Ability of Thigh-Worn ActiGraph and activPAL Monitors to Classify Posture and Motion

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[1]*Cancer Prevention Fellowship Program, Division of Cancer Prevention, National Cancer Institute, Rockville, MD;* [2]*Risk Factor Monitoring and Methods Branch, Division of Cancer Control and Population Sciences, National Cancer Institute, Rockville, MD;* [3]*Biometry Research Group, Division of Cancer Prevention, National Cancer Institute, Rockville, MD; and* [4]*Diabetes, Endocrinology, and Obesity Branch, National Institute of Diabetes and Digestive and Kidney Diseases, Bethesda, MD*

ABSTRACT

STEEVES, J. A., H. R. BOWLES, J. J. MCCLAIN, K. W. DODD, R. J. BRYCHTA, J. WANG, and K. Y. CHEN. Ability of Thigh-Worn ActiGraph and activPAL Monitors to Classify Posture and Motion. *Med. Sci. Sports Exerc.*, Vol. 47, No. 5, pp. 952–959, 2015. **Purpose**: This study compared sitting, standing, and stepping classifications from thigh-worn ActiGraph and activPAL monitors under laboratory and free-living conditions. **Methods**: Adults wore both monitors on the right thigh while performing activities (six sitting, two standing, nine stepping, and one cycling) and writing on a whiteboard with intermittent stepping under laboratory conditions (n = 21) and under free-living conditions for 3 d (n = 18). Percent time correctly classified was calculated under laboratory conditions. Between-monitor agreement and weighted κ were calculated under free-living conditions. **Results**: In the laboratory, both monitors correctly classified 100% of standing time and >95% of the time spent in four of six sitting postures. Both monitors demonstrated misclassification of laboratory stool sitting time (ActiGraph 14% vs activPAL 95%). ActivPAL misclassified 14% of the time spent sitting with legs outstretched; ActiGraph was 100% accurate. Monitors were >95% accurate for stepping, although ActiGraph was less so for descending stairs (86%), ascending stairs (92%), and running at 2.91 $m{\cdot}s^{-1}$ (93%). Monitors classified whiteboard writing differently (ActiGraph 83% standing/15% stepping vs activPAL 98% standing/2% stepping). ActivPAL classified 93% of cycling time as stepping, whereas ActiGraph classified <1% of cycling time as stepping. During free-living wear, monitors had substantial agreement (86% observed; weighted κ = 0.77). Monitors classified similar amounts of time as sitting (ActiGraph 64% vs activPAL 62%). There were differences in time recorded as standing (ActiGraph 21% vs activPAL 27%) and stepping (ActiGraph 15% vs activPAL 11%). **Conclusions**: Differences in data processing algorithms may have resulted in the observed disagreement in posture and activity classification between thigh-worn ActiGraph and activPAL. Despite between-monitor agreement in classifying sitting time under free-living conditions, ActiGraph appears to be more sensitive to free-living upright walking motions than activPAL. **Key Words:** SITTING, STANDING, STEPPING, TRANSITIONS, ACTIVITIES, INCLINATION

Physical activity and sedentary activity are challenging to measure with accuracy and precision. Previously, physical activity measurement and methods researchers have been more concerned with accurately measuring dynamic muscle actions (e.g., walking and running) than static muscle actions (e.g., standing) due to the initial interest in understanding the relationship between moderate to vigorous physical activity and health outcomes (26). Due to differences in the energy requirement of lying down, sitting, and standing (1), researchers have become interested in activity type classification based on posture (e.g., lying down, sitting, standing, and stepping).

The increased energy expenditure and postural demands of standing compared with sitting may be an important distinction to consider when evaluating health outcomes (15,24). For example, activities of myokines, such as lipoprotein lipase, may be stimulated by standing versus sitting, which can result in regulating lipid oxidation (30). Early accelerometers did not have the ability to capture the static acceleration component of an acceleration signal—only the dynamic component related to motion, hence their inability to identify static standing posture (7,8). When worn at the hip, accelerometers are currently unable to accurately differentiate between static seated and standing postures (7,10,17,19,23,24,29), which can result in the misclassification of standing (a light-intensity activity) as sedentary (18,27,32). Data from waist-worn accelerometers are typically examined using a threshold approach to classify sedentary time (e.g., <100 vertical axis counts per minute for ActiGraph) (17,22). However, laboratory

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studies using the <100 counts per minute threshold to predict sedentary time have shown that accelerometers are only 50% accurate (9,13,16,23,24). A thigh-mounted accelerometer, such as the activPAL (2) or ActiGraph monitor, may provide greater accuracy for assessing and differentiating between sedentary postures (particularly sitting and standing).

