Assessing Sedentary Behavior with the GENEActiv: Introducing the Sedentary Sphere

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[1]Health and Use of Time Group, Sansom Institute for Health Research, University of South Australia, Adelaide, AUSTRALIA; [2]Exercise for Health and Human Performance Group, Sansom Institute for Health Research, University of South Australia, Adelaide, AUSTRALIA; [3]Sport and Health Sciences, College of Life and Environmental Sciences, University of Exeter, UNITED KINGDOM; [4]GENEActiv, ActivInsights, Cambridgeshire, UNITED KINGDOM; [5]Centre for Research on Exercise, Physical Activity and Health, School of Human Movement Studies, University of Queensland, Brisbane, AUSTRALIA; and [6]International Centre for Allied Health Evidence, Sansom Institute for Health Research, University of South Australia, Adelaide, AUSTRALIA

ABSTRACT

ROWLANDS, A. V., T. S. OLDS, M. HILLSDON, R. PULSFORD, T. L. HURST, R. G. ESTON, S. R. GOMERSALL, K. JOHNSTON, and J. LANGFORD. Assessing Sedentary Behavior with the GENEActiv: Introducing the Sedentary Sphere. *Med. Sci. Sports Exerc.*, Vol. 46, No. 6, pp. 1235–1247, 2014. **Background**: The Sedentary Sphere is a method for the analysis, identification, and visual presentation of sedentary behaviors from a wrist-worn triaxial accelerometer. **Purpose**: This study aimed to introduce the concept of the Sedentary Sphere and to determine the accuracy of posture classification from wrist accelerometer data. **Methods**: Three samples were used: 1) free living (n = 13, ages 20–60 yr); 2) laboratory based (n = 25, ages 30–65 yr); and 3) hospital inpatients (n = 10, ages 60–90 yr). All participants wore a GENEActiv on their wrist and activPAL on their thigh. The free-living sample wore an additional GENEActiv on the thigh and completed the Multimedia Activity Recall for Children and Adults. The laboratory-based sample wore the monitors while seated at a desk for 7 h, punctuated by 2 min of walking every 20 min. The free-living and inpatient samples wore the monitors for 24 h. Posture was classified from wrist-worn accelerometry using the Sedentary Sphere concept. **Results**: Sitting time did not differ between the wrist GENEActiv and the activPAL in the free-living sample and was correlated in the three samples combined (rho = 0.9, $P < 0.001$), free-living and inpatient samples ($r \simeq 0.8$, $P < 0.01$). Mean intraindividual agreement was 85% ± 7%. In the laboratory-based and inpatient samples, sitting time was underestimated by the wrist GENEActiv by 30 min and 2 h relative to the activPAL, respectively ($P < 0.05$). Posture classification disagreed during reading while standing, cooking while standing, and brief periods during driving. Posture allocation validity was excellent when the GENEActiv was worn on the thigh, evidenced by the near-perfect agreement with the activPAL (96% ± 3%). **Conclusions**: The Sedentary Sphere enables determination of the most likely posture from the wrist-worn GENEActiv. Visualizing behaviors on the sphere displays the pattern of wrist movement and positions within that behavior. **Key Words:** SITTING, POSTURE, TRIAXIAL ACCELEROMETER, WRIST, THIGH, MARCA

The majority of most people's day is spent sedentary, with the proportion of time spent sedentary increasing as people age (22). This sedentary time has been associated with negative health outcomes that are not compensated for by the relatively small proportion of time (approximately 5%) (29) that most adults spend in moderate-to-vigorous physical activity (9). However, time spent sedentary is strongly inversely related to time accumulated in light-intensity activity, and it is proposed that the impact of this light-intensity activity as a biological stimulus for better health has been underestimated (9).

The associations between sedentary time and negative health outcomes have led to an increased interest in accurately

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assessing sedentary time and, in particular, differentiating it from light-intensity activity. Sedentary behaviors are characterized by posture (sitting or reclining) and low energy expenditure (1–1.5 multiples of resting metabolic rate) (24). Thus, to measure sedentary behavior, it is necessary to be able to classify posture in addition to estimating energy expenditure. Accelerometers have been used to estimate sedentary time (e.g., 22), but these classifications are based on minimal or no movement and thus do not address the posture specification. The activPAL inclinometer is worn on the thigh and has become the measurement tool of choice for sedentary behavior as it has been shown to be a valid and reliable measure of posture allocation (sit/lie or stand), sit-to-stand transitions, and stepping (15,21).

When assessing activity patterns, it is often recommended that a monitor be worn for 7 d (23). Compliance in large samples has been poor for hip-worn accelerometers. For example, in the 2003–2006 U.S. National Health and Nutrition Health Examination Survey, only 40%–70% of participants (compliance varied by age group) wore an accelerometer at the hip for 10 $h \cdot d^{-1}$ for 6 d (12). The current National Health and Nutrition Health Examination Survey has moved to using wrist-worn accelerometers in an effort to increase compliance. Early reports show much better compliance, with 70%–80% of participants wearing the monitors for 21–22 $h \cdot d^{-1}$ for 6 d (12). Low compliance and decision rules regarding wear time lead to selection bias and misclassification that disproportionately affect the precision of estimates of sedentary behavior and light-intensity activity (26). There is further bias evident in the estimation of sedentary time depending on the time of day that the monitor is worn (26). This is very pertinent as most studies simply require that a person wear a monitor for a given amount of time per day and do not specify when that wear should occur. In short, it does not matter if a monitor is 100% accurate if people will not wear them for a sufficient period, or if bias is introduced because of the characteristics of people who will comply with monitor wear periods. Further, when sedentary behavior is the outcome of interest, that wear period should ideally be 24 $h \cdot d^{-1}$. Wrist-worn monitors lead to high compliance (12); thus, it is preferable that a tool for assessing sedentary behavior and physical activity be worn on the wrist. The GENEActiv is a wrist-worn accelerometer that has been shown to be valid and reliable for the assessment of activity intensity (10,25) and activity type (32,33) but has not previously been used to classify sedentary behavior as defined by posture.

Recently, GENEActiv developed a novel method for the analysis, identification, and visual presentation of data from the wrist-worn GENEActiv—the Sedentary Sphere. When a person is inactive, gravity provides the primary signal to the wrist-worn monitor. Because the GENEActiv uses a triaxial accelerometer, data collected when inactive can be plotted on the surface of a sphere of radius 1g (9.8 $m \cdot s^{-2}$) with the location on the sphere determined by the wrist and arm orientation (Fig. 1, upper panel). The spatial and temporal distribution of the clusters on the Sedentary Sphere during specific behaviors provides a method for exploration into the classification of different types of behavior. Our application of the Sedentary Sphere for posture classification follows a very simple premise based on arm elevation. This method involves assumptions relating to the most likely posture for a given arm elevation, and there will clearly be times when misclassification occurs. The extent of misclassification will likely depend on the population under consideration and, depending on the research question and/or population, may be partially compensated for, or outweighed by, the reduced bias due to the increased compliance and high wear times possible with a wrist-worn monitor. The GENEActiv can also be worn at the thigh and posture classified as "stand," "lying side," "lying front," or "sitting/lying back" based on the relative values of the x, y, and z vectors. This provides an alternative method, using the same tool, for when a higher accuracy of the classification of posture is required.

Thus, we aimed to determine whether we could use the Sedentary Sphere to determine posture (sit/lie or stand) from a wrist-worn accelerometer in three distinct scenarios and to explore the visual presentation of behaviors on the Sedentary Sphere. We also explored the accuracy of posture classification from the GENEActiv worn on the thigh.

