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Physical Activity Behaviors of a Middle-Age South African Cohort as Determined by Integrated Hip and Thigh Accelerometry

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ABSTRACT

MICKLESFIELD, L. K., K. WESTGATE, A. SMITH, C. N. KUFE, A. E. MENDHAM, T. LINDSAY, K. WIJNDAELE, J. H. GOEDECKE, and S. BRAGE. Physical Activity Behaviors of a Middle-Age South African Cohort as Determined by Integrated Hip and Thigh Accelerometry. *Med. Sci. Sports Exerc.*, Vol. 54, No. 9, pp. 1493–1505, 2022. **Purpose:** Descriptive studies of objectively measured physical activity behaviors in African populations are rare. We developed a method of combining hip and thigh accelerometery signals to quantify and describe physical behaviors in middle-age South African men and women. **Methods:** We integrated signals from two triaxial accelerometers worn simultaneously during free-living, in a subsample of the Middle-age Soweto Cohort (n = 794; mean (SD) age, 53.7 (6.3) yr). Acceleration time series from the accelerometers were combined and movement-related acceleration was derived using Euclidean Norm Minus One (in milligrams), to determine total movement volume (mean Euclidean Norm Minus One) and nonmovement time (<28 mg), light-intensity physical activity (LPA; 28–85 mg), and moderate- to vigorous-intensity physical activity (MVPA; >85 mg); thigh pitch angle and a sleep diary were used to divide nonmovement time (in minutes per day) into sleep, awake sitting/lying, and standing. Sociodemographic factors were self-reported, and weight and height were measured. **Results:** Mean (SD) wear time was 128 (48) h. Movement volume was 15.0 (6.5) mg for men and 12.2 (3.4) mg for women. Men spent more time in MVPA and sitting/lying, whereas women spent more time standing. Age was inversely associated with movement volume, MVPA, and LPA. When compared with their normal-weight counterparts, men who were overweight or obese spent less time in MVPA, whereas women who were overweight or obese spent less time in LPA and more time sitting/lying. Socioeconomic status was inversely associated with total movement volume, MVPA, and time spent sleeping, and positively associated with time spent sitting/lying, in both men and women. **Conclusions:** Integrating signals from hip and thigh accelerometers enables characterization of physical behaviors that can be applied in an African population. **Key Words:** PHYSICAL ACTIVITY, SOCIOECONOMIC STATUS, ACCELEROMETRY, URBAN

It is widely accepted that physical activity is associated with a multitude of health benefits, as reflected in recent public health recommendations encouraging all individuals to move more and sit less (1). Physical inactivity has been identified as a major risk factor for noncommunicable diseases (2), the burden of which is nearly equal to the total burden from

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communicable, maternal, neonatal, and nutritional diseases combined in sub-Saharan Africa (3). Increasing urbanization, life expectancy, and population size in sub-Saharan Africa are expected to contribute to this growing burden (4).

One of the challenges in physical activity epidemiology is the measurement of physical behavior, and there continues to be debate about the use of self-report and objectively measured physical activity (5). It is clear that an understanding of time spent in the various physical activity behaviors is crucial, particularly in low-resourced settings where patterns of physical activity are unique (6). However, the instruments most often used in these settings to measure time spent in physical activity behaviors are questionnaires, which have been shown to have a mean percentage difference of −59.5% to 62.1% when compared with doubly labeled water, with activity monitors reporting a mean percentage difference of −48.5% to 7.47% when compared with doubly labeled water (5).

Accelerometers and other device-based methods provide objective assessment of physical behaviors, avoiding the key issues with self-report, namely, recall bias and social desirability bias. Wearable devices also provide more accurate estimates of activity across the whole day and across the entire intensity spectrum (i.e., from sedentary to vigorous activity), compared with subjective methods, which often do not capture light-intensity activity or incidental activity behaviors that are difficult to recall. In particular, hip-worn accelerometers have been suggested as a good method for accurate detection of activity (7), and thigh-worn accelerometers are used for more detailed postural assessment for classifying sedentary behavior by discriminating between sitting and standing postures (8). Recent World Health Organization guidelines for physical activity highlight the importance of limiting sedentary behavior and increasing activity of any intensity, including light-intensity activity for the prevention of chronic disease and premature mortality (1). Accurately capturing all physical behaviors occurring during the day is hence a priority for public health and physical activity surveillance. Although it is still relatively uncommon for wearable devices to be used in epidemiological studies in Africa (9), there is a need for more precise physical activity data from this region and for global physical activity surveillance in general (10,11).

We aimed to develop a method of combining the signals from two accelerometers, one worn on the hip and one on the thigh, to quantify physical behaviors as defined by their posture and movement intensity. This allowed us to describe these behaviors by sociodemographic characteristics in a cohort of middle-age South-African men and women.

METHODS

Study setting and participants. The Middle-age Soweto Cohort (MASC) is a longitudinal study of 2031 participants residing in Soweto, Johannesburg, and was designed to identify the determinants of noncommunicable disease and type 2 diabetes risk in middle-age South-African men and women (12). Soweto is an urban township southwest of Johannesburg, with a population of approximately 1.3 million people living in a 200-km^2 area. The follow-up assessment of this study included the objective assessment of physical activity in a subsample of participants, which forms the basis of the present cross-sectional analysis. A sample of 502 men and 527 women were invited to participate, and although 99.8% of the sample agreed, accelerometer data were only collected on 839 participants because of the availability of devices. Data were collected between January 2017 and August 2018.

The study was conducted in accordance with the tenets of the Helsinki Declaration and was approved by the Human Research Ethics Committee (Medical) of the University of the Witwatersrand (clearance certificate numbers M160604 and M160975). Before inclusion in the study, all the procedures and possible risks associated with the study were explained and all participants signed a consent form. All the tests and procedures were carried out at the South African Medical Research Council/Wits Developmental Pathways for Health Research Unit at the Chris Hani Baragwanath Hospital in Soweto, Johannesburg, South Africa.

Anthropometric measures. Height was measured to the nearest 0.1 cm using a stadiometer (Holtain, Crymych, United Kingdom), and weight was measured in light clothing using a TANITA digital scale (model: TBF-410; Tanita Corporation, Arlington Heights, Illinois) to the nearest 0.1 kg. Body mass index (BMI) was calculated as weight/height^2 (in kilograms per meter squared).

HIV status was originally acquired at baseline data collection. Participants who were HIV negative at baseline data collection completed an HIV antibody test (Wondfo One Step HIV-1/2; Guangzhou Wondfo Biotech Co., Ltd.) during this visit. Participants with a positive HIV result were retained in the study and referred to a clinic.

Socioeconomic status. Socioeconomic status (SES) was quantified using household asset index and education level completed and was assessed using an interviewer-administered questionnaire. Household asset index was calculated by summing assets reported to be owned in the household (out of a total of 12 assets), as has been used in previous studies in this setting (13). Participants reported the highest education level completed, which was categorized into no formal/elementary, secondary or tertiary education levels.

Physical activity assessment. Participants were asked to wear two triaxial accelerometers simultaneously; an ActiGraph GT3X+ (ActiGraph, Pensacola, FL) on the hip (ACC_{hip}) and an activPAL (PAL Technologies Ltd., Glasgow, United Kingdom) on the thigh (ACC_{thigh}). At the clinic visit, the ACC_{hip} was fitted on an elastic waistband on the right hip at the midaxillary line and the ACC_{thigh} to the right thigh (anterior midline) using a nitrile sleeve and adhesive dressing (3M Tegaderm). Participants were asked to wear both accelerometers continuously for 7 d and nights, with the exception of the ACC_{hip} being removed for bathing and water-based activities because of the device not being waterproof. Monitors were initialized to record raw triaxial acceleration at nominal sampling rates of 80 and 20 Hz with a dynamic range of ±6*g* and ±2*g* for the ACC_{hip} and ACC_{thigh},

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respectively. Participants were asked to record their daily sleep (including nap) and wake times using a sleep diary spanning the full measurement period.

