Comparison of single- and dual-monitor approaches to differentiate sitting from lying in free-living conditions

Running head: Two methods to distinguish sitting from lying

Esther J. Smits[1], Elisabeth A. H. Winkler[2], Genevieve N. Healy[2,3,4], Philippa M. Dall[5], Malcolm H. Granat[6], Paul W. Hodges[1]

[1]The University of Queensland, School of Health and Rehabilitation Sciences, Brisbane, Australia

[2]The University of Queensland, School of Public Health, Brisbane, Australia

[3]Baker IDI Heart and Diabetes Institute, Melbourne, Australia

[4]School of Physiotherapy, Faculty of Health Sciences, Curtin University, Perth, Australia

[5]School of Health & Life Sciences, Glasgow Caledonian University, Glasgow, United Kingdom

[6]University of Salford, Manchester, United Kingdom

Corresponding author:

Prof. Paul W. Hodges

The University of Queensland

School of Health and Rehabilitation Sciences

Services road, Therapies building 84A

Queensland 4072

Phone: +61 7 3365 2008

Fax: +61 7 3346 8789

Email: P.Hodges@uq.edu.au

Abstract

High levels of sedentary time have been detrimentally linked to health outcomes. Differentiating sitting from lying may help to further understand the mechanisms associated with these health impacts. This study compares the inter-method agreement between the 'single-monitor' method (thigh-worn activPAL3TM) and a more robustly validated 'dual-monitor' method (trunk and thigh-worn activPAL3TM) in their classifications of sitting and lying under free-living conditions. Thirty-five participants (20-50 years) who wore two activity monitors (thigh and trunk) for 24 hours. Total time spent lying and sitting was calculated for both methods and agreement was determined using ICC and Bland-Altman methods. As there was no gold standard, further data were collected from five participants during structured activities that were designed to challenge classification, to better understand any disagreement between the methods. ICCs were 0.81 for sitting time and 0.64 for lying time. The single-monitor method detected less lying time than the dual-monitor method, with a mean difference of -25 minutes (95% agreement limits: -172 to 221 minutes), including three cases with extreme disagreement (mostly in daytime lying classification). The additional data collection suggested a major source of disagreement was failure of the single-monitor method to identify lying that involved no rotation around the longitudinal axis. In conclusion, there was some agreement between the single- and dual-monitor estimates of lying time under free-living conditions, but measures were not interchangeable. The main disagreement was in how the methods classified daytime lying and lying tasks involving no lateral movement. Both methods yield promise for measuring time in bed.

Keywords: Sedentary behavior, activity monitoring, activPAL, physical activity, health

Introduction

High levels of time spent in sedentary behavior have been detrimentally associated with numerous health outcomes, including cardiovascular disease and diabetes.[1] Activity monitors are an excellent option for measuring time spent in sedentary behavior in free-living conditions, avoiding biases in self-report data. Their levels of accuracy range from acceptable to excellent, depending on the monitor, wear locations and applied data reduction techniques.[2,3] The thigh-worn activPAL monitor is one of the most accurate for monitors measuring sedentary behavior and distinguishes a sitting or reclining posture from an upright posture based on the inclination of the thigh, as estimated from acceleration signals.[4–6] Increasingly, research is showing posture, especially upright versus seated or reclined posture, has relevance for human health. For example, standing has shown beneficial associations with cardio-metabolic health relative to sitting or reclining.[7] Additionally, lying at night is associated with sleeping and is beneficial for human health, whereas prolonged sitting is not.[1] To assess whether a seated posture may have different musculoskeletal and cardio-metabolic consequences than a reclined (or 'lying') posture, measurement options are required that are accurate and feasible to use in free-living conditions and allow differentiation between sitting and lying. Furthermore, such methods could plausibly be used to improve the estimation of time in bed relative to those based on self-report data or classifications derived from standard output of the device.