METHODS

We explored the use of the Sedentary Sphere to determine posture in three distinct samples: 1) free living, 2) laboratory-based, and 3) hospital inpatient. The free-living sample enabled us to capture the diverse range of naturally occurring behaviors as and when they happened. The activPAL was the criterion for posture allocation, and the use of time was recalled for the entire period, so we had information about what participants did and when. The laboratory-based sample enabled the observation of participants during a sitting/walking protocol so their posture allocation was known at any given time. The agreement attained in this setting provided a comparator for the agreement attained when the activPAL was used as the criterion without an observation back up as in the other two samples. The inpatient sample enabled us to test the Sedentary Sphere in a specific very sedentary context.

Sample 1: Free Living

A convenience sample of 13 adults ages 20–60 yr (male, n = 8) was recruited from the local area in Adelaide (South Australia). The University of South Australia Human Research Ethics Committee granted approval, and all participants gave written informed consent.

Height and mass were measured to the nearest 0.1 cm and 0.1 kg, respectively. Each participant wore a GENEActiv on their nondominant wrist (left, n = 12). An activPAL and a GENEActiv monitor (without straps) were placed together

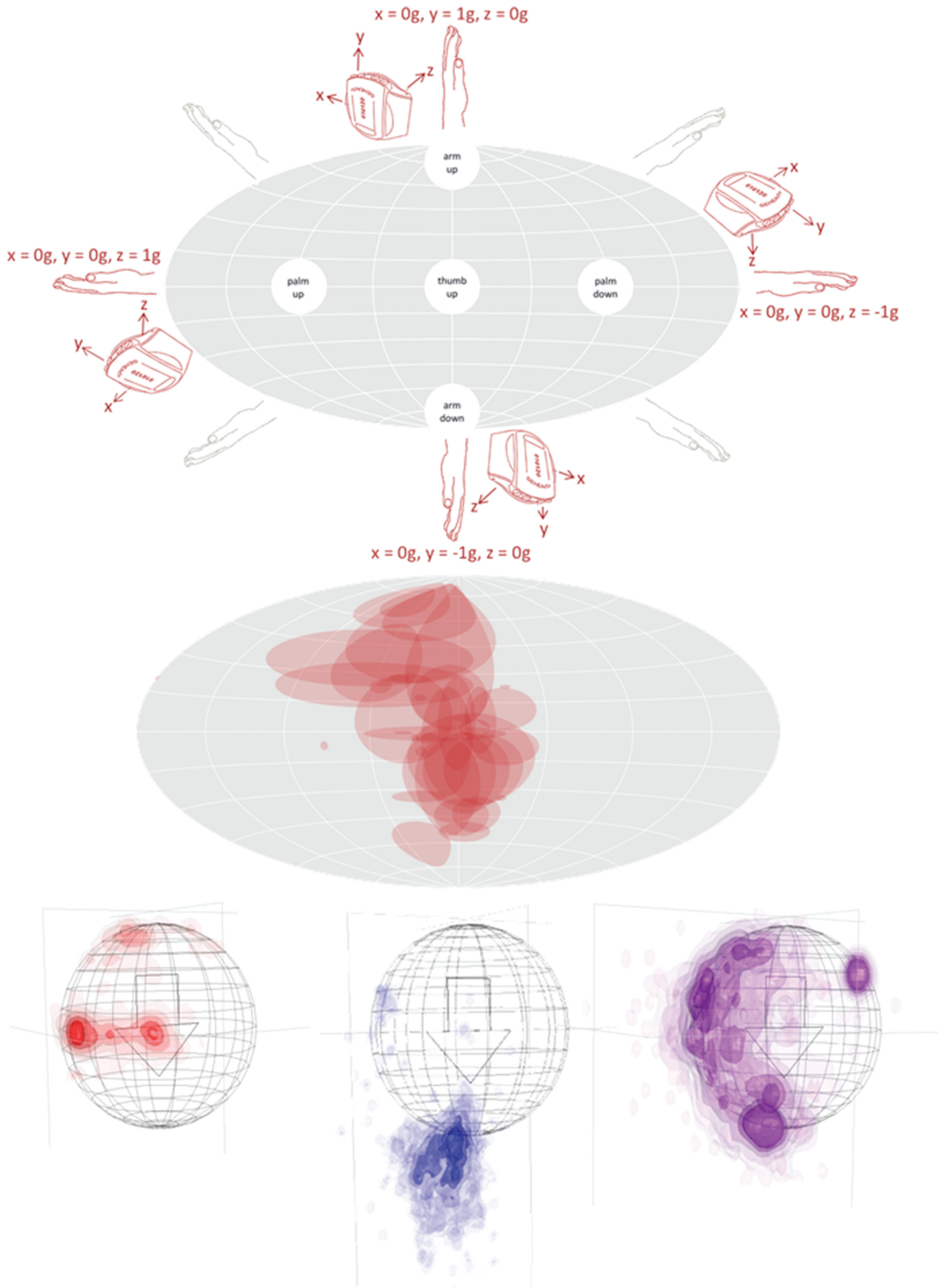

FIGURE 1—The Sedentary Sphere. ***Upper panel*****: the determination of wrist elevation (latitude) and rotation (longitude) from the Sedentary Sphere (left hand) displayed on a two-dimensional Aitoff projection. Specific positions of the wrist are shown for the GENEActiv worn on the left wrist, with the acceleration values for the *x*, y, and *z* axes and monitor orientation shown for four distinct wrist positions (in red).** ***Middle panel*****: the changing latitude of the clusters with arm elevation during the lowering and raising of weights.** ***Lower panel*****: raw triaxial acceleration data plotted on a three-dimensional sphere for a sedentary activity (sitting on a train), left; a moderate-to-vigorous activity (walking), middle; a light-intensity activity (light housework), right.**

in a waterproof finger cot, which was secured to the participant's right thigh (midanterior) using porous hypoallergenic tape. All monitors were worn continuously for 1–2 d and programmed to collect data for a 24-h period from midnight to midnight. On the day after accelerometer monitoring, participants completed the adult version of the

Multimedia Activity Recall for Children and Adults (MARCA [13]), a computerized use of time instrument, for the 24-h period of monitor wear.

Sample 2: Laboratory Based

Twenty-five male participants, ages 30–65 yr, were recruited from an existing research volunteer database "Exeter Ten-thousand" (Extend) held by the Clinical Research Facility in Exeter Lab (UK). Ethics approval was granted by the University of Exeter Research Ethics Committee (approval number 2013/410), and all participants gave written informed consent. These data were taken from a larger study investigating the effect of a full day of uninterrupted sitting and interrupted sitting trials on the plasma glucose and insulin responses to both an oral glucose tolerance test and a mixed test meal.

Height and mass were measured to the nearest 0.1 cm and 0.1 kg, respectively. Each participant wore a GENEActiv accelerometer on their left wrist and an activPAL on their right thigh (midanterior, attached using adhesive strips). Both monitors were worn and programmed to collect data for the 7-h duration of the trial.

Between 10:00 a.m. and 5:00 p.m., participants were seated quietly at a desk where they were allowed to work at the computer, watch DVDs, listen to music, or read. Newspapers and a computer with a DVD player and Internet access were provided. Time spent seated was punctuated by 2-min intervals of walking at 3.2 $km \cdot h^{-1}$ approximately every 20 min. Walking intervals took place on a walking platform (FitWork ™ Walkstation; Steelcase Inc., New York, NY) immediately next to the desk so that transit from sitting to walking was minimal. After each walking interval, participants resumed their sitting position immediately. Participants were observed at all times, and the timing of all bouts of sitting and walking was recorded.

Sample 3: Hospital Inpatients

Ten patients (male, $n = 4$) with chronic obstructive pulmonary disease (COPD), ages 60–90 yr, who had been admitted to hospital with an exacerbation of COPD symptoms as their primary diagnosis, were recruited. Ethics approval was granted by the Royal Adelaide Hospital Human Ethics Committee and the University of South Australia Human Research Ethics Committee, and all patients gave written informed consent. These data were collected as part of a larger study that aimed to describe the pattern of active and sedentary time in people with COPD during, and 1 month after, an admission to hospital for an acute exacerbation of their symptoms.

