Using Devices to Assess Physical Activity and Sedentary Behavior in a Large Cohort Study: The Women's Health Study

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In recent years, it has become feasible to use devices for assessing physical activity and sedentary behavior among large numbers of participants in epidemiologic studies, allowing for more precise assessments of these behaviors and quantification of their associations with health outcomes. Between 2011–2015, the Women's Health Study (WHS) used the Actigraph GT3X+ device to measure physical activity and sedentary behavior over seven days, during waking hours, among 17,708 women (M_{age}, 72 years) living throughout the United States. Devices were sent to and returned by participants via mail. We describe here the methods used to collect and process the accelerometer data for epidemiologic data analyses. We also provide metrics that describe the quality of the accelerometer data collected, as well as expanded findings regarding previously published associations of physical activity or sedentary behavior with all-cause mortality during an average follow-up of 2.3 years (207 deaths). The WHS is one of the earliest "next generation" epidemiologic studies of physical activity, utilizing wearable devices, in which long-term follow-up of participants for various health outcomes is anticipated. It therefore serves as a useful case study in which to discuss unique challenges and issues faced.

Keywords: accelerometers, activity classification, epidemiology, health outcomes, validation

Physical activity helps prevent non-communicable diseases, the major cause of death in the United States (US), and insufficient activity has been estimated to cause as many deaths globally each year as does smoking (Lee et al., 2012). Current guidelines, released by the US Department of Health and Human Services in 2008, advise adults to engage in at least 150 minutes/week of moderate-intensity aerobic physical activity and to perform muscle-strengthening exercises at least two days per week (U.S. Department of Health and Human Services, 2008). Since evidence-based guidelines should not remain static but evolve as the evidence base grows, any new information for helping to determine whether guideline modifications are needed is crucial.

The 2008 guidelines were based primarily on findings from studies investigating clinical outcomes (e.g., cardiovascular disease [CVD] or cancer). These studies, requiring large numbers of participants followed for long duration, largely relied on self-reported physical activity. Self-reports are more reliable and valid for activities of moderate-to-vigorous intensity physical activity (MVPA) than light-intensity physical activity (LPA; Pettee Gabriel et al., 2009); thus, epidemiologic studies of physical activity and

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clinical outcomes on which the 2008 guidelines relied typically assessed MVPA only (Physical Activity Guidelines Advisory Committee, 2008). As a consequence, current physical activity guidelines do not recommend LPA because few data are available, rather than because the available evidence indicates no benefit of LPA on clinical outcomes.

Since the 2008 guidelines, developments in technology have made it feasible to assess physical activity more precisely using accelerometers in large numbers of individuals, at reasonable cost (Lee & Shiroma, 2014; Troiano, McClain, Brychta, & Chen, 2014). Accelerometers can objectively assess LPA and can also measure sedentary behavior, both of which are common among older persons (Evenson, Buchner, & Morland, 2012), whose numbers are anticipated to rise rapidly in coming decades. Presently, there are few data from longitudinal studies on whether device-assessed LPA is beneficial for health (in particular, clinical outcomes), independently of MVPA, and conversely, whether sedentary behavior is detrimental.

To provide additional information, we initiated the collection of accelerometer-assessed physical activity and sedentary behavior in a large cohort of women participating in the Women's Health Study, who are being followed longitudinally for long-term health outcomes. In this article, we describe the methodology for accelerometer data collection and reduction, as well as expand on previously published findings for the associations of physical activity and sedentary behavior with all-cause mortality (Lee et al., 2018).

Methods

Study Design and Participants

The Women's Health Study (WHS) was a randomized trial testing low-dose aspirin and vitamin E for preventing cancer and CVD among 39,876 women aged ≥ 45 years throughout the US from 1992–2004 (Cook et al., 2005; Lee et al., 2005; Ridker et al., 2005). When the trial ended in 2004, women were invited to continue in an observational study and 33,682 (89% of those alive) consented.

From 2011–2015, an ancillary prospective cohort study that assessed physical activity using accelerometers was conducted. Among 29,494 women who were alive in 2011, 18,289 (62%) agreed to participate, 1,456 (5%) were ineligible because they were unable to walk outside the home without assistance, 6,931 (23%) declined, and the remaining 2,818 (10%) did not respond to the invitation. Of the 18,289 women who agreed to participate, 17,708 wore and returned their devices, while 581 lost theirs. Data were downloaded from the devices of 17,466 of the 17,708 women; no data were available from the other 242 (device failure).