Accelerometer data processing. After the download of the monitors, raw triaxial data were exported from proprietary software (Actilife software (ActiGraph) and activPAL software (PAL Technologies Ltd.)). Data from both devices were processed using Pampro, an open-source software package (14). Data were resampled to exactly 80 and 20 Hz for ACC_{hip} and ACC_{thigh}, respectively, and measured acceleration calibrated to local gravity (15). Vector magnitude was calculated from the three axes, and Euclidean Norm Minus One (ENMO) was derived by subtracting 1*g* from vector magnitude to remove the gravity component of the acceleration signal and isolate the activity-related signal, expressed in milligrams. Negative values were rounded to zero. High-frequency noise was additionally removed from the ACC_{hip} signal using a 20-Hz low-pass filter (16); this noise reduction is not possible for ACC_{thigh} because of its lower native sampling frequency.

Periods of nonwear were identified as time segments of low movement variability relative to sensor noise levels, that is, axis acceleration SD less than 13 m*g* for thigh acceleration (17) and less than 4 m*g* for hip acceleration (18) for ≥1 h. These periods were removed from the present analysis.

Sample-level data were collapsed to 1-min level data to ensure time synchronization between the two devices; this is the level at which the two time series are merged. Furthermore, to account for unexpected time drifts between the two accelerometers, time segments were set to nonwear if the correlation between hip and thigh acceleration was <0.5.

The time series of the ACC_{thigh} and ACC_{hip} were combined to derive the average ENMO of the two signals ($ENMO_{thigh+hip}$, main method); the two single-monitor signals were also analyzed, making a total of three assessment methods or processing pipelines. One-minute windows were initially classified as either moving or static, based on differing thresholds for ENMO for the three separate pipelines ($ACC_{thigh+hip}$, ACC_{thigh} or ACC_{hip}; Fig. 1).

For time segments classified as moving, magnitude of the acceleration signal(s) (ENMO) was used to classify physical activity intensity into time spent in light-intensity physical activity (LPA) and moderate- to vigorous-intensity physical activity (MVPA). Intensity thresholds were based on ACC_{hip} thresholds (19) and regression within the data set to derive the equivalent threshold from the ACC_{thigh} signal (from data surrounding the light and moderate threshold regions).

For time classified as static, thigh pitch angle was used for posture-based classification (Fig. 1). No specific postures were derived from the ACC_{hip} signal alone because of the poor accuracy of this signal for differentiating lying, sitting, and upright postures (20). When the thigh accelerometer is not moving, the measured acceleration is predominantly the gravitational component, from which angles with respect to vertical can be derived. Thigh pitch angle (from −90° to

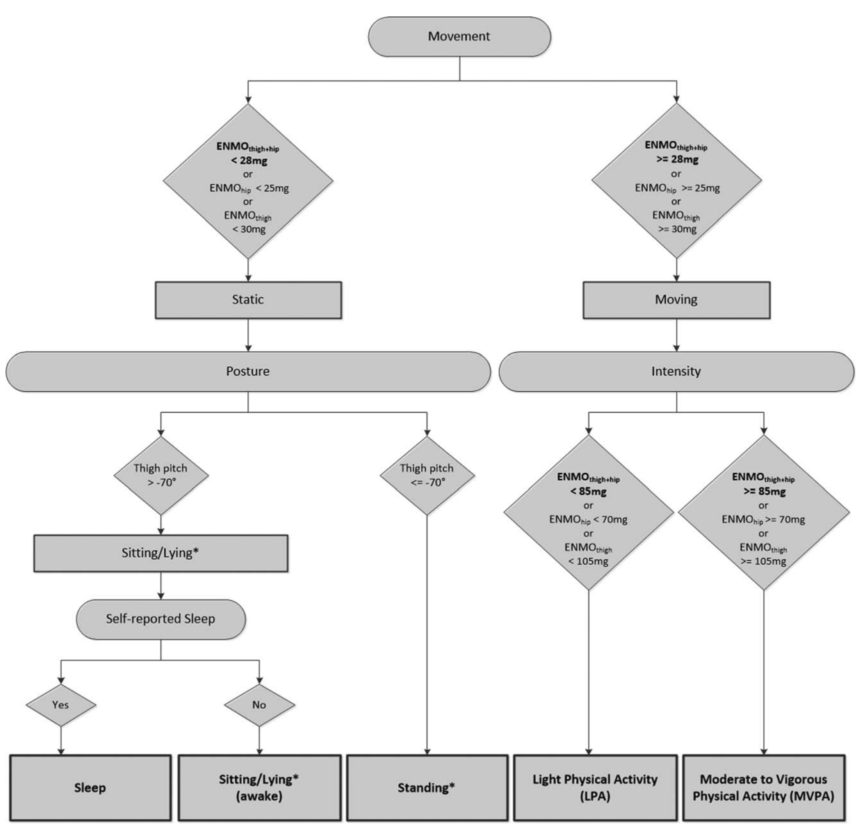

FIGURE 1—Decision tree for classifying physical behavior using thigh and hip acceleration signals. *No posture variables generated for the ACC_{hip} signal only.

+90°) was calculated (21) along the x axis of ACC_{thigh}; a pitch angle of 0° represents the accelerometer being horizontal (perpendicular to gravity), whereas −90° and +90° indicate the accelerometer being vertical (aligned with the gravitational acceleration). When considering anatomical mounting on the thigh, here negative pitch angles indicate an upright position (hip above knee), and hence, pitch angle from ACC_{thigh} was used to classify standing and sitting/lying. Adjustment (multiplication by −1) was made to the pitch results where it was evident that the thigh accelerometer had been worn upside down; that is, very little time is spent with the knee above the hip, particularly during movement during the day. Because of the horizontal position of the thigh during both sitting and lying, it is difficult to differentiate between these two postures with a thigh-worn monitor.

Finally, to further classify sitting/lying time into sleep time and awake sitting/lying time, the self-reported sleep timings were overlaid onto the accelerometry time series (Fig. 1). Where values were missing for one or more days, either within-person median values for other days were used, or where no sleep data were available for a participant, population sample median times were applied.

All data were plotted and manually/visually verified. An example of the raw signals and derived intensities and postures across a 24-h period for one participant is displayed in Supplemental Figure S1 (Supplemental Digital Content 1, Example of simultaneous hip and thigh acceleration and thigh angles, along with derived intensities and postures across 24-h period, http://links.lww.com/MSS/C586).

Data were summarized while minimizing potential bias caused by imbalance of nonwear (22). Summary results and the combined (dual) accelerometer signal being used preferentially were further consolidated. Inclusion criteria specified wear time of a minimum of 48 h with the additional requirement of ≥9 h cumulative wear in each quadrant (6-h block) of the day to ensure a balanced representation of the diurnal profile. When these criteria were not met (n = 31), or wear time from one device was significantly higher than the other (n = 23), or time synchronization failed between devices (n = 52), the signal with the higher wear time was used (Supplemental Fig. S2, Supplemental Digital Content 2, Participant/data flow, http://links.lww.com/MSS/C587). Alternatively, ACC_{thigh} was used preferentially in the event that wear time was similar between the signals (<24-h difference) to allow postural classification.

