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Measurement of Active and Sedentary Behavior in Context of Large Epidemiologic Studies

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Abstract

Introduction/Purpose—To assess the utility of measurement methods that may be more accurate and precise than traditional questionnaire-based estimates of habitual physical activity and sedentary behavior we compared the measurement properties of a past year questionnaire (AARP) and more comprehensive measures: an internet-based 24-hour recall (ACT24), and a variety of estimates from an accelerometer (ActiGraph).

Methods—Participants were 932 adults (50–74 y) in a 12-month study that included reference measures of energy expenditure from doubly labeled water (DLW) and active and sedentary time via activPAL.

Results—Accuracy at the group level (mean differences) was generally better for both ACT24 and ActiGraph than the AARP questionnaire. AARP accuracy for energy expenditure ranged from –4 to –13% lower than DLW, but its accuracy was poorer for physical activity duration (–48%) and sedentary time (–18%) vs. activPAL. In contrast, ACT24 accuracy was within 3 to 10% of DLW expenditure measures and within 1 to 3% of active and sedentary time from activPAL. For ActiGraph, accuracy for energy expenditure was best for the Crouter 2-regression method (–2 to

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Conflicts of Interest

The authors have no financial conflicts of interest regarding the results of this research.

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–7%), and for active and sedentary time the 100 count/minute cut-point was most accurate (–1% to 2%) at the group level. One administration of the AARP questionnaire was significantly correlated with long-term average from the reference measures ($\rho_{XT}=0.16-0.34$) overall, but 4 ACT24 recalls had higher correlations ($\rho_{XT}=0.48-0.60$), as did 4-days of ActiGraph assessment ($\rho_{XT}=0.54-0.87$).

Conclusion—New exposure assessments suitable for use in large epidemiologic studies (ACT24, ActiGraph) were more accurate and had higher correlations than a traditional questionnaire. Use of better more comprehensive measures in future epidemiologic studies could yield new etiologic discoveries and possibly new opportunities for prevention.

Keywords

accelerometer; calibration; exercise; measurement error; posture; sitting

INTRODUCTION

Epidemiologic studies utilizing questionnaire-based measures of habitual moderate-vigorous intensity exercise (e.g. in past year) and highly prevalent sedentary behaviors such as television viewing have provided essential evidence that physical inactivity is associated with increased risk for early mortality, cardiometabolic diseases (1, 2), and several cancers (1). While questionnaires have identified many activity-disease associations supporting development of physical activity recommendations (1), they have two basic problems that limit further progress. First, questionnaires are subject to considerable measurement error resulting from the cognitive challenges involved with accurately reporting one's long-term average of complex behaviors that vary substantially within and between days and by season, e.g., (3, 4). Second, questionnaires employed in most cohorts do not assess the full spectrum of sedentary behaviors or lower intensity activities of everyday living (3, 5); distinct classes of behavior that may have relevant health effects. In prospective studies these two problems result in the underestimation of the strength of the observable associations (attenuation), false negative results (6), and limit our ability to test critical hypotheses about behaviors that are not routinely measured (5).

Rapid development of wearable sensors and mobile communication technologies has dramatically reshaped the potential for measuring human behavior in large-scale epidemiologic studies, possibly offering solutions to these exposure assessment problems. Both accelerometer-based (7, 8) and previous day recall instruments (9, 10) often have higher validity than questionnaire-based measures of these behaviors (11), and both methods can measure the full spectrum of daily activities. Taking advantage of new technologies to apply better measures in future studies could lead to stronger associations and less controversy, expansion of our already extensive evidence-base, and ultimately fresh opportunities for prevention. However, the improvements in fidelity associated with these new measures for estimating long-term average behaviors compared to questionnaires is uncertain, and differences in the measurement properties between accelerometer-based measures and previous-day recalls are not well characterized.

Thus, our primary objective was to examine the measurement properties of a past year questionnaire; an internet-based previous day recall; and measures derived from the ActiGraph accelerometer—all compared to high quality reference measures of energy expenditure (12) and sedentary and physically active time from activPAL. A secondary objective was to describe the measurement properties of historically relevant ActiGraph calibration methods.

METHODS

Study Design

The **I**nteractive **D**iet and **A**ctivity **T**racking in **A**ARP (iDATA) study was designed to evaluate a variety of diet and physical activity measures suitable for use in epidemiologic studies. Participants were a convenience sample of AARP members (50–74 years) from Pittsburgh, PA who spoke English, had internet access, were not on a weight-loss diet, had a body mass index (BMI) < 40 kg/m², and were free of major medical conditions and mobility limitations. Initial contact was made via automated phone call and invitation letter directing those interested to contact the study (see Figure, SDC 1, Participant recruitment). The study was approved by the NCI Special Studies Institutional Review Board. All participants signed informed consent and those who completed the full study received \$450. Participants visited the study center up to 3 times over 12-months and completed several diet and physical activity measurements. Figure 1 shows the physical activity measurement schedule for group one (see Tables for full measurement schedule, SDC 2, Schedule for Group 1; SDC 3, Schedule for all Groups). A more extensive description of our methods is provided elsewhere (see Text, SDC 4, Detailed Methods).