Basset et al. developed a simple method[8] that requires concurrent wear of two activity monitors (activPAL3™): one placed on the thigh (the standard wear-location) and another on the trunk. The thigh-worn monitor can accurately identify when the thigh is horizontal, which is used to define 'sedentary' behavior (i.e., sitting or lying), or vertical, which defines an 'upright' position. The method[8] selects each 15-second period where the thigh-worn monitor was classified as 'sedentary' and then differentiates sitting from lying based on whether the trunk-monitor was mostly horizontal (lying) or vertical (sitting) during each period. The method showed excellent agreement with direct observation in a small-scale laboratory validation study in which 15 participants performed three lying tasks (lying supine, prone, and on the side) and one sitting task (sitting in a chair) for three minutes each. Performance across a wider range of activities, in the changes between tasks, or during free-living activities is unknown. An important disadvantage of this method is the need to wear two monitors, which not only has higher costs and analytic burden but may also reduce compliance to the protocol.

Later, Lyden et al.[9] described an alternative, highly feasible method that requires only a single activPAL3TM monitor worn on the thigh (in the standard position). This method takes each time period (i.e., 'event') that the device has classified as 'sedentary' (i.e., sitting or lying), and then classifies it as lying if the acceleration data (20Hz) indicates that the thigh rotated across a 65 degree threshold at any time during the time period. This method is based on the premise that the ability of the thigh to rotate is less constrained when the person is reclined ('lying') compared to when they are sitting. Such rotations are expected to occur regularly when a person changes their position during the sleeping period (e.g., change from lying supine to lying on the side). When compared against self-reported time in bed (treated as 'lying') and out of bed (treated as 'not lying'), the method showed 96.7% accuracy for 'lying' and 92.9% accuracy for 'not lying'.[9] Although these results are promising, validation against a high-quality referent assessment method is needed, as is testing with other forms of lying that may involve less thigh rotation than sleeping.

The current study aimed to test whether the single-monitor and dual-monitor methods are interchangeable in their estimation of lying and sitting time under free-living conditions. The more robustly validated method (dual-monitor method) was treated as the reference but is not a gold standard. Therefore, to understand the meaning of any disagreement observed, a small amount of further data were collected wherein both methods were compared with direct observation during a set of structured activities. The selection of activities was designed so that the performance of the sitting and lying measures could be evaluated across a diverse range of sitting and lying tasks, especially during tasks that should be challenging for accurate detection of sitting and lying. This laboratory testing was small and not designed to provide a validation of either method against direct observation.

Materials and Methods

The study involved 35 participants who were selected from a larger ambulatory monitoring study of adults aged 18 to 50 years with low back pain (LBP), recruited from the general population. Participants were included in the larger study if they had a history of LBP of longer than three months and expected that they would continue to experience pain for the one-month duration of the study. Participants were excluded if they had undergone spinal surgery, had another primary source of pain, were unable to undertake activities of daily living, or if they had any major medical condition. As part of the ambulatory monitoring study, participants were asked to wear two activity monitors at all times during their normal daily life activities, including during water-based activities and when going to bed. The current study includes only the participants who did not report removal of the monitors during the timeframe of interest for comparing the single- and dual-monitor method. The additional direct observation data were collected in five pain-free adults, who were recruited by convenience methods from the research laboratory. Participants wore two activity monitors the entire time while under observation. The sample size was determined based on feasibility. Both study protocols were approved by the Medical Research Ethics Committee of the University of Queensland and all participants provided written informed consent.

Structured activities

Participants performed a set of eleven tasks, each for a duration of three minutes under direct observation. The observer recorded the start and end time of each task and ensured that participants performed the task correctly. Participants were instructed to stand up and walk for approximately 30 seconds between the tasks so that each task could be clearly identified and recorded as separate 'sedentary' (i.e., sitting or lying) events. Table 1 shows each of the 11 tasks and includes a description of the expected classification by both methods.

