An Evaluation of Accelerometer-derived Metrics to Assess Daily Behavioral Patterns

SARAH KOZEY KEADLE[1,2], JOSHUA N. SAMPSON[3], HAOCHENG LI[4], KATE LYDEN[5], CHARLES E. MATTHEWS[1], and RAYMOND J. CARROLL[6,7]

[1]Metabolic Epidemiology Branch, Division of Cancer Epidemiology and Genetics, National Cancer Institute, Bethesda, MD; [2]Cancer Prevention Fellowship Program, Division of Cancer Prevention, National Cancer Institute, Bethesda, MD; [3]Biostatistics Branch, Division of Cancer Epidemiology and Genetics, National Cancer Institute, Bethesda, MD; [4]Departments of Oncology and Community Health Sciences, University of Calgary, Alberta, CANADA; [5]Misfit Inc., San Francisco, CA; [6]Department of Statistics, Texas A&M University, College Station, TX; and [7]School of Mathematical and Physical Sciences, University of Technology Sydney, AUSTRALIA

ABSTRACT

KEADLE, S. K., J. N. SAMPSON, H. LI, K. LYDEN, C. E. MATTHEWS, and R. J. CARROLL. An Evaluation of Accelerometer-derived Metrics to Assess Daily Behavioral Patterns. *Med. Sci. Sports Exerc.*, Vol. 49, No. 1, pp. 54–63, 2017. **Introduction**: The way physical activity (PA) and sedentary behavior (SB) are accumulated throughout the day (i.e., patterns) may be important for health, but identifying measurable and meaningful metrics of behavioral patterns is challenging. This study evaluated accelerometer-derived metrics to determine whether they predicted PA and SB patterns and were reliably measured. **Methods**: We defined and measured 55 metrics that describe daily PA and SB using data collected by using the activPAL monitor in four studies. The first two studies were randomized crossover designs that included recreationally active participants. Study 1 experimentally manipulated time spent in moderate-to-vigorous-intensity PA and sedentary time, and study 2 held time in exercise constant and manipulated SB. Study 3 included inactive participants who increased exercise, decreased sedentary time, or both. The study conditions induced distinct behavioral patterns; thus, we tested whether the new metrics could improve the prediction of an individual's study condition after adjusting for the overall volume of PA or SB using conditional logistic regression. In study 4, we measured the 3-month reliability for the pattern metrics by calculating intraclass correlation coefficients in a community-dwelling sample who wore the activPAL monitor twice for 7 d. **Results**: In each of the experimental studies, we identified new metrics that could improve the accuracy for predicting condition beyond SB and moderate-to-vigorous-intensity PA volume. In study 1, 23 metrics were predictive of a highly active condition, and in study 2, 24 metrics were predictive of a highly sedentary condition. In study 4, the median intraclass correlation coefficients (25–75th percentiles) of the metrics were 0.59 (0.46–0.65). **Conclusions**: Several new metrics were predictive of patterns of SB, exercise, and nonexercise behavior and are moderately reliable for a 3-month period. Applying these metrics to determine whether daily behavioral patterns are associated with health-outcomes is an important area of future research. **Key Words:** PHYSICAL ACTIVITY, EPIDEMIOLOGY, MEASUREMENT, ASSESSMENT, SEDENTARY BEHAVIOR

People who are more physically active have improved longevity and lower risk of chronic diseases (11). To date, the majority of research has focused on associations between the amount of time (i.e., volume) spent in sedentary (21,32), light-intensity (21), and moderate-to-vigorous-intensity physical activity (MVPA) (1) and health. However, recent evidence from controlled experimental trials suggests that the pattern by which activity is accumulated may also be related to health, even when accounting for the total volume of activity (4,13,38). The historical emphasis on sedentary and physical activity volume was pragmatic because the primary method of assessment was self-report questionnaires, from which accurately assessing the frequency and duration of active or sedentary bouts is probably impossible (26).

In contrast to questionnaires, wearable sensors (e.g., accelerometers) can collect and store dense data (i.e., 100 samples per second) for a period of many days or weeks, allowing a detailed examination of the duration and frequency of different postures and/or intensities of activity within a day. Given the dense and multidimensional data within a day of accelerometer data, there is a large and possibly infinite number of metrics that could be extracted from accelerometer data to describe the interrelated components (e.g., frequency, duration, and intensity) of physical behavior (8). Together, these components

Address for correspondence: Sarah Kozey Keadle, Ph.D., M.P.H. Metabolic Epidemiology Branch, Division of Cancer Epidemiology and Genetics, National Cancer Institute, 9609 Medical Center, Dr 6E-318, Bethesda, MD 20892-7335; E-mail: sarah.keadle@nih.gov.
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characterize the total volume of daily activity and inactivity (8,43), and throughout this manuscript, we will use the term *daily behavioral patterns* to refer to these components. Descriptive studies have used metrics that may reflect daily behavioral patterns, including time spent active or sedentary within various bout lengths (e.g., 1,5,10, and 20 min) (3,12,20,41). Other studies have identified associations between several accelerometer-derived metrics (e.g., number of breaks, Gini index, and bouts of sedentary time >20 min) in relation to obesity and metabolic health (5,18,19,44), and differences in sedentary behavioral patterns have been noted in cross-sectional analysis comparing healthy and diseased populations (6,36). Understanding whether there are links between daily behavioral patterns and health could lead to innovative opportunities for intervention and improve public health. An important step is to determine whether there are measurable accelerometer-based metrics that describe daily behavioral patterns that can be used in etiologic studies. To date, few studies have systematically evaluated whether accelerometer-based metrics provide an added benefit for characterizing daily behavioral patterns beyond standard volume metrics, or whether the metrics can be reliably measured.

The purpose of this paper is to first develop a broad list of metrics of activity and sedentary behavior using activPAL™ (AP) accelerometer data and then to test these metrics in two ways. First, we examined if the new metrics improve a model's ability to predict behavioral patterns beyond what is possible using total volume alone. To do this, we used three experimental studies that manipulated sedentary behavior, exercise, and nonexercise activities in physically active and sedentary adults. Second, we examined the within-person variation for a 3-month period in a community-based sample using intraclass correlation coefficient (ICC). Results from this study will inform the design and interpretation of future studies that explore etiologic associations between daily behavioral patterns and risk of disease.

METHODS

We first developed a list of physical activity and sedentary time metrics from an AP accelerometer, based on previously published literature (3,6,12,20,41). We also developed several novel approaches to AP data extraction through discussions among coauthors and considering relevant literature. We used data from three experimental trials conducted in Amherst, MA, to test whether the metrics could discriminate between behavioral patterns beyond standard volume measures. In a community-based observational study from Amherst, MA, and Nashville, TN, we examined how stable the metrics are within a person by comparing two measurement periods that were 3 months apart. The AP measurement protocol for physical activity and sedentary time (described in the next section) was similar across studies. All participants completed informed consent documents that were approved by the Institutional Review Boards at the University of Massachusetts, Amherst, and Vanderbilt University.

Measurement of Sedentary Time and Physical Activity

The AP is a small device worn on the thigh that uses information about static and dynamic acceleration to distinguish sitting/lying, standing, and stepping. It has been validated for assessing sitting, breaks from sitting, and steps in both laboratory and free-living environments (23,30). The AP software produces an event file that includes time-stamped rows (events) that are classified as sitting or lying, standing, or stepping. For each event, there is also an estimated MET value. We defined sedentary as time spent sitting or lying while awake and active time as time spent standing or stepping. Study participants reported time in/out of bed on a monitor log, and this was used in combination with a modified version of the Choi algorithm (9) to define monitor "wear time," which excluded time in bed/sleeping (24,28).

