Accuracy of posture allocation algorithms for thigh- and waist-worn accelerometers

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Abstract

Purpose: To compare the accuracy of the activPAL and ActiGraph GT3X+ (waist and thigh) proprietary postural allocation algorithms and an open source postural allocation algorithm applied to GENEActiv (thigh) and ActiGraph GT3X+ (thigh) data. **Methods:** 34 adults (≥18 years) wore the activPAL3, GENEActiv and ActiGraph GT3X+ on the right thigh and an ActiGraph on the right hip while performing four lying, seven sitting and five upright activities in the laboratory. Lying and sitting tasks incorporated a range of leg angles (e.g., lying with legs bent, sitting with legs crossed). Each activity was performed for five minutes while being directly observed. Percent time correctly classified was calculated. **Results:** Participants consisted of 14 males and 20 females (mean age 27.2±5.9 years; mean body mass index of 23.8±3.7kg/m^2). All postural allocation algorithms applied to monitors worn on the thigh correctly classified ≥93% of the time lying, ≥91% of the time sitting and ≥93% of the time upright. The ActiGraph waist proprietary algorithm correctly classified 72% of the time lying, 58% of the time sitting and 74% of the time upright. Both the activPAL and ActiGraph thigh proprietary algorithms misclassified sitting on a chair with legs stretched out (58% and 5% classified incorrectly respectively). The ActiGraph thigh proprietary and open source algorithm applied to the thigh worn ActiGraph misclassified participants lying on their back with their legs bent 27% and 9% of the time, respectively. **Conclusion:** All postural allocation algorithms when applied to devices worn on the thigh were highly accurate in identifying lying, sitting and upright posture. Given the poor accuracy of the waist algorithm for detecting sitting, caution should be taken if inferring sitting time from a waist-worn device.

Keywords: Sitting, standing, sedentary behaviour, inclinometer, open source.

Introduction

Sedentary behaviour, defined as sitting or reclining with low energy expenditure during waking hours (22~~16~~), has consistently been associated with morbidity and mortality (4~~2~~, 5~~3~~, 10~~6~~-12~~8~~, 23~~17~~, 27~~1~~, 29~~2~~) in adults. However, the majority of epidemiological studies to date have employed either self-reported sedentary behaviour measures or objective measures that infer sedentary behaviour through lack of movement (5~~3~~, 29~~2~~). Self-report questionnaires to assess sedentary behaviour have consistently demonstrated poor validity and underestimate sedentary behaviour (1). Objective measures that infer sedentary behaviour through lack of movement may overestimate sedentary behaviour (i.e., due to upright activities with very limited ambulation being recorded as sedentary) (18). A key factor in furthering our knowledge on sedentary behaviour and health, levels, patterns and determinants of sedentary behaviour and the effectiveness of sedentary behaviour interventions is to use objective devices that directly measure the posture of sitting and distinguish between sitting and upright postures with limited movement (e.g., standing). This is important given that recent experimental research has demonstrated that even light activity such as standing still can have a positive effect on markers of health (6~~4~~, 16, 26~~0~~).

Three devices that are capable of postural classification are the activPAL (all models), the thigh worn GENEActiv and the ActiGraph (when worn on the waist or thigh). The activPAL and ActiGraph are small tri-axial accelerometers that provide information on body posture (i.e., lying, sitting and upright postures such as standing and stepping) using proprietary software algorithms created by the manufacturers. Alternatively an open source algorithm is available, based on relative values of the x, y, z vectors, which can be applied to raw acceleration data from a thigh-worn tri-axial accelerometer to provide lying, sitting and standing information (20~~14~~). A key recommendation from the 2009 Objective Measurement of Physical Activity Meeting, co-sponsored by the National Institute of Health and American College of Sports Medicine, was that monitor data should be collected and saved as raw signals, with data transformation carried out post processing to facilitate comparisons between output regardless of which monitor is used (2, 7, 9, 28). This is only possible if open source algorithms are available for data processing. The open source algorithm for classifying posture from a thigh-worn monitor was ~~method was~~ initially developed by ActivInsights (Activinsights Ltd., Cambridgeshire, UK) for the GENEActiv; to date it has ~~and~~ been validated using GENEActiv data, but not with data from other devices (20~~14~~).