Of the 17,466 women with data, 17,062 (97.7%) had data recorded for at least 10 hours on at least one day. For the present analyses, only women who wore the device for at least 10 hours/day on at least four days (conventional standard for compliant wear (Tudor-Locke, Camhi, & Troiano, 2012)) are included ($n = 16{,}741$; 95.8%). Women provided written consent to participate, and the study was approved by the Brigham and Women's Hospital's institutional review board committee.

Assessment of Wear Time, Physical Activity, and Sedentary Behavior

Participants were mailed a triaxial accelerometer (ActiGraph GT3X+, ActiGraph Corp) and asked to wear this on their hip for seven consecutive days, removing it only during sleep and water-based activities. The devices were set to record accelerations at 30 Hz. Participants returned their devices by mail. Additionally, they were asked to complete a log detailing dates and times of wear. Because there had been little experience with large-scale studies previously, it was unclear how best to obtain valid estimates of wear time in as many participants as possible (i.e., distinguishing true physical activity from movement of devices occurring during the mail process).

Among women who returned both their device and log, ≤ 2.2% were missing information on the log regarding whether the device was worn for the day, but up to 23.4% were missing information on other details of wear (time put on/off; AM/PM; Keadle, Shiroma, Freedson, & Lee, 2014). In a prior study, we investigated how to minimize the amount of missing data while providing valid estimates of wear time (Keadle et al., 2014). We compared different uses of the log data, as well as different wear time algorithms, and concluded that using logs to simply determine whether the device was worn on a particular day (yes versus no) and the Choi algorithm for triaxial data (Choi, Liu, Matthews, & Buchowski, 2011; Choi, Ward, Schnelle, & Buchowski, 2012) achieved the goal of maximizing the number of participants with valid wear time estimates.

In the WHS, a sizeable proportion of participants, 14%, returned their devices but not logs. To assess whether we would be able to use the data from the women without logs, we conducted a validation study (Shiroma, Kamada, Smith, Harris, & Lee, 2015). Two blinded reviewers visually examined daily accelerometer output and judged whether the device was worn on a particular day (worn versus not worn). We then compared reviewer judgement of worn/not worn against participant logs (reported worn versus not worn) of 197 women who returned both device and log. Inter-rater agreement for whether the device was worn on a particular day was 99.5%; sensitivity was > 99% and specificity was at least 97%. We therefore concluded that visual inspection of accelerometer output data from women not returning a log could be used to validly determine the days on which a participant did wear the device.

For the present analyses, data were downloaded in 60-second epochs. We defined MVPA as any activity where the accelerometer vector magnitude, a summary measure of triaxial accelerations, was ≥ 2,690 counts per minute (cpm) and LPA was 200–2,689 vector magnitude cpm (Sasaki, John, & Freedson, 2011). Sedentary behavior was defined as activity < 200 vector magnitude cpm (Aguilar-Farias, Brown, & Peeters, 2014). For each woman, we calculated the average minutes per day spent in MVPA, LPA, and on sedentary behavior. Since there is presently no consensus on standard cutpoints (Migueles et al., 2017; Troiano et al., 2014), we chose these cutpoints as they were the first ones proposed for vector magnitude data, have been used in other studies (AlEssa et al., 2017; Chomistek et al., 2017), and a subsequent calibration study also yielded very similar cutpoints (Santos-Lozano et al., 2013). (In sensitivity analyses, we used lower cutpoints from a third calibration study (Evenson et al., 2015); details are provided below.)

Assessment of Potential Confounders

In the parent WHS, annual questionnaires solicited information on sociodemographic characteristics, health habits, and personal and family medical history. When women reported CVD and cancer, medical records were obtained to confirm the diagnoses (Cook et al., 2005; Lee et al., 2005; Ridker et al., 2005).

We obtained information from the questionnaire closest to the time the accelerometer was worn on weight, height, smoking, alcohol intake, post-menopausal hormone use, self-rated health, hypertension, high cholesterol, diabetes, CVD, cancer, cancer screening, and family medical history. Diet measured by a 131-item food frequency questionnaire was assessed at the start of the WHS.

Ascertainment of Mortality

Most deaths were reported by family members or postal authorities, and medical records and death certificates were obtained to confirm them. Other deaths were ascertained through the National Death Index. For the present study, women were followed through December 31, 2015 for mortality; in the WHS, mortality follow-up is > 99% complete (Shiroma, Sesso, Moorthy, Buring, & Lee, 2014).

Statistical Analyses

We first categorized women into quartiles of total accelerometer counts per day, a measure of overall volume (i.e., total amount) of physical activity, and compared characteristics of women across quartiles.

