Comparison of activPAL and Actiwatch for Estimations of Time in Bed in Free-Living Adults

Mary C. Hidde, Kate Lyden, Josiane L. Broussard, Kim L. Henry, Julia L. Sharp, Elizabeth A. Thomas, Corey A. Rynders, and Heather J. Leach

1Division of Hematology and Oncology and Cardiovascular Medicine, Medical College of Wisconsin, Milwaukee, WI, USA; 2KAL Research and Consulting, LLC, Denver, CO, USA; 3Department of Health and Exercise Science, Colorado State University, Fort Collins, CO, USA; 4Division of Endocrinology, Metabolism, and Diabetes, Department of Medicine, University of Colorado, Aurora, CO, USA; 5Department of Psychology, Colorado State University, Fort Collins, CO, USA; 6Department of Statistics, Colorado State University, Fort Collins, CO, USA; 7Anschutz Health & Wellness Center, University of Colorado, Aurora, CO, USA; 8Rocky Mountain Regional Veterans Administration, Aurora, CO, USA; 9Division of Geriatric Medicine, Department of Medicine, University of Colorado, Aurora, CO, USA; 10Department of Kinesiology, School of Education and Human Development, University of Virginia, Charlottesville, VA, USA

Introduction: Patterns of physical activity (PA) and time in bed (TIB) across the 24-hr cycle have important implications for many health outcomes; therefore, wearable accelerometers are often implemented in behavioral research to measure free-living PA and TIB. Two accelerometers, the activPAL and Actiwatch, are common accelerometers for measuring PA (activPAL) and TIB (Actiwatch), respectively. Both accelerometers have the capacity to measure TIB, but the degree to which these accelerometers agree is not clear. Therefore, this study compared estimates of TIB between activPAL and the Actiwatch accelerometers. Methods: Participants (mean ± SD age = 39.8 ± 7.6 years) with overweight or obesity (N = 83) wore an activPAL and Actiwatch continuously for 7 days, 24 hr per day. TIB was assessed using manufacturer-specific algorithms. Repeated-measures mixed-effect models and Bland–Altman plots were used to compare the activPAL and Actiwatch TIB estimates. Results: Statistical differences between TIB assessed by activPAL versus Actiwatch (p <.001) were observed. There was not a significant interaction between accelerometer and day of wear (p = .87). The difference in TIB between accelerometers ranged from –72.9 ± 15.7 min (Day 7) to –98.6 ± 14.5 min (Day 3), with the Actiwatch consistently estimating longer TIB compared with the activPAL. Conclusion: Data generated by the activPAL and Actiwatch accelerometers resulted in divergent estimates of TIB. Future studies should continue to explore the validity of activity monitoring accelerometers for estimating TIB.

Keywords: sleep, accelerometer, comparison studies, methodology, agreement

Cardiovascular disease (CVD), obesity, and diabetes contribute to an estimated $3.5 trillion in annual health care costs in the United States (National Center for Chronic Disease Prevention and Health Promotion, 2019). Physical activity (PA), reduced sedentary time, and adequate sleep duration and quality are important for prevention of these chronic diseases and improving mortality outcomes among those living with CVD, obesity, and diabetes (Donnelly et al., 2009; Fogelholm, 2010; Thorp et al., 2011; USDHHS, 2018). Additional evidence also exists for the benefits of adequate sleep duration and quality for reducing risk for obesity, diabetes, hypertension, CVD, and weight gain (Cooper et al., 2018; Grandner et al., 2016; Lao et al., 2018; Nagai et al., 2010). This evidence has prompted many PA researchers to expand their investigation of daily activity patterns to include both waking behaviors (PA of varying intensities—light PA and moderate–vigorous PA, standing, and sitting) and estimates of time in bed (TIB) (Rosenberger et al., 2019; Ross et al., 2020). However, a challenge in examining the 24-hr activity cycle is the availability of identifying a single accelerometer that is valid and reliable for measuring both waking behaviors and TIB.