Metric development. We considered seven previously defined and commonly used metrics that are related to volume (e.g., total sedentary time, total MVPA time, steps per day, and MET-hours). We next defined a set of 48 metrics; of these, 20 metrics were related to sedentary behavior (e.g., breaks from sitting, proportion of sedentary bouts greater than 20 min). We also extracted 16 metrics related to nonexercise activities, including standing and light-intensity (<3 METs) activity and 12 that are related to MVPA. For MVPA, we further distinguished between MVPA guidelines, defined as activity ≥3 METs for at least 10 consecutive minutes, allowing for 2 min below the 3-MET threshold, and sporadic MVPA defined as any 15-s interval that was higher than 3 METs. All metrics were computed for each participant on each day of wear and are described in detail as Supplemental Digital Content (see Table, Supplemental Digital Content 1, Description of physical activity and sedentary metrics, http://links.lww.com/MSS/A738). Broadly, the sedentary and activity metrics were categorized as follows:

1. Duration and number of bouts: these are based on the summation of time spent in bouts of activity/sedentary behavior above a certain threshold (e.g., total sitting time in bouts longer than 20 min).
2. Event distribution: For each participant on each day, the durations of the sedentary event at the 5th, 25th, 50th, 75th, and 95th percentiles were extracted and then repeated for active events. We also computed an alpha-statistic for overall sedentary and active time defined as ($1 + 1/M$), where M is the mean of log (sedentary or active) bout length/minimum sedentary and active bout length. This is an equivalent rearrangement of the equation from Chastin and Granat (7). We also computed the Gini index for active and sedentary events (7).
3. Proportions: these metrics assess the proportion of overall sedentary or active time that is spent in a particular bout length (e.g., proportion of total sedentary time that is in bouts of at least 20 min). We also computed the ratio between standing and stepping time.

An R package (PAactivPAL) is available for researchers to generate these metrics (46).

Experimental studies. To ensure that a range of behavioral patterns were evaluated, we used three experimental studies that manipulated different aspects of exercise, nonexercise, and sedentary time in both active and inactive individuals. The first two studies were randomized crossover designs where recreationally active participants completed three experimental conditions. Study 1 was designed to be consistent with activity levels defined in the 2008 physical activity guidelines and manipulated time spent in exercise and nonexercise activities. Study 2 held time in exercise constant and manipulated sedentary time. The study 3 included overweight, inactive participants who increased exercise, decreased sedentary time, or both. The basic study designs and descriptive characteristics for studies 1–3 are shown in Table 1.

Study 1: The study population included healthy, recreationally active individuals (mean ± SD, age = 25.2 ± 5.7 yr, BMI = 24.9 ± 4.3 kg·m^{-2}) (28–30). The three conditions, completed in a random order, were as follows: 1) *sedentary noEX + highSED*—no structured exercise, remain sedentary throughout the day, and achieve <5000 steps per day; 2) *moderately active (modEX)*—complete 150 min·wk^{-1} of moderate-intensity physical activity (and/or 75 min·wk^{-1} of vigorous activity), step-goal of 10,000 per day, and no recommendations regarding sedentary behavior; and 3) *very-active (highEX + lowSED)*—complete double current recommended physical activity guidelines (i.e., 300 min·wk^{-1} of moderate and/or 150 min·wk^{-1} vigorous activity) and decrease sedentary time with a step goal of 15,000 per day (28).

Study 2 was a randomized crossover design with three conditions that increased or decreased sedentary time among regular exercisers (mean ± SD, age = 25.5 ± 4.8 yr, BMI = 24.8 ± 5.1 kg·m^{-2}). In all three conditions, participants were instructed to do an identical amount of structured exercise (~30 min·d^{-1}). For example, if on day 2 of the baseline week they ran 30 min, they were asked to run 30 min on day 2 of each of the next conditions. Sedentary and active time were experimentally manipulated in the conditions as follows: 1) *baseline (EX + base)*—participants could exercise and sit as they typically would with no recommendations for physical activity or sedentary time; 2) *high-sedentary (EX + highSED)*—participants were instructed to sit as much of the day as possible when not exercising; or 3) *low-sedentary (EX + lowSED)*—participants were instructed to stand as much of the day as possible when not exercising. The order of conditions two and three was randomized.

Study 3 was a four-arm randomized trial that was conducted among overweight individuals with sedentary occupations who did not exercise (mean ± SD, age = 43.2 ± 5.4 yr, BMI = 35.3 ± 5.1 kg·m^{-2}). Participants were randomized to one of four groups: 1) *control*—maintain behavior (sedentary work, no exercise); 2) *exercise (EX)*—structured moderate-intensity exercise 5 d·wk^{-1} for 40 min per session; 3) *reduce sedentary time* (rSED)—increase steps by ~10% per week, break-up sedentary time, and reduce sitting without structured exercise; and 4) *EX-rSED*—exercise 5 d·wk^{-1} for 40 min and reduce sitting time. Additional details have been previously published (24,25). For the present analyses, we defined the intervention period as weeks 6, 9, and 12 and took the mean value for each metric for that period.

Study 4: To assess whether each metric captures a reproducible quantity that differs among individuals, we used data from an observational study that assessed physical activity in 400 community-dwelling individuals at two time periods that were 3 months apart. Participants were between 12 and 75 yr, fluent in English, and free of debilitating chronic diseases (e.g., heart failure, severe claudication, and terminal cancer), major cognitive or psychiatric disorders (e.g., dementia and schizophrenia), and major orthopedic problems. The study population was enrolled as a convenience sample. Informed

TABLE 1. Daily summary metrics in each of the three experimental studies across conditions.

Study 1	Condition	noEX + highSED	EX	highEX + lowSED	
	N	10	10	10	
	Steps	4977 ± 1797[a]	9528 ± 2815[b]	14668 ± 5587[c]	
	Sedentary (%)	71.6 ± 12.7[a]	64.5 ± 10.5[b]	55.4 ± 14.8[c]	
	MVPA (min)	1.2 ± 3.6[a]	23.4 ± 18.6[b]	54.0 ± 39.6[c]	
Study 2	**Condition**	**EX + base**	**EX + highSED**	**EX + lowSED**	
	N	10	10	10	
	Steps	11655 ± 3876[a]	9430 ± 3754[a,b]	13143 ± 5083[b]	
	Sedentary (%)	59.7 ± 12.1[a]	72.3 ± 9.7[b]	23.8 ± 12.4[c]	
	MVPA (min)	26.4 ± 24	24.0 ± 21.0	31.2 ± 22.8	
Study 3	**Group**	**Control**	**rSED**	**EX**	**EX + rSED**
	N	10	16	15	16
	Steps	5253 ± 1194	9548 ± 1792	8855 ± 1528	11392 ± 1828
	Sedentary (%)	70.4 ± 5.4	67.0 ± 5.2	63.4 ± 6.2	64.1 ± 5.6
	MVPA (min)	2.4 ± 4.7	35.4 ± 14.3[a]	27.7 ± 11.2[a]	47.6 ± 14.6[a]

Note: Values are presented as mean ± SD.
Study 1: noEX + highSED = no structured exercise, modEX = participants were instructed to exercise 150 min·wk^{-1}, and highEX + lowSED = exercise 300 min·wk^{-1} and reduce sitting time.
Study 2: All three conditions completed same structured exercise. EX + base = no instruction for nonexercise activity or sedentary time, EX + lowSED = either stand as much as possible, and EX + highSED = sit as much as possible.
Study 3: EX = exercise 5 d·wk^{-1}, rSED = reduce sedentary time, and EX + rSED = exercise and reduce sedentary time.
Studies 1 and 2 were crossover designs where the same participant completed each of the three conditions. Study 3 was 12-wk randomized trial, and values presented are for the last week (12) of the intervention. There were no significant between-group differences at baseline for these variables in study 3.

consent and/or assent documents were signed by 422 participants (and parents of adolescents) (see Table, Supplemental Digital Content 2, Participant characteristics from study 4, http://links.lww.com/MSS/A739). The mean age was 39.1 yr (range 12–75 yr), the mean BMI was 25.5 kg·m^{-2} (range = 14.2–56.1 kg·m^{-2}). During each visit, participants completed basic demographic information and were instructed to maintain their habitual behavior.