To investigate the associations of accelerometer-assessed physical activity or sedentary behavior with all-cause mortality, we used Cox proportional hazards models. The four accelerometer measures of interest were (1) total counts per day, and time per day in (2) MVPA, (3) LPA, and (4) sedentary behavior.

Initial models estimated hazard ratios (HRs) of mortality for quartiles of each measure, adjusting for age and accelerometer wear time (both continuous). A second model additionally adjusted for these potential confounders: smoking (never, past, current); alcohol intake (rarely, monthly, weekly, daily); intakes of saturated fat, fiber, fruit, and vegetables (quintiles of each); postmenopausal hormone therapy (never, past, current); self-rated health (excellent, very good, good, fair/poor); CVD; cancer; cancer screening; parental history of myocardial infarction before age 60 years; and family history of cancer (no, yes for each). A third model further adjusted for mediators through which physical activity influences mortality rates: body mass index (BMI; continuous); history of hypertension, high cholesterol, and diabetes (no, yes for each).

Because women who do a lot of LPA are likely to do more MVPA, we conducted additional analyses of LPA, adjusting for time in MVPA. Analogously, women who are highly sedentary tend to do little MVPA; additional analyses of sedentary behavior adjusted for time in MVPA. We could not adjust models simultaneously for time in LPA and sedentary behavior because they were highly correlated.

We conducted sensitivity analyses to evaluate the potential for "reverse causation" (i.e., spurious associations resulting from women who become sick or disabled and decrease their activity) by excluding women with CVD and cancer at the time of accelerometer wear, as well as those rating their health as fair or poor. A second sensitivity analysis used different, lower cutpoints for MVPA and LPA from a laboratory-based calibration study of women 60–91 years (MVPA, vector magnitude > 2,072 cpm; LPA, 73–2,072 cpm; sedentary behavior, < 73 cpm; Evenson et al., 2015).

In a last set of sensitivity analyses, we used restricted cubic spline functions to characterize any relationships (Desquilbet & Mariotti, 2010). Such functions have greater statistical power than categorical analyses, and also allow for formal testing of whether linear or non-linear relations exist. We used three knots, placed at the 5th, 50th, and 95th percentiles of distribution, as previously recommended (Desquilbet & Mariotti, 2010; Matthews et al., 2016).

All analyses were performed using SAS version 9.4.

Results

At the time that women were enrolled into the accelerometer component of the study, their mean age was 72.0 (*SD*, 5.7) years. All 16,741 women in the present analyses wore their device for at least 10 hours/day on at least four days (with 15,762, or 94.2% of the eligible sample, doing so on at least six days). Overall, participants wore the accelerometer for a mean of 14.9 (1.3) hours/day. The median time spent in MVPA was 28 minutes/day; LPA, 351 minutes/day; and sedentary behavior 503 minutes/day.

When women were divided into quartiles of accelerometer-assessed total counts/day, the most active women (highest quartile) spent a median of 68 minutes/day in MVPA, 427 minutes/day in LPA, and 415 minutes/day in sedentary behavior. The corresponding times for those least active (lowest quartile) were 8, 266, and 588 minutes/day, respectively. Exemplar plots showing minute-by-minute accelerometer data from a day of a random participant belonging to the most and the least active quartiles are shown in Figure 1.

Table 1 describes the characteristics of women by quartiles of total counts/day. Women in the higher quartiles had a healthier profile than those in the lower quartiles—they had lower BMI, were less likely to smoke, had a healthier diet, and lower prevalence of hypertension, high cholesterol, and diabetes. The more active women also had lower prevalence of CVD and cancer.

We then examined correlations among the different accelerometer measures (Table 2). Total counts were strongly and directly related to MVPA and LPA ($r = 0.7–0.9$), and strongly and inversely related to sedentary behavior ($r = –0.7$). LPA was strongly and inversely related to sedentary behavior ($r = –0.7$); therefore, any findings on sedentary behavior would be expected to mirror those for LPA but in the opposite direction.

Women were followed for an average of 2.3 years (range, 4 months to 4.6 years) during which 207 women died. As previously described (Lee et al., 2018), in analyses adjusting for age and wear time, total volume of physical activity was inversely related to mortality (Table 3). The HRs associated with increasing quartiles of total counts/day were 1.00 (referent), 0.67, 0.59, and 0.35, respectively; p, trend <.0001. Additional adjustment for potential confounders attenuated the associations to 1.00, 0.78, 0.73, and 0.44; p, trend = .002. Further adjustment for BMI, hypertension, high cholesterol, and diabetes shifted results to become more similar to initial findings adjusting for age and wear time only: 1.00, 0.69, 0.59, 0.32; p, trend <.0001.

