Sedentary Sphere: Wrist-worn accelerometer-brand independent posture classification

Short title - Sedentary Sphere: Posture classification

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Abstract

Introduction: Access to raw acceleration data should facilitate comparisons between accelerometer outputs regardless of monitor brand. **Purpose:** To evaluate the accuracy of posture classification using the Sedentary Sphere in data from two widely-used wrist-worn triaxial accelerometers. **Methods:** *Laboratory*: 34 adults wore a GENEActiv and an ActiGraph GT3X+ on their non-dominant wrist while performing four lying, seven sitting and five upright activities. *Free-living*: The same participants wore both accelerometers on their non-dominant wrist and an activPAL3 on their right thigh during waking hours for two days. **Results:** *Laboratory*: Using the Sedentary Sphere with 15-s epoch GENEActiv data, sedentary and upright postures were correctly identified 74% and 91% of the time, respectively. Corresponding values for the ActiGraph data were 75% and 90%. *Free-living*: Total sedentary time was estimated at 534±144 min, 523±143 min and 528±137 min by the activPAL, the Sedentary Sphere with GENEActiv data and with ActiGraph data, respectively. The mean bias, relative to the activPAL, was small with moderate limits of agreement (LoA) for both the GENEActiv (mean bias = -12.5 min, LoA = -117 to 92 min) and ActiGraph (mean bias = -8 min, LoA = -103 to 88 min). Strong intra-class correlations (ICC) were evident for the activPAL with the GENEActiv (0.93, 0.84-0.97 (95% confidence interval) and the ActiGraph (0.94, 0.86–0.97). Agreement between the GENEActiv and ActiGraph posture classifications was very high (ICC = 0.98 (0.94-0.99), mean bias = +3 min, LoA = -58 to 63 min). **Conclusion:** These data support the efficacy of the Sedentary Sphere for classification of posture from a wrist-worn accelerometer in adults. Importantly, the approach is equally valid with data from both the GENEActiv and ActiGraph accelerometers.

Keywords: GENEActiv; ActiGraph; activPAL; sitting; triaxial

Introduction

Large-scale population surveys are assessing physical activity using monitors composed of a triaxial microelectromechanical (MEMS) accelerometer and solid-state memory, packaged in a wrist-watch type device. The monitors allow continuous recording of acceleration data for a week at a time at a typical rate of 30-100 Hz. Compared to hip-worn monitors, wrist-worn monitors are increasingly used because they appear to lead to higher wear compliance, resulting in better quality and less biased data (9, 17).

Two widely used wrist-worn monitors are the ActiGraph GT3X+ and the GENEActiv. Surveys using the ActiGraph GT3X+ include the National Health and Nutrition Examination Survey (NHANES) in the US (9) and those using the GENEActiv include British Whitehall II (4), Brazilian birth cohorts (7) and the Growing up in Australia Checkpoint (https://www.mcri.edu.au/research/projects/longitudinal-study-australian-childrens-child-health-checkpoint). As the ActiGraph GT3X+ and the GENEActiv both provide raw acceleration output, theoretically the output should be comparable between brands and algorithms developed for use with data from one brand of monitors should be applicable to both. Equivalence of the data outcomes derived, e.g. average activity level and time spent at a given intensity, from the different brands and thus between studies would be advantageous. However, as cautioned by Welk and colleagues in 2012 (20), equivalence of the raw acceleration output cannot be assumed and rigorous equivalency testing is necessary to determine whether and under which conditions outputs from these monitor brands are comparable.

An emerging body of work shows that the magnitude of the features from the time domain (e.g. signal intensity), although highly correlated, is greater in data from the GENEActiv than from the ActiGraph GT3X+ (11, 15). However, features from the frequency domain (i.e.

underlying frequencies or repeating patterns) are near equivalent (11, 15). Consequently evidence suggests that algorithms that are based on the features from the frequency domain appear to be appropriate to be used interchangeably between the two monitor brands, with little loss in accuracy (11, 15). However, accuracy reduces if an algorithm based on features from the time domain is developed on GENEActiv data and applied to ActiGraph GT3X+ data (11).

We recently introduced a method for classifying posture from the GENEActiv wrist-worn accelerometer (16). Assessment of posture is important as sedentary behavior, defined as sitting or reclining and low energy expenditure (2), is associated with negative health outcomes (6, 8, 21). The estimation of posture from GENEActiv data is based on the Sedentary Sphere, a method for the analysis, identification and visual presentation of raw acceleration data from a wrist-worn accelerometer. The Sedentary Sphere has been described in detail previously (16), but in brief it exploits the gravitational component of the acceleration signal when a person is inactive to determine the orientation of the monitor and hence wrist position. As the method is based on the orientation of the gravity component, not the magnitude of accelerations, it has the potential to transfer well between monitor brands. This would provide a means to estimate sedentary time in the numerous surveys and studies, e.g. NHANES, British Whitehall II, currently using wrist-worn triaxial accelerometers, irrespective of the brand of monitor employed.