Activity monitoring

The activity monitors worn during both studies was the activPAL^{3TM}-micro. This is a small (23.5 x 43 x 5 mm) rectangular device with a weight of 10 grams that contains a tri-axial accelerometer to detect static and dynamic accelerations. The monitors were initialized (activPAL™ v7.2.32), waterproofed (using Tegaderm and a vacuum-seal) and then attached to participants by trained staff using a hypoallergenic bandage (Tegaderm) or a fabric adhesive (Fixomull). One activPAL^{3TM} monitor was attached to the midline of the right thigh, midway between the hip and the knee, as described in the manufacturer's manual. A second monitor was attached to the trunk, over the lower right rib cage, as for the dual-monitor method.[8] The trunk device was placed approximately in line with the thigh-monitor, so that the front of both monitors was facing in the same direction when standing.

Data processing

Using the proprietary software (activPAL™ v7.2.32) and the default settings, data were classified and downloaded. Further data processing and analysis were performed using Matlab software (MATLAB R2015b, The MathWorks, Inc., Natick, MA). The data extracted were: the events files; the 15-second summary files; and, files containing raw acceleration data (collected at 20 Hz in the x, y, and z directions, separately). The event files indicate the start and end of each stride and each continuous time period spent sedentary or standing. The summary files record the number of seconds (as integers) that are spent sitting, standing and stepping in each 15-second time. Both monitors were synchronized to the computer clock and were programmed to start recording at the same time. To limit possible desynchronization due to clock drift, only the first 24 hours monitoring between midday of Day 1 and midday the next day were examined out of the free-living data collection. Time during the structured activities was examined by limiting data to the observer-recorded times and by excluding stepping recorded by the thigh monitor (which only occurred between activities).

The classifications based on the dual-monitor method were derived as described by Bassett et al.[8] Briefly, each 15-second time period (epoch) was assigned to the category (sedentary or upright) in which most of the 15 seconds was spent. The epochs of the thigh-monitor identified as sedentary were then classified as either sitting or lying, based on whether that same epoch of the trunk-monitor was classified as sedentary or upright. Epochs classified as upright by the thigh-monitor were classified as upright time. The upright epochs which involved stepping during most of that epoch were classified as stepping. Total time in each activity (sitting, lying, and upright) was derived by summing up the number of relevant epochs and multiplying by 15 seconds.

The classifications for the single-monitor method were derived in the same manner as described by Lyden et al.[9] Briefly, the sedentary ‘events’ were selected from the proprietary analysis of the activPAL data. For the differentiation of lying and sitting, the raw accelerations in the y-axis (20Hz data) were used to calculate the rotation of the thigh[9], after converting the raw values to its equivalent g-force value using specifications released by the manufacturer.[10] Random noise was removed from the converted signal by a low-pass filter, using a 20-second moving average (simple finite impulse response) digital filter[9]. The tilt angle (in radians) of the y-axis was calculated using an inverse sine function of the filtered signal, which was then converted to degrees, yielding an angle between ±90 degrees. A threshold of ±65 degrees was used to identify rotations of the thigh. Each time the angle of rotation in the y-axis exceeded this threshold (i.e., an angle equal to or between +65 and +90, and -65 and -90 degrees) the algorithm recorded a value of '1'. When the angle was lower than the threshold, a value of '0' was recorded. Each sedentary event that had recorded both a '0' and a '1' was classified as lying whereas the remainder were classified as sitting. The duration of all lying and sitting events were summed separately to calculate the total amount of time spent lying and sitting. Standing and stepping time were calculated as all-time within standing events and stepping events.

The same methods were applied to measuring sitting and lying during the structured activities. The total time each method estimated was spent sitting, lying and standing was summarized for each observed task, during which the true posture (defined by task, verified by the observer) was either sitting or lying. Because task #8 involved both sitting and lying, its true sitting and lying times were only known to be >0s sitting and >0s lying. This task was therefore considered separately to the others.

