *	0.92	0.9	0.86	0.88
MVPA-1010/760 (Including every minute)				
Crude	0.95	0.92	0.95	0.92
Multivariable-adjusted *	0.94	0.91	0.93	0.9
PAEE				
Crude	0.99	0.99	0.98	0.98
Multivariable-adjusted *	0.99	0.99	0.97	0.97
PAEE (constant)				
Crude	0.97	0.97	0.94	0.95
Multivariable-adjusted *	0.96	0.96	0.92	0.94

MVPA: Min/day of moderate-to-vigorous physical activity; MVPA-1010/760: Min/day of MVPA using thresholds of 1010 counts/min (triaxial) or Matthews' cut point of 760 counts/min (vertical axis); PAEE: physical activity energy expenditure (kcal/kg/day) from the Sasaki (triaxial) and Freedson (vertical axis) prediction equations using extrapolation to estimate METs for light-intensity activity; PAEE (constant): physical activity energy expenditure (kcal/kg/day) from the Sasaki (triaxial) and Freedson (vertical axis) MET prediction equations using a constant 2.0 METs for light-intensity activity.

* Adjusted for weight, age, wear time, and fat-free mass