For MVPA, there also was a strong and inverse association (reflecting its high correlation with total counts); in analyses that adjusted for potential confounders, the HRs for increasing quartiles of time in MVPA were 1.00, 0.61, 0.58, and 0.35; p, trend <.0001.

With regard to LPA, in age and wear time adjusted analysis, there was a significant inverse association (p, trend = .04). With adjustment for potential confounders, there remained a non-significant lower risk of mortality (highest versus lowest quartile HR = 0.84) which disappeared when MVPA time was controlled (HR =

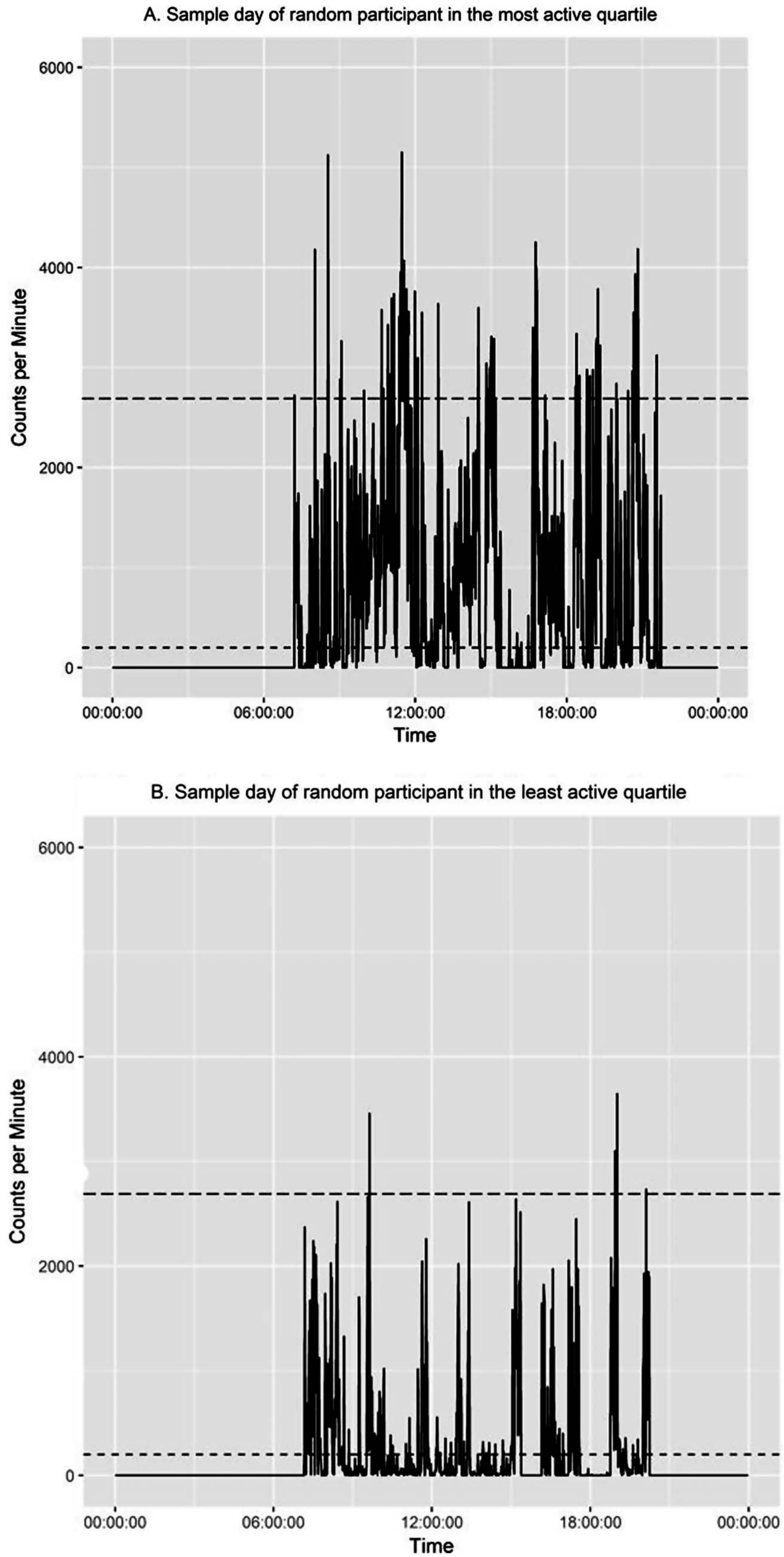

Figure 1 — Example of accelerometer-assessed counts by time of day for participant in (A) most active and (B) least active quartile. Upper dotted line is the cutpoint for moderate-to-vigorous intensity physical activity (2,690 vector magnitude counts per minute [cpm]); lower dotted line, the cutpoint for sedentary behavior (200 vector magnitude cpm).