Reference Measures

Doubly Labeled Water (DLW) and Resting Energy Expenditure (REE)—Total energy expenditure (TEE) was measured via DLW (12) using established methods (13, 14). The method is accurate compared to indirect calorimetry ($\pm 2\%$) with an individual level precision of 5 to 7%. REE_{pred} was estimated using the Mifflin-St. Jeor equation (15), developed on 498 adults (19–78 years; $R^2=0.71$). It has been cross-validated in men and women (20–78 yrs) classifying 82% of non-obese adults within 10% of measured REE (16). Thirty-two participants repeated TEE and REE_{pred} measures (6-months apart).

activPAL—activPAL 3D (PAL Technologies, Glasgow, SCT) is an accelerometer worn on the mid-right thigh. It estimates time spent lying, sitting, standing, stepping, and non-wear time. Participants were asked to wear it continuously (24-hours) for 7 consecutive days and to record the date/time they got out of bed in the morning and into bed each night to determine the “waking day”. Sedentary behavior was estimated as time sitting or lying during the waking day, and active time as the sum of standing and stepping, consistent with recent Sedentary Behavior Research Network definitions/concepts (17). This approach assumes that behaviors done while standing are in the physically active category. Accuracy for posture in laboratory settings is 90%–100% (18), and there is strong agreement ($R^2=0.94$ – 0.96) vs. direct observation in free-living studies (10, 19). Two 7-day administrations were obtained six-months apart (Figure 1).

Test Measures

AARP Physical Activity and Sedentary Behavior Questionnaire—This questionnaire asked, during the past 12 months, how much time participants spent in sleep, physical activity and sitting. The physical activity questions include 8 items focused on exercise and sports that have been evaluated previously (20), and 8 focused on non-exercise activities (e.g., household chores, lawn and garden, daily walking; see Figure, SDC 5, AARP Physical Activity Questionnaire). Sitting and non-exercise portions of the survey have not been evaluated previously, but have been associated with mortality (21). The AARP survey was administered twice, 6-months apart (Figure 1).

Activities Completed Over Time in 24 Hours (ACT24)—ACT24 is an internet-based previous-day recall designed to estimate total time (hrs/d) spent sleeping (in bed), sedentary, and in physical activity, and to estimate energy expenditure associated with these behaviors (MET-hrs/d). Building on content and methods developed and refined previously (6, 10), we developed a self-administered internet-based recall that captures details about individual behaviors over 24-hours. To complete ACT24, respondents select from more than 200 individual activities, record the duration of each, and answer pertinent follow-up questions including body position (see Image, SDC 6, ACT24 Screen-shot). Sedentary behaviors were defined as those performed during the waking day (out of bed) while sitting or reclining and that require little energy expenditure (typically < 1.8 METs). In contrast, active behaviors were those involving an upright posture, or performed in any posture with higher MET levels. Participants were cued via email to complete up to six recalls during the 12-month study, one recall every other month (Figure 1). Further ACT24 information is available on request.

ActiGraph Measures—ActiGraph (model GT3X) is a triaxial accelerometer and participants were asked to wear the monitor on the right hip for 7-days from the time they got out of bed for the day until they went to bed for the night. It was initialized to record tri-axial acceleration in 1-s epochs with the low-frequency extension enabled. On/off logs were used to confirm wear dates, estimate the waking day, and the Choi algorithm was used to estimate non-wear time during this period. We selected scoring methods reflecting the evolution of the underlying ActiGraph technology and its calibration methods over last 20 years (22–27). See Table, SDC 7, Detailed description of ActiGraph calibration methods). Two expenditure prediction equations were derived from calibration studies that used ambulatory activities to develop linear equations from 60-second epoch acceleration signals from the vertical (Freedson, (22)) or 3-dimensional axes (Sasaki, (23)). Two equations were calibrated to a broad range of activities and used shorter epochs and more sophisticated modeling. The Crouter method (24) applies two-regression equations developed from 18 activities to estimate energy expenditure from activity counts (vertical axis). Sojourn 3x (Soj3x) (25) employs three-dimensional acceleration features from 1 second epochs and hybrid machine-learning and neural networks trained on approximately 30 activities (28) to classify behaviors and estimate energy expenditure. Sedentary and active time was estimated from Crouter and Soj3x and two cut-point methods; 100 counts/min vertical axis (100VT; (26)) and 200 counts/min, vector magnitude (200VM) (27). We also calculated time spent in non-sedentary light (< 3 METs) and moderate-vigorous intensity activity (3+ METs) using

the above methods, and common cut-points (22, 29). Two 7-day ActiGraph administrations were obtained six-months (Figure 1).

Accounting for Monitor Non-wear and Missing Time on Self-Report Instruments

To minimize differences between measures due to non-wear time during the waking day, we imputed values for this time on valid monitor days. During the mean 15.8 hrs/d waking day reported, activPAL recorded 0.7 non-wear hrs/d, while the ActiGraph recorded 1.9 non-wear hrs/d. For valid activPAL and ActiGraph days, we imputed values for active and sedentary time and energy expenditure in proportion to time recorded in sedentary, light, and moderate-vigorous intensity activity during the waking day for each monitor. ACT24 missing time was minimal (0.005 hrs/d), so no adjustments were made. Missing time on the AARP Questionnaire was so large (6.2 hrs/d) that we felt there was inadequate information for meaningful imputation. See Figure, SDC 8, Description of imputation results.