Statistical Evaluation

We first examined Pearson correlations for active and sedentary metrics to describe the relationships between the metrics using baseline data in studies 1–3. Next, we used conditional logistic regression to test whether the metrics were significantly associated with study condition, after adjusting for the main volume measures, total sedentary, or MVPA time (min·d^{-1}). This analysis assumes the experimental manipulations also changed the underlying daily behavioral patterns (i.e., frequency × duration of behavior) as well as the total volume of sedentary time and MVPA (8). We were therefore testing a broad range of sedentary and physical activity pattern metrics for their ability to detect patterns of behavior associated with increasing or decreasing exercise, nonexercise activities, and/or sedentary time after accounting for total volume.

For study 1, we defined our outcome variable, Y, equal to 0 if a participant was in the Sedentary (noEX + highSED) group and Y equal 1 if a participant was in the modEx condition. Then for each metric, we regressed Y on that metric, adjusting for main volume metric (i.e., sedentary or MVPA min). Because we had daily measures for each individual, we performed conditional logistic regression, stratified by participant. We report P values from the Wald statistic for the metric of interest. The analysis was then repeated, where $Y = 0$ when in the inactive (noEX + highSED) condition (same as first analysis) and then $Y = 1$ when in the most active (highEX + lowSED) condition. The details of the regression for studies 2 and 3 are identical with those from study 1. In study 2, the baseline condition was EX + base ($Y = 0$), which we compared with the two experimental conditions (i.e., EX + highSED and EX + lowSED) in separate models. For study 3, the baseline week was the referent group ($Y = 0$), which was compared with the intervention period (weeks 6, 9, and 12) for each group.

We then evaluated the reliability of each of the sedentary and physical activity pattern metrics for a 3-month period. For each metric, we calculated the daily mean from each 7-d measurement periods that were 3 months apart. We used linear mixed models to calculate the ICC coefficients, which estimate the proportion of the total variance (between + within participants) that is attributable to the between-participant

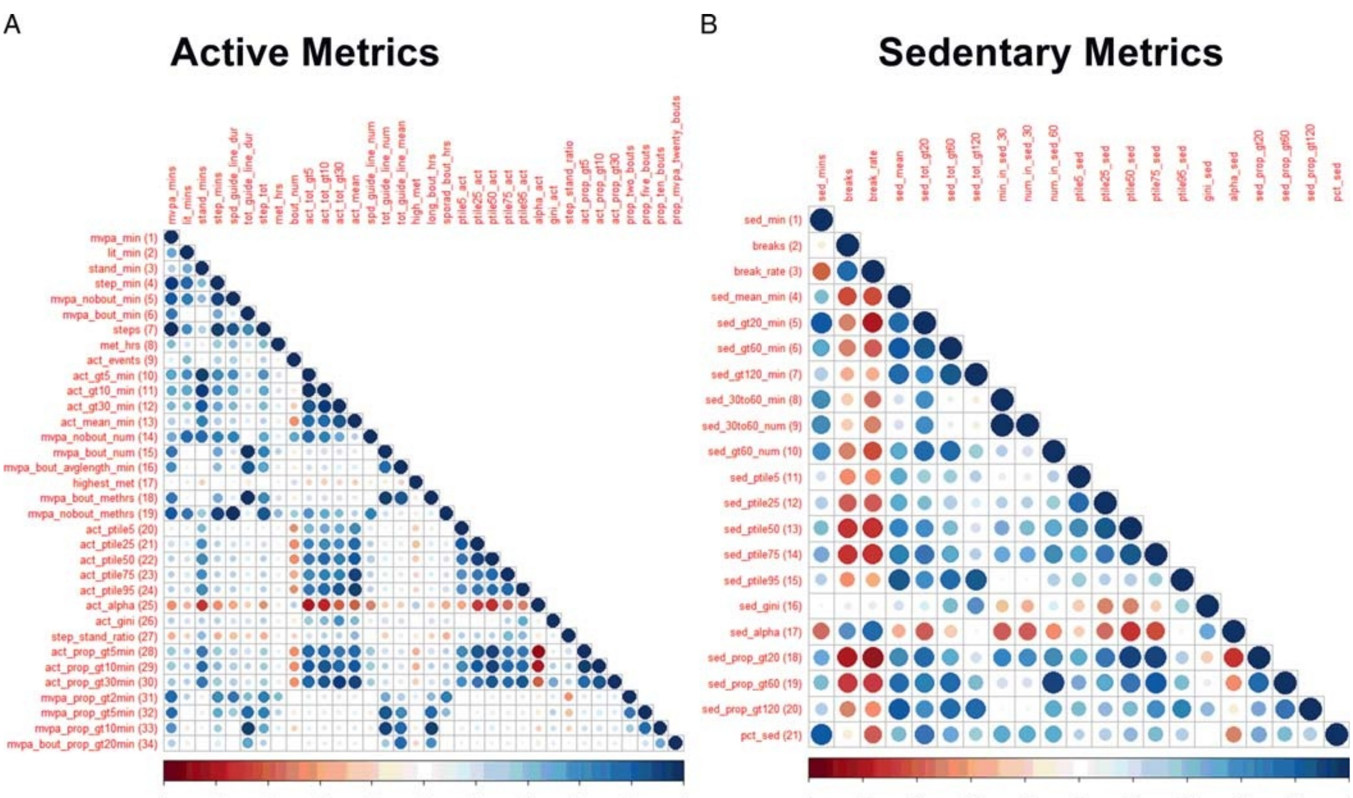

FIGURE 1—A, Pearson correlation coefficient for active metrics across studies 1–3 at baseline. Note: The variables shown are in the same order as Table 2, and described in Supplemental Digital Content 1, http://links.lww.com/MSS/A738. B, Correlation coefficient for sedentary metrics across studies 1–3 at baseline. Note: The variables shown are in the same order as Table 3 and described in Supplemental Digital Content 1, http://links.lww.com/MSS/A738.

variance. Higher ICC values indicate that there is less within-person variance or less random measurement error (15). For all statistical analyses, R-program was used, and *P* values were set at $P < 0.05$.