Table 1 Baseline Characteristics by Quartiles of Accelerometer-Assessed Total Counts per Day, Women's Health Study

	Quartiles of Total Counts/Day			
	Q1 (Lowest)	Q2	Q3	Q4 (Highest)
	(*n* = 4,185)	(*n* = 4,185)	(*n* = 4,186)	(*n* = 4,185)
Mean age, y (*SD*)	74.5 (6.4)	72.4 (5.6)	71.2 (5.1)	70.0 (4.4)
Mean BMI, kg/m^2 (*SD*)	28.5 (5.8)	26.7 (4.9)	25.5 (4.4)	24.3 (3.7)
% smokers	5.0	3.8	3.1	2.3
% alcohol use	54.0	61.6	65.2	67.0
% using postmenopausal hormones	8.2	10.0	10.9	10.5
Mean saturated fat intake, g/d (*SD*)	21.0 (6.2)	20.5 (6.0)	20.4 (6.0)	19.9 (5.9)
Mean fiber intake, g/d (*SD*)	21.8 (6.9)	22.2 (7.0)	22.4 (7.5)	22.9 (7.0)
Mean servings of fruits and vegetables/d (*SD*)	6.5 (3.7)	6.7 (3.9)	6.8 (3.7)	6.9 (3.6)
% with history of hypertension	83.0	71.5	63.8	54.7
% with history of high cholesterol	80.3	75.3	71.6	66.1
% with history of diabetes	17.0	9.1	6.0	3.7
% with CVD	3.9	2.5	1.7	1.3
% with cancer	13.6	12.7	10.9	9.7
Median total counts/d, 1000's (IQR)	305.2 (253.6–345.1)	439.8 (410.1–467.9)	559.3 (528.9–594.6)	746.9 (682.9–844.1)
Median MVPA min/d* (IQR)	7.7 (4.0–13.3)	20.4 (13.3–29.3)	36.4 (26.0–47.1)	67.9 (51.7–86.7)
Median LPA min/d* (IQR)	265.5 (226.3–302.0)	336.1 (299.0–372.7)	379.2 (337.7–423.9)	427.4 (379.0–477.2)
Median sedentary min/d (IQR)	588.0 (533.0–641.9)	526.7 (476.3–575.4)	481.4 (432.5–529.6)	415.3 (362.6–467.7)

* MVPA = moderate-to-vigorous intensity physical activity; LPA = light-intensity physical activity.

Table 2 Correlations among Accelerometer Measures* of Physical Activity and Sedentary Behavior

	Total Counts	MVPA Min/d	LPA Min/d
Total counts	–	–	–
MVPA min/d	0.87	–	–
LPA min/d	0.73	0.36	–
Sedentary min/d	–0.66	–0.44	–0.70

* MVPA = moderate-to-vigorous intensity physical activity; LPA = light-intensity physical activity.

1.06). Parallel (but directionally opposite) findings were seen with sedentary behavior, the HRs for highest versus lowest quartile were 1.71 in age and wear time adjusted analysis, and 0.92 in multivariable analyses that included MVPA.

To expand on the previously published results, we conducted sensitivity analyses to minimize bias from poor health or disability. In these analyses, we excluded women with CVD and cancer, and those rating their health as fair or poor. After exclusion of these women (14,141 women; 123 deaths), the findings (data not shown) were similar to those from the main analyses. After adjusting for confounders, the HR (95% confidence interval) for highest versus lowest quartile of MVPA was 0.38 (0.20–0.73). After additionally adjusting for MVPA, the HR for the highest versus lowest quartile of LPA was 1.25 (0.72–2.16), while that for the highest versus lowest quartile of sedentary behavior was 0.80 (0.44–1.47).