Statistical analysis

Statistical analyses were performed using SPSS (IBM SPSS Statistics 23). The agreement between the single- and dual-monitor methods in total time spent sitting and lying was examined using: Bland-Altman methods (mean difference and 95% limits of agreement (LoA)); mean absolute differences; and, Intra-class Correlation Coefficients (ICC) for absolute agreement. The agreement in total sedentary time was also examined, to indicate any disagreement arising from the manner in which the dual-monitor method alters total amount of sitting/lying time relative to the original activPAL classifications. The classifications of both methods during directly observed tasks were described, and agreement with direct observation was assessed for all sitting and lying tasks as the number of minutes correctly identified.

Results

Participants of the main study were 17 males and 18 females with low back pain with a mean (±SD) age of 33.1 (±7.8) years. On a numerical 11-point rating scale (where 0 is 'no pain' and 10 is the 'worst pain possible') the average pain of the participants over the week before the start of the study ranged between 2 and 8, with a mean of 4.7. During the study, participants had been lying down for approximately 6 to 14 hours per day with a mean of 10 hours according to the dual-monitor method (see supporting information).

Total sedentary time was estimated very similarly but not identically by the two methods, with a mean difference (single – dual-monitor) of only 8 minutes (95% LoA: -7, 23). On average, the single-monitor method recorded more sitting time (and conversely less lying time) than the dual-monitor method, as shown in the Bland-Altman plots (Figure 1). The mean differences in lying time and sitting time (single- versus dual-monitor) were -25 minutes (95% LoA: -222, 172) and 33 minutes (95% LoA: -165, 231), respectively. Much of the disagreement came from three highly discrepant cases (≥4 hours difference). The 33 remaining cases had mean differences and limits of agreement of -0.4 minutes (95% LoA: -118, 117) and 8.3 minutes (95% LoA: -111, 128) in sitting and lying, respectively. Overall, the absolute differences averaged (mean±SD) to 62±83 and 64±84 minutes for lying time and sitting time, respectively, in all participants, and 40±44 minutes and 42±44 minutes, respectively, in the 33 participants without extreme discrepancies. Agreement met the threshold for acceptable (ICC ≥0.7) in terms of sitting time (ICC=0.81, 95% CI: 0.65, 0.90), and almost met this threshold for lying time (ICC=0.64, 95% CI: 0.40, 0.80).

Close examination of both classifications for the most extremely discrepant case (Figure 2) highlights when the methods diverge in their classifications. Both methods similarly classified time between approximately 11pm and 7am as lying, however outside these hours, several periods of lying time were detected by the dual-monitor method but not the single-monitor method. A similar pattern was observed for the other two discrepant cases that had a difference of more than 4 hours.

The five pain-free participants from whom additional data was collected were 3 males and 2 females with a mean (±SD) age of 32.2 ± 5.0 years and with a body mass index (BMI) ranging from 20 to 23 kg.m^{-2}. Table 2 shows the time recorded as sitting, lying and standing by each method during the sitting, lying and combined sitting/lying tasks. The single-monitor method correctly classified all 60 minutes of the sitting tasks as sitting, but only correctly classified 30 out of 90 minutes of the lying tasks. Consistent with the reliance of the single-monitor method on thigh rotation to identify lying-periods, 'lying on the side' (task 6) and 'lying while changing position' (task 9), were always detected as lying. The remaining lying activities, which involved no rotation of the thigh, were all misclassified as sitting, as might be expected. The dual-monitor method correctly classified 58 of the 60 minutes in the sitting tasks and 89.5 of the 90 minutes in the lying tasks. The activities that caused misclassification were 'sitting cross-legged' (misclassified as lying) and 'lying while changing position' (misclassified as sitting).