Despite the inherent challenges and limitations of measuring sedentary behavior, there has been an increase in research focused on understanding the independent health effects of sedentary and light-intensity physical activities involving static muscle actions (6,15,17,21,25). The thigh-worn activPAL was one of the first accelerometry-based activity monitors to use static acceleration and inclination to interpret postures. It has been used to quantify postural allocation and partition behaviors into time spent sitting/lying, standing, and walking in laboratory (2,14,19,28) and free-living (12,20) studies.

Recent advances in accelerometer technology have made the measurement of body posture possible with other monitors (4,7,8). In October 2012, ActiGraph released a new software option that allows for GT3X+ and newer monitors (ActiSleep+, wGT3X+, wActiSleep+, wGT3X-BT, and wActiSleep-BT) to be worn on the thigh and provide three categorical activity type outputs: sitting/lying, standing, and stepping. We sought to determine whether the ActiGraph GT3X+ and activPAL monitors could successfully identify activity type in the laboratory by comparing them with direct observation. In addition, monitors were compared for agreement after a 3-d free-living collection period.

METHODS

Participants

Twenty-six adults (percent male, 27%; mean ± SD age, 37.9 ± 14.2 yr; mean ± SD body mass index, 32.0 ± 10.3 kg·m^{-2}; mean ± SD thigh circumference, 60.4 ± 10.6 cm; percent white, 35%; percent black, 19%; percent Hispanic, 42%; percent Asian, 4%) participated in this study conducted at the National Institutes of Health Clinical Center (Bethesda, MD). Individuals had no significant physical limitations, medical conditions, or psychiatric conditions. Before participation, participants read and signed an informed consent form approved by the National Institute of Diabetes and Digestive and Kidney Diseases Institutional Review Board.

Instrumentation

The physical and performance-related specifications of ActiGraph GT3X+ (ActiGraph LLC, Pensacola, FL) and activPAL3 (PAL Technologies Ltd, Glasgow, UK) are outlined in Table 1. Both ActiGraph and activPAL use proprietary software algorithms to determine time spent in different body positions, based on a combination of static and dynamic acceleration information, when the respective monitors are worn on the thigh. ActivPAL was designed to be worn on the thigh. The ActiGraph monitor, originally designed to be worn at the waist, has two algorithms for the inclinometer: 1) thigh and 2) everywhere else. At the thigh, ActiGraph uses raw data to estimate time spent in three categories: sitting/lying, standing, and stepping. "Stepping" in this case is determined by simply looking at movement, not step counts. For step counting, however, ActiGraph has one algorithm designed for waist-worn devices. When worn on the thigh, this could contribute to step count inaccuracy if actual step count was an outcome of interest.

ActiGraph and activPAL were worn on the front midline of the right thigh midway between the hip and the knee joint (Fig. 1), based on manufacturers' recommendations and previous validation studies (2,14). A slight gap between the ActiGraph monitor and the activPAL monitor was maintained to avoid any angular change due to contact during movement. Both ActiGraph and activPAL were attached to the skin using the double-sided adhesive PALstickies (PAL Technologies Ltd) and reinforced with a strip of Tegaderm (3M, St. Paul, MN). To minimize the effects of the relative orientation of the monitors, half of the participants wore ActiGraph above activPAL and half wore the monitors in the opposite orientation. Before being fitted to participants, all monitors were initialized using their respective software (ActiGraph: ActiLife software version 6.5.3 and Firmware version 3.1.0; activPAL: activPAL™ Research Edition version 6.4.1).