Each participant wore a GENEActiv on their nondominant wrist (left, $n = 7$). An activPAL was placed in a waterproof finger cot, which was secured to the participant's right thigh (midanterior) using porous hypoallergenic tape. Both monitors were worn continuously for 1–2 d and programmed to collect data for a 24-h period from midnight to midnight. Data collection commenced on the second day of each patient's hospital admission, and monitors were removed before each patient was discharged from hospital.

Measures

GENEActiv and the Sedentary Sphere. The GENEActiv is a triaxial accelerometry-based activity monitor with a dynamic range of $\pm 8g$ (Activinsights Ltd., Cambridgeshire, UK). The GENEActiv was configured with a sampling frequency of 100 Hz, the data were uploaded, and the .bin files were converted to 15-s epoch .csv files using GENEActiv PC software version 2.1. The 15-s epoch files from the wrist-worn and thigh-worn GENEActivs were imported into custom-built spreadsheets in Excel that computed the most likely posture, activity intensity (10), and sleep for each epoch (available on request from A. Rowlands). It is important to differentiate sedentary behavior from sleep; thus, sleep was classified using an algorithm based on the vector magnitude of the three axes, the sum of the SD from the three axes, and an arm elevation. Visualizations of the Sedentary Sphere, both the three-dimensional raw data plots (Fig. 1, lower panel) and the two-dimensional Aitoff projections (which plot the entire surface of a sphere onto a two-dimensional ellipse; Fig. 1, middle panel), were produced in R (available on request from Activinsights).

In our approach, the classification of posture from data plotted on the Sedentary Sphere follows a very simple premise. Data in latitudes at elevations greater than 15° below the horizontal indicate the wrist is elevated; if activity level is low (below the signal vector magnitude cut point for moderate intensity, 10) and the wrist is elevated, this is taken to indicate a sitting or reclining posture. Data plotted in the lower latitudes, lower than 15° below the horizontal, indicate that the arm is hanging more vertically; this is taken to indicate a standing position. If activity level is moderate or vigorous, posture is classified as standing, irrespective of wrist elevation. Thus, "stand" corresponds with active behaviors and with behaviors plotted in roughly the lower third of the Sedentary Sphere, and "sit/lie" corresponds with behaviors plotted in roughly the upper two thirds of the Sedentary Sphere (Fig. 1, upper panel).

Visualizations of specific behaviors are obtained by plotting data on the Sedentary Sphere. Periods of consecutive data points form distinct clusters, which can be differentiated by their position and distribution. The size of each cluster equates to the 50% confidence interval for the consecutive data points within that period. When inactive, the position of the cluster on the sphere shows the elevation (latitude) and rotation (longitude) of the wrist-worn monitor. Specific positions of the wrist are shown on Figure 1 (upper panel) for the GENEActiv worn on the left wrist, with the acceleration values for the x, y, and z axes and monitor orientation shown for four distinct wrist positions. The changing latitude of the clusters with wrist elevation is clearly illustrated in a plot of a person lowering and raising weights (Fig. 1, middle panel).

Different types of inactive behavior will have different "signatures" defined by the distribution of consecutive data points on the surface of the sphere, for example, sitting on a train as shown in Figure 1 (lower panel, left). The spatial and temporal distribution of the clusters on the Sedentary Sphere during specific behaviors provides a method for exploration into the classification of different types of behavior. If behaviors include significant levels of acceleration (i.e., they were active and therefore nonsedentary), the clusters will depart substantially from the surface of the sphere as there is an acceleration value greater than 1*g*, for example, walking as shown in Figure 1 (lower panel, middle). If behaviors are light intensity, but not inactive (i.e., >1*g*), they depart from the surface of the sphere to a lesser extent, for example, light housework as shown in Figure 1 (lower panel, right).

The assessment of posture from the thigh-worn GENEActiv was based on the relative values of the *x* (mediolateral), *y* (vertical), and *z* (anteroposterior) vectors. It is possible to further classify sitting/lying as "lying side," "lying front," or "sitting/lying back" based on values of the *z* vector, but these classifications were not used in this study.

activPAL. The activPAL physical activity monitor (PAL technologies Ltd., Glasgow, UK) is a uniaxial accelerometer worn midline on the anterior thigh, which detects limb position using an inclinometer. The activPAL samples data at 10 Hz, and these data were used to determine posture (sit/lie or upright) and step count in 15-s epochs. To match 15-s epochs between the GENEActiv and the activPAL, the classification of "sit/lie" or "stand" for a 15-s epoch was based on the posture that occurred for the majority of the epoch, that is, the posture that occurred for 8 s or more of that epoch. The activPAL has been shown to have acceptable validity and reliability as a measure of posture and step count (15,21).

MARCA (part 1, 24-h free-living sample only). The MARCA (13,28) was used to determine periods when specific activities were undertaken to enable the investigation into the accuracy of posture allocation in particular contexts and to plot specified types of behavior on the Sedentary Sphere.

The MARCA is a computerized 24-h use-of-time recall tool that asks participants to recall everything they did in the last 24 h from midnight to midnight, using meal times as anchor points. Participants can choose from more than 500 discrete activities, with the minimum time for an individual activity being 5 min. Each activity in the MARCA is assigned a MET value based on an expanded version of the Ainsworth compendium (2,3), so that energy expenditure and PAL (physical activity level, ratio of total energy expenditure to basal metabolic rate) can be estimated. The adult version of the MARCA has test–retest reliabilities in adults of 0.920–0.997 for major activity sets such as sleep, physical activity and screen time, and convergent validity between PAL and accelerometer counts per minute of rho = 0.72 (13). A recent comparison with doubly labeled water (11) showed correlations of rho = 0.70 for total daily energy expenditure.

Data analysis. The activPAL served as the criterion measure of sitting time for all three samples. In the laboratory-based sample, eight participants were excluded as the timing of sitting and standing bouts identified by the activPAL did not match the observed bouts, possibly due to irregular postures, as has been previously observed (7), and one participant was excluded because of an error in matching files. Thus, the final sample size for the laboratory-based sample was 16. Observation data were not available for the free-living or inpatient samples studied.

Data are reported separately for each study. The examination of variables revealed that total sitting times from the activPAL and wrist-worn GENEActiv were skewed for the three samples combined and for the laboratory-based sample; all other variables were normally distributed. Descriptive statistics (mean ± SD) were calculated for all variables. The difference and relationship between total sitting time, calculated from the wrist-worn GENEActiv and the activPAL, were examined using paired *t*-tests and Pearson's correlation, respectively. For data not normally distributed, nonparametric equivalents (Spearman's rank-order correlation and Wilcoxon signed rank test) were used. Limits of agreement were examined using the Bland–Altman analysis. Intraindividual classification agreement across 15-s epochs was reported as percent agreement and kappa. All analyses were repeated for the thigh-worn GENEActiv, relative to the activPAL, for the free-living sample. Alpha was set at 0.05.

The MARCA use of time data from the free-living sample detailed the activities that each participant undertook in 5-min epochs. This enabled the investigation of the type of activities where posture allocation from the GENEActiv (worn at the wrist or thigh) did not agree with posture allocation from the activPAL. The MARCA data also allowed the identification of distinct periods of common behaviors that it is desirable to classify (e.g., sleep, TV viewing, computer use, driving, and office work), where we were confident that the reported activity was temporally matched to the GENEActiv and activPAL data. This decision was based on concordance between the reported activity from the MARCA and the posture allocation from the activPAL. GENEActiv wrist acceleration data from these periods were plotted on the Sedentary Sphere and posture allocation agreement calculated for these distinct activities. The sample size for the MARCA analyses was 12, as one of the 13 participants did not complete the MARCA.