One of the validated devices often utilized in clinical research, current gold-standard devices to measure free-living waking activity, is the activPAL™ accelerometer, manufactured by PAL Technologies Ltd. (2010). The activPAL has been validated against direct observation for PA intensity, standing, stepping, and sitting (Lyden et al., 2012, 2017; PAL Technologies Ltd., 2010). However, whether the activPAL accelerometer provides an accurate estimate of TIB is not clear due to a lack of studies assessing validity against polysomnography (PSG). However, the Actiwatch, manufactured by Philips Respironics, has well-established reliability and validity against PSG to measure TIB in free-living adults (Lee & Suen, 2017; Marino et al., 2013). Yet, the reliability and validity of Actiwatch to measure waking behaviors has not yet been established (Lambiase et al., 2014; Philips Respironics, S.A.R.C.D., 2021). The Actiwatch is currently utilized to estimate TIB to estimate sleep parameters in a free-living environment using light, actigraphy sensors, and an event marker button (Lee & Suen, 2017). However, the Actiwatch does not have established reliability/validity to measure PA, sitting, or standing (Lambiase et al., 2014). Thus, researchers interested in activity patterns and TIB across the 24-hr cycle are required to use two accelerometers leading to increased costs and participant and researcher burden (Andre & Wolf, 2007). Therefore, an accelerometer with the ability to accurately measure both PA waking behaviors and TIB is highly desirable.

Recently, a new proprietary algorithm was released by PAL Technologies Ltd. (2018), which allows the activPAL to provide a measure of TIB by estimating the time participants went to bed (TIBSTART) and time participants got out of bed (TIBEND) (PAL Technologies Ltd., 2019). However, this algorithm has not yet been compared to the frequently utilized Actiwatch. Therefore, this study sought to compare the estimates of TIB between activPAL and Actiwatch accelerometers.
Methods

Adults aged 18–50 years with a body mass index of 27–45 kg/m² and weight stable (≤5% change over the previous 6 months) were recruited for a behavioral weight loss trial comparing the effects of time restricted eating plus caloric restriction with caloric restriction alone (NCT03571048). Participants were excluded for history of CVD, diabetes, uncontrolled hypertension, untreated thyroid, renal, hepatic diseases, dyslipidemia, and any other medical condition affecting weight or lipid metabolism, night shift work over the previous 6 months, night eating syndrome, or binge eating behaviors. Women who were pregnant, breastfeeding, or planning to become pregnant were also excluded. The Colorado Multiple Institutional Review Board approved the study protocol, and all participants provided written informed consent prior to participation. This study was conducted in accordance with the principles expressed in the Declaration of Helsinki.

Participants completed baseline assessments including height (without shoes to the nearest centimeters using a stadiometer) and fasted morning weight (in light clothing, measured to the nearest 0.1 kg using a digital scale) to calculate body mass index, and self-reported assessment of body composition via dual X-ray absorptiometry (Hologic Discovery W) and study questionnaires, including demographic information. The activPAL and Actiwatch accelerometers were fitted at the conclusion of the baseline visit and worn for 7 continuous days. Data presented here are from the baseline assessment period prior to any intervention. Both accelerometers are water resistant, allowing for the accelerometers to be worn during showering. Participants were instructed to remove the accelerometers for activities that involved completely submerging the accelerometers in water. Participants were provided instructions on proper wear technique as well as written instructions for proper removal and re-attachment of accelerometers. Additionally, participants were provided logs to self-report TIB, which were compared with the activPAL and Actiwatch as a secondary analysis. The wear time protocol for both accelerometers was 7 days, 24 hr per day. Recordings were considered valid if the devices were worn for at least 4 days, 24 hr per day over the 7-day period. This wear-time protocol was chosen as this time period has been shown to result in a high intraclass correlation value and include both weekend and week days (Edwardson et al., 2017). For both accelerometers, the primary measurement of interest was TIB. The TIB was the difference, in minutes, from TIBSTART, or the time participants got into bed for the night, to TIBEND, or the time participants got out of bed in the morning, as detected by the accelerometers in water. Participants were provided instructions on the proper removal and re-attachment of accelerometers. Additionally, participants were provided logs to self-report TIB, which were compared with the activPAL and Actiwatch as a secondary analysis. The wear time protocol for both accelerometers was 7 days, 24 hr per day. Recordings were considered valid if the devices were worn for at least 4 days, 24 hr per day over the 7-day period. This wear-time protocol was chosen as this time period has been shown to result in a high intraclass correlation value and include both weekend and week days (Edwardson et al., 2017). For both accelerometers, the primary measurement of interest was TIB. The TIB was the difference, in minutes, from TIBSTART, or the time participants got into bed for the night, to TIBEND, or the time participants got out of bed in the morning, as detected by the specific algorithm for each individual accelerometer described below. Variables representing TIBSTART and TIBEND rather than initiation of sleep and wake were utilized for the Actiwatch in order to keep measurement metrics consistent between accelerometers (i.e., activPAL only gives TIBSTART and TIBEND).