Laboratory Activity Protocol

Participants' height, weight, and right thigh circumference were measured using standardized procedures (5). With

TABLE 1. Specifications of activPAL and ActiGraph GT3X+.

	activPAL3	ActiGraph GT3X+
Physical		
Dimensions	5.3 cm × 3.5 cm × 0.7 cm	4.6 cm × 3.3 cm × 1.5 cm
Weight	15 g	19 g
Communication	Five-port docking station with data transfer port	Full-speed USB 2.0
Performance		
Transducer/sensor	Capacitance-based accelerometer	Triaxis solid-state accelerometer (ambient light photodiode)
Dynamic range	±2*g*	±6*g*
Sample rate	20 Hz	30–100 Hz in 10-Hz increments
Resolution	8-bit A/D conversion	12-bit A/D conversion; 2.93 mG (raw data)
Memory capacity	16 MB	512 MB
Battery life	10 d	30 d (fully charged)
Water resistance	Can be waterproofed to allow wear in shower	1 m for 30 min
Calibration	Internal	Internal
Wear location	Thigh	Wrist, waist, ankle, and thigh

EPIDEMIOLOGY

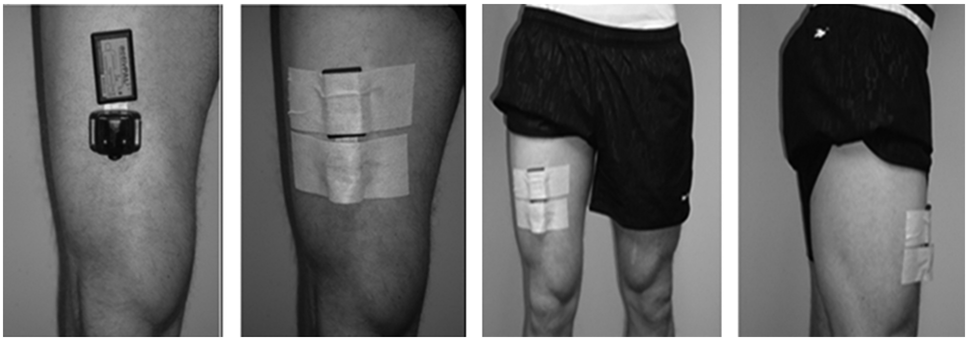

FIGURE 1—Monitor arrangement. ActiGraph and activPAL™ were worn on the front midline of the right thigh midway between the hip and the knee joint.

participants in light clothing and without shoes, weight was measured to the nearest 0.05 kg using the 5702 Bariatric Stand-on Scale (Scale-Tronix 5702; Scale-Tronix, Carol Stream, IL). Height was measured to the nearest 0.1 cm using a stadiometer (Seca Corporation, Columbia, MD). Thigh circumference measurements were taken using a Gulick tape measure with a tension handle midway between the hip and the knee joint. The average of three measurements was recorded. After being fitted with the monitors, participants were asked to engage in a range of sitting and standing postures, different walking scenarios, standing while writing on a whiteboard with intermittent steps, and cycling on an upright cycle ergometer (17960 Lode Corival upright ergometer) (Table 2):

- Sitting (on a 40-cm-tall chair)
  - Self-selected posture
  - Legs crossed at the knee
  - 90-Degree hip and knee angles
  - Legs crossed with ankle on opposite knee
  - Legs crossed at the ankle
  - On a 70-cm-tall laboratory stool
- Standing
  - Self-selected posture
  - Rigid upright posture
- Walking
  - Self-selected pace (slow and normal over 85 m)
  - Stair descending and ascending (four flights of stairs)
  - Treadmill walking (0.67, 1.12, and 1.56 $m{\cdot}s^{-1}$)
  - Treadmill running (2.45 and 2.91 $m{\cdot}s^{-1}$)
- Standing while writing on a whiteboard with intermittent steps
- Upright cycling (50 rpm)

Each posture or movement was explained and demonstrated to participants. Participants completed 2 min of each posture/activity (2), except for self-paced overground 85-m walk at slow and normal speeds, descending four flights of stairs, and ascending four flights of stairs, which were of fixed distance for all participants.