RESULTS

The free-living sample was aged 34.5 ± 13.2 yr (height = 174.8 ± 7.4 cm, mass = 72.7 ± 9.4 kg, body mass index [BMI] = 23.7± 1.8 kg·m^{-2}), the laboratory sample was ages 39.8 ± 12.4 yr (height = 176.3 ± 5.7 cm, mass = 81.9 ± 20.6 kg, BMI = 26.1 ± 4.9 kg·m^{-2}), and the hospital inpatient sample was ages 75.9 ± 9.7 yr. Height, mass, and BMI are unavailable for the inpatient sample. Sitting time, standing time, correlation, and agreement statistics by sample are shown in Table 1.

Mean minutes classified as sitting/lying and standing by the wrist-worn GENEActiv did not differ from activPAL

TABLE 1. Comparison of activPAL and GENEActiv data for 1) free-living sample (24 h), 2) laboratory-based sample (7 h), and 3) inpatient sample (24 h).

Sample[a]	activPAL (Thigh)	GENEActiv (Wrist)	GENEActiv (Thigh)
Sitting/lying time (nb, includes sleep for samples 1 and 3), mean ± SD, min			
1 (n = 13)	1014.8 ± 99.0	1014.8 ± 127.0	1006.8 ± 104.4
2 (n = 16)	347.5 ± 19.6	313.5 ± 44.6[bc]	
3 (n = 10)	1329.7 ± 80.1	1197.7 ± 155.9[c]	
Standing time, mean ± SD, min			
1 (n = 13)	425.2 ± 98.9	425.3 ± 126.9	433.5 ± 104.6
2 (n = 16)	64.1 ± 9.3	98.2 ± 36.8[c]	
3 (n = 10)	110.4 ± 80.1	242.3 ± 155.9[c]	
Correlation with activPAL			
1 (n = 13)		0.79[d]	0.93[d]
2 (n = 16)		0.17[b]	
3 (n = 10)		0.78[d]	
Root mean squared error (min, relative to activPAL)			
1 (n = 13)		62.9	37.3
2 (n = 16)		19.4	
3 (n = 10)		52.8	
Bias relative to activPAL (95% limits of agreement)			
1 (n = 13)		−0.1 ± 151.4	−8.0 ± 73.8
2 (n = 16)		−34.0 ± 75.2	
3 (n = 10)		−133.6 ± 111.9	
Intraindividual epoch-by-epoch % agreement with activPAL, mean ± SD			
1 (n = 13)		85.3 ± 4.4	95.5 ± 3.3
2 (n = 16)		83.8 ± 8.6	
3 (n = 10)		85.7 ± 7.0	
Intraindividual epoch-by-epoch agreement, kappa, mean ± SD calculated using Fisher transformations			
1 (n = 13)		0.65 ± 0.25	0.90 ± 0.40
2 (n = 16)		0.59 ± 0.50	
3 (n = 10)		0.38 ± 0.11	

[a] 1) 24-h free-living sample, 2) 7-h controlled laboratory-based protocol (sitting interspersed with three 2-min light-intensity walking bouts per hour), and 3) 24-h hospital inpatients with COPD.
[b] Test of significance was nonparametric (correlation: Spearman's rank order correlation, test for mean difference: Wilcoxon signed rank test).
[c] Significantly different from minutes recorded by activPAL ($P < 0.05$).
[d] Significant relationship $P < 0.05$.

classifications in the free-living sample. However, significantly fewer minutes sitting and more minutes standing were classified from the wrist-worn GENEActiv data than from the activPAL data in the laboratory-based sample (≃30 min) and the inpatient sample (≃130 min). Minutes classified as sitting by the wrist-worn GENEActiv were significantly correlated with minutes classified as sitting by the activPAL in the three samples combined (rho = 0.90, $P < 0.001$, see Figure, Supplemental Digital Content 1, http://links.lww.com/MSS/A397, Sitting time estimated by the activPAL [x axis] and the wrist-worn GENEActiv [y axis] by sample [free-living, laboratory-based, and hospital inpatients]), in the free-living sample ($r = 0.79$, $P < 0.001$) and the inpatient sample ($r = 0.78$, $P < 0.01$), but not for the laboratory-based sample (rho = 0.17). The mean biases for the free-living sample and laboratory-based sample were relatively low, although 95% limits of agreement were large. The mean bias and limits of agreement were large for the highly sedentary inpatient sample (Table 1). The root mean squared error was highest for the free-living sample (63 min) and lowest for the laboratory protocol (19 min; Table 1).

Intraindividual classification agreement across 15-s epochs was greater than 80% for every participant in the free-living sample, 69% of the laboratory-based sample, and 90% of the inpatient sample, and the three sample mean values were all greater than 80% (Table 1). Kappa scores indicated moderate to substantial agreement between the activPAL and the wrist-worn GENEActiv for the free-living sample (77% kappa > 0.6), and fair to moderate agreement for the laboratory-based (63% kappa > 0.4) and inpatient samples (40%, kappa > 0.4, 70% kappa > 0.3) (31).

Posture classification from the GENEActiv worn at the thigh was more accurate and precise, relative to the activPAL, than the GENEActiv worn at the wrist (free-living sample only; Table 1). This was evidenced by a high correlation ($r = 0.93$, $P < 0.001$), narrower limits of agreement, more than 89% epoch-by-epoch intraindividual agreement in all participants (mean = 96%), and a kappa score indicating a near-perfect agreement in 77% participants (kappa > 0.81) and substantial agreement in the remaining 23% (kappa > 0.75) (29).

Comparison with MARCA data (free-living sample only). Figure 2 shows a temporogram for a representative participant. The temporogram graphically displays contemporaneous activPAL posture allocation (top), GENEActiv wrist posture allocation (second from top), GENEActiv wrist accelerometer vector magnitude (third from top), and MARCA data (bottom), plotted against time. The vertical bars on the upper two plots show standing, whereas the absence of a bar indicates sitting or lying. The agreement between posture allocation from the wrist-worn GENEActiv and the activPAL for this participant was slightly lower than the mean for the sample (82.4%, mean = 85.3%). The colors on the MARCA plot indicate the activities that were reported, and the height of the bars represents the energy expenditure associated with the activity; some of these activities are labeled on the plot. Comparison of the top 2 posture allocation plots with the MARCA plot (bottom) allows the identification of activities where the activPAL and wrist-worn GENEActiv agreed or did not agree. For example,