Calculation of Indices for Total and Physical Activity Energy Expenditure

We calculated TEE from the test measures using their energy cost estimates (MET-hrs) for time in bed (sleeping), sedentary, and in physical activity using REE_{pred} from the Mifflin-St Jeor equation, including an addition of 10% of TEE for the thermic effect of food. For all measures, PAEE was calculated as $PAEE = (TEE \times 0.9) - REE_{pred}$; physical activity index (PAI) as $PAI = PAEE / \text{body mass}$ (30). We also calculated physical activity levels ($PAL = TEE / REE_{pred}$).

Statistical Methods

First, for our reference measures we described the mean (SD) of their summary metrics and evaluated their variation over 6-months using correlations. Second, to assess the overall accuracy of our test measures at the group level we calculated the mean (SD) of all available data for each measure and then calculated mean differences (SD) between these values and our reference measures (DLW, 1 administration; activPAL, mean of all valid days) and conducted t-tests of these differences. We then modeled the error structure of each test instrument using the replicate measures of each (i.e., replicate administrations of AARP and replicate days of observation for ACT24 and ActiGraph) while accounting for intra-individual variation in our reference measures. To do so, we assumed each instrument's objective was to estimate the long-term (yearly) average of the summary metric (e.g. PAEE). Let T_j be the true long term average. Then, we modeled the test instrument's value of that metric at time j as Q_{ij}

$$Q_{ij} = \beta_0 + \beta_1 T_i + R_i + \varepsilon_{ij} \quad (1)$$

where $T_i \sim N(\mu_T, \sigma_T^2)$ is a random variable representing the true yearly average, $R_i \sim N(0, \sigma_R^2)$ is a random variable representing person-specific bias and $\varepsilon_{ij} \sim N(0, \sigma_\varepsilon^2)$ is a random variable representing intra-individual variability and measurement error. We then estimated model parameters: bias (β_0), slope (β_1), and relevant variances including total

variance ($V = \beta_1^2 \sigma_T^2 + \sigma_R^2 + \sigma_\varepsilon^2$), and the percent of variance attributable to person-specific bias ($P_R = 100 \sigma_R^2 / V$) and random error ($P_\varepsilon = 100 \sigma_\varepsilon^2 / V$).

We estimated these parameters by incorporating information from the reference instruments. We modeled the reference instrument's value at time j as F_{ij}

$$F_{ij} = T_i + U_{ij} \quad (2)$$

where $U_{ij} \sim N(0, \sigma_U^2)$ is a random variable representing intra-individual variability and measurement error. Then the combined data follows a multivariate normal described by equations (1) and (2). For example, if we consider DLW and the AARP questionnaire as the reference and test instruments, the data for an individual with two measures from each instrument would follow equation (3)

$$\begin{bmatrix} Q_{i1} \\ Q_{i2} \\ F_{i1} \\ F_{i2} \end{bmatrix} \sim N \left(\begin{bmatrix} \beta_0 + \beta_1 \mu_T \\ \beta_0 + \beta_1 \mu_T \\ \mu_T \\ \mu_T \end{bmatrix}, \begin{bmatrix} \sigma_r^2 + \sigma_e^2 + \beta_1^2 \sigma_T^2 & \sigma_r^2 + \beta_1^2 \sigma_T^2 & \beta_1 \sigma_T^2 & \beta_1 \sigma_T^2 \\ \sigma_r^2 + \beta_1^2 \sigma_T^2 & \sigma_r^2 + \sigma_e^2 + \beta_1^2 \sigma_T^2 & \beta_1 \sigma_T^2 & \beta_1 \sigma_T^2 \\ \beta_1 \sigma_T^2 & \beta_1 \sigma_T^2 & \sigma_T^2 + \sigma_U^2 & \sigma_T^2 \\ \beta_1 \sigma_T^2 & \beta_1 \sigma_T^2 & \sigma_T^2 & \sigma_T^2 + \sigma_U^2 \end{bmatrix} \right) \quad (3)$$

We can obtain estimates by maximizing the complete likelihood (over all subjects and replicate measures) using the mle function in R and obtain standard errors by the bootstrap procedure. When the test and reference instrument occurred during overlapping time periods (i.e., same day of activPAL and ActiGraph measures), we allowed the error terms, U_{ij} and ε_{ij} , to be correlated. Note, this approach incorporates the sub-group with replicate DLW measures and the number of measures per subject can differ across subjects. We then estimated the correlation, ρ_{TX} , between X replicates of the test instruments (i.e., number of AARP administrations or days of ACT24 and ActiGraph), and the true yearly average

$$\rho_{TX} = \frac{\beta_1 \sigma_T^2}{\sqrt{(\beta_1^2 \sigma_T^2 + \sigma_R^2 + \sigma_\varepsilon^2 / X) \sigma_T^2}}$$

and we estimated the corresponding attenuation factor, λ_X ,

$$\lambda_X = \frac{\beta_1}{\beta_1^2 + \sigma_R^2 / \sigma_T^2 + (\sigma_\varepsilon^2 / X) / \sigma_T^2}.$$

As X increases, random error is reduced and the correlation and the attenuation factors increase.