Direct observation. Direct observation via continuous focal sampling was used as the validation criterion to determine postures and activities. Researchers recorded the exact time of the beginning and the end of each activity or posture during the laboratory protocol. Two researchers (JAS and JW) were present throughout data collection. They explained and demonstrated the activities, documented the start and stop times of each activity, and took other notes specific for data collection. This documentation enabled the time-stamped information from the activPAL and ActiGraph monitors to be matched and compared with the directly observed (validation criterion) activities and postures. Each testing section lasted less than 60 min. Standing while writing on a whiteboard was coded as standing because our pilot work showed that it resulted in few steps. Participants were given a dry erase marker and a blank copy of the informed consent form and were positioned standing facing a dry erase board (2.44 m × 1.21 m). Participants were instructed to transcribe the text of the document onto the whiteboard; when they reached the right edge of the board, they were asked to return to the left edge and to continue transcribing until the end of the 2-min activity. The few intermittent steps that occurred between bouts of standing were not counted. Cycle ergometer activity was coded as stepping because it was hypothesized that the dynamic acceleration associated with thigh movement would be classified as stepping by the thigh-worn monitors. However, it must be noted that stepping is not representative of cycling, and that the two activities are not comparable from the points of view of both activity type and energy expenditure. Although it may be inappropriate to use "stepping" to represent an activity that does not involve heel strike/toe off and the generation of ground impact forces (i.e., ambulation), it may be relevant to determine how thigh-worn monitors classify cycle ergometer activity.

Free-Living Protocol

Participants were asked to wear the two monitors for three consecutive days during all waking hours, except when showering, bathing, or swimming. Participants were instructed

TABLE 2. Percent time anatomical posture was coded correctly (±95% CI) and incorrectly (as sitting, standing, or stepping) for each monitor and activity conducted in the laboratory (n = 21).

		activPAL					ActiGraph				
	Assigned Code	Mean Coded Correctly (%)	95% CI	% Coded Sitting	% Coded Standing	% Coded Stepping	Mean Coded Correctly (%)	95% CI	% Coded Sitting	% Coded Standing	% Coded Stepping
Sitting[a]											
Self-selected posture[b]	Sitting	95.2	85.3–100	95.2	4.8	–	100	–	100	–	–
Legs crossed at the knee (n = 20)	Sitting	100	–	100	–	–	100	–	100	–	–
90-Degree joint angles	Sitting	100	–	100	–	–	100	–	100	–	–
Cross-legged with ankle on the opposite knee	Sitting	100	–	100	–	–	100	–	100	–	–
Legs outstretched and crossed at the ankle[c]	Sitting	85.7	69.4–100	85.7	14.3	–	100	–	100	–	–
70-cm laboratory stool[d]	Sitting	4.8	0–14.7	4.8	95.2	–	85.7	69.4–100	85.7	14.3	–
Standing											
Self-selected comfortable posture	Standing	100	–	–	100	–	99.9	99.8–100	–	99.9	0.1
Rigid upright posture (like a soldier)	Standing	100	–	–	100	–	100	–	–	100	
Stepping											
Overground slow pace[e]	Stepping	100	–	–	–	100	99.7	99.3–100	–	0.3	99.7
Overground normal pace[e]	Stepping	98.5	95.5–100	–	1.5	98.5	98.9	96.6–100	–	1.1	98.9
Stair descending (four flights)	Stepping	95.1	90.9–99.4	–	4.9	95.1	86.0	78.3–93.6	0.9	13.1	86.0
Stair ascending (four flights)	Stepping	95.1	91.3–98.9	–	4.9	95.1	91.9	87.1–96.8	0.6	7.5	91.9
Treadmill at 0.67 $m{\cdot}s^{-1}$	Stepping	100	–	–	–	100	97.8	94.4–100	–	2.2	97.8
Treadmill at 1.12 $m{\cdot}s^{-1}$	Stepping	100	–	–	–	100	98.6	96.4–100	–	1.4	98.6
Treadmill at 1.56 $m{\cdot}s^{-1}$ (n = 19)	Stepping	100	–	–	–	100	99.4	98.4–100	–	0.6	99.4
Treadmill at 2.45 $m{\cdot}s^{-1}$ (n = 15)	Stepping	100	–	–	–	100	98.7	97.1–100	–	1.3	98.7
Treadmill at 2.91 $m{\cdot}s^{-1}$ (n = 12)	Stepping	100	–	–	–	100	92.8	76.9–100	–	7.2	92.8
Mixed posture (standing and stepping)											
Writing on a whiteboard	Standing	97.8	96.0–99.6	–	97.8	2.2	82.8	78.6–86.9	1.8	82.8	15.4
	Stepping	2.2	0.4–4.0				15.4	12.4–18.5			
Other posture											
Upright cycling (50 rpm) (n = 19)[f]	Stepping	93.3	82.2–100	6.2	0.5	93.3	0.2	0–0.4	99.8	–	0.2