The activPAL device has been extensively validated in both laboratory and free-living studies (14~~9~~, 15~~0~~, 17~~1~~-19~~3~~, 21~~15~~), however very little research has been published on the validity of the waist (3~~1~~, 8~~5~~) and thigh worn (24~~18~~, 25~~19~~) ActiGraph inclinometer algorithm~~feature~~ and the thigh worn GENEActiv (20~~14~~). Furthermore, the majority of validation studies, including those with the activPAL, have usually involved lying and sitting activities that are not fully representative of daily postures. For example, lying in daily life usually involves lying on the back or side with legs sometimes straight and sometimes bent. Sitting usually involves different leg positions such as crossed legs or tucked under a chair for example. Studies to date have not considered these types of activities in their validation methods. One exception is the recently published study by Steeves and colleagues (25~~19~~) where participants wore the activPAL and the ActiGraph on the thigh whilst completing sitting activities with different leg positions (e.g., sitting with legs crossed at the knee). They found that the activPAL and ActiGraph were highly accurate for some (e.g., sitting with legs crossed), but not all (e.g., sitting on a laboratory stool), sitting activities, To expand our understanding of the accuracy of the devices that are capable of posture classification it is important to include, in validation studies, a wide range of activities that are as representative of daily life as possible.

Therefore, the purpose of this study was to investigate the accuracy of the activPAL, waist and thigh worn ActiGraph GT3X+ proprietary postural allocation algorithms and the open source thigh postural allocation algorithm (applied to GENEActiv and ActiGraph data). Accuracy for identifying a range of lying and sitting positions, representative of daily postures, and light intensity upright activities was examined in a laboratory-based setting. Application of the open source postural allocation algorithm to both the GENEActiv and ActiGraph data will enable the assessment of the generalizability of the open source algorithm and comparison of the accuracy of the open source and ActiGraph proprietary algorithm.

Methods

Participants

A convenience sample of 34 adults ~~(≥18 years)~~ was recruited from Loughborough University and University of Leicester (staff and students) via word of mouth and email. Participants needed to be ≥18 years, English speaking, and without mobility issues which would prevent full participation in the protocol of activities. Ethical approval was received from Loughborough University.

Procedure

Participants visited the research centre at Loughborough University between March 2014 and August 2014. Participants provided written informed consent and basic demographic information (date of birth, sex). Body weight (Tanita, West Drayton, UK) and height (Leicester portable height measure) were measured to the nearest 0.1 kg and 0.5 cm respectively. Participants were fitted with an activPAL3™, GENEActiv and ActiGraph GT3X+ on the mid-line anterior aspect of their~~ir~~ right thigh and an ActiGraph GT3X+ on their right hip. Participants were directly observed continuously (criterion measure) whilst completing a protocol consisting of 16 activities (Figure 1), each performed for five minutes with a 30 second gap in between activities. Participants started with the lying activities and each participant completed the activities in the same order. The start and stop time for each of the activities was measured and recorded by the observer using the clock function on the same computer used to initialize the devices.

Objective Sedentary and Activity Measures

The activPAL3™ is a small (35x53x7 millimeters), lightweight (15g) tri-axial accelerometer and via proprietary algorithms (Intelligent Activity Classification), accelerometer-derived information about thigh position and acceleration are used to determine body posture (i.e., sitting/lying and upright) and transition between these postures and stepping. Default settings were used during initialisation (i.e, 20Hz, 10 second minimum sitting and upright period). The activPAL was attached midline on the anterior aspect of the right thigh using Hypafix medical dressing.