The application of the Sedentary Sphere to estimate posture, i.e. sedentary (sitting/reclining) or upright, is very simple; it is based on arm elevation with an elevated arm indicating sitting/reclining and a more vertical arm indicating upright. The accuracy of posture classification in a free-living sample, relative to the activPAL (which is frequently used as a criterion measure of posture in free-living individuals), was over 80% (16). The method has been successfully cross-validated in an independent free-living sample using GENEActiv monitors (14). However, to date it has not been tested in data from other brands of accelerometer or been tested in a laboratory sample. While accuracy in a free-living environment is paramount, testing in a laboratory environment is also important in enabling comparison with direct observation and will highlight particular postures that lead to errors in classification.

The aim of this study was to evaluate and compare the accuracy of posture classification using the Sedentary Sphere in data from two widely-used wrist-worn triaxial accelerometers, the GENEActiv and the ActiGraph GT3X+, in laboratory and free-living settings.

Methods

Participants

A convenience sample of 34 adult participants was recruited from Loughborough University and University of Leicester (staff and students) via email and word of mouth. All participants provided written informed consent, and the study was approved by the Ethics Committee of Loughborough University. Data were collected between March 2014 and August 2014. The study consisted of a laboratory-based component and a free-living component with each participant performing both components.

Laboratory protocol

Height and body mass were measured to the nearest 0.5 cm and 0.1 kg, respectively. Each participant wore a GENEActiv and an ActiGraph GT3X+ on their non-dominant wrist; the monitors were adjacent with the GENEActiv distal to the ActiGraph. Both monitors were worn and programmed to collect data for the 2-h duration of the laboratory protocol.

Participants undertook a protocol consisting of 16 consecutive activities: nine sedentary (four lying, five seated) and seven upright activities. See Table 1 for a detailed description of the activities. Each activity was performed in an identified sequence for five minutes with a 30 second gap between activities. Participants were observed at all times and the start and stop time for each of the activities was recorded from the clock function on the computer used to initialize the devices.

INSERT TABLE 1 ABOUT HERE

Free-living protocol

Participants undertook the free-living protocol over two days following the laboratory protocol. Each participant wore a GENEActiv and an ActiGraph GT3X+ on their non-dominant wrist; as in the laboratory protocol, the monitors were adjacent with the GENEActiv distal to the ActiGraph. An activPAL3™ was fitted on their right thigh. Participants were requested to wear all monitors continuously for two days and monitors were programmed to collect data for a 24-h period from midnight to midnight. Participants completed a log-book recording when they woke up, got up, got into bed, went to sleep, whether they removed any of the monitors for bed and details of whether they removed any of the monitors for >15 min during the day.

Measures and data processing

Accelerometers

The GENEActiv is a triaxial accelerometry-based activity monitor with a dynamic range of +/- 8*g*); where *g* is equal to the Earth' gravitational pull (Gravity Estimator of Normal Everyday Activity, 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 containing x, y and z vectors and the vector magnitude (VM) using GENEActiv PC software version 2.2. The 15 s epoch values for the x, y and z vectors are the mean acceleration over the epoch (expressed in *g* and retaining the gravity vector), whereas the 15 s epoch VM values are the summed acceleration values over the epoch, corrected for gravity (VM = $\sum \left| \sqrt{x^2 + y^2 + z^2} - g \right|$) (16).

The ActiGraph GT3X+ is a triaxial accelerometry-based activity monitor with a dynamic range of +/- 6 g (ActiGraph LLC, Pensacola, FL, USA). The ActiGraph was configured to collect data at 100 Hz, the data were uploaded and the gt3x files converted to raw 100 Hz csv files containing x, y and z vectors using Actilife version 6.11.8. In order to match the format to the GENEActiv and to that required for the Sedentary Sphere, a purpose built Excel template was used to convert the raw 100 Hz files to 15 s epoch files containing x, y and z vectors (mean acceleration over the epoch, retaining the gravity vector) and VM values (summed over the epoch, corrected for gravity).