CIs may not be symmetric because they were truncated at 0% and 100%. Because of missing data, n for certain activities may not be equal to total N.
[a]Chair height for all sitting postures (except for laboratory stool sitting) is 40 cm.
[b]One of 21 activPAL monitors incorrectly coded standing 100% of the time.
[c]Three of 21 activPAL monitors incorrectly coded standing 100% of the time.
[d]One of 21 activPAL monitors correctly coded sitting 100% of the time, 20 of 21 activPAL monitors coded standing 100% of the time, and 3 of 21 ActiGraph monitors incorrectly coded standing 100% of the time.
[e]Eighty-five meters at self-selected pace.
[f]One of 19 activPAL monitors incorrectly coded sitting 100% of the time.

to maintain normal daily activities and were provided with a mobile phone and a smartphone application to record when the monitors were taken off and put back on. A 3-d free-living protocol was chosen to collect sufficient data to make interdevice comparisons and to assess the reliability of the devices in the field. In adults, at least 3 d are needed to obtain reliable measures of habitual physical activity (31). After 3 d of wear, participants returned all monitors and the mobile device to the study center for downloading.

Data Processing

Data from ActiGraph were recorded as raw triaxial signals (80 Hz) and processed at the 1-s epoch level with ActiLife software. The time-stamped event data file from the activPAL software was converted into second-by-second data. Data from the two monitors were aligned using time stamps and analyzed with SAS version 9.3 (SAS Institute Inc., Cary, NC), allowing for the comparison of times spent sitting, standing, and stepping at the 1-s time resolution in relation to each of the time-stamped laboratory activities recorded using continuous focal sampling.

The first and last 15 s of each 2-min laboratory observation were removed to avoid capturing any transitions at the beginning and end of an activity. Postural data from the middle 90 s of each activity were used for analysis. Data were visually inspected to identify monitor malfunctions. Of the 25 participants who completed the laboratory protocol, four individuals were removed from data analysis. For one participant, the activPAL monitor was not properly initialized by the researcher. For three participants, activPAL malfunctioned, classifying the entire data collection period (19 of 19 activities) as sitting. The number of participants differed from the total (N = 21) for sitting with legs crossed at the knee (n = 20) and treadmill speeds 1.56 $m{\cdot}s^{-1}$ (n = 19), 2.46 $m{\cdot}s^{-1}$ (n = 15), and 2.91 $m{\cdot}s^{-1}$ (n = 12) due to the inability of some participants to complete 2 min of the activity (Table 2).

A smartphone application was used by participants to self-report nonwear time during the 3-d free-living collection period, and this information was used to identify time when the monitors were not worn during the free-living protocol. Of the 22 participants who completed the free-living component, four participants were removed from data analysis; two participants were removed due to activPAL malfunction, and two participants were removed for not wearing the monitors for all 3 d. If activPAL classified the majority of the 3-d data collection period as sitting whereas ActiGraph suggested a variety of sitting, standing, and stepping postures, the activPAL unit was judged to be malfunctioning. Of the two participants who did not wear both monitors for all 3 d, one participant stopped wearing the monitors due to skin irritation from PALstickies and/or Tegaderm. Two other participants reported small abrasions on the skin due to the rigid edges of the ActiGraph monitor, but this did not affect wear time compliance. The remaining 18 participants who had a total of 54 valid days of simultaneously recorded information from the ActiGraph and activPAL monitors were analyzed.

Statistical Analyses

In-laboratory data were used to validate the activPAL and ActiGraph monitors by comparing the percentage of each 90-s window that each monitor correctly coded the specified postures as sitting, standing, or stepping. Simple binomial approximation was used to construct 95% confidence intervals (CIs) around an observed agreement for each coded posture for each monitor, with upper confidence limits top coded at 100%. The 3-d free-living protocol data were summarized to produce percentages of time spent in each posture over the whole 3-d wear time period and the average number of postural transitions per day for each monitor. Percent time was calculated by dividing the number of minutes in each posture by the total time. A transition was coded any time the postural output changed from one posture to another. To show the classification accuracy of the two monitors, we calculated percent agreement (sum of concordant cells/sum of all cells in the 3 $\times$ 3 confusion matrix) and weighted κ for the whole 3-d wear time period. κ values greater than 0.75 represent excellent agreement. Paired *t*-tests were used to compare the percentage of time spent in each posture and the number of transitions recorded between monitors.