**activPAL Accelerometer**

The activPAL accelerometer is a thigh-worn, triaxial accelerometer validated against direct observation to measure free-living light PA, moderate–vigorous PA, sitting, standing, and sedentary behavior (Edwardson et al., 2017; Lyden et al., 2017). The activPAL was wrapped in a nitrile sleeve and Tegaderm to waterproof the accelerometer for continuous wear (3M, F.D., 2021). The activPAL was attached at the midline of the nondominant thigh, one third of the way between the hip and the knee, with a Tegaderm patch. The activPAL was worn for 7 days, 24 hr per day, and collected data at 30-s epochs. Wear time was considered valid if worn for at least 4 days, 24 hr per day.

To measure TIB, TIBSTART, and TIBEND, raw activPAL.datx files were processed using the CREA algorithm in the PALBatch software (PAL Technologies Ltd., 2010), removing days where the device was not oriented correctly on the participant (25%–75% alignment and/or dominant sitting dice face >1), which measures the dominant orientation of the accelerometer relative to an upright position. Files were also autocorrected for inverted wear. Briefly, the processing steps used by the CREA algorithm are as follows: identification of nonupright events and categorization into either primary lying time (i.e., sleep) or a secondary lying time (i.e., sedentary). The primary lying container is the longest time duration without a change to an upright position and typically contains rolling behaviors. Rolling behaviors include accelerations when the activPAL is oriented horizontally (i.e., lying position). If rolling behaviors are present in other nonupright portions of the day, this behavior is classified as a secondary rolling container. These behaviors may include behaviors such as lying on the couch or daytime napping. The minimum amount of time needed for the activPAL to detect either primary or secondary lying is 60 min. If an upright position or sitting bout of greater than 15 min occurs, the container period is ended. However, if a subsequent rolling event occurs, the upright time counter will be reset. Additionally, if rolling is present in the container, the first and last nonupright events in the container must include rolling. Simply, when the primary lying period contains rolling of the thigh, any additional sections of nonupright with rolling are marked as secondary lying (i.e., daytime napping or couch lying). In this instance, secondary lying is counted in sitting totals, not sleep (PAL Technologies Ltd., 2018). TIBSTART is determined when nonupright events last >1 hr. To allow for common sleep interruptions (i.e., bathroom breaks, wake after sleep onset), events are expanded to adjacent nonupright events >1 hr. The time period with the longest nonupright event is marked as “Primary Lying Time,” beginning the estimates of TIBSTART and TIBEND (PAL Technologies Ltd., 2019).

**Actiwatch Accelerometer**

The Actiwatch Spectrum Plus accelerometer was worn on the nondominant wrist. The Actiwatch was programmed to collect activity and light exposure data at 30-s epochs and was worn for 7 days, 24 hr per day. Wear time was considered valid if worn for at least 4 days, 24 hr per day. To measure TIB, TIBSTART, and TIBEND, raw AW5 files were processed using the auto scoring settings on the Actiwatch software (Actiware, version 6.1.1, Philips Respironics). The processing steps used by the Actiwatch is a piezoelectric sensor which allows for algorithm are as follows: detection of accelerations and light to measure sleep and wake patterns. In addition to the measurement of accelerations, the Actiwatch has a light detector to aid in differentiating between sleep and wake intervals. The sensor is oriented to detect vertical accelerations, has a bandwidth of 0.5–7 Hz, and allows for integration of raw counts over an epoch (Chen & Bassett, 2005).

**Data Cleansing/Processing**

Data from all participants were evaluated to exclude participants who did not meet the wear-time criteria. Normality was evaluated using histograms. Unrealistic values from both accelerometers were present in the data (minimum: 69.0 min of TIB and maximum: 1,310.4 min of TIB); therefore, the data were trimmed to include
observations within 3 SDs of the mean (minimum: 151.8 min of TIB and maximum: 844.8 min of TIB). If one accelerometer had an estimation removed or did not meet the minimum wear requirement, that day was removed from analyses (i.e., estimations from both accelerometers were excluded). For both accelerometers, the automated algorithms were used. Additionally, Day 1 was removed from all analyses since the accelerometers did not start recording until midnight on the day of placement.