Final accelerometry outcomes included overall movement volume measures (average $ENMO_{thigh + hip}$ (in milligrams), $ENMO_{thigh}$ (in milligrams), and $ENMO_{hip}$ (in milligrams)), as well as time spent in sleep (in minutes per day), awake sitting/lying (in minutes per day; labeled as sitting/lying from here onward), standing (in minutes per day), LPA (in minutes per day), and MVPA (in minutes per day). Moving (in minutes per day) is a composite of LPA and MVPA, and static (in minutes per day) is a composite of time spent standing and sitting/lying.

Statistics. To facilitate direct comparison to other studies using only one accelerometer on either the hip or the thigh, we derived harmonization equations by regressing each source acceleration onto the combined acceleration signal from the two anatomical positions, using multilevel time-series regression (level 1, minute-by-minute acceleration; level 2, participant) with linear, square root, and square terms for the input signals.

Distributions of person-minutes (time-series level) for key accelerometer signal components are described in histograms by the classified behavior types across the whole sample.

Descriptive characteristics at participant level are presented as mean (SD) for continuous data and n (%) for categorical data, stratified by sex. Further stratifications included age group (41–49, 50–59, and 60–72 yr), BMI category according to standard World Health Organization categories (underweight, <18.5 kg·m^{-2}; normal weight, 18.5–24.9 kg·m^{-2}; overweight, 25–29.9 kg·m^{-2}; obesity class I, 30–34.9 kg·m^{-2}; obesity class II, 35–39.9 kg·m^{-2}; obesity class III, ≥40.0 kg·m^{-2}) (23), HIV status (infected, uninfected), and level of education completed (no formal/elementary, secondary or tertiary). Data visualized as box plots represent unadjusted median and interquartile ranges (IQR), stratified by sex for age categories, BMI categories, and SES (education) categories. For household assets, bin scatter plots were used (in 5% bins), adjusted for age.

Sex-stratified multivariable linear regression was used to model the independent associations of age, BMI, HIV status, education level, SES (asset count), and season of measurement, with physical behaviors.

All statistical analyses were performed using STATA/SE version 16 (StataCorp, College Station, TX).

RESULTS

Participant characteristics. Complete accelerometry data for both hip and thigh were available on 794 participants (Supplemental Fig. S2, Supplemental Digital Content 2, Participant/data flow, http://links.lww.com/MSS/C587). A total of 357 women and 437 men were included in the current analysis, with data available from at least one of the two accelerometers. This subsample did not differ significantly from the sample who did not have accelerometry data with respect to BMI and sociodemographic factors; however, women included in these analyses were approximately 1.5 yr younger than women who were not included (Supplemental Table 1, Supplemental Digital Content 3, Descriptive characteristics of subsample included and excluded from the current study, http://links.lww.com/MSS/C588). Descriptive characteristics of the participants in this study are presented in Table 1. Overall, mean (SD) age was 53.7 (6.3) yr, with no difference between men and women. Mean (SD) BMI for women was 33.6 (6.9) kg·m^{-2} compared with 25.6 (6.0) kg·m^{-2} for men, whereas overweight and obesity were reported in 90% of women and in 51% of men.

Movement characteristics at the time-series level. Mean (SD) wear time for the hip and thigh accelerometers were 143 (29) and 142 (36) h, respectively, with the combined signal based on 128 (48) h of wear. The hip and thigh acceleration signals were highly correlated with each other in the

TABLE 1. Descriptive characteristics of the MASC study (2017–2018).

	Total (n = 794)		Men (n = 437)		Women (n = 357)		
	n or Mean	% or SD	n or Mean	% or SD	n or Mean	% or SD	P
Age (yr)	53.7	6.0	53.6	6.2	53.9	5.8	0.518
Age categories							0.179
41–49 yr	253	31.9	147	33.6	106	29.7	
50–59 yr	387	48.7	200	45.8	187	52.4	
60–72 yr	154	19.4	90	20.6	64	17.9	
BMI (kg·m^{-2})	29.2	7.6	25.6	6.0	33.6	6.9	<0.001
BMI categories							<0.001
<18.5 kg·m^{-2}	43	5.4	41	9.4	2	0.6	
18.5–24.9 kg·m^{-2}	208	26.2	175	40.0	33	9.2	
25–29.9 kg·m^{-2}	204	25.7	125	28.6	79	22.1	
30–34.9 kg·m^{-2}	173	21.8	67	15.3	106	29.7	
35–39.9 kg·m^{-2}	98	12.3	18	4.1	80	22.4	
≥40 kg·m^{-2}	68	8.6	11	2.5	57	16.0	
HIV status							0.617
Infected	155	19.5	88	20.2	67	18.8	
Education categories							0.001
No formal/elementary	74	9.3	49	11.2	25	7.0	
Secondary	595	74.9	305	69.8	290	81.2	
Tertiary	125	15.7	83	19.0	42	11.8	
SES							
Asset count	8.8	2.2	8.7	2.3	8.8	2.0	0.946
Accelerometry							
$ENMO_{thigh + hip}$ (mg)	13.8	5.5	15.0	6.5	12.2	3.4	<0.001
$ENMO_{hip}$ (mg)	11.5	4.2	12.5	4.8	10.3	3.0	<0.001
$ENMO_{thigh}$ (mg)	16.0	6.5	17.4	7.6	14.2	4.3	<0.001
Moving (min·d^{-1})	164.9	91.1	175.7	108.9	151.7	60.4	<0.001
LPA (min·d^{-1})	118.6	78.2	118.4	95.7	118.8	49.0	0.112
MVPA (min·d^{-1})	46.4	36.8	57.3	42.2	32.9	22.5	<0.001
Static (min·d^{-1})	857.6	101.6	843.8	110.0	874.5	87.4	<0.001
Standing (min·d^{-1})	223.6	98.1	195.9	86.4	257.6	101.0	<0.001
Sitting/Lying (min·d^{-1})	632.9	129.4	646.9	127.3	615.8	130.0	<0.001
Sleep (min·d^{-1})	417.5	79.9	420.5	85.3	413.8	72.8	0.281

Data are presented as mean (SD) or n (%). P values are for sex differences.
Sample sizes where different: Total: n = 777 (ACC_{hip}), n = 756 (ACC_{thigh}), n = 734 (stand, sit/lie), n = 778 (sleep diary). Men: n = 428 (ACC_{hip}), n = 417 (ACC_{thigh}), n = 404 (stand, sit/lie), n = 433 (sleep diary). Women: n = 349 (ACC_{hip}), n = 339 (ACC_{thigh}), n = 330 (stand, sit/lie), n = 345 (sleep diary).

multilevel time series analyses of 5,493,937 person-minutes of valid double-sensor data (82% explained within-person variance, 77% explained variance between persons), resulting in strong predictions of the combined acceleration signal from either of the two single sources of acceleration, with standard errors of the predictions being 5.4 mg from thigh acceleration and 7.2 mg from hip acceleration (Table S2, Supplemental Digital Content 4, Relationships between individual measures of hip and thigh acceleration with combined hip-thigh acceleration, http://links.lww.com/MSS/C589).