RESULTS

A total of 932 participants completed baseline measures and had valid reference measures for TEE (n=689) or activPAL (n=932), see Table 1. From 9,553 valid activPAL days we had

a mean of 10.3 days/participant. There were 5,009 valid ACT24 recalls (5.4 recalls/participant (SD=1.1)), 24.2 episodes (SD=7.9) of sedentary and active behaviors per recall, and median completion time was 30 minutes. There were 8,731 valid ActiGraph days, and a mean of 9.3 (SD=3.5) days per participant. Evaluation of intra-individual variability over 6-months in our reference instruments revealed TEE from DLW to be relatively stable for all participants ($r=0.81$), but physical activity indices were more variable ($r=0.57-0.65$; see Table, SDC 9, Six-month correlations). Using the mean of valid days in each period, activPAL stability was $r=0.62$ to 0.65 overall. Stability was marginally higher in men than women for both reference measures.

Average accuracy (mean differences) of TEE reported on AARP and ACT24 were similar to DLW (within 3–4%), while ActiGraph TEE measures ranged from –21% to –2% lower than DLW (Table 2). In terms of PAEE, PAL, and PAI, accuracy for AARP and ACT24 was often similar, but AARP underestimated activity duration by 48% and sedentary time by 18%, while ACT24 was within 1–3% of activPAL values. The most accurate ActiGraph expenditure estimates were from Crouter, while 100VT was most accurate for active and sedentary time. Overall, the accuracy for ACT24 and ActiGraph measures were better than AARP, and ACT24 and ActiGraph methods were often comparable. We also examined accuracy by sex and BMI and did not find large consistent differences in both reference measures (see Tables, SDC 10, Mean differences by sex; SDC 11, Mean differences by BMI; SDC 12, Correlations in all participants and by sex).

Next, using measurement error models we evaluated the ability of test instruments to estimate the yearly average of each metric (Table 3). Comparing self-report methods across all metrics, the AARP questionnaire had flatter slope terms reflecting larger amounts of systematic error (i.e., less sensitivity) than did ACT24, particularly for active and sedentary time. ACT24 also had less person-specific bias than AARP, but a single ACT24 recall usually had more random error. Better results, larger slope terms and less person-specific bias and random error, were also noted for ActiGraph in comparison to AARP. ACT24 and ActiGraph often had comparable slope terms (except for PAL) and person-specific bias, but random error was greater for ACT24.

We then evaluated correlations between the long-term average from our reference measures and a given number of replicates of each test instrument. Although one administration (replicate) of AARP had significant positive correlations for physical activity and sedentary behavior overall ($\rho_{TX}=0.16-0.34$; see Table C, just 1 day (replicate) of ACT24 or ActiGraph had equal or higher correlations ($\rho_{TX}=0.33-0.66$). Four ACT24 recalls had substantially higher correlations overall ($\rho_{TX}=0.48-0.60$), as did 4 days of ActiGraph ($\rho_{TX}=0.54-0.87$). There were differences in patterns of correlation in men and women (Figure 2). For expenditure metrics, AARP correlations were higher in men than women, while for ACT24 and ActiGraph the reverse was true. Among women there was more variation in strength of the correlations between ACT24 and ActiGraph, with device-based measures having higher correlations than ACT24, but there were minimal differences in men. Comparing strength of the correlations between older simpler ActiGraph calibration methods (Freedson, 100VT) to newer and more sophisticated methods (Crouter, Soj3x), the correlations were modestly

stronger in women for newer methods, but differences in correlation strength between older and newer methods were not evident in men.

Next, to describe the impact of measurement error induced attenuation in the context of an epidemiologic study we calculated attenuation factors (λ_x ; see Table, SDC 13, Attenuation factors by sex) and the associated reduction in observable relative risk, assuming a true RR of 4.0 (i.e., $RR_{obs}=4.0^{\lambda_x}$). Sex differences here were generally small and inconsistent across test instruments, so we present results for all participants (Figure 3). A single administration (replicate) of the AARP questionnaire would find $RR_{obs}=1.36$ – 1.38 for physical activity and only an $RR_{obs}=1.10$ for sedentary time when the true association was 4.0. In contrast, 4 ACT24 replicates would find $RR_{obs}=1.84$ – 1.87 for both physical activity and sedentary time, while 4 ActiGraph replicates would find $RR_{obs}=2.03$ – 2.64 . Freedson PAEE estimates unexpectedly produced attenuation factors greater than 1.0 due to flattened slope terms and total variance values that were lower than the DLW measures, resulting in $RR_{obs} > 4.0$ (Figure 2, top panel).

To evaluate light and moderate-vigorous intensity activity (hrs/d) from AARP and ACT24 we made comparisons to Soj3x by averaging all available data for each instrument. For light and moderate-vigorous activity mean values were: Soj3x, 4.58 and 1.96 hrs/d; AARP, 1.13 and 1.97 hrs/d; and ACT24, 4.19 and 1.93 hrs/d, respectively (see also SDC Figure 2). Pearson correlations with Soj3x were lower for AARP (Light, $r=0.23$; moderate-vigorous, $r=0.25$) compared to ACT24 (Light, $r=0.34$; moderate-vigorous, $r=0.47$).