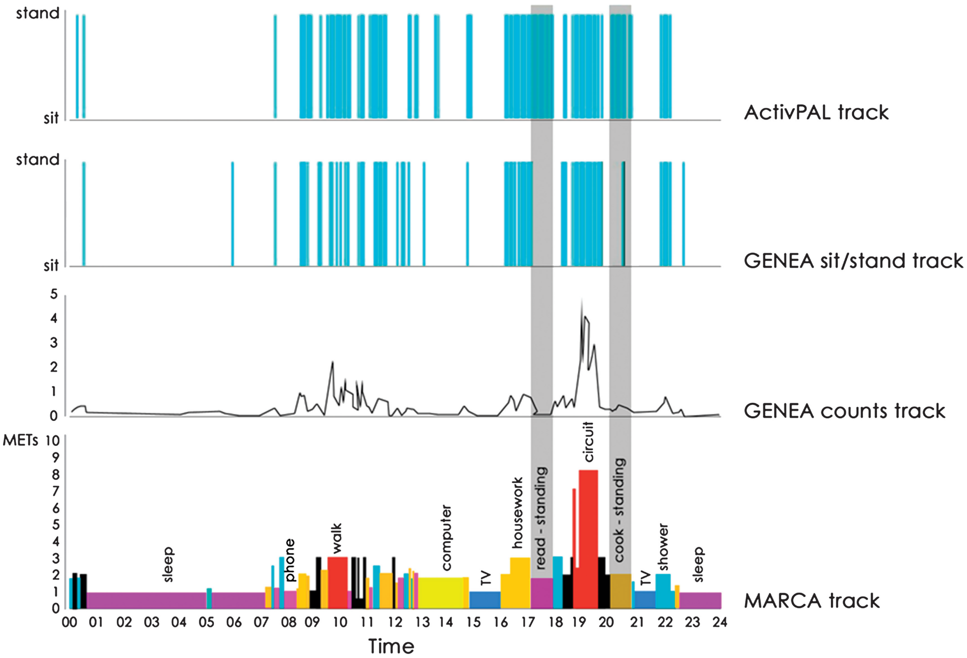

FIGURE 2—Temporogram (plot of activities against time, measured by multiple methods) for a representative participant. The agreement between posture allocation from the wrist-worn GENEActiv and the activPAL was slightly lower than the mean for the sample (82%, mean = 85%). ActivPAL posture allocation (top), GENEActiv wrist posture allocation (second from top), GENEActiv wrist accelerometer vector magnitude (*g*·min, third from top), and MARCA data (energy expenditure in METs, bottom). Gray-shaded vertical bars indicate periods where posture allocation from the wrist-worn GENEActiv and the activPAL did not agree.

around 1730–1800 and 2000–2040 h, indicated with shaded gray vertical bars, the activPAL classified standing (top, vertical bars) but the GENEActiv classified sitting/lying (second from top, no vertical bars). From the MARCA (bottom), it can be seen that the activities undertaken were reading and cooking while standing, respectively.

The highest posture allocation agreement between the activPAL and the wrist-worn GENEActiv was 95.9%. [For the traces for this participant, see Figure, Supplemental Digital Content 2, http://links.lww.com/MSS/A398, Temporogram (plot of activities against time, measured by multiple methods) for a participant with high posture allocation agreement between the GENEActiv and the activPAL (96%). ActivPAL posture allocation (top), GENEActiv wrist posture allocation (second from top), GENEActiv wrist accelerometer vector magnitude (*g*·min, third from top), and MARCA data (energy expenditure in METs, bottom), plotted against time]. The poorest posture allocation agreement between the activPAL and the wrist-worn GENEactiv was 80% [e.g., see Figure, Supplemental Digital Content 3, http://links.lww.com/MSS/A399, Temporogram (plot of activities against time, measured by multiple methods) for a participant with low posture allocation agreement between the GENEActiv and the activPAL (80%). ActivPAL posture allocation (top), GENEActiv wrist posture allocation (second from top), GENEActiv wrist accelerometer vector magnitude (*g*·min, third from top), and MARCA data (energy expenditure in METs, bottom), plotted against time]. The examination of the temporograms for each participant reveals that activities where the activPAL and wrist-worn GENEActiv sometimes disagreed include reading while standing, cooking while standing, brief periods during office work (activPAL = standing, GENEActiv = sitting/lying) and brief periods during driving (activPAL = sitting/lying, GENEActiv = standing). Time reported sleeping in the MARCA correlated significantly with time classified as sleeping from the GENEActiv data ($r = 0.70$, $P < 0.05$), and epoch-by-epoch agreement was high (89.6% ± 6%, kappa = 0.8 ± 0.4).

Visualization on the Sedentary Sphere. From the MARCA collected in the free-living sample, we identified participant reports of behaviors including sleeping ($n = 12$), TV viewing ($n = 7$), computer use ($n = 5$), driving ($n = 6$), and office work ($n = 3$), where we were confident that the activity reported in the MARCA was temporally matched to the GENEActiv and activPAL data. The mean ± SD percent epoch-by-epoch posture allocation agreement from the wrist-worn GENEActiv and activPAL during these activities was as follows: sleeping, 97.6% (4.3); TV, 94.3% (5.4); computer, 94.9% (4.6); driving, 74.9% (16.1); office work, 73.0% (8.9).

Figure 3 shows two-dimensional images of GENEActiv acceleration data plotted on the Sedentary Sphere for six representative participants for periods of sleep. Periods were selected based on reported sleep in the MARCA and the absence of standing from the activPAL data. The greater number and size of clusters on the plots on the right, relative to the plots on the left, indicate a greater range of movement within a given position and more changes of position (agreement = 99.7% top, 100% bottom two plots). The plots on the left depict participants who did not move much in any given position (clusters are very small) and had relatively

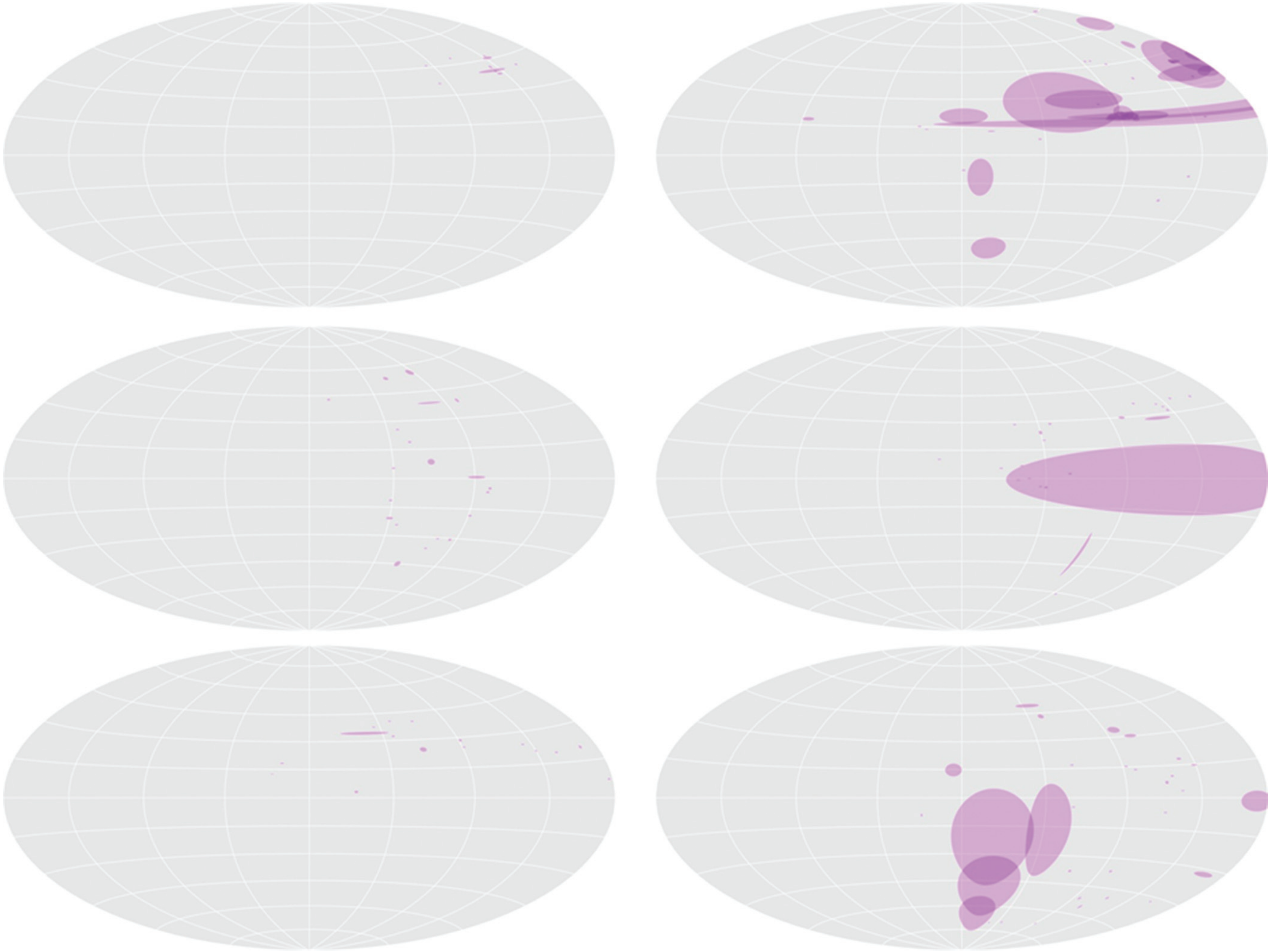

FIGURE 3—Two-dimensional images of GENEActiv acceleration data plotted on the Sedentary Sphere for representative participants for sleep for people who moved very little (left, few very small clusters) and who moved more (right, more larger clusters). Agreement for plots on the left (top to bottom) was 99.8%, 85.9%, and 100%. Agreement for plots on the right (top to bottom) was = 99.7%, 100%, and 100%.