The person-time distribution of hip acceleration, thigh acceleration, and thigh pitch angles are shown by the five classified physical behavior types in Supplemental Figure S3 (Supplemental Digital Content 5, Person-time distribution of hip acceleration, thigh acceleration and thigh angles across classified behavior types, http://links.lww.com/MSS/C590). Some aspects of the distributions are defined by the specific decisions in the classification method such as the cutoff for the thigh pitch angle of −70° to separate standing from the other two static postures of sleep and sitting/lying, and therefore by definition, there are no data on the other side of a thigh pitch angle of −70° for sleeping and sitting/lying. Other results reflect the natural unconstrained variation of movement behaviors in this population. For example, participants assume a range of thigh angles around the horizontal position (0°) during sleep and sitting/lying (median (IQR), 2° (−8° to 9°) and −1° (−14° to 9°), respectively), including angles where the knee is almost vertically above the hip. Comparatively, the majority of LPA and MVPA is performed with the knee below the hip (upright position akin to standing) but with LPA displaying a wider range of thigh angles including some approaching horizontal. Similarly, hip and thigh acceleration are by definition restricted to a low range for the three static behaviors, but there is still a degree of movement in all three, with the thigh displaying a wider range and moving the most compared with the hip. This observation can also be made for LPA and MVPA, which are characterized by more movement at both anatomical locations (note, scale factor 10 larger) compared with the static behaviors. For LPA, median (IQR) hip acceleration is 34 (27 to 45) mg with most data less than 100 mg, and median (IQR) thigh acceleration is 49 (38 to 66) mg with most data less than 120 mg; the theoretical maximal acceleration for both anatomical locations is 170 mg, that is, twice the combined intensity cut point. For MVPA, median (IQR) hip acceleration is 107 (84 to 139) mg with not much time above 300 mg, whereas the thigh typically moves more during MVPA, with median (IQR) acceleration at 161 (127 to 208) mg and most data less than 400 mg.

Descriptive epidemiology of physical behaviors at the participant level. The descriptive characteristics, including the physical behaviors, of the total sample and men and women separately are presented in Table 1. Physical behaviors were different between the sexes. Men spent more time moving than women, particularly at higher intensity, as can be seen from higher values of ENMO and more time spent in MVPA.

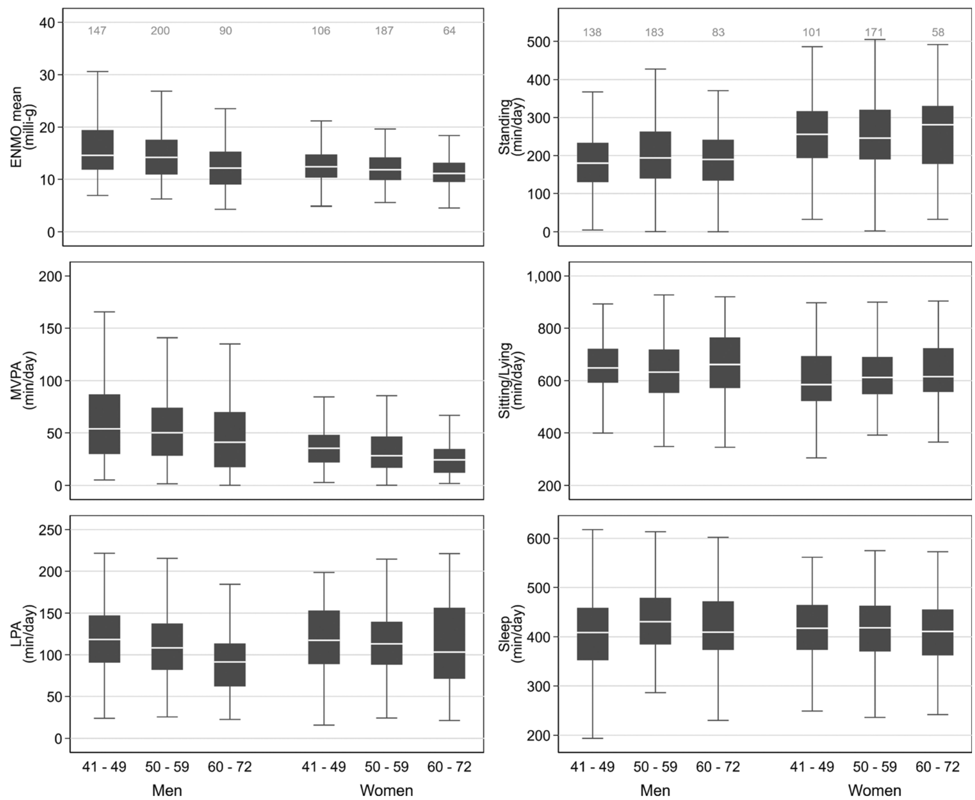

FIGURE 2—Physical activity behaviors by age and sex in the MASC study 2017–2018. Sample sizes for ENMO, MVPA, LPA, and sleep are the same and only displayed in the ENMO panel; the sample sizes for standing and sitting/lying are also the same and displayed in the standing panel.

Women spent more time standing and less time sitting/lying compared with men. There were no sex differences for time spent sleeping or in LPA.

The box plots (unadjusted) of all the physical behaviors by three age categories and stratified by sex are presented in Figure 2. For both men and women, total volume of movement (ENMO), LPA, and MVPA decreased with age, with no associations for time spent standing, sitting/lying, and sleeping. In the multivariable analysis with adjustment for BMI, HIV status, SES, and season of measurement, total volume of movement (ENMO) and time spent in MVPA were lower in the oldest age group (60–72 yr) compared with the youngest age group (40–49 yr) in both men (Table 2) and women (Table 3). Both men and women in the oldest age group spent ~13 min·d^{-1} less in MVPA compared with the youngest age group, but differences in time spent in LPA and sitting/lying were only shown in women where the oldest age group spent 19 min·d^{-1} less in LPA and 46 min·d^{-1} more time in sitting/lying compared with the youngest age group. Men between the ages of 50 and 59 yr slept an average of 22 min·d^{-1} than men between the ages of 40 and 49 yr. Similar associations with age were observed when considering hip acceleration only (Supplemental Table S3, Supplemental Digital Content 6, Multivariable analysis of physical activity volume and time in MVPA using hip-worn accelerometer signal (ACC$_{hip}$) only, http://links.lww.com/MSS/C591) and thigh acceleration only (Supplemental Table S4, Supplemental Digital Content 7, Multivariable analysis of physical activity volume and time in MVPA using thigh-worn accelerometer signal (ACC$_{thigh}$) only, http://links.lww.com/MSS/C592). Although HIV status was not associated with any of the physical behaviors in men, women living with HIV spent 30 min·d^{-1} less in standing than women not infected by HIV (Table 3).

Figure 3 presents box plots of the physical behaviors stratified by BMI category. They show lower levels of MVPA in the higher BMI categories in men and similarly for LPA in the women. No clear pattern with BMI was seen for standing in men, whereas women in higher BMI categories stood less than women in lower BMI categories. Time spent sitting was higher at higher BMI levels in both men and women, and underweight and normal-weight individuals tended to sleep more. Multivariable analysis shows that when compared with the normal-weight category, men who were overweight or obese had significantly lower ENMO (1.9 m*g* and 3 m*g*) and spent less average daily time in MVPA (16 and 21 min) and sleeping (17 and 30 min), and more time standing (18.9 min in the men who were overweight; Table 2). When compared with normal-weight women, women who were overweight or obese spent significantly less time in LPA (27–35 min·d^{-1}) and standing, and more time sitting/lying (Table 3). When only considering hip or thigh acceleration alone, similar patterns were observed in men and women (Supplemental Table 3, Supplemental Digital Content 6, Multivariable analysis of physical activity volume and time in MVPA using hip-worn accelerometer signal (ACC$_{hip}$) only, http://links.lww.com/MSS/C591, and Supplemental Table 4, Supplemental Digital Content 7, Multivariable

TABLE 2. Multivariable regression analysis of physical behaviors in men.

