Introduction: Current best practice for objective measurement of sedentary behavior and moderate-to-vigorous intensity physical activity (MVPA) requires two separate devices. This study assessed concurrent agreement between the ActiGraph GT3X and the activPAL3 micro for measuring MVPA to determine if activPAL can accurately measure MVPA in addition to its known capacity to measure sedentary behavior. Methods: Forty participants from two studies, including pregnant women (n = 20) and desk workers (n = 20), provided objective measurement of MVPA from waist-worn ActiGraph GT3X and thigh-worn activPAL micro3. MVPA from the GT3X was compared with MVPA from the activPAL using metabolic equivalents of task (MET)- and step-based data across three epochs. Intraclass correlation coefficient and Bland–Altman analyses, overall and by study sample, compared MVPA minutes per day across methods. Results: Mean estimates of activPAL MVPA ranged from 22.7 to 35.2 (MET based) and 19.7 to 25.8 (step based) minutes per day, compared with 31.4 min/day (GT3X). MET-based MVPA had high agreement with GT3X, intraclass correlation coefficient ranging from .831 to .875. Bland–Altman analyses revealed minimal bias between 15- and 30-s MET-based MVPA and GT3X MVPA (−3.77 to 8.63 min/day, p > .10) but with wide limits of agreement (greater than ±27 min). Step-based MVPA had moderate to high agreement (intraclass correlation coefficient: 681−810), but consistently underestimated GT3X MVPA (bias: 5.62–11.74 min/day, p < .02). For all methods, activPAL appears to better estimate GT3X at lower quantities of MVPA. Results were similar when repeated separately by pregnant women and desk workers. Conclusion: activPAL can measure MVPA in addition to sedentary behavior, providing an option for concurrent, single device monitoring. MET-based MVPA using 30-s activPAL epochs provided the best estimate of GT3X MVPA in pregnant women and desk workers.

Keywords: accelerometer, exercise, objective measurement, validation

The health benefits of regular moderate-to-vigorous intensity physical activity (MVPA) are well established (Piercy et al., 2018). More recent evidence has demonstrated independent and deleterious health effects of high sedentary time (SED), defined as time spent in a seated, reclined, or lying posture at low intensity (<1.5 metabolic equivalents of task [METs]; Gibbs et al., 2015; Tremblay et al., 2017). When studying these behaviors, objective activity monitors provide a better assessment of MVPA and SED than self-report (Dyrstad et al., 2014; Gibbs et al., 2019; Prince et al., 2020). Given the important independent health effects of MVPA and SED, there is a growing interest in measuring these behaviors concurrently.

Objective free-living MVPA is commonly measured with a waist- or wrist-worn ActiGraph GT3X accelerometer (Ardvisson et al., 2019). While this method provides an accurate measure of MVPA when recommended processing procedures are applied and, especially when worn on the waist (Migueles et al., 2017; Sasaki et al., 2011), it has several limitations when measuring SED (Gibbs et al., 2019; Kuster et al., 2021; Lyden et al., 2017). These include the inability of waist or wrist wear protocols to differentiate postures such as standing, lying, or reclining; rather, SED is estimated from stationary time, that is, the absence of movement. A second limitation of the waist-worn GT3X is that a common protocol allows for monitor removal at night, which likely results in biased missed data that is more often SED (e.g., watching television in bed before going to sleep). To address these limitations of the GT3X, the activPAL3 micro (PAL Technologies Ltd., Glasgow, Scotland), a small, thigh-mounted, triaxial accelerometer that detects posture, movement, and step cadence (Bassett Jr et al., 2014) was developed to more accurately quantify SED. Despite limitations of this device (e.g., potential to misclassify active sitting as SED) (Kuster et al., 2020), wearing the activPAL following a 24-hr wear protocol is now considered the gold standard measurement of SED (Grant et al., 2006). Therefore, current best practice (Grant et al., 2006; Matthews et al., 2012) for the objective measurement of free-living MVPA is measured using the ActiGraph GT3X, and SED is measured using the activPAL. This requirement of two devices for best practice measurement increases research costs and participant burden. The use of a single device to measure both MVPA and SED could simplify concurrent measurement of these behaviors from a participant and research administration perspective.