A second sensitivity analysis using lower cutpoints to define MVPA and LPA (Evenson et al., 2015) did not affect conclusions (data not shown). Using these cutpoints, the median time among all women spent in MVPA now was 63 minutes/day; LPA, 399 minutes/day; and sedentary behavior 418 minutes/day. Across quartiles of accelerometer-assessed total counts/day, the most active women (highest quartile) now had a median of 123 minutes/day in MVPA, 456 minutes/day in LPA, and 328 minutes/day in sedentary behavior. The corresponding times for the least active (lowest quartile) now were 24, 323, and 512 minutes/day, respectively. The HRs for mortality comparing highest versus lowest quartiles were 0.52 (0.32–0.84) for MVPA (*p*, trend across quartiles = .005); 0.93 (0.61–1.42) for LPA (*p*, trend = .58); and 1.11 (0.66–1.84) for sedentary behavior (*p*, trend = .64).

In a last set of sensitivity analyses using restricted cubic splines, we confirmed a significant inverse dose-response relation that showed both linear ($p < .0001$) and non-linear ($p = .03$) shapes for MVPA, but no significant associations for either LPA (*p* for linear and non-linear components = .54 and .26, respectively) or sedentary behavior ($p = .47$ and .37, respectively).

Discussion

In the Women's Health Study, we found that it was feasible to use devices for assessing physical activity and sedentary behavior, with high quality data, among large numbers of participants (~18,000) from throughout the United States. In the initial findings regarding the associations of physical activity or sedentary behavior with all-cause mortality, we found a strong inverse relation (~60–70% reduction, comparing extreme quartiles) between overall volume of physical activity and all-cause mortality. This magnitude of rate reduction is larger than that estimated from meta-analyses of studies using self-reported physical activity (~20–30%; Lollgen, Bockenhoff, & Knapp, 2009; Woodcock, Franco, Orsini, & Roberts, 2011). The strong inverse association for overall volume of activity was primarily attributable to the strong inverse relation

Table 3 Hazard Ratios and 95% Confidence Intervals for All-Cause Mortality by Physical Activity and Sedentary Behavior

Accelerometer Measure*	No. of Cases/ No. of Women	Hazard Ratio (95% Confidence Interval)		
		Adjusted for Age and Wear Time	Additionally Adjusted for Confounders[a]	Additionally Adjusted for MVPA
Total counts/d				—
Q1 (lowest)	95/4185	1.00 (referent)	1.00 (referent)	
Q2	52/4185	0.67 (0.48–0.95)	0.79 (0.55–1.12)	
Q3	40/4186	0.59 (0.40–0.87)	0.73 (0.49–1.09)	
Q4 (highest)	20/4185	0.35 (0.21–0.58)	0.44 (0.26–0.74)	
p, trend		<.0001	.002	
MVPA min/d				—
Q1 (lowest)	111/4182	1.00 (referent)	1.00 (referent)	
Q2	43/4180	0.53 (0.37–0.76)	0.61 (0.42–0.88)	
Q3	35/4195	0.47 (0.32–0.71)	0.58 (0.38–0.87)	
Q4 (highest)	18/4184	0.27 (0.16–0.46)	0.35 (0.20–0.60)	
p, trend		<.0001	<.0001	
LPA min/d				
Q1 (lowest)	75/4186	1.00 (referent)	1.00 (referent)	1.00 (referent)
Q2	55/4186	0.79 (0.55–1.12)	0.89 (0.62–1.27)	0.97 (0.67–1.39)
Q3	37/4183	0.58 (0.38–0.86)	0.67 (0.44–1.02)	0.79 (0.52–1.21)
Q4 (highest)	40/4186	0.72 (0.48–1.08)	0.84 (0.56–1.29)	1.06 (0.69–1.64)
p, trend		.04	.23	.82
Sedentary min/d				
Q1 (lowest)	39/4185	1.00 (referent)	1.00 (referent)	1.00 (referent)
Q2	48/4185	1.24 (0.81–1.91)	1.15 (0.75–1.77)	0.97 (0.62–1.50)
Q3	63/4185	1.70 (1.13–2.57)	1.54 (1.02–2.33)	1.18 (0.77–1.82)
Q4 (highest)	57/4186	1.71 (1.10–2.66)	1.38 (0.88–2.16)	0.92 (0.56–1.50)
p, trend		.007	.09	.99

*MVPA = moderate-to-vigorous intensity physical activity; LPA = light-intensity physical activity.

[a]Smoking; alcohol; intakes of saturated fat, fiber, fruits and vegetables; hormone therapy; parental history of myocardial infarction; family history of cancer; general health; history of cardiovascular disease; history of cancer; cancer screening.

between MVPA and mortality; we did not find any associations of LPA or sedentary behavior with mortality after accounting for MVPA participation.