	ENMO (m*g*), *β* (95% CI)	MVPA (min·d^{-1}), *β* (95% CI)	Light PA (min·d^{-1}), *β* (95% CI)	Standing (min·d^{-1}), *β* (95% CI)	Sitting/Lying (min·d^{-1}), *β* (95% CI)	Sleep (min·d^{-1}), *β* (95% CI)
Age (yr)						
40–49	Reference	Reference	Reference	Reference	Reference	Reference
50–59	−1 (−2.2 to 0.3)	−5.9 (−14.2 to 2.4)	−0.9 (−21.6 to 19.7)	7.6 (−11.9 to 27.1)	−23.5 (−51.6 to 4.5)	21.5 (3.5 to 39.5)
60–72	−3.0** (−4.6 to −1.4)	−12.6* (−23.1 to −2.2)	−14.3 (−40.3 to 11.6)	−11.5 (−36.1 to 13.1)	12.3 (−23.2 to 47.7)	18.7 (−3.8 to 41.3)
BMI (kg·m^{-2})						
<18.5	−2.5* (−4.5 to −0.5)	−6 (−19.2 to 7.2)	−15.9 (−48.8 to 17)	−25.9 (−57.2 to 5.3)	4.8 (−40.4 to 49.9)	38.0** (9.4 to 66.6)
18.5–24.9	Reference	Reference	Reference	Reference	Reference	Reference
25–29.9	−1.9** (−3.3 to −0.6)	−16.2** (−25.1 to −7.3)	6.3 (−15.8 to 28.5)	18.9 (−2.1 to 39.9)	7.5 (−22.9 to 37.8)	−17.2 (−36.4 to 2.1)
30–34.9	−3.0** (−4.7 to −1.3)	−21.4** (−32.5 to 10.3)	−15.0 (−42.6 to 12.7)	5.5 (−20.8 to 31.8)	58.4** (20.5 to 96.4)	−30.2* (−54.2 to −6.1)
35–39.9	−1.8 (−4.8 to 1.1)	−6.6 (−25.4 to 12.1)	−18.2 (−64.7 to 28.4)	−29.7 (−74.6 to 15.1)	50.4 (−14.3 to 115.1)	0.2 (−40.2 to 40.7)
≥40	−0.9 (−4.5 to 2.7)	−29.8* (−53.3 to −6.3)	123.5** (65 to 181.9)	−53.2 (−106.7 to 0.3)	6.2 (−71 to 83.3)	−47.1 (−97.9 to 3.7)
HIV status						
HIV uninfected	Reference	Reference	Reference	Reference	Reference	Reference
HIV infected	−1.1 (−2.5 to 0.3)	−4.5 (−13.8 to 4.9)	−16.5 (−39.7 to 6.7)	−7.9 (−29.8 to 13.9)	14.1 (−17.5 to 45.7)	15.8 (−4.3 to 36)
Education level						
No formal/elementary	Reference	Reference	Reference	Reference	Reference	Reference
Secondary	1.6 (−0.2 to 3.4)	10.4 (−1.3 to 22)	12.3 (−16.5 to 41.2)	7.1 (−20.1 to 34.4)	−14.1 (−53.4 to 25.2)	−10.2 (−35.3 to 14.9)
Tertiary	1.1 (−1.1 to 3.2)	8.3 (−5.8 to 22.4)	21.3 (−13.8 to 56.4)	−5.4 (−38.3 to 27.4)	1 (−46.4 to 48.3)	−16.8 (−47.3 to 13.7)
SES						
Asset count in household[a]	−0.5** (−0.7 to −0.2)	−6.2** (−7.9 to −4.6)	1.5 (−2.5 to 5.6)	−1 (−4.9 to 2.8)	9.1** (3.5 to 14.7)	−3.4 (−7.0 to 0.1)
Seasonality						
Spring	0.3 (−0.6 to 1.2)	4.2 (−1.5 to 9.9)	3.4 (−10.8 to 17.5)	−10.5 (−24.1 to 3.1)	13.3 (−6.4 to 32.9)	−13.0* (−25.3 to −0.7)
Winter	0.2 (−0.7 to 1.1)	2.9 (−2.8 to 8.5)	−3.4 (−17.5 to 10.7)	6.2 (−7.3 to 19.8)	−19.6* (−39.1 to 0)	15.5* (3.3 to 27.8)
Constant[a]	16.4** (14.3 to 18.5)	63.0** (49.3 to 76.6)	114.2** (80.2 to 148.1)	186.2** (154.3 to 218.2)	659** (613.7 to 705.9)	412.4** (382.9 to 441.9)

ENMO, MVPA, and LPA estimates are based on $ENMO_{thigh + hip}$ time series where available, and (scaled) from either $ENMO_{thigh}$ or $ENMO_{hip}$ where not. Seasonal parameters are continuous cosinor coefficients, oscillating from −1 to +1, peaking at October 1 (spring) and July 1 (winter).
[a]Centered at nine assets.
*$P < 0.05$.
**$P < 0.01$.

analysis of physical activity volume and time in MVPA using thigh-worn accelerometer signal (ACC_{thigh}) only, http://links.lww.com/MSS/C592).

The variation in PA behaviors by three education categories is presented as box plots in Figure 4. The patterns of associations observed for men were lower PA (ENMO, MVPA, and LPA) and more time sleeping in those with no formal education compared with those more educated. Women with higher educational attainment spent less time in MVPA, less time sleeping, and more time sitting compared with those less educated. Multivariable analysis shows that when compared with no formal/elementary education, men with secondary education

TABLE 3. Multivariable regression analysis of physical behaviors in women.