In addition to gold standard SED, the activPAL and related software also estimate metrics relevant to MVPA including METs and stepping accumulation per epoch. However, few studies have examined the concurrent agreement of MET- or step-based MVPA measured using the activPAL3 micro with the ActiGraph GT3X. Previous research has found that activPAL-measured MVPA has high agreement with ActiGraph in adolescents (r = .96, p < .01) (Dowd et al., 2012), and adults (average bias: 6 ± 32 min/day) (Lee & Dall, 2019). However, the previous study in adults only included one assessment day and used a relatively young and highly active (range: 60–145 MVPA min/day) convenience sample (Lee & Dall, 2019).
accretions into different intensities with more accurate classification of MVPA when worn on the waist (Aadland & Ylvisåker, 2015; Jarrett et al., 2015). Both studies employed a standard protocol where all participants were instructed to wear the monitor on a waist belt during all waking hours, only to be removed for sleep and water activities. In the sample of pregnant women, pictures adapted from a previous validation study (Connolly et al., 2011) were provided to facilitate correct positioning of the device to help account for changing anatomy across pregnancy. Specifically, women were told to position the device directly above the right knee and below the gravid abdomen.

Accelerometer data in 60-s epochs were processed in ActiLife software (version 6.12.2) using recommended procedures for adults including epochs, cut points, valid wear days, and waist-worn location in both studies (Migueles et al., 2017). Using Freedson (2011) vector magnitude cut points, epochs at ≥2,690 counts were summed to quantify daily MVPA (Sasaki et al., 2011). A minimum of 4 days with 10 hours of wear time was needed to be considered valid wear. Nonwear time was identified as any 60-min interval with 0 counts/min but with an allowance for 2 min of <100 counts/min (Choi et al., 2011). MVPA minutes were averaged across valid wear days.

Activity Measurement—activPAL3 Micro

The activPAL uses accelerometer-derived information about thigh posture and accelerations postural sensors to determine sitting/lying versus upright posture as well as transitions between these postures (Edwardsen et al., 2017). Both studies used a standard protocol where the activPAL was affixed directly to the anterior thigh using a transparent, waterproof dressing. Participants were instructed to wear the device continually for 24 hours for 7 full days, only to be removed for swimming in accordance with published protocol recommendations (Edwardsen et al., 2017). In both samples, the activPAL and GT3X were initialized using the same computer to ensure times were synchronized and monitors were disbursed and worn concurrently for 7 days.

Using PALTechnology software (version 8.11.7.95), 15-, 30-, and 60-s epoch files were exported for each participant. Nonwear and sleep times were removed by trained research personnel using standardized procedures which combine participant diary logs and objective data to identify waking wear periods. Epochs spent in MVPA were identified using two methods: (a) MET value ≥3.0 (Piercy et al., 2018) or (b) moderate stepping accumulation ≥100 steps/min (Marshall et al., 2009). For each day, epochs with ≥3 METs were summed to calculate total daily time in MET-based MVPA. Step accumulation per epoch was used to estimate moderate step cadence (≥100 steps/min) (Dall et al., 2013). Accumulation of ≥100 steps per 60-s epoch, ≥50 steps per 30-s epoch, and ≥15 steps per 15-s epoch were summed to calculate daily time spent in a step-based MVPA. Similar to the GT3X criteria, a minimum of 4 days with 10 hr of wear time was needed to be considered valid wear. MET-based MVPA and step-based MVPA minutes were averaged across valid wear days.

Statistical Analysis

All data processing were conducted using STATA (version 16, StataCorp) and analyses used SPSS (version 26, SPSS Inc.). Estimated time spent in MVPA from each monitor and across activPAL epoch lengths (i.e., 15-, 30-, and 60-s epochs) were summarized using means and SDs.
Agreement of MET-based MVPA and step-based MVPA measured from the activPAL in 15- (AP15), 30- (AP30), and 60-s (AP60) epochs was examined using intraclass correlation coefficients (ICCs). Agreement was graded using standard ICC cut points as follows: < .5 indicates poor, .5–.75 moderate, .75–9 good, and > 9 excellent agreement (Koo & Li, 2016). Mean bias, limits of agreement, and patterns of agreement between activPAL and GT3X MVPA measures was further examined using Bland–Altman analyses (Altman & Bland, 1983). All analyses were conducted with samples combined (n = 40) and separately in pregnant women and desk workers (n = 20 in each sample).