The present study is one of the "next generation" epidemiologic studies of physical activity, utilizing wearable devices—instead of self-report—for measurement and with anticipated long-term follow-up of participants after assessment (Bassett, Toth, LaMunion, & Crouter, 2017; Troiano et al., 2014). What unique information can these next generation studies provide, and what are some challenges? The WHS may be useful as a case study to examine several of these issues.

First, devices are able to provide more precise measurements in such studies, compared with self-reports. The present study also represents one of the first investigations of physical activity and long-term health outcomes using newer accelerometers that are capable of measuring activity along three planes. Several recent studies have used accelerometers to address associations with mortality (Diaz et al., 2017; Dohrn, Sjostrom, Kwak, Oja, & Hagstromer, 2017; Ensrud et al., 2014; Evenson, Wen, & Herring, 2016; Fishman et al., 2016; Koster et al., 2012; LaMonte et al., 2017; Loprinzi, Loenneke, Ahmed, & Blaha, 2016; Matthews et al., 2016; Schmid, Ricci, Baumeister, & Leitzmann, 2016; Schmid, Ricci, & Leitzmann, 2015), but most employed older devices that measured activity along one plane only. Using triaxial instead of uniaxial data increases the sensitivity for recognizing physical activity, detecting more time in LPA and less time in sedentary behavior (Keadle et al., 2014). Understanding the role of LPA in relation to health outcomes has been identified as a critical research gap (Physical Activity Guidelines Advisory Committee, 2018). The recently released 2018 Physical Activity Guidelines Advisory Committee Scientific Report noted under the needs for future research that: "The development and wide use of wearable monitors that permit quantification of light physical activity . . . now permit and promote a new series of investigations critical to the understanding of the role of total range of physical activity on health." (At the time of publication of this paper, while the scientific report was available, the 2018 guidelines for physical activity had not yet been developed.)

With regard to the findings on mortality presented above, there is broad congruence with data from the self-report studies of total physical activity and MVPA, although the present study noted larger magnitudes of association, likely reflecting the greater precision of physical activity measurement using devices. The strong inverse associations with total physical activity and MVPA broaden the evidence base supporting current guidelines that emphasize MVPA. We did not see any associations with LPA or sedentary behavior after accounting for MVPA participation, as noted by some but not all other device-assessment studies (Diaz et al., 2017; Dohrn et al., 2017; Ensrud et al., 2014; Evenson et al., 2016; Fishman et al., 2016; Koster et al., 2012; LaMonte et al., 2017; Loprinzi et al., 2016; Matthews et al., 2016; Schmid et al., 2016; Schmid et al., 2015). These different findings may reflect chance variation, non-adjustment for MVPA in some studies, the use of different devices, and population characteristics. As evidence accumulates from studies with device assessments, we will be able to form more definitive conclusions about the roles of LPA and sedentary behavior independent of MVPA, as well as in combination (e.g., will participation in sufficient amounts of MVPA offset deleterious effects—if any—from high amounts of sedentary behavior?)

Second, devices provide a recording of movement (accelerations) in real time over the day(s) they are worn. This allows for investigation of diurnal patterns. For example, preliminary cross-sectional analyses in the WHS assessed whether the time of day when exercise is performed—a highly discretionary aspect of behavior—may impact weight control. This was of interest because of circadian rhythms in hormones as well as their interaction with feeding. We found women who performed less of their total physical activity during the morning had higher odds of obesity compared with those who performed more (Chomistek, Shiroma, & Lee, 2016).

Third, device assessments allow for detailed examinations of patterns of activity over time, such as: How long are bouts of activity/sedentary behavior? Does activity occur regularly over the week, or is it accumulated over a few days (e.g., the "weekend warrior" pattern)? Such examination of patterns will enable investigators to address current questions of interest. Specific questions could include, for example: for the same amount of sedentary time, does it make a difference for health outcomes whether sedentary time occurs in fewer prolonged bouts, or many shorter bouts (Jefferis et al., 2018; Jefferis et al., 2015)? The "weekend warrior" pattern—of relevance since many individuals work during the week and may only have time for recreational physical activity during the weekend—has been investigated in relation to mortality using self-reported data (Lee, Sesso, Oguma, & Paffenbarger, 2004; O'Donovan, Lee, Hamer, & Stamatakis, 2017). Device measurements can provide more precise classification of this pattern and has recently begun to be used (Evenson, Herring, & Wen, 2017). As endpoints accrue in the continued follow-up of participants in the WHS, we will be able to address such patterns of activity in relation to different health outcomes. Future studies will examine bout duration and pattern in relation to mortality, as well as other long-term health outcomes.