The ActiGraph GT3X+ (Actigraph LLC, Pensacola, FL, USA) is a small (45×33×15 millimeters), lightweight (19 g) tri-axial accelerometer that can be worn on various body locations including waist, wrist, ankle and thigh. T~~t~~hrough a proprietary postural algorithm the ActiGraph, when worn on the waist, is capable of describing positional information (lying, sitting, standing and non-wear) during periods of inactivity due to gravitational forces acting on the orientation on the 3 axes. When the device is worn on the thigh, the lying and sitting category is grouped together. ActiGraph devices were initialised to record at a frequency of 100Hz and the low frequency extension filter was selected. Participants wore two ActiGraph GT3X+ devices; one on an elastic belt around the waist on the right midaxillary line of the hip and one on an elastic belt on the midline on the anterior aspect of the right thigh (below the activPAL3^{TM}).

The GENEActiv (Gravity Estimator of Normal Everyday Activity, Activinsights Ltd., Cambridgeshire, UK) is a small (43x40x13 mm), lightweight (16 g) triaxial accelerometer that can be worn on various body locations including wrist, waist, ankle, upper arm and thigh. ~~that~~ W~~w~~hen worn on the thigh the GENEActiv can assess posture based on the relative values of the x (mediolateral), y (vertical), and z (anteroposterior) vectors. The GENEActiv was initialised to record at a frequency of 100Hz. Participants wore the GENEActiv on the midline on the anterior aspect of the right thigh using an elastic belt.

Data Reduction and Analysis

Proprietary algorithms

ActivPAL data were downloaded using activPAL Professional Research Edition v7.2.29 (PAL Technologies, Glasgow) and 15 second epoch csv files were created. ActiGraph data were downloaded using ActiLife v6.10.2 (ActiGraph, Pensacola, FL, USA) and converted into 15 second epoch csv files. Posture classification is determined proprietarily within the manufacturer's software for the thigh-worn activPAL, thigh-worn ActiGraph and waist-worn ActiGraph (APAL$_{\mathbf{PROP}}$ and T_AGRAPH$_{\mathbf{PROP}}$, and W_AGRAPH$_{\mathbf{PROP}}$, respectively).

Open source algorithms

GENEActiv data were downloaded using GENActiv PC software v2.2 and the raw .bin files were converted into 15 second epoch csv files. The 15-s epoch files were imported into a custom-built template in Excel that computed the most likely posture based on the relative values of the x, y, z vectors measured at the thigh (T_GACTIV$_{\mathbf{OPEN}}$). This method was developed by ActivInsights for use with the GENEActiv when it is worn on the thigh and has been described previously (20). The~~is~~ method is open source and we have made the Excel template ~~is~~ available on the Leicester-Loughborough Diet, Lifestyle and Physical Activity Biomedical Research Unit website (http://www.ll.dlpa.bru.nihr.ac.uk/Sedentary_Sphere-5483.html~~http://www.ll.dlpa.bru.nihr.ac.uk~~/) ~~(Note: This will be made available at this location on acceptance of this manuscript)~~.

The 100 Hz GT3X+ files from the thigh-worn ActiGraph were converted to 100 Hz csv files containing x, y and z vectors using Actilife version 6.10.2. In order to match the format to the GENEActiv and to that required for the open source algorithm, 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). The 15 s epoch files were then imported into the custom-built Excel template for computation of the most likely posture (T_AGRAPH$_{\mathbf{OPEN}}$). The first and last 30 seconds of each activity were excluded from the analyses to protect against the potential of imperfect time synchronization and transition between activities.

For each participant, the percentage of epochs that were~~as~~ correctly coded as lying, sitting and upright against direct observation was calculated for each of the 16 activities for each method of measurement (APAL$_{\mathbf{PROP}}$, T_AGRAPH$_{\mathbf{PROP}}$, W_AGRAPH$_{\mathbf{PROP}}$, T_GACTIV$_{\mathbf{OPEN}}$, T_AGRAPH$_{\mathbf{OPEN}}$). Percentages were then summarised and presented as means and 95% confidence intervals for each individual activity and by activities grouped as lying, sitting and upright activity. Analyses were conducted in IBM SPSS Statistics v20.0.

Results

Participants consisted of 14 males and 20 females (mean age 27.21 ± 5.94 years (range 20-40 years); mean BMI 23.82 ± 3.68 kg/m^2; range 18.64-32.58kg/m^2). Table 1 presents the mean percentage of time coded correctly, against direct observation, for each individual activity and activities grouped by type (i.e., lying, sitting and upright) by each measurement method.