Sedentary Sphere

The 15 s epoch GENEActiv and ActiGraph files were imported into a custom built Excel spreadsheet that calculated the most likely posture (available from the Leicester-Loughborough Diet, Lifestyle and Physical Activity Biomedical Research Unit website, LINK TO BE PROVIDED IF PAPER ACCEPTED). Posture is estimated based on arm elevation and intensity. If arm elevation is higher than 15 degrees below the horizontal and intensity light to moderate (<489 g•15 s, or 326 mg), this indicates a seated or reclining position and is classified as “sedentary”. If arm elevation is lower than 15 degrees below the horizontal the arm is hanging more vertically, this indicates a standing position and is classified as “upright”. If intensity level is moderate to vigorous (>489 g•15 s, or 326 mg), posture is classified as “upright”, irrespective of wrist elevation.

activPAL

The activPAL3TM (PAL technologies Ltd., Glasgow, UK) is a small lightweight tri-axial accelerometry-based activity monitor. Default settings were used during initialisation. It applies proprietary algorithms to accelerometer-derived information about thigh position to determine body posture (i.e., sitting/lying (sedentary) and upright). The activPAL was waterproofed and attached midline on the anterior aspect of the right thigh using Hypafix medical dressing. ActivPAL data were downloaded using activPAL Professional Research Edition v7.2.29 (PAL Technologies, Glasgow) and 15 second epoch csv files were created. To match 15-s epochs from the activPAL to the GENEActiv and the ActiGraph, the classification of ‘‘sedentary’’ or ‘‘upright’’ 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 high validity as a measure of posture (sitting/lying as opposed to upright (12, 13)).

Data Analysis

Laboratory protocol

For each participant, the percentage of epochs that were correctly coded as sedentary and upright was calculated compared to direct observation for each of the 16 activities for the Sedentary Sphere method applied to both GENEActiv data and to ActiGraph data. Percentages were then summarised and presented as means and 95% confidence intervals for each individual activity, by activities grouped as lying, sitting and upright and by the classification categories (sedentary and upright).

Free-living protocol

Only waking time periods where at least two monitors were worn for a minimum of eight hours, as recorded in the participant log and confirmed by visual verification of data, were included in analyses.

The activPAL served as the criterion measure of sedentary and upright time. All data were normally distributed. Descriptive statistics (mean ± SD) were calculated for all variables. Differences between the three measures of sedentary time were examined with a repeated measures ANOVA. Intraclass Correlation Coefficients (ICC, single measures, absolute agreement) with 95% confidence intervals (CI) were used to determine the associations between the three measures of sedentary time and limits of agreement (LoA) were examined using Bland–Altman analyses (5). Intra-individual classification agreement across 15-s epochs was reported as percent agreement, sensitivity, specificity and Cohen's kappa.

Analyses were conducted in IBM SPSS Statistics v20.0. Alpha was set at 0.05.

Results

Thirty-four participants (14 males and 20 females, mean age 27.2 ± 5.9 years; mean BMI 23.8 ± 3.7 kg/m^2, left handed N = 3) completed both the laboratory and the free-living protocol.

Laboratory protocol

One data file was unavailable for each of the monitors for the laboratory protocol due to monitor failure reducing the sample size to 33. Table 2 presents the mean percentage of time coded correctly for each individual activity, for activities grouped by type and by classification category, for each measurement method.

INSERT TABLE 2 ABOUT HERE

Results were similar for the Sedentary Sphere method, irrespective of which monitor brand the algorithm was applied to with lying (sedentary), sitting (sedentary) and upright (upright) activities correctly classified for 98%, 60% and 91% of epochs, respectively with GENEActiv data and 100%, 60% and 90% with ActiGraph data. Overall, the accuracy for classification during the observed protocol was around 80%.

Lying and upright activities were correctly classified the majority of the time ($\geq$94%), with the exception of washing pots, where around 65% of epochs were classified correctly. Sixty percent of sitting epochs were classified correctly, with the majority of misclassifications occurring during the sitting postures that did not involve any accompanying hand movement, particularly sitting with knees at 90 degrees (35% and 40% classification accuracy for the GENEActiv and ActiGraph, respectively), sitting with legs stretched out (18%, 30%) and sitting on edge of chair (20%, 33%). Accuracy did not drop as much for sitting with legs crossed (78%, 74%) and sitting with right foot resting on thigh (68%, 54%).

Free-living protocol

Nine of the thirty-four participants were excluded due to failure to wear at least two monitors concurrently for a minimum of eight waking hours during the day in the free-living phase of the study, verifiable both in the participant log and by data visualisation. Characteristics (age, height, mass and BMI) of participants did not differ between included and excluded participants. Unreadable data files (activPAL, N =2, GENEActiv, N=1 and ActiGraph, N = 1) resulted in an N of 21 for listwise analyses, 22 for pairwise analyses with the activPAL and 23 for pairwise analyses between the GENEActiv and ActiGraph.