RESULTS

Comparison of Posture Measured by Each Monitor and Observed Posture during the Laboratory Protocol

In the laboratory, both monitors correctly classified the two standing activities 100% of the time (Table 2). ActivPAL correctly classified four of the six sitting activities more than 95% of the time, but only correctly classified sitting with legs outstretched 86% of the time and laboratory stool sitting 5% of the time. ActiGraph correctly classified five of the six sitting activities 100% of the time, with laboratory stool sitting correctly classified 86% of the time. ActivPAL correctly classified all nine walking activities >95% of the time. Of the remaining walking activities, ActiGraph correctly classified six of the nine walking activities >95% of the time. Time spent stepping was misclassified by ActiGraph during ascending (8% misclassified), descending (14% misclassified), and running at 2.91 m·s^{-1} (7% misclassified). Time spent writing on the whiteboard with intermittent steps was classified differently between monitors (ActiGraph 83% standing/15% stepping vs activPAL 98% standing/2% stepping), as was time spent cycling (ActiGraph <1% stepping vs activPAL 93% stepping).

Comparison of Posture Measured by Each Monitor during the 3-d Free-Living Protocol

During free-living wear, participants wore the monitors for 15.3 ± 1.9 h·d^{-1} (mean ± SD). The second-by-second aligned ActiGraph and activPAL data had high percent agreement (86%) and substantial agreement when accounting for chance (weighted κ = 0.77; 95% CI, 0.770–0.771) (Table 3), driven primarily by the high volume of sitting (>60% of time in free living). The volume of time classified as sitting did not significantly differ between monitor types (ActiGraph 64% ± 12% vs activPAL 62% ± 12%). However, there were significant differences between monitors in time classified as standing and stepping. ActiGraph (21% ± 10%) classified less time standing than did activPAL (27% ± 11%; P < 0.0001) but more time stepping (ActiGraph 15% ± 4% vs activPAL 11% ± 4%; P < 0.0001).

The most common discrepancies between monitors were seen when activPAL registered standing and ActiGraph registered stepping (~5% of total time) or sitting (~4% of total time) (Table 3). ActiGraph identified a significantly greater number of stand-to-step, step-to-stand, sit-to-step, and step-to-sit transitions than did activPAL (Table 4).

DISCUSSION

Despite high levels of correct classification for both monitors for most postural activities under controlled laboratory conditions, each monitor's ability to differentiate sitting and stepping postures varied based on some task-specific conditions. For the laboratory stool sitting posture, the dis-

TABLE 3. Confusion matrix for synchronized activPAL and ActiGraph data during the 3-d free-living protocol (n = 18).

ActiGraph (% Time)	activPAL (% Time)		
	Sitting	Standing	Stepping
Sitting	60.0	4.0	0.5
Standing	1.1	17.9	2.2
Stepping	1.3	5.0	8.1

Percent agreement, 86.0%; weighted κ = 0.770 (95% CI, 0.770–0.771).

TABLE 4. Number of transitions per day, by device, during the free-living protocol (n = 18).

Transition type	activPAL	ActiGraph
Sit-to-stand	43 ± 11	44 ± 52
Stand-to-sit	41 ± 10	59 ± 52
Stand-to-walk*	312 ± 87	1143 ± 423
Walk-to-stand*	310 ± 87	1159 ± 426
Sit-to-walk*	1 ± 1	524 ± 173
Walk-to-sit*	3 ± 2	508 ± 170
Total	710	3437

Data are presented as mean ± SD.
*Number of transitions with activPAL significantly different from that with ActiGraph ($P < 0.001$).