RESULTS

Table 1 shows the mean daily steps per day, the sedentary time, and the minutes of MVPA for studies 1–3. In both of the randomized crossover trials (studies 1 and 2), the participants were compliant to the condition requirements. For example, in study 1, the measured steps were within 500 steps of the goal for each condition (i.e., 5000 for noEX + highSED, 10,000 for modEX, and 15,000 for highEX + lowSED). Per study design, exercise increased in the two experimental conditions, and sedentary time decreased (Table 1). In study 2, per protocol MVPA guidelines were not significantly different across conditions EX + base (29.8 min), EX + highSED (23.9 min), or EX + lowSED (33.9 min) ($P > 0.05$). By contrast, the percentage of time sedentary at baseline (59.7%) was significantly increased in the EX + highSED condition (72.3%) and reduced in the EX + lowSED condition (23.8%), all $P < 0.01$. For study 3, at week 12, all intervention groups had significantly higher minutes of MVPA and steps per day compared with baseline, but there were no significant changes in sedentary time.

Figure 1 shows the Pearson correlation coefficients for the active and sedentary metrics, respectively, and indicates the metrics are multidimensional. For active metrics, the correlation coefficients between MVPA minutes and 54 other metrics ranged from $R = -0.06$ (highest MET value) to $R = 0.98$ for total steps. Alpha ($R = -0.45$) and standing to stepping ratio ($R = -0.34$) were negatively correlated with total MVPA time, and the others were positively correlated, with a median correlation of 0.43. For sedentary time, the weakest correlation was the Gini index ($R = -0.04$) and the strongest was sedentary time in bouts greater than or equal to 20 min ($R = 0.82$). Break rate, alpha, and sedentary breaks were negatively correlated with overall sedentary time, whereas the rest were positive. The median correlation for sedentary time was $R = 0.45$.

Prediction of behavioral patterns. The mean value for each metric is shown in Table 2 (Sedentary metrics) and Table 3 (Activity metrics). The values in bold in the tables indicate which of the metrics from the conditional logistic

TABLE 2. Daily mean values for activity related metrics in each of the three experimental studies, by condition.

		Study 1			Study 2			Study 3			
		noEX + highSED	modEX	highEX + lowSED	EX + base	EX + lowSED	EX + highSED	Control	rSED	EX	EX + rSED
Main metric Volume	Total MVPA min (≥3 METs)	39.6	**77.9**†	**118.2**†	89.5	**100.1**†	**71.4**†	43.7	**69.9**†	**75.0**†	**90.3**†
	Light (1.5–2.99 METs) min	20.5	24.8	29.1	36.4	**48.2***	30.4	25.6	**32.9***	**24.7***	28.8
	Standing time (min)	156.1	181.7	220.3	230.7	**526.9***	**148.5***	180.6	211.7	**175.6***	195.2
	Stepping time (min)	60.1	102.7	147.3	125.9	**148.3***	101.8	69.3	**102.8***	**99.7***	119.1
	Sporadic MVPA (min)	37.7	**46.6***	**52.7***	59.8	66.8	47.5	41.6	51.6	**41.6***	**49.0***
	MVPA guideline (min)	2.0	**31.3***	**65.5***	29.8	33.3	23.9	2.2	18.2	**33.4***	**41.3***
	Steps per day	4944	9698	14,980	11,815	**13,250.2***	9639	5523	8706	**9426***	11134
	Total MET·h	26.3	29.0	30.8	30.0	31.6	29.7	27.5	29.0	**29.3***	29.7
Duration and number of events	No. active events	50.8	**48.2***	**46.3***	48.4	**35.3***	**57.1***	44.3	42.3	**38.6***	**45.5***
	Active Time ≥5 min event (min)	153.3	224.9	312.7	296.4	**630.1***	**174.7***	194.4	264.4	**229.4***	257.1
	Active Time ≥10 min event (min)	108.3	180.1	264.6	237.8	**591.6***	**125.5***	149.0	217.3	187.6	**211.8***
	Active Time ≥30 min event (min)	34.6	83.4	**161.5***	130.5	**446.3***	**55.3***	63.6	106.1	98.4	**117.1***
	Mean length of active event (min)	4.5	6.4	**8.6**	7.6	**22.4***	**4.7***	6.1	8.0	7.7	**8.0***
	No. sporadic MVPA events	34.6	36.3	37.8	41.3	**53.5***	**36.4***	36.3	**38.9***	**32.9***	37.5
	Number MVPA guideline bouts	0.2	**2.1***	**3.8***	2.4	2.6	1.8	0.2	1.6	1.1	2.0
	Mean length of MVPA guideline (min)	1.7	**14.3***	**19.7***	9.3	10.4	9.9	1.5	6.8	**25.3***	**20.9***
	Highest MET value	4.2	4.3	4.2	4.4	4.5	4.5	4.3	4.2	**4.2***	4.2
	MET·h in MVPA guideline	0.1	**2.1***	**4.5***	2.0	2.3	1.7	0.1	1.2	**2.2***	**2.7***
	MET·h in sporadic MVPA	2.3	**2.9***	**3.3***	3.7	4.1	3.0	2.5	3.1	**2.5***	**3.0***
Event Distribution	5th percentile of active time (min)	0.28	0.32	0.33	0.34	**0.8***	**0.28***	0.32	**0.4***	0.34	0.4
	25th percentile of active time (min)	0.8	1.0	1.1	1.2	**3.4***	**0.9***	1.0	1.3	1.2	1.3
	50th percentile of active time (min)	2.1	2.5	3.1	3.3	**10.5***	**2.2***	2.7	3.6	3.3	3.4
	75th percentile of active time (min)	5.3	7.0	9.0	8.3	**29.0***	**5.1***	6.8	9.7	8.8	**8.8***
	95th percentile of active time (min)	17.0	**28.2***	**38.7***	32.5	**93.4***	**17.3***	25.0	32.1	34.0	33.8
	Alpha[a]	1.45	1.42	**1.40***	1.38	**1.33***	**1.44***	1.4	1.4	1.4	1.4
	Gini[a]	0.62	**0.60***	**0.68***	0.65	0.64	**0.62***	0.6	**0.6***	0.7	**0.7***
Proportions	Standing/Stepping ratio	2.7	**1.9***	1.5	2.0	**4.0***	**1.6***	3.6	2.2	2.0	2.1
	Active time ≥5 min (%)	24.0	31.0	35.0	36.0	**61.0***	**24.0***	31.0	38.0	36.0	**35.0***
	Active time ≥10 min (%)	11.0	17.0	21.0	19.0	**47.0***	**11.0***	16.0	23.0	20.0	**20.0***
	Active time ≥30 min (%)	2.0	4.0	**7.0***	6.0	**23.0***	**2.0***	4.0	6.0	6.0	**6.0***
	MVPA time ≥2 min (%)	17.0	**26.0***	30.0	28.0	**23.0***	23.0	16.0	22.0	**20.2***	24.0
	MVPA time ≥5 min (%)	3.0	11.0	14.0	11.0	**9.0***	9.0	2.0	**8.0***	7.0	9.0
	MVPA time ≥10 min (%)	0.0	**3.0***	7.0	4.0	**3.0***	4.0	0.0	2.0	3.0	4.0
	MVPA guidelines ≥20 min (%)	0.0	26.0	33.0	9.0	**6.0***	9.0	0.0	3.0	**56.0***	**40.0***

EX, exercise; SED, sedentary time; rSED, reduce sedentary time. Studies 1 and 2 were crossover designs where the same participant completed each of the three conditions. Study 3 was a 12-wk randomized trial, and values presented are for intervention period (weeks 6, 9, and 12). A definition of each metric is found in Supplemental Table 1, http://links.lww.com/MSS/A738.

†Significant difference in total MVPA between study conditions ($P < 0.05$).