few position changes (top plot: shown by few tightly gathered clusters, agreement = 99.8%), or a greater variety of positions (bottom two plots: shown by multiple, spread out clusters, agreement = 85.9% (middle) and 100% (bottom)). Sixty percent of participants had plots similar to those on the left, and 40% had plots similar to those on the right.

Sedentary Sphere plots for representative participants for TV viewing (left, agreement [top to bottom] = 95.4%, 88.2%, and 100%) and computer use (right agreement [top to bottom] = 99.1%, 94.7%, and 98.2%) are shown in Figure 4. As for sleep, periods were selected based on the reported activity (TV viewing or computer use) in the MARCA and the absence of standing from the activPAL data. In general, more positions and greater movement in any given position were seen for computer use than TV viewing (the clusters were bigger and there were more of them), but not always (see bottom pair of plots where this observation is reversed). Figure 5 shows plots for representative participants for office work (left, agreement [top to bottom] = 88%, 69.7%, and 66.3%) and driving (right, agreement [top to bottom] = 85.5%, 76.6%, and 67.5%). As for sleep, TV viewing, and computer use, periods for driving were selected based on MARCA report and the absence of standing from the activPAL data. This was not possible during office work as this activity could contain sitting and standing. Therefore, office work was selected based on the MARCA data and observed alignment between MARCA data and other activity measures. During office work, 17%, 54%, and 63% of the time depicted in the top, middle, and bottom plot, respectively were spent standing. The greater coverage on the Sedentary Sphere indicates the greater movement during this activity.

DISCUSSION

There were two aims to this paper: the first was to introduce the concept of the Sedentary Sphere, and the second was to determine whether we could use the Sedentary

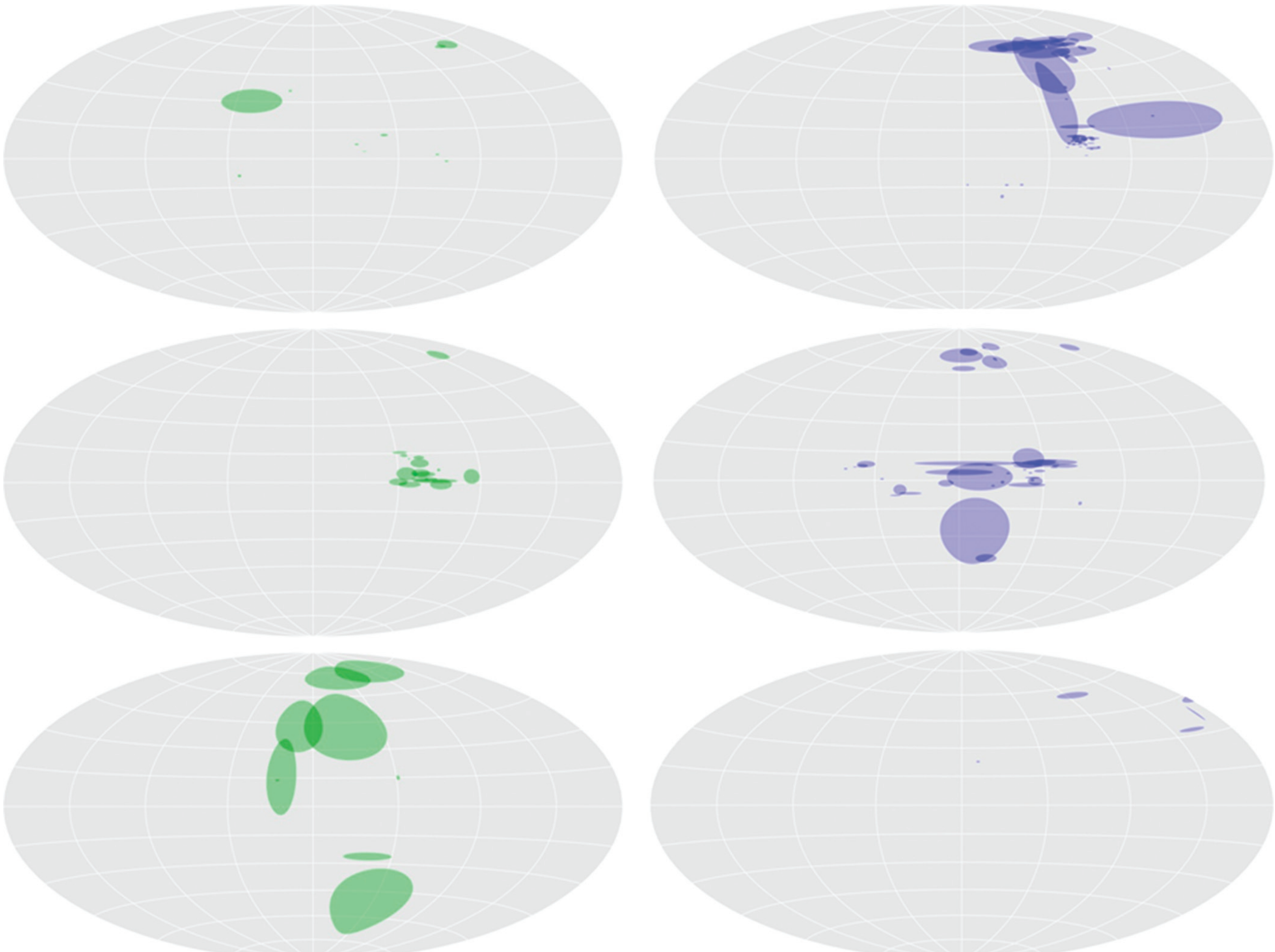

FIGURE 4—Two-dimensional images of GENEActiv acceleration data plotted on the Sedentary Sphere for representative participants for TV viewing (left, agreement (top to bottom) = 95.4%, 88.2%, and 100%) and computer use (right agreement (top to bottom) = 99.1%, 94.7%, and 98.2%). The upper two rows of plots show more movement for computer use than TV viewing, the lower row of plots shows the converse.

Sphere to determine posture (sit/lie or stand) from a wrist-worn accelerometer. The assessment of posture considered in this paper relies on the Sedentary Sphere to provide a framework enabling the most likely posture to be determined from triaxial acceleration data from the wrist-worn GENEActiv. However, as detailed earlier, the assessment of posture when inactive is based on wrist elevation only and is thus a very basic interpretation of the Sedentary Sphere. To highlight the potential of the Sedentary Sphere for more sophisticated analysis, identification, and visualization of triaxial acceleration data measured at the wrist, we have plotted free-living data on the sphere for specific behaviors: sleeping, TV viewing, computer work, driving, and office work. We believe that the sphere potentially provides a paradigm whereby wrist-worn accelerometers are not used simply because they improve compliance but also because they offer a richer, more detailed picture of a person's behaviors than is possible with waist-worn accelerometers. First, we will discuss results in relation to our preliminary posture allocation algorithm and then move on to the potential implications of the Sedentary Sphere and future research directions.