crepancies between monitors were likely due to differences in the thigh angle thresholds used by their respective algorithms to identify sitting and standing postures. The angular parameters of ActiGraph allow for individuals to be classified as sitting while stretching out their legs at a thigh angle closer to standing posture or while crossing their legs. Raw acceleration samples are rectified and averaged over 1-s periods. If the magnitude of axis 3 (Z) measures >0.55g (corresponding to an angle relative to gravity/down vector of ~56°) or if the magnitude of X-axis is >0.4g (corresponding to an angle relative to gravity/down vector of ~66°), then the subject is deemed to be sitting/lying. Because activPAL was more likely to classify laboratory stool sitting as a standing posture, it appears that the proprietary angular parameters of activPAL for the classification of sitting require the thigh to be closer to parallel to the ground, highlighting a potential difference between the software algorithms of the monitors used to determine posture. Recent research has shown that activPAL classifies postures as standing when the angle of inclination exceeds approximately 20° from horizontal (0°) (3). Previous research has reported that activPAL is a valid and reliable monitor for measuring sitting, standing, and walking (2,12,14,19,28), but most previous studies have not reported on the accuracy of activPAL for specific activities. One previous study compared ActiGraph worn on the waist to activPAL and found activPAL to be more accurate, precise, and sensitive for examining time spent sitting and standing (19). Our study is the first study to compare the thigh-worn ActiGraph and activPAL monitors for correct postural and movement classification under laboratory and free-living conditions.

Writing on a whiteboard was challenging to classify in the laboratory with either monitor. The majority of this activity involved both standing in place and intermittent shuffle-like steps. This activity was meant to mimic similar free-living activities that involve intermittent bouts of shuffling and standing, such as cooking, certain household chores, and other activities of daily living. This activity was difficult to rate through direct observation on a second-by-second basis; thus, no statement can be made about the accuracy of the monitors. However, the discrepancy in the percentage of time classified as stepping (15% for ActiGraph vs 2% for activPAL) allowed us to hypothesize a potential difference in the way the two monitors detect stepping. The discrepancies may be the result of differences in an amplitude-based or frequency-based threshold for classifying stepping.

ActivPAL classified upright cycling as stepping 93% of the time, which was the postural classification that we selected for cycle ergometer activity. ActiGraph classified it as sitting 100% of the time. As such, ActiGraph was able to detect the static posture accurately, whereas activPAL detected it as an activity but incorrectly distinguished posture. Despite the differences in energy expenditure between stepping and cycling, the ability of activPAL to detect activity is relevant despite erroneously classifying cycling (a nonambulatory activity) as stepping. The differences between monitors may be due to differences in the decision-tree structure for classifying posture (prioritizing thigh angle vs the amplitude and frequency of acceleration) between ActiGraph and activPAL. ActiGraph GT3X+ relies on a threshold-based movement classification system, using a hierarchical algorithm structure to differentiate between postures. Visual inspection of raw ActiGraph data confirmed that it was registering counts at magnitudes high enough to be classified as stepping (axis 3 (Z) counts >25). Based on angular data that it was registering for thigh position, the algorithm may not have considered whether the count threshold was surpassed. If a certain thigh angle is not obtained, the information could be funneled to an alternate branch of the decision tree that ignores acceleration, leading to a sitting postural classification during cycling activity. Using thigh angle estimations based on static acceleration to identify sitting or standing improves the classification of posture and activity. Incorporation of this postural classification into the dynamic acceleration signal to determine an active or inactive state may allow for a broader classification of activity that could include seated active behaviors such as cycling and rowing machine. Davies et al. (12) found that nonstandard postures (crouching, squatting, kneeling up, and crawling) and transitions to upright posture from these postures were challenging for activPAL to characterize. Taken together with our results, this highlights one limitation of attempting to classify all postures into three distinct posture categories (12,14).