DISCUSSION

In this free-living evaluation of three distinct exposure assessment methods suitable for use in large epidemiologic studies, we found evidence of significant correlations for a past-year questionnaire (AARP), but this instrument underestimated physical activity duration by 48% and sedentary time by 18%. In comparison, an internet-based previous-day recall (ACT24) and an accelerometer (ActiGraph) provided better accuracy, perhaps because of their more complete coverage of common daily activities, and these instruments also were more strongly correlated with the reference measures. In addition, the lower measurement error in ACT24 and ActiGraph were predicted to result in less attenuation in observed risk estimates compared to the AARP questionnaire. Notably, ACT24 often had correlations of similar strength as ActiGraph, although the accelerometer was predicted to produce less attenuated risk estimates. Overall, these findings suggest that either ACT24 or accelerometer-based measures of long-term average behavior may overcome the two major limitations of traditional physical activity questionnaires. Below, we discuss findings for our self-report measures (AARP, ACT24), the ActiGraph, and then all methods in context of possible application in future epidemiologic studies.

Questionnaires which rely on long-term recall to assess habitual behaviors have been the mainstay of physical activity epidemiology, and their weaknesses have been widely discussed (e.g., (4, 5)). Nevertheless, consistent with previous studies (5, 31–33) the AARP questionnaire demonstrated some utility for ranking participants, with significant correlations ranging from 0.33 for PAEE to 0.16 for sedentary time with one administration.

However, the limited accuracy at the group level for total physical activity duration (−48%) and sitting time (−18%) suggests incomplete assessment of these behaviors and points to challenges in translating etiologic associations derived from this tool to public health practice. Two studies recently evaluated more comprehensive physical activity and sedentary time questionnaire and reported marginally higher correlations with PAEE from DLW of $r=0.40$ (34) and $r=0.46$ (32), and a correlation of $r=0.27$ for sedentary time vs. accelerometer (32). Correlations for the AARP-based measures of sedentary time were lower but in-line with those derived from a single sitting time question vs. activPAL (35). In contrast, ACT24 had minimal bias (<10%) and just 4 replicates had higher correlations for PAEE ($r=0.53$), active time ($r=0.58$), and sedentary time ($r=0.60$) than the AARP survey. These findings are in-line with other previous day recall studies in adults (10, 36). Overall, our findings suggest that ACT24 can produce estimates of physical activity and sedentary time that have less bias and are more strongly correlated with strong reference measures than traditional questionnaires, presumably because it is more accurate for participants to report what they did yesterday than what they did last year.

Our results for ActiGraph were also stronger than those for AARP, although there were substantial differences in accuracy of the monitor-based estimates depending on the processing/calibration method evaluated. Otherwise, our ActiGraph results for rank-ordering participants (correlations) were largely consistent with previous studies. They also suggest that newer calibration methods provided modest improvements over earlier methods for this purpose. Jeran and colleagues (37) systematically reviewed 19 accelerometer-DLW studies and reported a median correlation for PAEE of $r=0.50$, primarily from first generation accelerometers using simple summary metrics (e.g., activity counts). Here, we focus on correlations for 4 replicate days of monitor wear for comparability with previously discussed ACT24 results. Evaluating PAEE, the Crouter (24) and Soj3x (25) methods calibrated with 18 to 30 and activities of everyday living including walking and running, coupled with more sophisticated prediction models had modestly stronger correlations ($r=0.64$ – 0.65) than methods which employed only linear models derived from 3 ambulatory activities (Freedson, $r=0.59$; Sasaki, $r=0.54$). There was a suggestion of marginally higher correlations for active and sedentary time for methods that used 3-dimensional acceleration signals (Sasaki, Soj3x) compared to methods using vertical acceleration (100VT, Crouter). Both of these findings are consistent with Lyden (25) who used direct observation as a reference. Similarly, Kim (38) reported validity estimates (ϕ) for sedentary time of 0.89, 0.72, 0.61, and 0.54 for activPAL, Soj3x, 100VT, and Crouter, respectively using a wearable camera for reference. Newer movement metrics derived from raw acceleration signals compared to the activity count-based methods we used here have shown better performance in a laboratory studies (e.g., (39)), but rigorous testing of these methods in free-living study samples vs. strong reference measures remains limited, making comparison to this study difficult. Interestingly, we found that the most sophisticated calibration/modeling method (Soj3x) had modestly higher correlations than simpler methods in women, but not in men. Reasons for this are not clear, but it may be that the suite of activities employed by Soj3x was a better match for the daily activities of women than men. Additional research is needed to confirm and better understand this finding, and to understand the potential improvements associated with modeling raw acceleration data.

Studies that have employed measurement error models to estimate attenuation factors for questionnaires are relatively few, and variation in the questionnaires tested, measurement error models fit, and the reference measures employed makes comparison challenging. To simplify comparison between previous studies and this one, we calculate RR_{obs} for a true RR of 4.0 using attenuation factors reported in previous studies (i.e., $RR_{obs}=4.0^\lambda$). Spiegelman (40) compared a past year questionnaire to 28-days of physical activity diaries and reported results consistent with $RR_{obs}=1.52$ ($\lambda=0.30$), while Ferrari (41) compared a past year questionnaire to both activity diaries and an accelerometer using structural equation modeling and reported results consistent with a $RR_{obs}=1.20$ ($\lambda=0.13$). These findings are in line with the current study. In contrast, Tooze (33) compared a questionnaire that assessed the last 30 days to PAL measured by DLW and reported data consistent with $RR_{obs}=2.75$ ($\lambda=0.73$) in men and an $RR_{obs}=1.82$ ($\lambda=0.43$) in women. It may be that shorter recall periods (30-days) are reported more accurately than longer recall periods of one year. Collectively, these findings and our results suggest that either ACT24 or ActiGraph measures can identify stronger true associations than past year questionnaires.