	ENMO (m*g*), *β* (95% CI)	MVPA (min·d^{-1}), *β* (95% CI)	Light PA (min·d^{-1}), *β* (95% CI)	Standing (min·d^{-1}), *β* (95% CI)	Sitting/Lying (min·d^{-1}), *β* (95% CI)	Sleep (min·d^{-1}), *β* (95% CI)
Age (yr)						
40–49	Reference	Reference	Reference	Reference	Reference	Reference
50–59	−0.4 (−1.4 to 0.5)	−3.7 (−9.1 to 1.8)	−6.1 (−18.5 to 6.4)	−8.7 (−34.4 to 17)	24.9 (−7.3 to 57.1)	−8.3 (−26.8 to 10.2)
60–72	−2.0** (−3.3 to −0.6)	−13.0** (−20.4 to −5.5)	−18.6* (−35.5 to −1.7)	−3.3 (−38.6 to 32)	46.0 (1.7 to 90.3)	−15.4 (−40.6 to 9.7)
BMI (kg·m^{-2})						
<18.5	−4.7 (−9.9 to 0.5)	−24.6 (−55.2 to 6.1)	−72.7* (−142.2 to −3.1)	19 (−120.6 to 158.6)	41.7 (−133.3 to 216.8)	40.2 (−63.3 to 143.7)
18.5–24.9	Reference	Reference	Reference	Reference	Reference	Reference
25–29.9	−0.7 (−2.2 to 0.8)	0.3 (−8.3 to 9.0)	−27.6** (−47.3 to −7.8)	−12.1 (−52.0 to 27.8)	55.0* (5.0 to 104.9)	−19.5 (−48.8 to 9.9)
30–34.9	−0.6 (−2.1 to 0.8)	0.6 (−7.7 to 9.0)	−13.1 (−31.9 to 5.8)	−13.0 (−51.6 to 25.5)	44.0 (−4.4 to 92.3)	−19.0 (−47.1 to 9.1)
35–39.9	−2.0** (−3.5 to −0.5)	−6.9 (−15.6 to 1.7)	−27.8** (−47.4 to −8.3)	−62.8** (−102.3 to −23.2)	111.3** (61.8 to 160.8)	−13.8 (−42.9 to 15.3)
≥40	−1.9* (−3.5 to −0.3)	−8.9 (−18.0 to 0.3)	−34.8** (−55.6 to −14.1)	−95.4** (−137.9 to −52.9)	146.7** (93.4 to 199.9)	−9.3 (−40.2 to 21.6)
HIV status						
HIV uninfected	Reference	Reference	Reference	Reference	Reference	Reference
HIV infected	−0.6 (−1.7 to 0.5)	−0.5 (−6.7 to 5.7)	−7.4 (−21.4 to 6.6)	−30.3* (−58.9 to −1.7)	21.3 (−14.5 to 57.2)	13.4 (−7.5 to 34.3)
Education level						
No formal/elementary	Reference	Reference	Reference	Reference	Reference	Reference
Secondary	−0.2 (−1.8 to 1.4)	−1.0 (−10.2 to 8.2)	10.9 (−10 to 31.8)	13.1 (−29.9 to 56.2)	−5.7 (−59.7 to 48.4)	−21.0 (−52.1 to 10.1)
Tertiary	−1.6 (−3.6 to 0.4)	−9.1 (−20.5 to 2.3)	−0.6 (−26.4 to 25.3)	−3.1 (−57.3 to 51.0)	60.9 (−6.9 to 128.8)	−46.2* (−84.6 to −7.7)
SES						
Asset count in household[a]	−0.2* (−0.4 to 0)	−2.9** (−4.1 to −1.8)	1.2 (−1.4 to 3.8)	−2.9 (−8.3 to 2.5)	9.0** (2.2 to 15.8)	−3.6 (−7.4 to 0.3)
Seasonality						
Spring	−0.1 (−0.7 to 0.4)	0.1 (−2.9 to 3.1)	−0.6 (−7.4 to 6.3)	7.2 (−7.1 to 21.5)	4.9 (−13.0 to 22.8)	−12.0* (−22.2 to −1.8)
Winter	−0.6 (−1.3 to 0)	−2.7 (−6.3 to 1.0)	−8.4* (−16.6 to −0.2)	10.7 (−6.4 to 27.7)	−6.5 (−27.8 to 14.8)	4.1 (−8.1 to 16.3)
Constant[a]	14.6** (12.4 to 16.9)	41.7** (28.8 to 54.7)	141.3** (111.8 to 170.7)	292.0 (231.6 to 352.4)	516.9** (441.1 to 592.6)	454.8** (411.0 to 498.6)

ENMO, MVPA, and LPA estimates are based on $ENMO_{thigh + hip}$ time series where available, and (scaled) from either $ENMO_{thigh}$ or $ENMO_{hip}$ where not. Seasonal parameters are continuous cosinor coefficients, oscillating from −1 to +1, peaking at October 1 (spring) and July 1 (winter).
[a]Centered at nine assets.
*$P < 0.05$.
**$P < 0.01$.

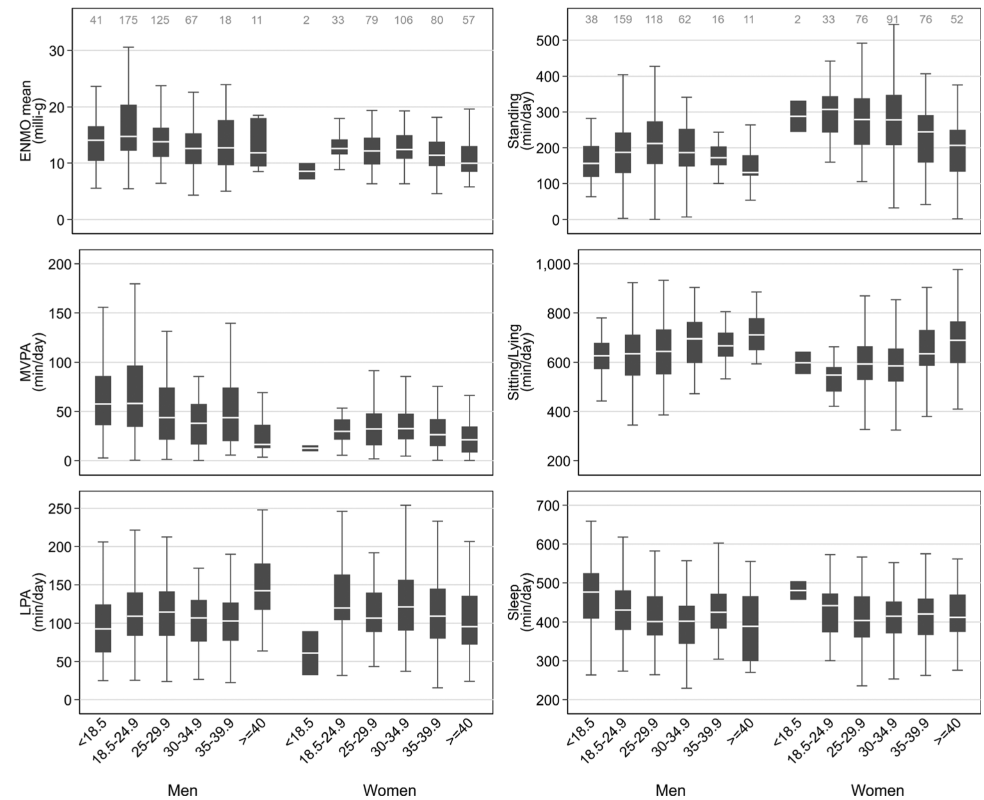

FIGURE 3—Physical activity behaviors by BMI (in kilograms per meter squared) and sex. The MASC study 2017–2018. Sample sizes for ENMO, MVPA, LPA, and sleep are the same and only displayed in the ENMO panel; the sample sizes for standing and sitting/lying are also the same and displayed in the standing panel.

were more active overall (ENMO difference of 1.6 m*g*) and also spent more time in MVPA (10 $min{\cdot}d^{-1}$; Table 2). Women with a tertiary education spent less time sleeping (46 min) compared with women with no formal/elementary education (Table 3). Similar associations with both ENMO and MVPA were observed in the men, and women are observed when considering hip acceleration only (Supplemental Table 3, Supplemental Digital Content 6, Multivariable analysis of physical activity volume and time in MVPA using hip-worn accelerometer signal (ACC_{hip}) only, http://links.lww.com/MSS/C591) and thigh acceleration only.

The number of assets, a measure of SES, and its association with physical behaviors in men and women are presented in bin scatter diagrams in Figure 5. These show a similar trend in both men and women, with a higher asset count associated with lower MVPA and sleep, and more time sitting/lying. Multivariate analyses show similar associations in both men (Table 2) and women (Table 3), with a higher asset count associated with lower ENMO (0.5 m*g* and 0.2 m*g* per asset), less daily time in MVPA (6.2 and 2.9 min per asset) and sleeping (3.4 and 3.6 min per asset), and more time spent sitting/lying (9.1 and 9.0 min per asset). Similar associations were observed in both men and women when only considering hip acceleration or thigh acceleration (Supplemental Table 3, Supplemental Digital Content 6, Multivariable analysis of physical activity volume and time in MVPA using hip-worn accelerometer signal (ACC_{hip}) only, http://links.lww.com/MSS/C591, and Supplemental Table 4, Supplemental Digital Content 7, Multivariable analysis of physical activity volume and time in MVPA using thigh-worn accelerometer signal (ACC_{thigh}) only, http://links.lww.com/MSS/C592).