Statistical Analyses

Descriptive characteristics such as age, sex, and body fat percentage are presented as mean ± SD or n (%) for categorical variables. Normality was evaluated using histograms. Extreme values from both accelerometers were present in the data (minimum: 69.0 min of TIB and maximum: 1,310.4 min of TIB); therefore, the data were trimmed to include observations within 3 SDs of the mean (minimum: 151.8 min of TIB and maximum: 844.8 min of TIB). If one accelerometer had an extreme value, that day was removed from analyses (i.e., estimations from both accelerometers were excluded). Additionally, Day 1 was removed from all analyses since the accelerometers did not start recording until midnight on the day of placement. Estimates from the activPAL and Actiwatch were compared using two statistical procedures. First, to account for lack of independence of measures within subjects, a repeated-measures mixed-effects model was used to estimate the difference between activPAL and Actiwatch within person for the response variable TIB. This statistical method has been used in previous literature to compare free-living activity measurement (Courtney et al., 2020). Fixed effects were accelerometer (activPAL or Actiwatch), day (categorical from 2 to 7), and Accelerometer × Day interaction. A random effect for participant was included to account for repeated measurements (up to 7 days) over time. As a secondary analysis, repeated-measures mixed-effects models were used to estimate differences between each accelerometer (activPAL and Actiwatch) and self-reported TIB following the same procedure as above. Second, mean difference and level of agreement were calculated using repeated-measures Bland–Altman plots (Altman & Bland, 1983; Myles & Cui, 2007). For all comparisons, the Actiwatch estimates served as the referent scores given extensive validation against PSG (Ancoli-Israel et al., 2003; Chen & Bassett, 2005; Lee & Suen, 2017). Analyses were conducted using R (version R-4.0.3). A significance level of .05 was used for all tests of hypotheses.

Results

Eighty-five participants with 621 days of measurement were originally collected. After removal of Day 1, estimations greater than 3 SDs from the mean, and minimum wear days (two participants excluded), 83 participants completed waking behavior and sleep monitoring using the activPAL and Actiwatch accelerometers for a total of 484 days of data collection. Participants wore the accelerometers on average for 4.1 ± 2.1 days. Participants were 39.8 ± 7.6 years of age, White (81%), and mostly female (85.88%; Table 1).

There was a significant difference in estimated TIB between the Actiwatch and activPAL accelerometers (β = 437.87, p < .001). There was not a significant interaction between accelerometers and day of wear (F = 0.36, p = .87). The difference in TIB between accelerometers, with Actiwatch as the reference value, ranged from −72.9 ± 16.2 min (Day 7) to −97.2 ± 15.0 min (Day 3). In general, the Actiwatch average TIB was longer in duration compared with activPAL, regardless of day (89.8 min; Table 2, Figure 1). More specifically, it appears that the activPAL detects TIBSTART after the Actiwatch (−51.7 ± 36.6 min) and TIBEND prior to the Actiwatch (−37.88 ± 36.2 min), resulting in a shorter TIB duration from the activPAL (Table 2).

The Bland–Altman plot (Figure 2) also indicated differences between the Actiwatch and activPAL TIB estimates with an average difference of 89.8 min (95% confidence interval [81.1, 98.6]), with wide upper limit of agreement of 101.6 min (95% confidence interval [86.6, 116.65]) and lower limit of agreement of −281.3 min (95% confidence interval [−296.3, −266.3]) across all days.

When comparing to self-report, there was not a significant interaction between activPAL/self-report and day of wear (p = .40) or Actiwatch/self-report and day of wear (p = .76). TIB measured by the Actiwatch was significantly different from self-reported TIB, consistently overestimating TIB (β = 532.87, p < .0001). Similarly, TIB measured by the activPAL was significantly different from self-reported TIB, consistently underestimating TIB (β = 437.57, p < .0001).

Table 1 Demographics, Physical Activity, Sedentary Time, and Time in Bed

| Age (years) | 39.8 ± 7.6 |
| Body mass index (kg/m²) | 34.0 ± 5.6 |
| Body fat (%) | 43.0 ± 6.0 |
| Actiwatch time in bed (min) | 539.3 ± 119.34 |
| activPAL time in bed (min) | 450.5 ± 92.34 |

Table 2 Difference in TIB, TIBSTART, and TIBEND between the activPAL and Actiwatch

<table>
<thead>
<tr>
<th>Day</th>
<th>TIB difference (min)</th>
<th>p</th>
<th>TIBSTART difference (min)</th>
<th>TIBEND difference (min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2 (n = 84)</td>
<td>−95.2 ± 15.1</td>
<td>&lt;.001</td>
<td>49.7 ± 35.9</td>
<td>−48.6 ± 35.4</td>
</tr>
<tr>
<td>3 (n = 84)</td>
<td>−97.2 ± 15.0</td>
<td>&lt;.001</td>
<td>43.2 ± 35.7</td>
<td>−55.3 ± 35.3</td>
</tr>
<tr>
<td>4 (n = 83)</td>
<td>−81.3 ± 15.2</td>
<td>&lt;.001</td>
<td>54.2 ± 36.3</td>
<td>−28.3 ± 35.9</td>
</tr>
<tr>
<td>5 (n = 81)</td>
<td>−90.7 ± 15.3</td>
<td>&lt;.001</td>
<td>54.6 ± 36.6</td>
<td>−36.9 ± 36.2</td>
</tr>
<tr>
<td>6 (n = 80)</td>
<td>−93.6 ± 15.3</td>
<td>&lt;.001</td>
<td>64.6 ± 36.6</td>
<td>−29.0 ± 36.2</td>
</tr>
<tr>
<td>7 (n = 72)</td>
<td>−72.9 ± 16.2</td>
<td>&lt;.005</td>
<td>43.7 ± 38.6</td>
<td>−29.2 ± 38.1</td>
</tr>
</tbody>
</table>

Note. TIB = time in bed; TIBSTART = time participants went to bed; TIBEND = time participants got out of bed.