*The metric distinguishes between the conditions after adjustment for minutes of MVPA in a conditional logistic regression model ($P < 0.05$). Study 1 noEX + highSED was the comparison group and in study 2 the comparison group was EX + base. In study 3, the average of weeks 6, 9, and 12 within each intervention groups was compared with baseline. A definition of each metric is found in Supplemental Table 1, http://links.lww.com/MSS/A738, and the betas and SE for each metric are shown in Supplemental Table 3 (http://links.lww.com/MSS/A740).

[a]Defined by Chastin and Granat (7).

TABLE 3. Daily mean values for sedentary related metrics in each of the three experimental studies, by condition.

		Study 1			Study 2			Study 3			
		noEX + highSED	modEX	highEX + lowSED	EX + base	EX + lowSED	EX + highSED	Control	rSED	EX	EX + rSED
Main metric	Total Sedentary minutes	582.8	527.7	457.9	530.4	216.1	650.6	614.6	548.6	569.5	574.6
Duration and number of bouts	Sit-to-stand transitions (i.e., breaks)	50.9	48.3	**46.4***	48.3	35.3	**57.2***	44.3	42.4	**38.7***	45.6
	Break-rate (breaks per sedentary hour)	5.7	**5.8***	6.9	5.9	12.0	**5.5***	4.6	5.0	**4.4***	**5.1***
	Mean length of sedentary event (min)	12.4	**12.3***	**10.9***	11.9	6.9	**13.1***	16.4	14.6	**20.2***	15.1
	Sedentary time ≥20 min (min)	356.6	321.8	**266.6***	318.9	**97.4***	414.2	411.8	367.3	405.6	**376.0***
	Sedentary time ≥60 min (min)	132.2	127.7	**118.8***	130.6	**38.9***	185.7	186.2	139.6	197.3	145.5
	Sedentary time ≥120 min (min)	34.6	31.5	**42.8***	34.7	12.2	**36.7***	72.7	50.6	**106.7***	56.0
	Time in 30–60 min sedentary event (min)	156.0	132.9	98.1	122.2	**28.6***	160.3	153.0	147.5	**139.8***	**150.9***
	No. sedentary events 30–60 min	3.6	3.2	2.3	2.9	0.7	3.8	3.7	3.5	**3.4***	3.7
	No. sedentary events ≥60 min	1.5	1.5	1.3	1.5	**0.4***	2.1	1.9	1.5	1.7	1.4
Event distribution	5th percentile of sedentary time (min)	0.4	0.3	0.3	0.4	0.3	0.4	0.4	0.4	0.5	0.4
	25th percentile of sedentary time (min)	1.6	1.3	1.2	1.6	1.0	1.7	1.9	1.9	2.0	1.7
	50th percentile of sedentary time (min)	5.5	5.2	4.0	5.2	2.9	5.8	6.8	6.6	7.4	6.3
	75th percentile of sedentary time (min)	15.4	15.2	12.2	13.6	7.5	15.6	19.8	19.3	25.8	**18.1***
	95th percentile of sedentary time (min)	48.3	**53.8***	**48.7***	48.7	28.3	55.1	71.4	56.3	92.3	66.4
	Gini[a]	0.65	0.66	**0.68***	0.66	0.65	0.66	0.65	0.64	0.66	0.65
	Alpha[a]	1.35	1.35	1.37	1.36	1.45	1.35	1.34	**1.34***	1.34	**1.34***
Proportions (%)	Sedentary time ≥20 min	18.0	18.0	14.0	16.0	**7.0***	19.0	22.0	22.0	23.0	**21.0***
	Sedentary time ≥60 min	4.0	**4.0***	**3.0***	4.0	**1.0***	5.0	6.0	4.0	6.0	4.0
	Sedentary time ≥120 min	0.0	1.00	1.00	1.0	0.0	**1.0***	1.0	1.0	2.0	1.0
	Percent sedentary	72.0	**65.0***	**55.0***	60.0	**24.0***	**72.0***	71.0	**63.0***	67.0	**64.0***

EX, exercise; SED, sedentary time; rSED, reduce sedentary time. Studies 1 and 2 were crossover designs where the same participant completed each of the three conditions. Study 3 was a 12-wk randomized trial, and values presented are for the last week (12) of the intervention.

*Metric distinguishes between the conditions after adjustment for minutes of sedentary time in a conditional logistic regression model. In study 1, the exponential groups were compared with NoEX + highSED; in study 2, the comparison group was EX + base; and in study 3, the average of weeks 6, 9, and 12 within each intervention groups was compared with baseline. A definition of each metric is found in Supplemental Table 1, http://links.lww.com/MSS/A738, and the betas and SE for each metric are shown in Supplemental Table 3 (http://links.lww.com/MSS/A740).

[a]Defined in Chastin and Granat (7).

regression predicted study condition (i.e., behavioral pattern) beyond the main volume measures (i.e., sedentary and MVPA time). The specific betas and SE from conditional logistic regression models are available as supplemental tables (see Table, Supplemental Digital Content 3, Results from conditional logistic regression for Studies 1–3, http://links.lww.com/MSS/A740).

For study 1, 12 active metrics, primarily related to MVPA guideline (e.g., length of MVPA guideline, the 95th percentile of activity), were significant predictors of the ModEX condition and just five sedentary metrics ($P < 0.05$) (Tables 2 and 3). Compared with noEX + highSED, there were 14 of the active metrics that predicted the HiEX + lowSED condition, mainly those reflecting higher levels of structured MVPA (e.g., number and length of bouts, active time >30 min). There were also nine sedentary metrics that were significant predictors of condition (e.g., sedentary event length, sedentary time >20, 60, 120 min, 95th percentile, and Gini index). Overall, the majority of the significant predictors in study 1 were MVPA guideline metrics that reflect a more active behavioral pattern of a person who is meeting recommended levels of MVPA.

In study 2, participants were instructed to maintain exercise behavior across the three conditions and alter their sedentary time (and consequently nonexercise activity). Consistent with this experimental design, the activity metrics related to structured exercise (e.g., number and length of MVPA guideline minutes) were not significantly different between conditions (Tables 2 and 3). By contrast, there were significant differences in the nonexercise activity and sedentary metrics. Compared with EX + base, the EX + lowSED had higher percentiles of activity (5th through 95th); both minutes and proportion of active time >5, 10, and 30 min were significantly higher; and the ratio of standing to stepping was lower. The duration and time in long sedentary bouts also significantly differentiated between conditions. Per protocol, the pattern for the EX + highSED was almost completely opposite the EX + lowSED. Compared with EX + base, the EX + highSED group had much lower active time >5, 10, and 30 min and lower proportion of active time above those thresholds. The percentiles (5th through 95th) were also significantly different, and the ratio of standing to stepping was higher. Interestingly, the number of sit-to-stand transitions ("breaks") was higher in the highSED condition compared with EX + base, but the mean sedentary event length and time in bouts >120 min were all higher (Tables 2 and 3). Compared with baseline, the strongest differences in both highly sedentary and high standing conditions were largely driven by increased or decreased nonexercise activity long sedentary bouts (2 h) and the mean sedentary even length.

In study 3, the observed difference in EX + rSED group during the intervention were largely driven by differences in structured exercise (e.g., MVPA bout length, 75th percentile, active time >20 min). The group also changed the pattern of nonexercise activity (e.g., active time >5 and 10 min) and sedentary time (e.g., duration and proportion of sedentary time >20 min). The EX group had expected changes in structured MVPA (e.g., MVPA bout length). There were no changes in total sedentary time for the EX group, but these participants spent more time in 120 min sedentary bouts and a longer mean length of sedentary events during the intervention. The stepping time, the number of sporadic MVPA events, the active time >5 min, and the duration and proportion of sedentary bouts >20 and 60 min were significant predictors of intervention status in the rSED group (Tables 2 and 3). In summary, the two groups who received the sedentary intervention decreased longer bouts of sedentary time, whereas the EX group had increases in longer bouts of sedentary time. In addition to total MVPA time, additional metrics reflecting bouts of MVPA were significant predictors in both exercising groups.