The $APAL_{PROP}$ and T_GACTIV_{OPEN} classified all lying activities correctly 100% of the time. The T_AGRAPH_{PROP} and T_AGRAPH_{OPEN} classified three of the four lying activities 100% of the time, with lying on the back with legs bent classified correctly 73% of the time (93% correctly classified for all lying activities) and 91% of the time (98% correctly classified for all lying activities) respectively. The W_AGRAPH_{PROP} correctly classified lying activities between 67-77% of the time (72% overall for lying activities).

When examining sitting activities, the $APAL_{PROP}$ correctly classified six out of seven sitting activities ≥97% of the time, with sitting with legs stretched outs classified correctly 42% of the time (91% overall for all sitting activities). The T_GACTIV_{OPEN} and T_AGRAPH_{OPEN} correctly classified all sitting activities 100% of the time. The T_AGRAPH_{PROP} correctly classified six out of seven sitting activities 100% of the time; sitting with legs stretched out was classified correctly 95% of the time (99% overall for all sitting activities). The W_AGRAPH_{PROP} correctly classified sitting activities between 46-70% of the time (58% overall for sitting activities).

Four out of five upright activities were correctly classified 100% of the time by the $APAL_{PROP}$, with self-paced walking correctly classified 97% of the time (99% overall for all upright activities). The T_GACTIV_{OPEN}, T_AGRAPH_{OPEN} and the T_AGRAPH_{PROP} correctly classified upright activities ≥88% (93% overall for all upright activities), ≥97% (98% overall for all upright activities) and ≥91% (96% overall for all upright activities) of the time respectively. The W_AGRAPH$_{\mathbf{PROP}}$ correctly classified upright activities between 61-97% of the time (74% overall for upright activities).

Discussion

This study adds to the literature by comparing the accuracy of several accelerometers, with proprietary and/or open source postural allocation algorithms applied to the data, across a range of different postures and activities. This study demonstrated that all thigh-worn monitors were highly accurate in identifying lying, sitting and upright postures, irrespective of whether proprietary (activPAL and ActiGraph) or open source algorithms (GENEActiv and ActiGraph) were applied to the data. As noted recently by Steeves and colleagues (2519) there is a need for improvements in algorithms to increase their ability to correctly classify a wider range of postures and activities. They further highlight that broader access to appropriate hardware and firmware to support postural and activity classification would be a major advancement for the research community. The open source algorithm applied in the current study demonstrated high accuracy across monitor brands and across the range of postures and activities typical during free-living; this is a significant step forward.

The high validity of the activPAL monitor has been demonstrated in numerous laboratory studies (149,150), however to our knowledge this is only the second study utilising the activPAL whilst including sitting postures with a variety of leg angles. Recently, Steeves and colleagues examined the accuracy of the activPAL for identifying different sitting postures (e.g., legs crossed at knee, legs crossed at ankle, legs crossed with ankle on opposite knee) and found that the activPAL was highly accurate for most sitting postures. In agreement with the current study they found that the activPAL misclassified (15% of the time) sitting with legs outstretched but not to the extent of the current study (58%). This sitting position changes the angle of the thigh slightly (i.e., knee angle increases above 90° and front of thigh dips) and t~~T~~he misclassification ~~during this particular activity~~ suggests that the activPAL proprietary angular parameters for the classification of sitting require the thigh to be close to parallel to the ground (25~~19~~). As the activPAL algorithm is proprietary it is not possible to investigate whether accuracy can be improved by adjusting the parameters, as would be possible with an open source algorithm. It is important to acknowledge that the extent to which this would impact on misclassification of sitting time during a typical 7-day free-living data collection would depend on the prevalence of this type of sitting posture.