Waking wear time was 840 ± 147 min. There were no significant differences in minutes estimated sedentary by method: 534 ± 144 min (mean ± SD), 523 ± 143 min and 528 ± 137 min by the activPAL, the Sedentary Sphere with GENEActiv data and with ActiGraph data, respectively. The mean bias, relative to the activPAL, was small with moderate limits of agreement (LoA) for the Sedentary Sphere applied to both the GENEActiv data (mean bias = -12.5 min, LoA = -117 to 92 min, Figure 1a) and the ActiGraph data (mean bias = -8 min, LoA = -103 to + 88 min, Figure 1b). Strong intra-class correlations (ICC) were evident for the activPAL with the Sedentary Sphere applied to both GENEActiv data (0.93, 0.84-0.97 (95% confidence interval)) and to ActiGraph data (0.94, 0.86–0.97).

INSERT FIGURE 1 ABOUT HERE

Agreement between posture classifications from the Sedentary Sphere applied to the GENEActiv data and to ActiGraph data was very high (ICC = 0.98 (0.94-0.99), mean bias = +3 min, LoA = --57 to + 63 min, Figure 2).

INSERT FIGURE 2 ABOUT HERE

Intra-individual classification agreement across 15-s epochs (agreement, sensitivity and specificity, kappa) is shown in Table 3. Results for posture allocation from the Sedentary Sphere were similar irrespective of the monitor brand used with agreement around 77%, sensitivity around 80% and specificity around 69%. Kappa scores were around 0.5, indicating moderate agreement with the activPAL.

INSERT TABLE 3 ABOUT HERE

Epoch-by-epoch agreement between posture classifications of GENEActiv data and ActiGraph data processed using the Sedentary Sphere was moderate to substantial with agreement and sensitivity over 80%, specificity 74% and a kappa of 0.62 (19).

Discussion

Large existing and ongoing population surveys are utilising wrist-worn triaxial accelerometers to assess physical activity. Although not employing a consistent brand of monitor, these surveys are all using triaxial MEMS wrist-worn accelerometers and storing the raw acceleration data. This has driven a pressing need to establish the comparability of accelerometer output between brands and the extent to which algorithms developed for use with data from one brand of monitors are applicable to other brands.

The present study adds to the evidence for the validity of the classification of posture from the wrist-worn GENEActiv using the Sedentary Sphere concept (14, 16), but crucially it also shows that the classification algorithm is equally valid for use with ActiGraph data. The development of analytical procedures that are accurate for use with these data, independent of monitor brand represents a significant step forward in physical activity research. Previous research has shown differences in the magnitude of output across these two brands of monitor (11, 15). As the posture classification approach is predominantly based on the orientation of the gravitational component of acceleration, it is robust to differences in acceleration magnitude, working equally well irrespective of whether it is applied to GENEActiv or ActiGraph data. We hypothesise that similar results would be attained with other monitor brands, but this hypothesis needs to be formally tested; primarily with the Axivity monitor which is being deployed in UK Biobank and has already been used to collect physical activity data from >79000 participants.

Epoch-by-epoch agreement with the activPAL in the free-living protocol was 80% and kappa around 0.5, irrespective of monitor brand, indicating moderate agreement (18). This is consistent with previous research investigating the accuracy of posture classification using the Sedentary Sphere concept with GENEActiv data (14, 16). However, agreement with mean sedentary time assessed by the activPAL was stronger in the present study than previously reported with ICCs ≥0.93 and 95% limits of agreement of 96 min (ActiGraph) and 104 min (GENEActiv), compared to correlations around 0.8 (14, 16) and 95% limits of agreement of 141 min (14) and 151 min (16). The increased agreement seen here may simply reflect the nature of the activities carried out by participants in the different samples. A known limitation of this posture classification algorithm is that activities that require the arms to be elevated while standing will be misclassified, e.g. waitressing, hairdressing (14, 16); differences in the prevalence of these activities in different samples would impact on the level of agreement. Further research in larger, more diverse samples is needed to explore whether classification accuracy differs by characteristics such as occupation type, activity level and age group.

As cautioned previously (14, 16), the limits of agreement are moderate indicating inter-individual variability. This suggests that, in its current form, the algorithm is most appropriate for group-level estimates. Notably, the estimates of mean sedentary time are more accurate than those obtained using self-report (validity coefficients generally <0.5, (1)) or cut-points with waist-worn accelerometers (+132 min, relative to activPAL, r = 0.56, (11)). These findings are not surprising; classification of sedentary time with accelerometer cut-points relies on the magnitude of accelerations which is very similar whether sitting or standing still. To differentiate between postures different features of the acceleration signal need to be considered, e.g. monitor orientation as utilised herein.