Results

Pregnant women in this sample (n = 20) had a mean (SD) age of 30.5 (4.2) years, with a prepregnancy body mass index of 29.2 (5.2) kg/m². Desk workers (n = 20) were 50% female, 49.5 ± 11.0 years, and had an average body mass index of 29.9 (5.9) kg/m². Average time in MET-based MVPA and step-based MVPA ranged from 10.1 years, and had an average body mass index of 29.9 (5.9) kg/m². Average time in MET-based MVPA and step-based MVPA minutes regardless of epoch length. Step-based activPAL MVPA minutes were similar when separated by samples. Overall, MET-based activPAL MVPA and step-based activPAL MVPA compared with the GT3X MVPA of 31.4 min/day. Ranges for MET-based activPAL MVPA from 60-s epochs (i.e., AP60) provided the lowest estimate of MVPA and MET-based activPAL MVPA from 60-s epochs was displayed in Table 1. Across epoch lengths in the combined sample, mean MET-based activPAL MVPA ranged from 22.7 to 35.2 min/day and mean step-based activPAL MVPA ranged from 19.7 to 25.8 min/day. These ranges can be compared with the GT3X MVPA of 31.4 min/day. Ranges for MET-based activPAL MVPA and step-based activPAL MVPA minutes were similar when separated by samples. Overall, MET-based activPAL MVPA and step-based activPAL MVPA minutes were similar with ICC ranging from .701 to .810, indicating moderate to high consistency between devices. When separated by sample, results were largely similar with ICC ranging from .701 to .782 in pregnant women and .659 to .807 in desk workers.

The ICC between step-based MVPA from AP15, AP30, and AP60 with GT3X MVPA are presented both combined and separately by pregnant women and desk workers in Table 3. Combined sample ICC ranged from .681 to .810, indicating moderate to high consistency between devices. When separated by sample, results were largely similar with ICC ranging from .701 to .782 in pregnant women and .659 to .807 in desk workers.

Bland–Altman plots comparing agreement of steps between the activPAL from AP15, AP30, and AP60 with the GT3X are presented in Figure 2. Step-based estimates systematically underestimated GT3X MVPA minutes. In the combined sample, the bias ranged from 5.62 to 11.74 min/day and increased with higher epoch lengths (all p < .02). Limits of agreement were ±30.72, 32.13, and 33.50 min/day for AP15, AP30, and AP60, respectively. The same trends were observed when the samples were analyzed separately, though the bias was greater in RESET-BP (underestimating between 10.10 and 17.22 min/day, p < .01). Bland–Altman plots for pregnant women and desk workers are presented in Supplementary Figure S3 and Supplementary Figure S4, respectively (available online).

Discussion

The main findings of this report are that MVPA measured by activPAL and GT3X are comparable, as demonstrated by moderate

Agreement of activPAL Step-Based MVPA With GT3X MVPA

The ICC between step-based MVPA from AP15, AP30, and AP60 with GT3X MVPA is displayed in Table 1. Across epoch lengths compared with the GT3X MVPA of 31.4 min/day. Ranges for MET-based activPAL MVPA and step-based activPAL MVPA minutes were similar when separated by samples. Overall, MET-based activPAL MVPA and step-based activPAL MVPA minutes were similar with ICC ranging from .701 to .810, indicating moderate to high consistency between devices. When separated by sample, results were largely similar with ICC ranging from .701 to .782 in pregnant women and .659 to .807 in desk workers.

Agreement of MET-based MVPA and step-based MVPA measured from the activPAL in 15- (AP15), 30- (AP30), and 60-s (AP60) epochs was examined using intraclass correlation coefficients (ICCs). Agreement was graded using standard ICC cut points as follows: < .5 indicates poor, .5–.75 moderate, .75–9 good, and > 9 excellent agreement (Koo & Li, 2016). Mean bias, limits of agreement, and patterns of agreement between activPAL and GT3X MVPA measures was further examined using Bland–Altman analyses (Altman & Bland, 1983). All analyses were conducted with samples combined (n = 40) and separately in pregnant women and desk workers (n = 20 in each sample).

Table 1

<table>
<thead>
<tr>
<th>Table 1 Summary of MVPA From GT3X and MET-Based MVPA and Step-Based MVPA Minutes From activPAL</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>MVPA</strong>&lt;br&gt;(min/day)</td>
</tr>
<tr>
<td><strong>GT3X</strong></td>
</tr>
<tr>
<td><strong>Combined (N = 40)</strong></td>
</tr>
<tr>
<td>Mean (SD)</td>
</tr>
<tr>
<td>Min, max</td>
</tr>
<tr>
<td><strong>Pregnant women (n = 20)</strong></td>
</tr>
<tr>
<td>Mean (SD)</td>
</tr>
<tr>
<td>Min, max</td>
</tr>
<tr>
<td><strong>Desk workers (n = 20)</strong></td>
</tr>
<tr>
<td>Mean (SD)</td>
</tr>
<tr>
<td>Min, max</td>
</tr>
</tbody>
</table>