The use of the activPAL monitor in physical activity and sedentary behaviour research is increasing rapidly (13) due to its ability to correct identify posture (14, 15,~~9~~-17~~1~~). The high accuracy of the ActiGraph thigh proprietary algorithm and open source algorithm applied to both ActiGraph and GENEActiv data observed in the current study suggests that these could also be an option for postural identification in research. This finding is consistent with a small body of previous research (24~~18~~,25~~19~~) that has shown the ActiGraph thigh proprietary algorithm to be highly accurate. Skotte et al (24~~18~~) under free-living conditions, compared the hip and thigh worn ActiGraph postural allocation algorithms against a pressure logger to detect sitting posture. They found that the thigh algorithm was more precise than hip algorithm. Furthermore, in a recent study by Steeves et al (25~~19~~) the ActiGraph thigh algorithm demonstrated 100% accuracy in detecting five different sitting postures, an accurate ability to identify standing and light movement at a whiteboard and >95% accuracy for stepping activities. The ActiGraph thigh algorithm did however misclassify 14% of the time sitting on a laboratory stool as standing time (25~~19~~). Although we, and others, have found the ActiGraph thigh algorithms to be highly accurate for the majority of activities, i~~I~~t is important to acknowledge ~~however,~~ the design limitations of this ~~e ActiGraph~~ device. The device, although small and lightweight, is considerably thicker than the activPAL for example, and has sharp edges where the elastic belt sits. This may make it visible under some clothing and uncomfortable on the thigh, possibly resulting in compliance issues when worn on the thigh. Ideally a device needs to be both accurate and comfortable to wear. Before deciding upon a particular device pilot testing with the target population would be advantageous.

In a small free living study, the accuracy and precision of the open source algorithm applied to GENEActiv data has been demonstrated against the activPAL monitor (2014), however the current study is the first to compare against direct observation. This is also the first study to apply a transparent open source algorithm to ActiGraph data and compare it to the manufacturer's proprietary algorithm. The open source algorithm applied to the ActiGraph thigh data performed slightly better than the ActiGraph proprietary algorithm for identifying lying and sitting activities, specifically on the individual activities of lying on the back with legs bent and sitting with legs stretched out, but had marginally lower accuracy for upright activities.

Few published studies have investigated the accuracy of the ActiGraph algorithm when worn on the waist (31,85 2418). All studies reported poor accuracy of the algorithm which corroborates the current findings. Given the poor accuracy of the waist algorithm for identifying lying, sitting and upright activities, caution should be taken when considering employing this device in research studies especially those with a focus on time spent sitting.

The strengths of this study include the comparison of five different postural identification measurement methods (including application of an open source algorithm), the range of lying, sitting and upright activities that were chosen to be more representative of daily postures, and the use of direct observation as the criterion measure for comparisons.

However, it is important to acknowledge that although activities and postures included were designed to mimic everyday behaviours, participants were instructed how to lie or sit and in a free-living environment may perform the same behaviours in a slightly different manner. Furthermore, our homogeneous sample of participants (i.e., narrow age range and 74% in the normal weight category) may limit generalizability of results.

In summary we demonstrated that all thigh worn monitors, irrespective of type (proprietary or open source) of algorithm, were highly accurate. It is important to note that it is not the device or the algorithm per se that is accurate, it is the combination of the two. A major limitation of any proprietary algorithm, in addition to the lack of transparency, is that it is limited to a single device. In contrast, open source methods are much more flexible for researchers to use (e.g., modifications can be made to angle thresholds for different population groups) and allow algorithms to be applied to different devices enabling assessments across devices to be made. The current study demonstrated accuracy of an open source algorithm across monitor brands and across a range of postures and activities.

Authors Contributions:

CE, TY and AR conceived the study and TG, DE, MD and KK refined the study, CE wrote the first draft of the manuscript, SB and JS carried out data acquisition, SB, SOC and AR analysed the data. All authors reviewed/edited the manuscript and approved the final manuscript.

Conflict of Interest Statement:

Alex Rowlands provides consultancy services to Activinsights, the manufacturer of the GENEActiv. The authors declare that there are no other conflicts of interests. The results of the present study do not constitute endorsement by ACSM.

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Figure Titles

Figure 1. Flow of 16 lying, sitting and upright activities.