DISCUSSION

In this study, we have developed a method for combining the signals from hip- and thigh-mounted accelerometers to describe physical behaviors in a middle-age cohort of men and women living in urban South Africa. This simple method is based on first-principles, which discriminates sitting from standing postures using the thigh pitch angle, and a combination of hip and thigh acceleration quantifies different intensities of activity. Using this method, we have shown that men spend nearly double the amount of time in daily MVPA compared with women, but also more time in awake sitting or lying. In identifying factors associated with different physical behaviors, we have shown clear associations with age, BMI, and SES, with some of these associations different in men and women.

Integrating accelerometry data from multiple anatomical locations, such as the hip and thigh, has advantages in terms of combining methodological strengths from both methods, to optimize accuracy of derived physical activity subcomponents (7). Previous research has used multiple accelerometry sensors placed at different anatomical locations, from which information

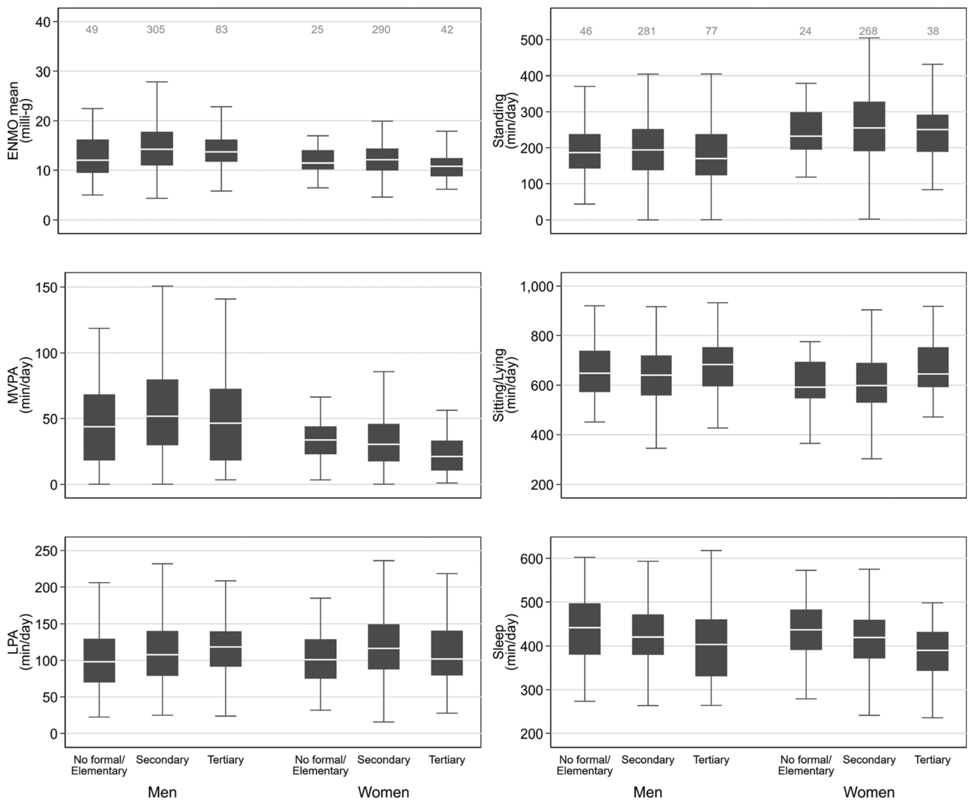

FIGURE 4—Physical activity behaviors by education and sex. The MASC study 2017–2018. Sample sizes for ENMO, MVPA, LPA, and sleep are the same and only displayed in the ENMO panel; the sample sizes for standing and sitting/lying are also the same and displayed in the standing panel.

is wired into, and processed by, one centralized unit (24–27). Because of this complexity, utility of such devices for long-term monitoring of physical behaviors during free-living in large-scale studies is limited, and often, proprietary algorithms are used for activity type classification (28). On the contrary, modern research-grade accelerometers allow for storage of raw data over prolonged monitoring times. Raw acceleration data, when calibrated to local gravity and expressed in milli-grams, are universal and hence device independent, and even derived angles relative to the gravitational acceleration gradient (i.e., vertical) during periods of little movement can be considered universal. Compared with device-specific proprietary algorithms, open-source algorithms applied to raw data allow more flexibility for researchers for optimization and are also applicable across different devices. Algorithmic integration of raw data from such accelerometers collected from different anatomical positions therefore opens up new possibilities to optimize measurement of habitual physical activity behavior types in large-scale studies. Thigh pitch, as derived from thigh accelerometry, has shown great utility for accurate discrimination of sitting/lying postures from upright postures (29) and outperforms hip accelerometry for this classification task, using direct observation as the criterion (20,30). On the contrary, hip accelerometry seems to be better for the assessment of whole-body acceleration and hence movement intensity, likely given the closer proximity to the body's center of mass. However, as we show in the present study, the acceleration from both these anatomical locations is highly correlated. Some studies have combined data from separate hip- and thigh-mounted accelerometers in an algorithm-based manner for discrimination between specific activity types, such as walking, running, cycling, walking stairs, sitting, lying, and standing (28,31,32). In African settings, objective assessment of activity is limited (9) and nonexistent using multiaccelerometer methods. Developing a dual-accelerometer methodology to quantify physical behaviors in an understudied population and describing the sociodemographic factors associated with these behaviors contribute to the limited literature available in African populations; however, to ensure feasibility in research constrained environments, we have provided mapping equations and sensitivity analyses for single devices to allow for comparison to our results.

As with epidemiological studies in other populations including South Africa, we have shown that men are more physically active than women of the same age (10,33–37). Although this difference was observed for total movement volume and MVPA, there was no difference in time spent in LPA between the sexes. In African countries, occupational and ambulatory activity make the largest contribution to overall physical activity, with leisure time activity contributing very little (6,38,39). Ambulatory activity, a requirement of both men and women as a means of transport in a setting such as Soweto, is typically performed at a light intensity; however, occupational and leisure-time activity, normally performed at a higher intensity, is more likely to be undertaken by men in these low-resourced settings (6).

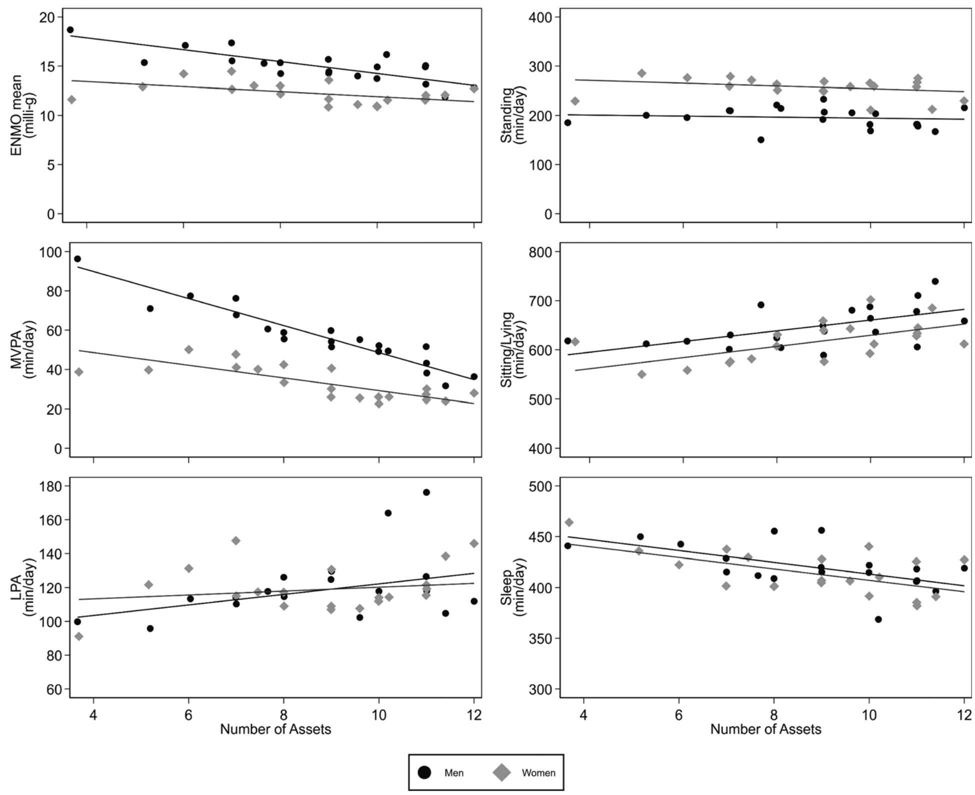

FIGURE 5—Association between household assets and physical activity behaviors, stratified by sex. The MASC study 2017–2018.