Note. MVPA = moderate-to-vigorous intensity physical activity; GT3X = ActiGraph GT3X; AP = activPAL3 micro; METs = metabolic equivalents of task; SPM = steps per minute; AP15 = activPAL3 micro using 15-s epochs; AP30 = activPAL3 micro using 30-s epochs; AP60 = activPAL3 micro using 60-s epochs.
to high consistency for every comparison. MET-based activPAL estimates of MVPA had better agreement (bias ranging from -3.77 to 8.63) than step-based activPAL estimates (bias ranging from 5.62 to 11.74). MET-based AP30 MVPA appeared to be the best estimate of GT3X values (ICC: .875, bias: 3.08 ± 28.5 min). Estimates of MVPA varied considerably in both samples by device or processing method, ranging from 19 to 34 min/day. Both samples were slightly more active than previous research in similar populations estimating 15.1 min/day in pregnant women and samples were slightly more active than previous research in similar populations estimating 15.1 min/day in pregnant women and 25.7 min/day in desk workers (Bojsen-Møller et al., 2019; Evenson & Wen, 2011). Agreement varied across MVPA levels, such that differences in estimation between devices were smaller at lower average durations of MVPA. Importantly, the present study compares two activity monitors used to estimate MVPA; thus, the true value of MVPA is unknown as it was not directly measured. Therefore, we did not evaluate the true validity of activPAL for assessment of MVPA, though activPAL did have high agreement with the GT3X, which is the research standard best practice measure of free-living MVPA.

The inability to detect posture is a critical limitation of waist-worn GT3X for measuring the full range of activity behaviors, and in particular for distinguishing SED from other stationary activities (Kuster et al., 2021; Lyden et al., 2017). However, the activPAL (gold standard for measuring SED) also appears to accurately measure MVPA based on our data and others. One previous study comparing the activPAL to direct observation found the MET algorithm embedded in the activPAL technology accurately categorizes activity intensity with an accuracy rate of 96.2% (Lyden et al., 2017). This same study also found high agreement between MET-based activPAL MVPA using 1-s epochs with direct observation (ICC: .98, bias: -2.6 min; Lyden et al., 2017).

Few previous studies have also compared the activPAL to GT3X as we did, with similar findings concluding that the activPAL had high agreement with GT3X-measured MVPA. One previous study in examining one day of monitor wear in 24 adults (Lee & Dall, 2019) aligned with our findings in that MET-based MVPA provided a better estimate of GT3X than step-based with a mean bias of 6 min, compared with our mean bias of 3.1 min. We are unable to ascertain the reason for the difference in MET and step-based MVPA due to the proprietary algorithm used by activPAL to estimate METS. A second study conducted in adolescent females differed from the present study by the use of activPAL activity counts, which have not been validated for use in adult populations. Nevertheless, this study found high agreement of activity estimates between the activPAL and GT3X ($r = .93; p < .01$) (Dowd et al., 2012). An additional consideration is methodological differences, which may influence estimation of MVPA.

The use of different cut points or vertical axis over vector magnitude can substantially influence MVPA estimation between methods (Keadle et al., 2014). While recommended processing procedures (Edwardson et al., 2017; Migueles et al., 2017) were followed in the present study, we can only determine that MET-based activPAL MVPA had good concurrent agreement with the ActiGraph GT3X MVPA when using Freedson (2011) vector magnitude cut points. Though 30-s activPAL epochs provided the best estimate of MVPA, standard procedures for quantifying SED using event-type data (Edwardson et al., 2017) should be used when measuring both behaviors with the single activPAL device. Taken together, this evidence suggests activPAL is a suitable measure of MVPA that provided good approximation of waist-worn ActiGraph GT3X. Given the desirability of concurrent measurement of MVPA and SED, using activPAL as the sole monitor for measuring these behaviors could provide several benefits. These include improved participant adherence and cost-effectiveness of research, without compromising the accuracy of SED or MVPA measurement.

