

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

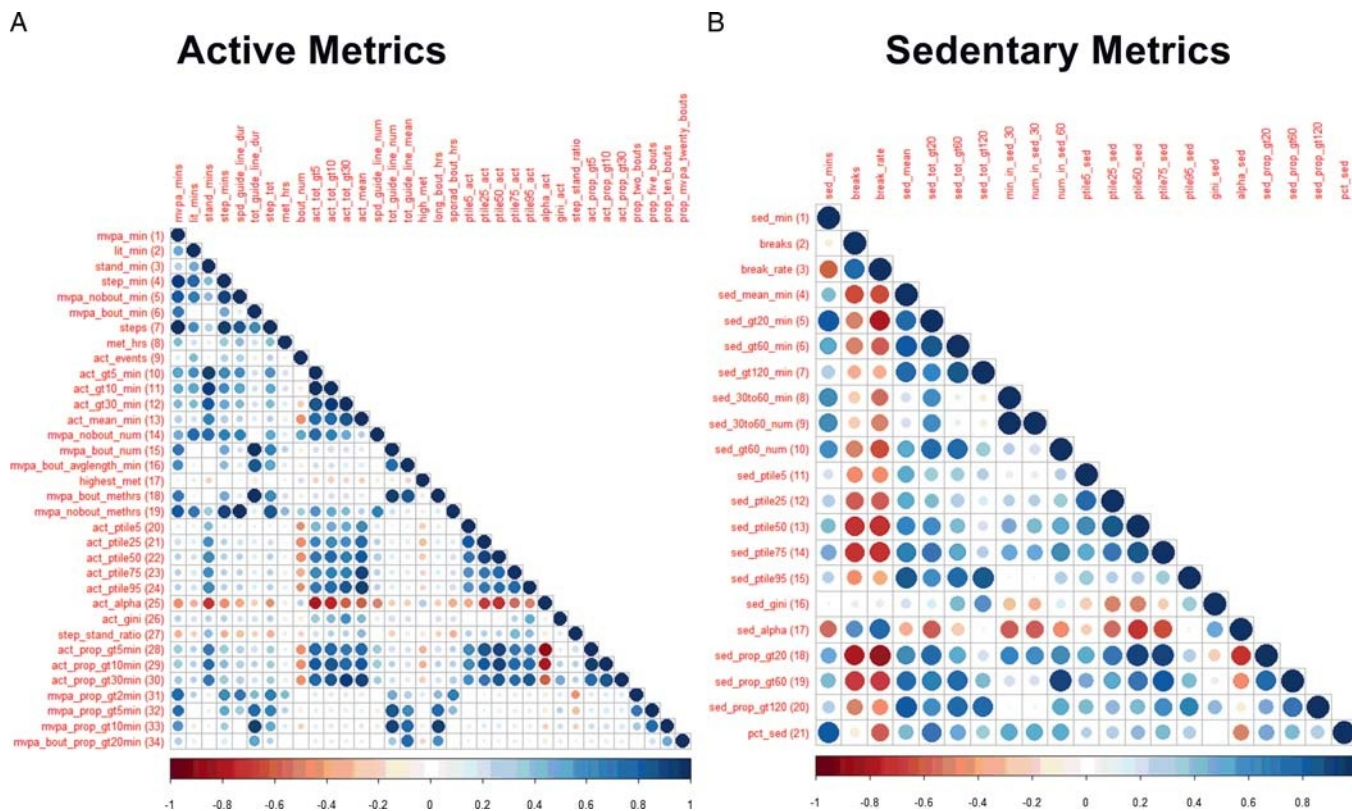


FIGURE 1—A, Pearson correlation coefficient for active metrics across studies 1–3 at baseline. Note: The variables shown are in the same order as Table 2, and described in Supplemental Digital Content 1, <http://links.lww.com/MSS/A738>. B, Correlation coefficient for sedentary metrics across studies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

^aDefined 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>).

^aDefined 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).

DISCUSSION

This study derived and evaluated a panel of 55 metrics of active and sedentary behavior from an AP accelerometer. An

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.

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 |
| 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.

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.

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.

The authors thank the study participants and staff and Drs. Patty Freedson and Jay Fowke. The study was supported by funding from the National Institutes of Health (NR011477 PI, Fowke; U01-CA057030 PI, Carroll; and RC1HL099557 PI, Freedson), the Natural Sciences and Engineering Research Council of Canada (NSERC, RGPIN-2015-04409, Li), the Intramural Research Program at the National Cancer Institute (Sampson, Keadle, and Matthews), and an American College of Sports Medicine Paffenbarger Award (Lyden).

The authors declare no conflicts of interest.

The results of the present study do not constitute endorsement by the American College of Sports Medicine.

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