Posture Allocation

Across the three samples considered, the minutes classified as sitting/lying from wrist elevation were highly correlated with the criterion measure (activPAL), the intraindividual epoch-by-epoch agreement was greater than 80% in 85% of participants, and the group mean values did not differ in the free-living scenario. However, in the laboratory-based sample and in the elderly hospital, inpatients' sitting time was significantly underestimated by approximately half an hour and 2 h, respectively. The bias was zero in the free-living sample; however, the root mean squared error and limits of agreement were higher than that in the other samples. This suggests the error was random in the free-living sample with overestimation in some individuals, cancelling out underestimation in others, whereas there tended to be a systematic underestimation of sitting time in the more controlled samples. It is unusual for

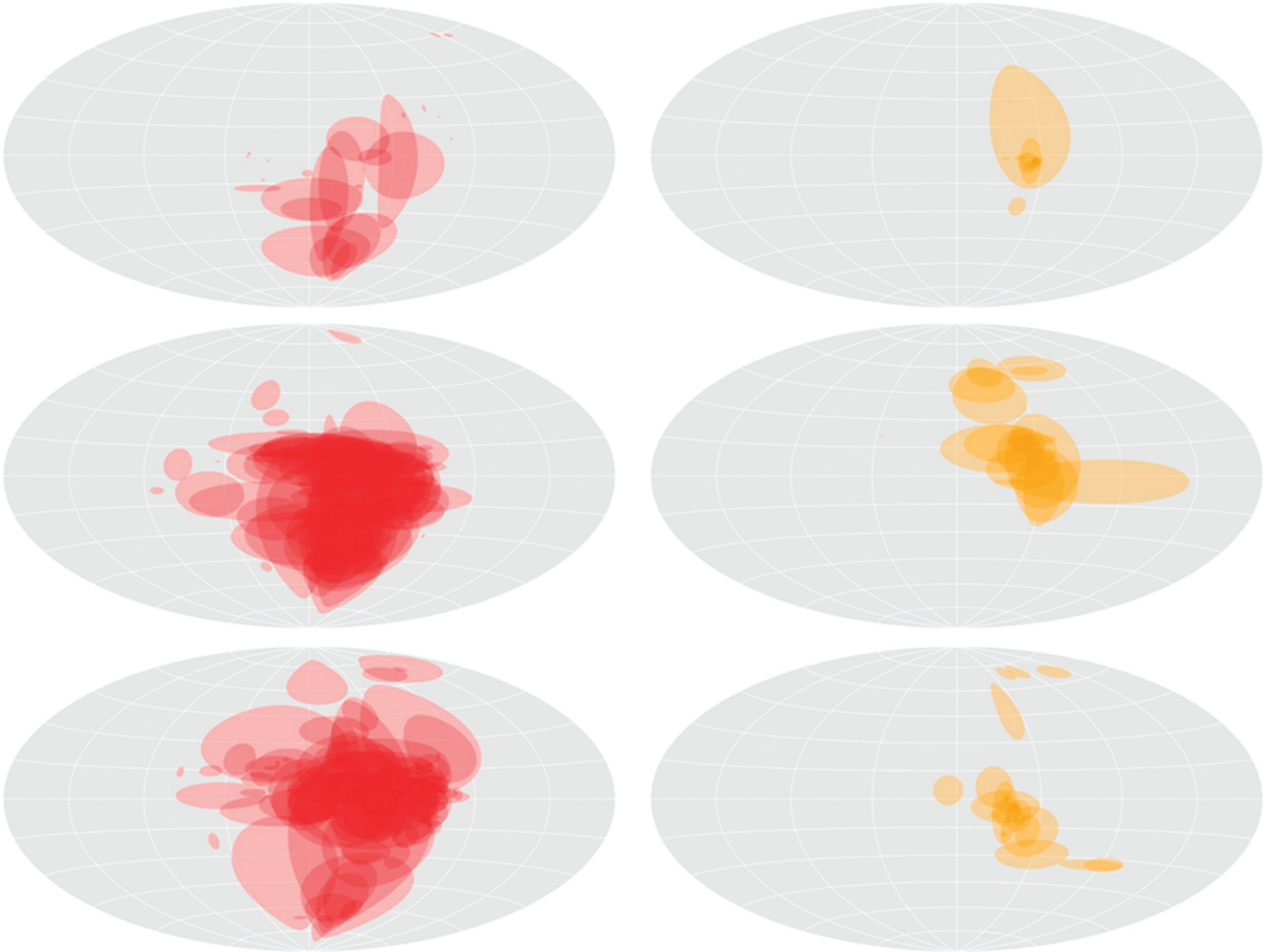

FIGURE 5—Two-dimensional images of GENEActiv acceleration data plotted on the Sedentary Sphere for representative participants for office work (left, agreement [top to bottom] = 88%, 69.7%, and 66.3%) and driving (right agreement [top to bottom] = 85.5%, 76.6%, and 67.5%). During office work, 17%, 54%, and 63% of the time depicted in the top, middle, and bottom plot, respectively, was spent standing.

classification accuracy to be higher in a free-living sample than a laboratory sample (30), but the threshold used to differentiate standing from sitting/lying (wrist elevation ≥15° below horizontal) was set empirically based on free-living data rather than developed in a controlled laboratory setting. Overall, these results compare well to estimates of sedentary time from the hip-worn ActiGraph GT3X+ relative to the activPAL; Aguilar-Farías et al. (1) recently reported epoch-by-epoch agreement ranging from 73% to 85% and biases of −4 to 124 min with 95% limits of ± 2 h in free-living older adults.

It is notable that the activPAL data were classified as standing for 30% of the assessed time in the free-living sample, whereas only 16% of time was spent standing in the laboratory-based sample and 8% of time in the inpatient sample. These values compare well to previously reported values from the activPAL for free-living women ages 40–75 yr (≃24.2% [6]), overweight and obese adults ages 20–60 yr (≃20% [19]), adults ages 74 ± 5 yr (≃ 25% [14]), adults ages 75 ± 8 yr attending a day hospital (≃16% [14]), and elderly hospital inpatients (≃5%–6% [14]). It is possible that the accuracy of the total minutes classified as sitting/lying and standing from the wrist acceleration data may be decreased in highly sedentary samples. In the present study, the two samples with sitting/lying underestimated were constrained in their posture allocation to some extent: the laboratory-based sample due to the imposed protocol and the inpatient sample due to the context and the exacerbation in their COPD symptoms that led to them being admitted to hospital. Constraints on standing may affect the degree of elevation and rotation of the wrist during sitting and lying. For example, during prolonged and/or imposed sitting, people may be more likely to spend time with their arms hanging down over the edge of a chair; this would be misclassified by our algorithm as standing. A moderate or vigorous activity level while seated would also result in misclassification as standing. Differing levels of validity across samples highlight the importance of developing and cross-validating tools for the assessment of sedentary behavior and physical activity in a variety of contexts and in free-living scenarios (12,30).

Correlations with the activPAL were high for the free-living and inpatient sample. All participants in the laboratory-based sample were prescribed equal amounts of sitting and light walking; thus, the low correlation observed in the laboratory-based sample is probably due to the resulting narrow range of values in the data. Despite the relatively high and similar levels of intraindividual agreement in the three samples, the kappa values were quite discrepant (0.65, 0.59, and 0.38 in the free-living, laboratory-based, and inpatient samples, respectively). The relatively low prevalence of standing in the latter two samples may contribute to this discrepancy. Kappa is affected by the prevalence of the finding under consideration, and for rare findings, low values of kappa may not necessarily reflect low rates of overall agreement (31).