Table 2: ICCs Between Minutes of GT3X MVPA With activPAL3 Micro MET-Based MVPA Across Three Epoch Lengths

<table>
<thead>
<tr>
<th></th>
<th>AP15 vs. GT3X</th>
<th>AP30 vs. GT3X</th>
<th>AP60 vs. GT3X</th>
</tr>
</thead>
<tbody>
<tr>
<td>Combined</td>
<td>.871</td>
<td>.875</td>
<td>.831</td>
</tr>
<tr>
<td>Pregnant women</td>
<td>.785</td>
<td>.832</td>
<td>.825</td>
</tr>
<tr>
<td>Desk workers</td>
<td>.886</td>
<td>.878</td>
<td>.823</td>
</tr>
</tbody>
</table>

Note. ICC = intraclass correlation coefficient; GT3X = ActiGraph GT3X-measured MVPA; MVPA = moderate-to-vigorous intensity physical activity; MET = metabolic equivalents of task; AP15 = activPAL3 micro using 15-s epochs; AP30 = activPAL3 micro using 30-s epochs; AP60 = activPAL3 micro using 60-s epochs.

Figure 1 — Combined sample Bland–Altman plots of agreement between activPAL MET-based MVPA minutes and ActiGraph GT3X MVPA. Note. Solid line represents mean difference (GT3X-AP) in minutes per day, and dotted lines represent the upper and lower limits of agreement. MVPA = moderate-to-vigorous intensity physical activity; MET = metabolic equivalent of task.
Strengths and Limitations

This study has several strengths including concurrent measurement of MVPA across 7 days of wear and the recommended free-living monitoring interval to capture habitual behavior. The present study also adds to the current literature by examining MVPA derived from activPAL using 15-, 30-, and 60-s epochs, compared with only 15-s epochs in previous research. Given the standard use of 60-s epochs for GT3X, evaluation of the agreement across various activPAL epochs informs best practices for estimating MVPA. Finally, this study examined two unique populations, adding to the current research including only adolescents and healthy highly active adults. Expanding this evidence to pregnant women and desk workers supports the use of activPAL-measured MVPA in these populations.

Of note, this study also had several limitations. First, the GT3X detects ambulatory MVPA well, but does not capture some other forms of MVPA (e.g., stationary cycling). Yet, waist-worn GT3X is widely used and accepted as best practice for measuring free-living MVPA as more valid measures such as observation or calorimetry cannot realistically be used to measure free-living activity for several days. While recommended procedures for GT3X data processing and analysis were followed, agreement with the activPAL measured MVPA may differ with other GT3X cut points or epochs. An additional limitation of this study is the potential anatomical changes across pregnancy, which may result in MVPA estimation error from the waist-worn GT3X in the pregnant sample. Furthermore, this study included more women (75%) than men, which may limit the generalizability of these findings. Despite this, the sample of desk workers was balanced (50% men) and analyses by cohort were similar to combined analyses. Finally, half of participants in this study did not meet physical activity recommendations based on either the activPAL or the GT3X estimates. Given our findings that agreement between devices decreased with higher average minutes of MVPA, future studies should examine agreement in highly active populations across a standard wear period of 7 days.

Conclusion

We found good agreement between concurrently measured MET-based MVPA by activPAL and GT3X among pregnant women and desk workers. Overall, activPAL accurately estimated GT3X MVPA, though agreement was better with lower average MVPA durations. Considering the desirability of a single monitor protocol to measure the spectrum of activity along with the shortcomings of the GT3X for measuring SED, the apparent accuracy of activPAL to estimate MVPA suggests it is a suitable single monitor to measure both MVPA and SED. Our data suggests MET-based MVPA using 30-s activPAL epochs provides the best estimate of GT3X MVPA in pregnant women and desk workers. Future studies should examine the agreement of activPAL with GT3X for estimating MVPA among more active populations.

Acknowledgments

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References


Table 3  ICCs Between Minutes of GT3X MVPA With activPAL3 Micro Step-Based MVPA Across Three Epochs Lengths

<table>
<thead>
<tr>
<th></th>
<th>AP15 vs. GT3X</th>
<th>AP30 vs. GT3X</th>
<th>AP60 vs. GT3X</th>
</tr>
</thead>
<tbody>
<tr>
<td>Combined</td>
<td>.810</td>
<td>.758</td>
<td>.681</td>
</tr>
<tr>
<td>Pregnant women</td>
<td>.782</td>
<td>.755</td>
<td>.701</td>
</tr>
<tr>
<td>Desk workers</td>
<td>.807</td>
<td>.746</td>
<td>.659</td>
</tr>
</tbody>
</table>

Note. ICC = intraclass correlation coefficient; GT3X = ActiGraph GT3X-measured MVPA; MVPA = moderate-to-vigorous intensity physical activity; MET = metabolic equivalents of task; AP15 = activPAL3 micro using 15-s epochs; AP30 = activPAL3 micro using 30-s epochs; AP60 = activPAL3 micro using 60-s epochs.


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