Decisions about whether ACT24 or an accelerometer are optimal for future studies depend on the etiologic question of interest and the resources available to administer the measures in large populations. Such studies can be very large (e.g., $N=200,000$) and often strive to enroll participants in a short time-period (e.g., 3 years). In this context, rates of accrual can exceed 1,000 participants per week, which requires a substantial allocation of study resources to complete accelerometer-based measures in all participants. While ACT24 has better measurement properties than many questionnaires and would provide greater contextual detail about specific types of activity than ActiGraph, the more sophisticated accelerometer measures had less overall error and would provide more granular time-stamped data. Accelerometers are being implemented in increasingly large studies such as the UK Biobank ($n\sim 100,000$), but the costs of administering devices in such studies can still be a major challenge and ACT24 could be a less expensive alternative. The present study demonstrated that it is possible to collect large numbers of high quality self-administered previous-day recalls using ACT24, but additional research is needed to refine and optimize its application in larger prospective studies.

This study had several strengths and limitations. Its strengths include a large sample-size and a 12-month study period, use of two strong reference measures which largely provided convergent results, evaluation of two different approaches to self-report and a variety of ActiGraph data analysis methods specifically selected to represent evolution of the device over 20 years. Although our modeling approach accounted for intra-individual variation in our reference measures and allowed us to test measures on a per replicate basis, the modest sample-size for the DLW replicates could have reduced our precision of the intra-individual variation in these measures. Additionally, we imputed non-wear time during the waking day so that differences observed between instruments would reflect the underlying measurement properties of each instrument, rather than differences in missing/non-wear time. See SDC Figure 2 for comparison of the original and adjusted mean duration values. Imputation had minimal impact on the correlation and attenuation results. Further limitations include use of: a convenience sample of healthy mostly non-obese adults; only one physical activity questionnaire to assess past year behavior; and only one type of accelerometer worn on the

waist that did not collect raw acceleration data. Also, our comparisons of activPAL and ActiGraph were for total duration of sedentary and physically active time accumulated over the day. It may be that the pattern of accumulation as measured by each instrument was more different than our results for total duration indicates. Last, the reference measure (Soj3x) we used to evaluate ACT24 and AARP for light and moderate-vigorous intensity activity has only limited validity information for these metrics (25), so our results should be interpreted accordingly.

In conclusion, in this large study evaluating three different methods for measuring physical activity and sedentary behavior we found evidence that the AARP questionnaire can rank order participants but that physically active and sedentary time were substantially underestimated, perhaps due to incomplete coverage of these behaviors. In contrast, replicate measures of a previous-day recall (ACT24) and an accelerometer (ActiGraph) provided more accurate and thus more comprehensive estimates of these behaviors and had higher correlations and attenuation factors indicating less overall measurement error. This study provides important new evidence that new improved measures can overcome the two main limitations of traditional questionnaires that limit further progress in our field. Application of these new methods could lead to key scientific advances that would inform future public health recommendations.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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Measurement Schedule (for group 1)

Figure 1.
Measurement schedule over 12-months for group one participants, IDATA Study, Pittsburgh, PA, 2012–2013

Figure 2.
Correlations for Each Test Instrument, by Sex and Number of Replicate Measures, IDATA Study, Pittsburgh, PA, 2012–2013
References measures for PAEE and PAI were from DLW
References measures for Active and Sedentary time were from activPAL

Figure 3.
Relative Risk Observed with Measurement Error for True Association of 4.0 for Each Test Instrument, by Number of Replicate Measures, IDATA Study, Pittsburgh, PA, 2012-201

Participant Characteristics and Description for Reference Measure Values, IDATA Study, Pittsburgh, PA, 2012–2013

Table 1

	All participants			Men			Women			<i>P</i>
	Mean	SD		Mean	SD		Mean	SD		
<i>Participant characteristics</i>										
Age (yrs)	63.2	5.9		64.2	5.7		62.3	6.0		<0.01
Height (cm)	169.4	9.3		176.1	6.9		162.8	6.1		<0.01
Weight (kg)	81.0	16.3		88.4	14.7		73.6	14.2		<0.01
BMI (kg/m ²)	28.1	4.7		28.5	4.3		27.7	5.0		<0.01
REE _{pred} (kcal/d)	1478	259		1673	178		1286	167		<0.01
Weight change (kg)	−0.13	3.40		−0.27	3.45		0.0	3.5		0.24
<i>Doubly labeled water (first administration)</i>										
Total energy expenditure (TEE, kcal/d)	2467	527		2781	483		2163	365		<0.01
Physical activity energy expenditure (PAEE, kcal/d)	743	337		828	372		660	277		<0.01
Physical activity level (PAL, units)	1.68	0.25		1.66	0.25		1.69	0.25		0.16
Physical activity index (PAL, kcal/kg/d)	9.40	4.32		9.53	4.47		9.28	4.17		0.44
<i>activPAL (all valid days)</i>										
Valid days (days)	10.3	3.6		10.1	3.6		10.4	3.5		0.30
Time out bed _{PALog} (hrs/d)	15.8	1.0		15.9	0.9		15.6	1.0		<0.01
Sedentary time (hrs/d)	9.8	1.8		10.2	1.7		9.4	1.7		<0.01
Active time (hrs/d)	6.0	1.7		5.7	1.7		6.2	1.7		<0.01
Steps (number/d)	7629	3115		7884	3221		7379	2991		0.01