The high level of postural agreement between monitors in the free-living setting was driven primarily by the high agreement for sitting (89%), which took up the largest proportion of wear time (>60%). The large discrepancy in the number of transitions recorded between monitors may explain the lower agreement for standing and stepping postures. ActiGraph identified many more transitions involving stepping than did activPAL, which may be due to ActiGraph having a more liberal step detection algorithm or less step filtering than activPAL. The protocol was not specifically designed to test accurate identification of transitions. Because actual transitions were not counted, the monitor closest to the truth cannot be determined. One laboratory-based study, which included both a controlled section (sitting, standing, and walking) and activities of daily living (wash and dry dishes, vacuum paper from floor, remove clothes from basket and iron, etc.), reported on the accuracy of activPAL in detecting sit-to-stand and stand-to-sit transitions (14). Compared with direct observation with video recording, Grant et al. (14) found activPAL to be 100% accurate for detecting the total number of sit-to-stand and stand-to-sit transitions during the study protocol. The normal number of daily postural transitions in adults is unknown. Previous research in free-living adults (n = 140) using activPAL reported on sit-to-stand transitions only and found that adults completed 60 ± 22 sit-to-stand transitions per day (11). This is not out of line with our finding of approximately 44 sit-to-stand transitions per day. However, the lack of documentation on the true number of transitions into/out of sitting in a free-living setting, coupled with the large between-monitor discrepancy in the number of transitions to and from stepping, is troubling because it suggests potential inaccuracies in the measurement of transitions by one or both of these monitors. The sensitivity of the step detection algorithms used and the thresholds of measurements for classifying transitions may vary between manufacturers. Therefore, researchers interested in reporting on relations between health outcomes and monitor-detected transitions in free-living populations should select their measurement instrument and interpret their findings with caution (23) until future research in this area has verified the accuracy of the chosen monitor.

Despite the high level of agreement under free-living conditions, ActiGraph demonstrated a presumably greater sensitivity for detecting stepping. The higher percentage of stepping time reported by ActiGraph (15%) compared with activPAL (11%) matches the one mixed activity from the laboratory (writing on a whiteboard). This may suggest that the ActiGraph algorithm may classify intermittent stepping more readily than activPAL. A 4% difference in stepping between the monitors should not be considered trivial as it amounts to an additional 37 $\mathrm{min{\cdot}d^{-1}}$ of stepping according to ActiGraph.

This study was strengthened by the presence of both controlled laboratory and free-living protocols (4). The laboratory activities were diverse and closely resembled activities of daily living, with a specific focus on varying the sitting and standing postures and the inclusion of a number of nonstandard activities. Each posture or movement was explained and demonstrated to participants so that the activities may be performed as similarly as possible between participants in terms of types and amounts of movement. Our sample consisted of a range of ages (20–65 yr) and body compositions (20–56 $\mathrm{kg{\cdot}m^{-2}}$). We obtained a criterion measure of posture and movement through direct observation throughout the laboratory protocol.

There were limitations to this study. We did not have the power to test whether thigh or body size had any influence on monitor accuracy, and this may be an area for future inquiry. In the free-living protocol, the ActiGraph and activPAL monitors were not compared with a criterion measure (direct observation) to inform about validity. However, the examination of how different monitors classify posture and movement under the same conditions provided an important demonstration of the caution needed when assuming that objective devices may be exchangeable and is conceptually akin to examining interrater reliability between judges. The thickness and sharp edges of the ActiGraph GT3X+ case may detract from the feasibly of wearing it on the thigh until these structural design limitations are addressed, at least using the attachment method utilized in this study. The number of activPAL monitor malfunctions was a concern and highlights the importance of having data quality controls in place to identify possible spurious data. All monitors were tested for functionality before the study; other than the one researcher error, the reason for monitor malfunctions was unknown.

In an effort to improve the precision with which researchers measure the complex construct of physical activity, new objective measurement tools and algorithms continue to be developed and need to be validated in laboratory and free-living situations (4). Based on both laboratory and free-living results, ActiGraph appears to be more sensitive to motion than activPAL, but further work is needed to determine whether this greater sensitivity translates into greater accuracy for step detection. Due to the high percentage of correct classification of sitting in the laboratory and a lack of significant difference in sitting during free living, differences between monitors appeared to be restricted to certain nonsitting behaviors. There remain challenges and discrepancies in classifying some activities using these thigh-worn monitors, which may have resulted from differences in filtering and algorithm-specific angle thresholds. Ultimately, these discrepancies expose the need for more transparency in manufacturer-specific algorithms and for improvements in algorithms to increase their ability to correctly classify a wider range of postures and activities. Broader access to appropriate hardware and firmware to support postural and activity classification would be a major advancement for the research community, allowing researchers to further explore the amount and type of postures and activities associated with various health outcomes. In summary, our results showed that ActiGraph worn on the thigh may be an alternative to activPAL for obtaining more detailed information on posture and for classifying activities.

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