*Activiwatch has been used as the reference value.
Discussion

This study sought to determine if estimates for TIB, using TIB-START and TIBEND, are comparable between the activPAL and Actiwatch accelerometers. Our findings suggest that the activPAL and Actiwatch do not derive similar estimates of TIB with the Actiwatch estimating TIB significantly longer than the activPAL. The activPAL provides a significantly different estimate of TIBSTART and TIBEND compared with the Actiwatch. Similarly, the Actiwatch and activPAL both provided significantly different estimates for TIB compared with self-report. However, this is consistent with previous findings suggesting self-reported TIB to have poor agreement with actigraphy- and PSG-derived TIB (Girschik et al., 2012; Jackson et al., 2018).

For both accelerometers, the algorithms used to derive estimates of TIB are proprietary, making it difficult to know the exact sources of disagreement between the two accelerometers. However, there are two fundamental differences between the activPAL and Actiwatch methods that likely contribute to the discrepancy observed in the current study. First, the activPAL uses actigraphy alone to estimate TIB, whereas the Actiwatch in the current study uses actigraphy as well as measures of light exposure. Actigraphy-based estimates of TIB rely on lack of movement and body position (e.g., rolling) to infer TIB. This can make distinguishing periods of
couch lying (e.g., watching TV) from TIB difficult. Although we are not aware of studies that have specifically investigated the benefit of adding information on light exposure to actigraphy-based estimates of TIB, this additional contextual information could help improve estimates of TIB under challenging conditions like couch lying. Second, the activPAL is worn on the thigh, whereas the Actiwatch is worn on the wrist, thus the acceleration signals collected at the thigh will be different than those collected at the wrist, depending on the behavior. Furthermore, thigh placement of the activPAL can provide important information about rolling, which is not possible with wrist-worn accelerometers.

Individuals with overweight and obesity, like the participants in this study, are at increased risk for sleep disorders and often present with decreased TIB, and experience poor sleep quality (Cooper et al., 2018; Morgenthaler et al., 2007). Accurately estimating TIB for participants with disrupted sleep may be particularly challenging for methods that rely on actigraphy alone, such as the activPAL. Of note, this study utilized the automatic algorithm for Actiwatch scoring, though decision trees for manual input or correction of TIB<sub>START</sub> and TIB<sub>END</sub> exist. The various decision trees available utilize written sleep logs, event markers, light exposure, and activity marker to determine TIB<sub>START</sub> and TIB<sub>END</sub>, all of which improve free-living estimates of TIB. Therefore, these decision trees should be evaluated to determine if manual input of TIB<sub>START</sub> and TIB<sub>END</sub> is necessary to see equivalent measures of TIB from the activPAL (Fekedulegn et al., 2020).

Strengths of this study include a sample with multiple days of measurement for each participant. Limitations include a majority of female participants, limiting generalizability to males due to known sex differences in sleep health (Mallampalli & Carter, 2014). Of note, this study lacks of gold-standard measurement, such as PSG or direct observation. Although not a limitation due to the scope of this study, it is important to understand this study does not determine the validity and reliability of the activPAL for TIB estimates or other measures related to sleep health in a population with overweight/obesity.

Future research should evaluate other PA accelerometers for estimations of TIB. To improve the activPAL specifically, utilization of self-reported TIB<sub>START</sub> and TIB<sub>END</sub> in conjunction with activPAL estimates has been shown to increase accuracy of 24-hr activity estimates; therefore, additional research should be conducted to determine an appropriate decision tree process when utilizing activPAL alone to measure TIB (Courtney et al., 2020). This additional research could also allow for development of adjustment algorithms, similar to those typically utilized with the Actiwatch for varying populations including healthy and sleep-disturbed populations. Until development of validated decision trees and/or adjustment algorithms, it is recommended that the Actiwatch or another wrist-worn accelerometer be utilized to estimate TIB.

In conclusion, the activPAL and Actiwatch provide different estimates of TIB. Therefore, the Actiwatch should continue to be utilized when objectively measured TIB estimates are needed.

### References