Participant characteristics, N=932 All participants; n=461 Men; n=471 Women

Doubly labeled water, n=689 All participants; n=339 Men; n=350 Women

activPAL, N=932 All participants; n=461 Men; n=471 Women

P = test of differences by sex

Population Mean and Mean Differences Comparing Reference and Test Measures, IDATA Study, Pittsburgh, PA, 2012–2013

Table 2

Metric	Measures	N	Mean	SD	Mean difference	SD difference	Percent difference
Total energy expenditure (kcal/d) (TEE from DLW)	Reference	689	2467	527			
	AARP	619	2368	563	-103	485	-4%
	ACT24	683	2548	534	83	382	3%
	AG Freedson	683	2268	411	-199	328	-8%
	AG Sasaki	683	1941	383	-527	335	-21%
	AG Crouter2	683	2421	474	-47	327	-2%
	AG Soj3x	683	2288	457	-180	320	-7%
	Reference	689	743	337			
	AARP	619	652	386	-93	436	-12%
	ACT24	683	816	305	75	344	10%
Physical activity energy expenditure (kcal/d) (PAEE = TEE - REE _{pred})	AG Freedson	683	563	142	-179	295	-24%
	AG Sasaki	683	268	189	-474	302	-64%
	AG Crouter2	683	701	239	-42	294	-6%
	AG Soj3x	683	581	226	-162	288	-22%
	Reference	689	1.68	0.25			
	AARP	619	1.61	0.28	-0.07	0.33	-4%
	ACT24	683	1.73	0.20	0.05	0.25	3%
	AG Freedson	683	1.54	0.08	-0.14	0.23	-8%
	AG Sasaki	683	1.32	0.14	-0.36	0.22	-22%
	AG Crouter2	683	1.64	0.16	-0.04	0.22	-2%
Physical activity index (kcal/kg/d) (PAI = PAEE/body mass(kg))	AG Soj3x	683	1.55	0.15	-0.13	0.22	-8%
	Reference	689	9.4	4.3			
	AARP	619	8.3	4.8	-1.2	5.5	-13%
	ACT24	683	10.2	3.5	0.8	4.2	9%
	AG Freedson	683	7.1	1.6	-2.3	3.8	-25%
	AG Sasaki	683	3.4	2.4	-6.0	3.8	-64%
	AG Crouter2	683	8.8	2.8	-0.6	3.7	-7%
	AG Soj3x	683	7.3	2.7	-2.1	3.6	-22%
	Reference	932	6.0	1.7			
Physical activity time (hrs/d)							

Metric	Measures	N	Mean	SD	Mean difference	SD difference	Percent difference
(activPAL, standing or stepping)	AARP	842	3.1	1.8	-2.8	2.2	-48%
	ACT24	923	6.1	2.1	0.2	1.9	3%
	AG 100VT	924	6.1	1.5	0.1	1.5	2%
	AG 200VM	924	7.8	1.7	1.9	1.5	31%
	AG Crouter	924	8.9	1.6	3.0	1.5	50%
	AG Soj3x	924	6.5	1.6	0.6	1.4	10%
Sedentary time (hrs/d) (activPAL, sitting or lying down)	Reference	932	9.8	1.8			
	AARP	842	8.0	3.3	-1.8	3.5	-18%
	ACT24	923	9.9	2.2	0.1	2.0	1% [*]
	AG 100VT	924	9.7	1.6	-0.1	1.5	-1% [*]
	AG 200VM	924	8.0	1.7	-1.8	1.5	-18%
	AG Crouter2	924	6.9	1.6	-2.9	1.5	-30%
	AG Soj3x	924	9.3	1.6	-0.5	1.4	-6%

SD difference = SD of difference scores

Percent difference = mean difference/reference mean

AG = ActiGraph

^{*} indicates non-significant difference from reference measure, $p > 0.05$

Reference measures for DLW are first administration, while values for activPAL are averages of all valid days

Table 3

Measurement Properties of Long-term Average of Test Instruments Compared to Reference Measures, IDATA Study, Pittsburgh, PA, 2012–2013