Reliability of physical activity and sedentary metrics. The mean, SD, and ICC values for each of the active and sedentary metrics are shown in Tables 4 and 5. The majority of the active (32/34) and sedentary (15/21) metrics had ICC values greater than 0.4, suggesting at least moderate reliability for a 3-month period. As seems natural, the ICC values tended to be lower for the more extreme activity pattern metrics (e.g., 5th and 95th percentile of active time, highest MET value). The lowest ICC values were for the 75th percentile of active time (ICC = 0.28) and the Gini index (ICC = 0.29). Similarly, the lowest ICC values for sedentary time were for time in sedentary bouts >120 min (ICC = 0.19), 95th percentile of sedentary time (ICC = 0.08), and proportion of sedentary time >120 min (ICC = 0.38).

TABLE 5. Means and reliability of sedentary metrics in the community-dwelling sample (study 4).

		Mean	SD	ICC
Duration and number of bouts	Sit-to-stand transitions	53.6	20.1	0.68
	Rate of sedentary breaks	5.9	2.9	0.72
	Mean length of sedentary event (min)	12.6	9.1	0.38
	Sedentary time ≥20 min	374.9	167.0	0.47
	Sedentary time ≥60 min	140.0	150.9	0.34
	Sedentary time ≥120 min	46.2	117.6	0.19
	Time in 30–60 min sedentary event	157.5	90.6	0.41
	No. sedentary events 30–60 min	3.8	2.1	0.41
	No. sedentary events ≥60 min	1.4	1.3	0.50
Event distribution	5th percentile of sedentary time	0.3	0.2	0.48
	25th percentile of sedentary time	1.4	1.1	0.50
	50th percentile of sedentary time	5.1	3.4	0.60
	75th percentile of sedentary time	15.3	9.8	0.70
	95th percentile of sedentary time	52.3	57.7	0.08
	Gini	0.66	0.07	0.36
	Alpha	1.35	0.05	0.59
Proportions (%)	Sedentary time ≥20 min	18.2	9.6	0.68
	Sedentary time ≥60 min	3.5	4.2	0.57
	Sedentary time ≥120 min	0.7	1.8	0.38
	Percent sedentary	66.3	13.4	0.66

A definition of each metric is found in Supplemental Table 1, http://links.lww.com/MSS/A738. The ICC values are for the weekly average measured at baseline and 3 months later.

DISCUSSION

This study derived and evaluated a panel of 55 metrics of active and sedentary behavior from an AP accelerometer. An important strength was the use of experimental studies that both increased and decreased sedentary and activity behavior, and thus the metrics were evaluated relative to known and relevant behavioral patterns. We also examined reproducibility for a 3-month period and showed a median ICC of 0.6, suggesting at least moderate stability within a person. This comprehensive evaluation of the accelerometer-derived metrics provides a foundation for future epidemiologic studies examining daily behavioral patterns in relation to disease risk factors and end points.

TABLE 4. Means and reliability of active metrics in the community-dwelling sample (study 4).

		Mean	SD	ICC
Main metric	MVPA min (≥3 METs)	61.7	34.7	0.61
Volume	Light min (1.5–2.99)	35.6	19.6	0.62
	Standing time (min)			
	Stepping time (min)	97.3	47.5	0.59
	Sporadic MVPA (min)	51.7	26.0	0.57
	MVPA guideline (min)	10.0	20.1	0.66
	Steps per day	8007	4325	0.60
	Total MET·h	29.0	5.2	0.45
Duration and number of bouts	Standing/stepping ratio	2.44	2.77	0.46
	No. active events	53.5	20.1	0.68
	Active Time ≥5 min event (min)	236.5	128.4	0.69
	Active Time ≥10 min event (min)	186.4	124.7	0.68
	Active Time ≥30 min event (min)	86.3	103.1	0.60
	No. sporadic MVPA events	40.9	11.6	0.64
	Mean length of active event (min)	6.3	5.6	0.59
	Number MVPA guideline bouts	0.81	1.60	0.60
	Mean length of MVPA guideline bout (min)	4.1	7.2	0.60
	Highest MET value	4.3	0.6	0.41
	MET·h in MVPA guideline	0.66	1.34	0.66
	MET·h in sporadic MVPA	3.2	1.6	0.57
Event distribution	5th percentile of active time (min)	0.3	0.1	0.42
	25th percentile of active time (min)	0.9	0.5	0.60
	50th percentile of active time (min)	2.5	1.7	0.68
	75th percentile of active time (min)	7.1	11.8	0.28
	95th percentile of active time (min)	26.4	29.0	0.54
	Alpha	1.43	0.07	0.59
	Gini	0.64	0.07	0.29
Proportions (%)	Active time ≥5 min	5.0	6.8	0.63
	Active time ≥10 min	1.00	2.46	0.62
	Active time ≥30 min	3.1	14.6	0.51
	MVPA time ≥2 min	20.3	13.2	0.55
	MVPA time ≥5 min	5.0	6.8	0.63
	MVPA time ≥10 min	1.0	2.5	0.62
	Proportion of MVPA guidelines ≥20 min	3.1	14.6	0.51

Note: A definition of each metric is found in Supplemental Table 1, http://links.lww.com/MSS/A738. The ICC values are for the weekly average measured at baseline and 3 months later.

The broad adoption of wearable sensors enables researchers to examine much more detail about daily behavior as compared with standard volume-based metrics that are captured by self-reported questionnaires (e.g., minutes per week of MVPA). In this analysis, we showed the accelerometer metrics captured unique aspects of behavior. In study 1, the metrics related to number, frequency, and intensity of MVPA guideline were significant predictors of the experimental conditions, which were designed to mimic the 2008 physical activity guidelines. By contrast, in study 2 where time in exercise was held constant and sedentary time was manipulated, the metrics related to MVPA guideline were not significant, whereas more metrics related to sporadic activity (e.g., percentiles of active time) and sedentary time were significant predictors of the conditions. Study 3 was a longer-term free-living intervention, and we identified numerous metrics related to structured exercise that were predictive of intervention status in both of the exercising groups and several metrics for spontaneous activity and sedentary time that were predictive among the sedentary intervention groups (Tables 2 and 3). As an example to highlight the translational potential of these metrics, the exercise-only group increased the length of their sedentary events and had more long bouts of sitting. If this finding is replicated, it could be an example of a discrete intervention target for individuals starting an exercise program to ensure they do not compensate for exercise by increasing prolonged sedentary periods.

Some of the metrics we examined have been used in previous studies. Healy et al. (19) showed associations between bouts of accelerometer-measured sedentary time >30 min and obesity, and Carson et al. (5) showed bouts of 20 min of sedentary time associated with cardiometabolic biomarkers. Research has also begun to differentiate the relative benefits of sporadic MVPA and MVPA guideline in relation to cardiovascular health and metabolic syndrome (10). The present findings provide reassurance that the metrics used in these studies are reproducible and predictive of behavioral patterns. One interesting exception was "breaks" from sedentary time, which we defined as a sit–stand transition from the AP. Previous studies have shown better health outcomes are associated with more "breaks" estimated using an ActiGraph accelerometer count threshold (17,18,40). However, we found that breaks were predictive of a more sedentary behavioral pattern, even when adjusting for differences in total sedentary time. These findings suggest that the ActiGraph "breaks" are likely capturing sporadic movements rather than true transitions from sitting to standing (2,30) (Table 3). Future research should examine the metrics of sedentary time beyond simply the number of breaks, including long bouts or distributions of sporadic activity to understand how patterns of sedentary time accumulation relate to health.