A 2016 systematic review of objectively and subjectively measured sedentary time from studies conducted in North America, Europe, Australia, New Zealand, and Asia reported that in the studies that examined sex differences in sedentary time, most reported that women were more sedentary than men (40). Conversely, data from the Caribbean, a region predominantly made up of developing countries, reported no sex difference in sedentary time (41). They defined sedentary time as time spent at <1.5 METs, which may include standing time and reported this to be ~8 $h \cdot d^{-1}$, which was lower than the current study, which reported 10–11 $h \cdot d^{-1}$ of sitting/lying and a further 3–4 h of standing time. Combining signals from a hip-mounted accelerometer and a thigh-mounted accelerometer, which provides additional information on thigh pitch angle, we were able to not only capture body movement more comprehensively but also differentiate sitting/lying from standing and determine the sociodemographic factors associated with a range of physical behaviors including those static postures. Women in our study stand for an average of just over 4 $h \cdot d^{-1}$, which is significantly longer than men who stand for about 3 $h \cdot d^{-1}$, whereas time spent in awake sitting/lying was higher in men than women, although both were over 10 $h \cdot d^{-1}$. Associations between self-reported sitting and standing time, and all-cause mortality, have been explored suggesting that every additional hour of sitting time greater than 8 $h \cdot d^{-1}$ is associated with a 4% higher mortality risk, and standing for more than 8 $h \cdot d^{-1}$ is associated with a 24% reduced mortality risk compared with standing 2 $h \cdot d^{-1}$ (42,43). Chastin et al. (44) have highlighted the limitations of self-report measures of sedentary time, an illustration of which may be the mismatch between the median sitting time of 3 $h \cdot d^{-1}$ reported by Gradidge et al. (38) in the same cohort of women from Soweto using self-report and the objectively assessed sitting time reported in the current study, albeit 12 yr later. We have also shown that, although BMI is associated with time spent standing and time spent sitting/lying in men and women, age and SES were only associated with time spent sitting/lying. This confirms the importance of discriminating between these two behaviors in this population.

Although increasing physical activity and reducing sedentary time are promoted as methods of reducing body weight and the risk of overweight and obesity, this relationship is likely to be bidirectional (45–47). In the current study, men who were overweight or obese (BMI, 25–35 $kg \cdot m^{-2}$) had a lower total volume of physical activity and spent less time in MVPA compared with their normal-weight counterparts. In women, higher BMI was more closely associated with less time spent in LPA and more time spent sitting/lying. This may just reflect differences in physical behavior patterns between the sexes in this population. When compared with men with the same BMI (>35 $kg \cdot m^{-2}$), women spent more than double the amount of time sitting/lying, and when these women were compared with their normal-weight counterparts, they spent 1–1.5 h less time standing and 2–2.5 h more sitting/lying.

Various South African studies in adolescents and adults have confirmed that SES is closely linked to physical activity patterns (35,36,38,48,49). Findings from the current study report that a higher asset count, a well-recognized measure of SES, was associated with a lower total volume of physical activity, less time in MVPA, and more time sitting/lying in both men and women. The positive association between SES and sedentary time has been confirmed by other South African studies including a study of adolescents from rural South Africa (48,49); however, the adolescent study also reported that lower SES was associated with lower MVPA, contrary to the findings of the current study. The discrepancy in these findings may be due to the use of self-reported physical activity in the adolescent study as well as SES being measured at the maternal, household, and community levels rather than the individual level. Similarly, in a Caribbean sample between 25 and 54 yr of age, education level and occupational grade were inversely associated with objectively measured physical activity and positively associated with sedentary time (41). What is apparent is that the relationship between SES and physical behaviors is complex because physical activity patterns and volumes differ between urban and rural populations as well as between low-middle and high-income countries.

Irrespective of country or setting, it is well accepted that age is a significant correlate of physical activity. In the current study, this seems to be more marked for both volume (ENMO) and higher-intensity physical activity (MVPA) in older men and women (between 60 and 72 yr of age). Findings from the Health and Aging in Africa: a longitudinal study of an INDEPTH community in South Africa study in rural South African adults older than 40 yr identified age as a significant correlate of self-reported physical activity with adults older than 70 yr to be less likely to meet physical activity guidelines than those between 40 and 49 yr of age (50).

Although there is an increasing interest in the association between sleep duration and quality, and disease risk in South African women, to our knowledge, this is the first study reporting sleep duration in South African men. Our measure of sleep was a combination of self-report via the sleep diary and the accelerometry data indicating absence of movement and a sitting/lying posture, with the mean sleep duration being about 7 $h \cdot d^{-1}$ for both men and women. This is approximately 1 h less than self-reported data from a cohort of younger Black women from Cape Town, in which sleep was associated with weight status, with women sleeping less than 7 $h \cdot d^{-1}$ being less likely to present with obesity than those sleeping 7–9 h (51). In the current study, BMI was not associated with sleep in the women; however, when compared with normal-weight men, underweight men spent more time sleeping, whereas men who were overweight or obese spent less time spent sleeping than their normal-weight counterparts.

A major strength of the study includes the use of objective methods to measure physical behaviors, and particularly integrating and combining raw sensor data from accelerometers worn on different anatomical locations. Similar associations with other epidemiological studies confirm the robustness of this approach and provides further detail on postural differentiation of sedentary time. Using this integrated methodology, we were able to explore individual- and household-level correlates of physical behaviors, which has previously only been described in women using either self-report or single-accelerometer methods; however, because of the cross-sectional nature of the study, the direction of associations with modifiable determinants cannot be confirmed. Furthermore, although objective methods are preferable when measuring physical activity to avoid issues such as recall bias, these methods are not able to distinguish the domains in which physical behaviors are performed such as leisure time and occupation. Physical activity time spent in these domains is important particularly in settings where physical activity patterns may differ to high-income settings. Domain-specific information could help in designing effective interventions in these settings. Another limitation of the current study is the use of sleep diaries to determine awake and sleep time. Sleep diaries are also prone to recall bias and reporting time in bed rather than sleep duration; however, the combination of sleep diaries and accelerometry may have reduced misclassification errors.

CONCLUSIONS

In this study, we have described a method of integrating signals from hip and thigh accelerometers to more comprehensively describe physical behaviors of middle-age men and women from urban South Africa. Identifying factors associated with physical activity and sedentary behavior contributes to our understanding of lifestyle behaviors in this population and provides possible areas for intervention.

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The results of this study are presented clearly, honestly, and without fabrication, falsification, or inappropriate data manipulation. The results of the present study do not constitute endorsement by the American College of Sports Medicine. The authors declare that they have no conflict of interest.

EPIDEMIOLOGY

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