Reference measure	Metric/Test Measure	Variance of Test Instrument	Intercept (β_0)	Slope (β_1)	Person-specific bias (R_i , %)	Random error (ϵ_i , %)
<i>DLW</i> (<i>n</i> =689)	Total Energy (kcal/d)					
	AARP	335595 (27303)	411 (176)	0.79 (0.07)	35.85 (4.35)	22.2 (2.92)
	ACT24	399666 (22129)	208 (165)	0.95 (0.07)	15.42 (3.65)	34.9 (1.58)
	Freedson	183732 (9202)	357 (201)	0.77 (0.08)	19.81 (7.43)	8.08 (0.51)
	Sasaki	183144 (9844)	184 (151)	0.71 (0.06)	16.29 (5.12)	23.23 (1.4)
	Crouter2	281945 (14476)	166 (139)	0.91 (0.06)	12.73 (4.49)	22.68 (1.27)
	Soj3x	255284 (13485)	118 (182)	0.88 (0.07)	13.31 (5.50)	20.71 (1.10)
	PAEE (kcal/d)					
	AARP	163649 (14022)	283 (75)	0.49 (0.10)	51.94 (4.92)	37.44 (4.13)
	ACT24	183627 (12666)	336 (86)	0.64 (0.12)	23.25 (3.60)	61.49 (2.76)
<i>PAI</i> (kcal/kg/d)	Freedson	30150 (1800)	314 (68)	0.33 (0.09)	35.66 (7.35)	39.93 (1.96)
	Sasaki	64581 (40209)	-42 (118)	0.41 (0.16)	29.29 (8.82)	53.46 (4.50)
	Crouter2	102157 (6421)	224 (106)	0.63 (0.14)	23.48 (5.41)	50.74 (2.48)
	Soj3x	87131 (4750)	136 (91)	0.59 (0.12)	24.56 (5.79)	49.25 (2.77)
	AARP	25.99 (2.31)	3.37 (1.06)	0.51 (0.11)	51.04 (4.48)	37.12 (3.75)
	ACT24	25.44 (1.51)	4.63 (0.79)	0.59 (0.09)	19.63 (2.94)	65.03 (2.71)
	Freedson	4.12 (0.26)	3.36 (0.84)	0.39 (0.09)	23.27 (7.49)	47.57 (2.46)
	Sasaki	10.42 (0.46)	-0.79 (0.93)	0.44 (0.10)	27.17 (4.96)	52.90 (2.10)
	Crouter2	14.82 (0.77)	3.35 (1.02)	0.57 (0.11)	21.93 (5.01)	54.49 (2.54)
	Soj3x	12.95 (0.76)	2.05 (1.04)	0.55 (0.11)	22.72 (5.54)	52.27 (2.99)
<i>PAL</i> (TEE/REE)	AARP	0.09 (0.01)	0.81 (0.20)	0.47 (0.12)	51.67 (4.53)	39.35 (3.79)
	ACT24	0.08 (0.01)	0.86 (0.24)	0.52 (0.14)	19.86 (3.28)	69.16 (2.27)
	Freedson	0.01 (0.00)	0.04 (0.19)	0.89 (0.11)	0.00 (2.11)	56.86 (2.86)
	Sasaki	0.04 (0.00)	0.59 (0.31)	0.43 (0.19)	28.73 (7.51)	54.10 (2.69)
	Crouter2	0.05 (0.00)	0.01 (0.37)	0.97 (0.22)	7.33 (8.00)	57.73 (2.44)

Reference measure	Metric/Test Measure	Variance of Test Instrument	Model Results			
			Intercept (β_0)	Slope (β_1)	Person-specific bias (R_i , %)	Random error (ϵ_{ij} , %)
<i>activPAL</i> (<i>n</i> =932)	Soj3x	0.04 (0.00)	0.69 (0.35)	0.51 (0.21)	23.94 (8.58)	55.78 (2.68)
	Active time (hrs/d)					
	AARP	3.43 (0.19)	1.28 (0.26)	0.30 (0.05)	61.68 (3.28)	31.23 (3.19)
	ACT24	8.13 (0.26)	1.52 (0.25)	0.76 (0.04)	18.64 (1.82)	63.46 (2.00)
	100VT	4.29 (0.15)	2.97 (0.2)	0.52 (0.03)	24.31 (1.97)	59.63 (2.37)
	200VM	5.48 (0.19)	3.73 (0.24)	0.68 (0.04)	22.25 (2.37)	56.65 (2.02)
	Crouter	5.03 (0.17)	5.54 (0.23)	0.57 (0.04)	24.89 (1.96)	59.16 (2.02)
	Soj3x	4.89 (0.16)	2.36 (0.2)	0.69 (0.03)	19.31 (2.35)	56.29 (1.84)
	Sedentary time (hrs/d)					
	AARP	13.47 (0.68)	4.38 (0.85)	0.36 (0.08)	31.29 (5.10)	66.04 (5.18)
	ACT24	9.30 (0.28)	2.01 (0.49)	0.81 (0.05)	15.78 (1.86)	66.01 (2.42)
	< 100VT	5.27 (0.18)	3.74 (0.38)	0.61 (0.04)	22.78 (1.92)	58.23 (1.91)
	< 200VM	5.94 (0.21)	1.01 (0.41)	0.72 (0.04)	21.23 (2.67)	55.63 (2.33)
	Crouter	5.08 (0.15)	1.06 (0.38)	0.59 (0.04)	24.81 (1.98)	56.72 (2.06)
	Soj3x	5.43 (0.19)	2.24 (0.31)	0.72 (0.03)	17.95 (2.01)	56.61 (1.83)