In this analysis, we were interested in identifying metrics that provide additional information to help distinguish between conditions beyond what is possible with volume alone; thus, we elected to control for volume. All metrics are in some way conceptually related to total volume, which is made up of frequency and duration; thus, they are not truly independent (8). It should be noted there are other applications of these metrics where it may not be appropriate or necessary to adjust for volume. To determine what metrics are most strongly related to health, there may not be an *a priori* reason to include volume as a covariate. In addition, an intervention study may be interested in assessing the proximal behavioral target (long bouts of sitting), even if it is highly correlated with total volume, because it was an explicit target of the intervention (8).

Although there is expected day-to-day or year-to-year behavioral variation in activity, in epidemiologic studies, this variability is a source of random measurement error that will attenuate observed risk estimates (15,35). We evaluated the stability of our metrics for a 3-month period using ICC. For the majority, the ICC indicated moderate agreement (ICC = 0.4–0.75). The Gini index for both active (ICC = 0.29) and sedentary (ICC = 0.36) were relatively low. In general, more sedentary metrics had ICC values below the level of moderate agreement compared with active metrics. Interestingly, the 95th percentile for sedentary time, despite the low ICC, was the only percentile metric that was significantly different in studies 1 and 2. For metrics with low ICC values, null associations with health should be interpreted cautiously as the within-person measurement error could attenuate the true associations and more days or measurement period may be needed.

Overall, this evaluation lends support to the utility of these accelerometer-derived metrics, and this area is ripe for future research. From a measurement perspective, the day-to-day variability in these metrics within a week or between weekend and weekdays is not well understood. Future research could explore data reduction techniques (e.g., principal component analyses) using the accelerometers as latent variables that represent daily patterns of active and sedentary behavior, similar to work that's been done with socioeconomic deprivation indices (33). Several investigations have identified clustering of activity patterns using latent class analyses based on volume measures (e.g., sedentary time) (5,14,34). The pattern metrics evaluated in this study, and those proposed by others (e.g., [1,8,36]), may add discriminative ability for future studies to identify behavioral clusters. In addition, these metrics could be integrated with ongoing efforts to understand the temporal patterns in activity throughout the day (31,42,45) and other accelerometer-derived metrics (8,36).

Strengths of this study include the use of three experimental studies that represent comprehensive behavioral patterns of activity and inactivity and different populations (young and normal weight, older, and overweight/obese). The studies that included a range of experimental manipulations of behavior patterns were designed to reflect public health recommendations, highly sedentary populations, and longer-term intervention on exercise and sedentary time (28,39). Study 4 included a wide range of age and activity levels to enhance the generalizability of the ICC analysis and to describe these metrics in a community-dwelling sample. We also used the AP monitor, which has been well validated in free-living settings estimating sedentary time (23,30). However, a limitation is that the AP device software underestimates energy expenditure (16), which we saw with a peak MET value of 4.5 across studies and no differences in this metric between studies. Although the underlying conceptual framework of the metrics is generalizable to other activity monitors, these results are most applicable to studies using the AP monitor because the accuracy and precision of wrist- and waist- worn accelerometers to distinguish sitting from standing is lower than the AP (22,37). We used linear mixed methods to calculate the ICC coefficients. Nonlinearity could be an issue that may lead to the loss of valuable information, and future research could consider functional data analyses to assess a flexible model pattern by including smooth curves measured at various time points (27). We focused primarily on means and medians for this analysis. For some metrics, where >50% of bouts equal the minimal bout length, the median may not adequately distinguish subjects' behavior. We conducted several statistical tests, and some significant findings may have occurred by chance. The fact that the significant metrics predicted differences in patterns that reflected the experimental design gives us confidence, but certainly these results should be replicated.

CONCLUSIONS

We found several accelerometer-derived metrics that were predictive of behavioral patterns and that were sufficiently reliable within a person for a 3-month period to be useful in future epidemiologic research. This study provided important information on previously published metrics and expanded this literature by evaluating novel metrics. The systematic evaluation included controlled experimental trials that manipulated behavioral patterns related to sedentary, nonexercise, and exercise behavior. These metrics may be used as indicators of behavioral patterns to examine associations with cardiometabolic biomarkers or disease incidence and may ultimately lead to new behavioral targets for future intervention.