The posture allocation algorithm for the thigh-worn GENEActiv resulted in very high accuracy and precision for estimates of mean total sitting time and for intraindividual epoch-by-epoch agreement. Thus, the thigh site is a viable alternative when high individual-level accuracy of posture allocation is required. The examination of the 15-s epoch activPAL and GENEActiv plots indicates that the number of transitions identified at the wrist would be considerably higher than at the thigh, and if transitions are an outcome measure, the use of a thigh monitor (activPAL or GENEActiv) would likely be required. However, it should be noted that with a thigh-worn monitor, it is not possible to obtain the visualization and analysis of sedentary behaviors possible with a wrist-worn monitor as only the wrist location provides the richness of data due to different orientations. That is, most sedentary behaviors are differentiated by upper limb, and not lower limb, position and movements.

The MARCA enables insight into the types of activities where posture allocation from the GENEActiv and activPAL did not agree. In general, these made sense. For example, reading while standing was classified as sitting by the wrist-worn GENEActiv. It is likely that the arms would be elevated higher than 15° below the horizontal to hold a book if standing and reading. Thus, based on the theoretical premise used to allocate posture from the wrist-worn GENEActiv data, it is not surprising that this activity was misclassified. Similarly, the same reasoning would explain the misclassification of cooking while standing and suggests that working at a standing desk or workstation would be misclassified as sitting. Understanding the types of activities that are likely to be misclassified and the prevalence of these in different populations allows an informed decision to be made whether the posture allocation algorithm is appropriate for use in a given population for a given research question. Systematic misclassification would likely be evident in populations with a high prevalence of activities that are typically misclassified, for example, any activity that requires individuals to have their arms elevated higher than 15° below the horizontal for prolonged periods while standing. Further research should investigate populations where systematic misclassification may be evident and whether misclassification can be reduced by the inclusion of extra features from the Sedentary Sphere in the posture allocation algorithm.

The Sedentary Sphere

Triaxial wrist acceleration data from periods of sleeping, TV viewing, computer use, driving, and office work were plotted on the Sedentary Sphere. In addition to wrist elevation, this provided information on rotation of the wrist and the range of wrist movement and positions covered for the behavior during the period plotted. This allows the examination of individual differences within and between behaviors. For example, the greater coverage of clusters on the Sedentary Sphere evident in the plots on the right on Figure 3, relative to the plots on the left, indicates that these participants moved and changed positions more when sleeping. The coverage of the Sedentary Sphere may provide a marker of sleep quality and/or provide further information on fidgeting or nonexercise activity thermogenesis (NEAT [20]) within and between sedentary behaviors.

The features of different behaviors plotted on the Sedentary Sphere may provide information that can be used to classify behaviors. The data presented suggest that distinguishing between similar behaviors such as computer use and TV viewing may not be possible with the features considered here; however, some groups of behaviors may be characterized by distinct clustering of data points potentially enabling the classification of these behaviors. It should be noted that this preliminary approach did not explore dynamic characteristics, for example, the movements of points across the activity space over time or events and clusters of events in relation to each other, or examine the frequency content of the raw signal; these are avenues for further exploration. The inclusion of dynamic characteristics may be particularly pertinent for the detection of sit-to-stand transitions. Static and dynamic position data, combined with sociodemographic and time of day data, are a promising avenue for activity classification through pattern recognition. Thus, feature(s) can be extracted from the Sedentary Sphere for the classification of behaviors, as exemplified for posture herein, and/or images from plotted behaviors can be analyzed. Notably, the introduction of the Sedentary Sphere extends the analysis problem from a time series issue to more of an image analysis problem opening up the possibility of using different tools. This shift differentiates this approach from other pattern recognition approaches such as hidden Markov models (e.g., 15,17,27), decision trees (e.g., 4), and artificial neural networks (e.g., 8) and thus offers a complementary visual tool that also has the advantage of focusing on patterns within inactive behaviors—the type of behavior undertaken for the vast majority of most people's time (22).

Strengths and Limitations

The inclusion of three very diverse samples was a strength of this study. Further, the inclusion of a free-living sample was very important as laboratory-based validity is typically not replicated when applied to free-living data (16,30). Sedentary and light-intensity behaviors can be very diverse and incorporate a wide range of arm and hand positions and/or movements, including gesticulation. It would be difficult to capture this diversity of naturally occurring movement during sedentary and light-intensity behaviors in a laboratory setting. Thus, given the use of a wrist-worn device it was particularly important that a person was not acting out a prescribed protocol and was able to engage in their normal daily activities.

The inclusion of MARCA time use data in the free-living sample provided context to the behaviors undertaken and enabled specific behaviors to be plotted on the sphere. Further, the time use data enabled the identification of activities where the activPAL and GENEActiv classifications did not agree. It should be noted that those activities identified were exemplars, where it was possible to confidently identify the activity from the MARCA data. The MARCA has high validity for the assessment of physical activity and energy expenditure (11,13), but the nature of recalled information and larger epochs relative to the objective measures means that the temporal alignment between MARCA and monitor data will not be perfect. This precludes the matching of all posture classification data to an activity. However, the availability of acceleration, posture and time use data enabled us to align timelines and identify sufficient activities of long enough duration to address our research questions. The SenseCam, a "lifelogging" lightweight camera worn via a lanyard around the neck that takes photographs automatically could provide an alternative or complementary measure in future studies (18).

The criterion for posture allocation was the activPAL, which has been shown to be a valid and reliable measure of posture (e.g., 15,21). However, evidence is emerging for the misclassification of certain types of postures, including irregular sitting styles (5), for example, sitting on the edge of a chair. In the laboratory-based sample, nearly one-third (8/25) of participants were excluded based on discrepancies between the activPAL posture classification and the observation data. On the basis of this, it is likely that misclassification would have been present in the activPAL data in the free-living and inpatient samples.

CONCLUSIONS

The Sedentary Sphere provides a framework that enables the most likely posture to be determined from triaxial acceleration data from the wrist-worn GENEActiv. This is important as wear compliance is high for wrist-worn monitors. Using an algorithm based only on wrist elevation, agreement with posture allocation determined from the activPAL was more than 80%. Further research in a variety of populations using the activPAL as a criterion and the MARCA to determine types of activity where mismatches occur should be used to refine the posture allocation algorithm and consider the inclusion of additional features from the Sedentary Sphere. The Sedentary Sphere framework uses the signal from a wrist-worn triaxial accelerometer when gravity provides the primary signal to the monitor, that is, when a person is inactive. Thus, theoretically, this framework could be applied to the signal from any wrist-worn accelerometer providing gravity had not been removed from the signal, the hand on which it was fitted is known and the product containing the accelerometer was consistently worn in the same orientation on the wrist.

This paper has introduced the Sedentary Sphere, which enables the analysis, identification, and visualization of triaxial acceleration data measured at the wrist. Although we have focused here on posture determination, the Sedentary Sphere concept offers possibilities for identifying specific activities using pattern recognition. This might be done by a statistical analysis of the location, density, and distribution of points on various regions of the sphere and changes in these characteristics over the duration of an activity, for example, the movement of clusters over time in relation to each other and the frequency content of the raw data signal. One possibility would be to use image-recognition software to identify clusters of patterns typical of specific activities, extending the tools applicable to accelerometer data analysis to image analysis tools as well as time series tools, thus complementing current pattern recognition approaches. Further, the focus on sedentary and light-intensity behaviors is pertinent given the emerging evidence for the impact of sedentary behavior and light-intensity activity on health.

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There are no other conflicts of interest.

The results of the present study do not constitute endorsement by the authors or the American College of Sports Medicine of the products described in this article.

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