A strength of this study was the inclusion of a protocol with direct observation as the criterion. The activPAL has been extensively validated as a measure of sedentary behaviour (12, 13); however the majority of studies have employed standardised sitting and lying postures that are not representative of the variety of postures engaged in during daily life. Recently Steeves et al. (18) reported that while the activPAL was very accurate across most sitting postures accuracy fell for specific postures such as sitting with legs outstretched and sitting on a stool. This highlights the importance of employing observation as a criterion measure.

The overall classification accuracy during the observed protocol was around 80%, consistent with the agreement between the Sedentary Sphere classifications and the activPAL observed in the free-living protocol. Accuracy of classifying sedentary behaviour using the Sedentary Sphere was lowest for sitting with knees at 90 degrees, sitting with legs stretched out and sitting on the edge of the chair. While seated, participants were requested to rest their hands on their thighs, explaining the misclassifications observed. During these three seated postures, the thighs will have been at waist level or lower, leading to a low arm elevation and a greater likelihood of a classification of upright. For the remaining sitting postures (sitting with legs crossed and sitting with foot resting on thigh), the thighs will have been elevated due to the legs being crossed, leading to more elevated arms and a greater likelihood of a classification as sedentary. It is possible that the low accuracy observed during some of the sitting postures contributed to the moderate kappa and limits of agreement in the free-living study. We were not able to determine the accuracy for lying and sitting separately and recommend future free-living studies use two activPALs as the criterion posture measure, one worn on the trunk and one on the thigh (3); this would enable exploration of whether misclassification is more likely to occur during sitting or lying.

Accuracy of classification of upright activities was $\geq$94%, except for washing pots which was misclassified about 35% of the time, reflecting the changing elevation of the arms to perform the task. It is difficult to speculate on the significance of the misclassified postures identified, as this will depend on the prevalence of those postures during free-living. The greater sensitivity (≈80%), relative to specificity (≈70%), observed in the free-living protocol suggests that misclassification of upright activities as sedentary, as e.g. washing pots, was more likely than misclassification of sedentary time as upright. Note, this also reflects the greater proportion of time sedentary relative to time upright, i.e. for the same number of misclassified epochs sensitivity (sedentary classified as sedentary) will be higher than specificity (upright classified as upright), assuming the participant spent more time sedentary than upright.

As mentioned in our earlier paper, this is a simple application of the Sedentary Sphere concept based only on wrist elevation. Inclusion of other data and/or additional features from the acceleration signal could reduce the incidence of misclassifications. For example, data on the likely frequency of sit-to-stand transitions could be used to reduce the misclassifications due to frequent shifting of the arms above and below the 15 degrees threshold as can occur in activities like washing pots, cooking, waitressing and manual work. Data collected using observation as the criterion is essential in order to achieve this.

A limitation of this study is the generalizability of the sample. Participants were taken from university staff and students and may not be representative of people in other occupations, particularly manual occupations. There was also a high rate of exclusion in the free-living part of the protocol with approximately one quarter of participants excluded for insufficient concurrent wear of the monitors. It is possible that the number of monitors that participants were required to wear and the completion of the laboratory protocol prior to the free-living protocol reduced compliance.

In conclusion, the data support the efficacy of the Sedentary Sphere concept for the assessment of posture, and hence sedentary time, from a wrist-worn accelerometer in adults. Some laboratory based sitting postures were prone to misclassification, it is important to explore the extent to which this occurs in a free-living context. Importantly, the approach is equally valid with data from both the GENEActiv and ActiGraph accelerometers and the method can be applied ‘as is’ to existing datasets. Further research is needed to test the posture allocation algorithm in more diverse populations, particularly children and older adults, assess the accuracy of the algorithm in the Axivity monitor and explore whether the inclusion of additional features from the acceleration signal can reduce the incidence of misclassifications.

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List of figures

Figure 1. Mean bias (solid line) and 95% limits of agreement (dashed lines) for sedentary time estimated from the Sedentary Sphere posture algorithm applied to a) GENEActiv data relative to the activPAL and b) ActiGraph data relative to the activPAL.

Figure 2. Mean bias (solid line) and 95% limits of agreement (dashed lines) for sedentary time estimated from the Sedentary Sphere posture algorithm applied to GENEActiv data and to ActiGraph data.