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REFERENCES

1. Bai J, He B, Shou H, Zipunnikov V, Glass TA, Crainiceanu CM. Normalization and extraction of interpretable metrics from raw accelerometry data. *Biostatistics*. 2014;15(1):102–16.
2. Barreira TV, Zderic TW, Schuna JM, Jr, Hamilton MT, Tudor-Locke C. Free-living activity counts-derived breaks in sedentary time: are they real transitions from sitting to standing? *Gait Posture*. 2015;42(1):70–2.
3. Bellettiere J, Carlson JA, Rosenberg D, et al. Gender and age differences in hourly and daily patterns of sedentary time in older adults living in retirement communities. *PLoS One*. 2015;10(8):e0136161.
4. Blankenship JM, Granados K, Braun B. Effects of subtracting sitting versus adding exercise on glycemic control and variability in sedentary office workers. *Appl Physiol Nutr Metab*. 2014;39(11):1286–93.
5. Carson V, Wong SL, Winkler E, Healy GN, Colley RC, Tremblay MS. Patterns of sedentary time and cardiometabolic risk among Canadian adults. *Prev Med*. 2014;65:23–7.
6. Chastin SF, Baker K, Jones D, Burn D, Granat MH, Rochester L. The pattern of habitual sedentary behavior is different in advanced Parkinson's disease. *Mov Disord*. 2010;25(13):2114–20.
7. Chastin SF, Granat MH. Methods for objective measure, quantification and analysis of sedentary behaviour and inactivity. *Gait Posture*. 2010;31(1):82–6.
8. Chastin SF, Winkler E, Eakin EG, et al. Sensitivity to change of objectively-derived measures of sedentary behavior. *Meas Phys Educ Exerc Sci*. 2015;19(3):138–47.
9. Choi L, Ward SC, Schnelle JF, Buchowski MS. Assessment of wear/nonwear time classification algorithms for triaxial accelerometer. *Med Sci Sports Exerc*. 2012;44(10):2009–16.
10. Clarke J, Janssen I. Sporadic and bouted physical activity and the metabolic syndrome in adults. *Med Sci Sports Exerc*. 2014;46(1):76–83.
11. Committee PAGA. *Physical Activity Guidelines Advisory Committee Report*. Washington (DC): Department of Health and Human Services; 2008.
12. Diaz KM, Howard VJ, Hutto B, et al. Patterns of sedentary behavior in US middle-age and older adults: the REGARDS Study. *Med Sci Sports Exerc*. 2016;48(3):430–8.
13. Dunstan DW, Kingwell BA, Larsen R, et al. Breaking up prolonged sitting reduces postprandial glucose and insulin responses. *Diabetes Care*. 2012;35(5):976–83.
14. Evenson KR, Wen F, Metzger JS, Herring AH. Physical activity and sedentary behavior patterns using accelerometry from a national sample of United States adults. *Int J Behav Nutr Phys Act*. 2015;12:20.
15. Hankinson SE, Manson JE, Spiegelman D, Willett WC, Longcope C, Speizer FE. Reproducibility of plasma hormone levels in postmenopausal women over a 2–3-year period. *Cancer Epidemiol Biomarkers Prev*. 1995;4(6):649–54.
16. Harrington DM, Welk GJ, Donnelly AE. Validation of MET estimates and step measurement using the activPAL physical activity logger. *J Sports Sci*. 2011;29(6):627–33.
17. Healy GN, Dunstan DW, Salmon J, et al. Breaks in sedentary time: beneficial associations with metabolic risk. *Diabetes Care*. 2008;31(4):661–6.
18. Healy GN, Matthews CE, Dunstan DW, Winkler EA, Owen N. Sedentary time and cardio-metabolic biomarkers in US adults: NHANES 2003–06. *Eur Heart J*. 2011;32(5):590–7.
19. Healy GN, Winkler EA, Brakenridge CL, Reeves MM, Eakin EG. Accelerometer-derived sedentary and physical activity time in overweight/obese adults with type 2 diabetes: cross-sectional associations with cardiometabolic biomarkers. *PLoS One*. 2015;10(3):e0119140.
20. Jefferis BJ, Sartini C, Shiroma E, Whincup PH, Wannamethee SG, Lee IM. Duration and breaks in sedentary behaviour: accelerometer data from 1566 community-dwelling older men (British Regional Heart Study). *Br J Sports Med*. 2015;49(24):1591–4.
21. Katzmarzyk PT. Standing and mortality in a prospective cohort of Canadian adults. *Med Sci Sports Exerc*. 2014;46(5):940–6.
22. Koster A, Shiroma EJ, Caserotti P, et al. Comparison of sedentary estimates between activPAL and hip- and wrist-worn ActiGraph. *Med Sci Sports Exerc*. 2016;48(8):1514–22.
23. Kozey-Keadle S, Libertine A, Lyden K, Staudenmayer J, Freedson PS. Validation of wearable monitors for assessing sedentary behavior. *Med Sci Sports Exerc*. 2011;43(8):1561–7.
24. Kozey-Keadle S, Staudenmayer J, Libertine A, et al. Changes in sedentary time and physical activity in response to an exercise training and/or lifestyle intervention. *J Phys Act Health*. 2014;11(7):1324–33.
25. Kozey Keadle S, Lyden K, Staudenmayer J, et al. The independent and combined effects of exercise training and reducing sedentary behavior on cardiometabolic risk factors. *Appl Physiol Nutr Metab*. 2014;39(7):770–80.
26. Levine JA, Lanningham-Foster LM, McCrady SK, et al. Interindividual variation in posture allocation: possible role in human obesity. *Science*. 2005;307(5709):584–6.
27. Li H, Kozey Keadle S, Staudenmayer J, Assaad H, Huang JZ, Carroll RJ. Methods to assess an exercise intervention trial based on 3-level functional data. *Biostatistics*. 2015;16(4):754–71.
28. Lyden K, Keadle SK, Staudenmayer J, Braun B, Freedson PS. Discrete features of sedentary behavior impact cardiometabolic risk factors. *Med Sci Sports Exerc*. 2015;47(5):1079–86.
29. Lyden K, Keadle SK, Staudenmayer J, Freedson PS. A method to estimate free-living active and sedentary behavior from an accelerometer. *Med Sci Sports Exerc*. 2014;46(2):386–97.
30. Lyden K, Kozey Keadle SL, Staudenmayer JW, Freedson PS. Validity of two wearable monitors to estimate breaks from sedentary time. *Med Sci Sports Exerc*. 2012;44(11):2243–52.
31. Martin KR, Koster A, Murphy RA, et al. Changes in daily activity patterns with age in U.S. men and women: National Health and Nutrition Examination Survey 2003–04 and 2005–06. *J Am Geriatr Soc*. 2014;62(7):1263–71.
32. Matthews CE, George SM, Moore SC, et al. Amount of time spent in sedentary behaviors and cause-specific mortality in US adults. *Am J Clin Nutr*. 2012;95(2):437–45.

33. Messer LC, Laraia BA, Kaufman JS, et al. The development of a standardized neighborhood deprivation index. *J Urban Health*. 2006;83(6):1041–62.
34. Metzger JS, Catellier DJ, Evenson KR, Treuth MS, Rosamond WD, Siega-Riz AM. Patterns of objectively measured physical activity in the United States. *Med Sci Sports Exerc*. 2008;40(4):630–8.
35. Missmer SA, Spiegelman D, Bertone-Johnson ER, Barbieri RL, Pollak MN, Hankinson SE. Reproducibility of plasma steroid hormones, prolactin, and insulin-like growth factor levels among premenopausal women over a 2-to 3-year period. *Cancer Epidemiol Biomarkers Prev*. 2006;15(5):972–8.
36. Paraschiv-Ionescu A, Buchser E, Rutschmann B, Aminian K. Nonlinear analysis of human physical activity patterns in health and disease. *Phys Rev E Stat Nonlin Soft Matter Phys*. 2008; 77(2 Pt 1):021913.
37. Pavey TG, Gomersall SR, Clark BK, Brown WJ. The validity of the GENEActiv wrist-worn accelerometer for measuring adult sedentary time in free living. *J Sci Med Sport*. 2016;19(5):395–9.
38. Peddie MC, Bone JL, Rehrer NJ, Skeaff CM, Gray AR, Perry TL. Breaking prolonged sitting reduces postprandial glycemia in healthy, normal-weight adults: a randomized crossover trial. *Am J Clin Nutr*. 2013;98(2):358–66.
39. Physical Activity Guidelines Committee Report. 2008. US Department of Health and Human Services. Washington (DC). Available from: www.health.gov/paguidelines/report.
40. Sardinha LB, Ekelund U, dos Santos L, Cyrino ES, Silva AM, Santos DA. Breaking-up sedentary time is associated with impairment in activities of daily living. *Exp Gerontol*. 2015;72:278.
41. Shiroma EJ, Freedson PS, Trost SG, Lee IM. Patterns of accelerometer-assessed sedentary behavior in older women. *JAMA*. 2013;310(23):2562–3.
42. Steeves JA, Murphy RA, Crainiceanu CM, Zipunnikov V, Van Domelen DR, Harris TB. Daily patterns of physical activity by type 2 diabetes definition: comparing diabetes, prediabetes, and participants with normal glucose levels in NHANES 2003–2006. *Prev Med Rep*. 2015;2:152–7.
43. Thompson D, Batterham AM. Towards integrated physical activity profiling. *PLoS One*. 2013;8(2):e56427.
44. van der Berg JD, Stehouwer CD, Bosma H, et al. Associations of total amount and patterns of sedentary behaviour with type 2 diabetes and the metabolic syndrome: the Maastricht Study. *Diabetologia*. 2016;59(4):709–18.
45. Xiao L, Huang L, Schrack JA, Ferrucci L, Zipunnikov V, Crainiceanu CM. Quantifying the lifetime circadian rhythm of physical activity: a covariate-dependent functional approach. *Biostatistics*. 2015;16(2):352–67.
46. Zhang Y, Li H, Keadle S, Matthews CE, Carroll R. PAactivPAL: Summarize Daily Physical Activity from 'activPAL' Accelerometer Data: https://cran.r-project.org/web/packages/PAactivPAL/index.html; 2016.