While they yield major advantages, epidemiologic studies using wearable devices also face challenges. First, a major challenge is how to maximize use of the large amount of data collected. Presently, published studies of long-term health outcomes (primarily mortality) use cutpoints to demarcate different intensities of activity. There is no consensus on which cutpoints to use, although conventional standards do exist (Migueles et al., 2017). Further, proposed cutpoints have mostly been validated using older accelerometers that collect data along only one plane (vertical axis); few studies of triaxial accelerometers have been conducted. Cutpoints, while practical and easy to implement, do not make full use of the rich amount of data collected, and current efforts to maximize use of raw acceleration data, such as machine learning (Freedson, Lyden, Kozey-Keadle, & Staudenmayer, 2011; Staudenmayer, Pober, Crouter, Bassett, & Freedson, 2009), yield promise.

A second difficulty faced is the challenge of comparing/combining data across studies, since there is no consensus on standard protocols. The lack of standardization has resulted in protocols that use different wear times (waking hours vs. 24 hours), number of days of wear, and position of wear (hip vs. wrist; for wrist, dominant vs. non-dominant side). While conventional standards do exist (Tudor-Locke et al., 2012), the field would benefit from implementation of "best practice" standards.

Using accelerometers to measure sedentary behavior is a third challenge. Sedentary behavior is technically defined as any waking activity requiring low energy expenditure (≤1.5 METs) in the seated or reclining position (Tremblay et al., 2017). The GT3X+ used here does not assess posture well, but the WHS comprises older women; thus, periods recording no/low accelerations likely reflect seated/reclining positions rather than standing with little movement.

A fourth challenge is using appropriate analytic methods for behaviors that sum to 24 hours. That is, after excluding sleep time, time in sedentary behavior, LPA, and MVPA sum to total wear time. More time in sedentary behavior must displace time in another domain (likely LPA, given the correlations observed) and vice versa. Methods to address this, such as the use of isotemporal models or compositional data analyses, have been proposed (Buman et al., 2014; Chastin, Palarea-Albaladejo, Dontje, & Skelton, 2015).

A final challenge relates not so much to the measurement of behavior, but the follow-up of participants. Almost all epidemiologic studies using devices rely on funding mechanisms that are not permanent (e.g., five-year research grants). As a consequence, the vast majority of published studies with device measurements of behavior are cross-sectional. For example, a large number of cross-sectional studies have examined device-assessed sedentary behavior in relation to biomarkers, primarily cardiometabolic markers. In a recent systematic review of biomarker studies among older adults aged 60 years and older, 14 used objective assessments of sedentary behavior of which 11 (79%) were cross-sectional (Wirth et al., 2016). Another systematic review among all adults aged 18 years and older included 29 accelerometer studies, 25 (85%) of which employed a cross-sectional design (Brocklebank, Falconer, Page, Perry, & Cooper, 2015). These biomarker studies provide some evidence—more consistent in cross-sectional than prospective cohort or experimental studies—of decreased adiposity, better glycemic control, higher HDL, and lower triglycerides with less sedentary behavior. While biomarker studies provide complementary data to data from studies of long-term health outcomes, improved biomarkers do not always translate to better clinical outcomes (Look Ahead Research Group et al., 2013). The major limitation to cross-sectional studies of biomarkers is of course the temporal relationship of findings; that is, it is impossible to differentiate in such studies whether physical activity improved biomarkers, or whether healthy individuals—with better biomarkers—were able to be more active.

Apart from serving as a case study, the present study adds meaningfully to existing data due to its large sample size of compliant participants, use of triaxial accelerometer data, and investigation of a clinical outcome. The overall participation rate among eligible women was 63% (17,708 / 29,494 – 1,456). This rate compares favorably with the rates of participation in other studies that have used devices to measure physical activity and sedentary behavior (e.g., 44% in the UK Biobank study [Doherty et al., 2017]; 50% in the REGARDS study [Howard et al., 2015]). Since WHS women are primarily white and of higher socioeconomic status, it is desirable for the findings described above to be replicated in more diverse samples. Follow-up time in the present study was short; in the future, with longer follow-up, the increased numbers of different health endpoints will yield greater statistical power for analyses.

In conclusion, the WHS represents an example of a large, mail-based epidemiologic cohort study, with participants followed over the long term, where it is possible to collect high quality data on physical activity and sedentary behavior using devices. The data from this study, as well as other epidemiologic studies with device measurements of behavior, are crucial for informing the evidence base on which physical activity guidelines are based.

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