Neither method misclassified any of the tasks as standing. Over the 15 minutes spent rapidly changing between sitting and lying, both the single and dual-monitor methods tended to record this time as sitting (15 and 12 minutes, respectively). Notably, when participants regularly interchanged between sitting and lying, the trunk-monitor sometimes recorded stepping, which contrasted with the sitting tasks, during which the trunk-monitor primarily recorded standing.

Discussion

The aim of this study was to test whether a single-monitor method that uses routinely collected activPAL data (thigh-monitor) can yield equivalent classifications of sitting and lying time when compared with a more robustly validated method that uses a second monitor attached to the trunk. On average, and for many participants, the two methods had only a modest amount of difference, but there were large discrepancies for a few individuals. The discrepancies observed under free-living conditions occurred more in daytime lying rather than nighttime lying. While part of the discrepancy between the methods was in how total sitting and lying time was measured; the vast majority was due to how they differentiated sitting from lying. The additional data collection indicated that both methods appeared to classify some types of sitting and lying well but not others. Chiefly, the single-monitor method regularly failed to detect non-lateral lying and the dual-monitor method occasionally failed to detect cross-legged sitting. Both of these problems are more likely relevant for sitting and lying during the daytime than the nighttime. As such, it is likely, but not definite, that much of the disagreement occurring under free-living conditions reflects underestimation of non-lateral lying by the single-monitor method. One alternate possibility is the overestimation of lying by the dual-monitor method among participants who do large amounts of cross-legged sitting. Another possibility is the overestimation of lying by the dual-monitor method during sitting while reclining at an angle steeper than was evaluated in this study.

The previous validation of the dual-monitor method[8] demonstrated it had excellent agreement with direct observation in four stereotypical lying and sitting positions. Supporting its original validation, the present study also observed this to be the case across a wide range of sitting and lying tasks deliberately selected to pose challenges for accurate detection. Agreement was, however, somewhat variable across tasks, with cross-legged sitting proving most challenging. Notably, this method has been validated mainly with respect to distinguishing lying from sitting, with limited evaluation of validity for other activities. As the dual-monitor method allocated each 15-second epoch to an activity (sedentary, standing or stepping), the amount of time spent sedentary (sitting or lying), standing, and stepping might be altered relative to the original output of the activPAL software, which uses the raw data to create activity events (sedentary, upright, stepping) of different durations. If the preference is to preserve the original classifications (and validity properties) of the standard activPAL measures, it would be possible to use the times classified as sedentary, standing, or stepping using the original event classification, and then to use the dual-monitor method only to decide which sedentary events (or parts of sedentary events) are sitting and which are lying. Although the dual-monitor method had superior accuracy for complex tasks, it was not free of error as it was based on simple decision rules. Future work might more accurately capture activities by optimizing the threshold to delineate horizontal and vertical trunk positioning rather than use the standard thresholds that were developed for the thigh.

The single-monitor method relies on rotation between lateral and supine positions to classify sedentary events as lying. The promising 96% accuracy observed in the single-monitor method's initial validation[9] was based on a reference method derived from self-reported time in bed. Healthy individuals typically change positions regularly during the night [11,12] and time in bed would nearly always involve rotating between lying supine, prone and on the side, except when mobility is extremely restricted. The present study compared the single-monitor method against the dual-monitor method over a full 24-hour period. The results suggest that the accuracy reported in the initial validation[9] may be correct for forms of lying common at night time (involving lateral movement), but accuracy for other forms of lying (namely those that do not involve lateral movement, which may be more common in the daytime than at night) may be lower. Because the agreement was variable between participants and by task, the mean levels of agreement observed in this study are not necessarily reflective of the overall degree of accuracy that would be obtained in other low-back pain samples or in other populations. The overall accuracy will depend on how commonly certain types of sitting and lying are performed. However, the broader findings likely are applicable; i.e., that agreement is good for nighttime lying, and for lying involving lateral movement.

The findings suggest the dual-monitor method would be preferable to the single-monitor method from the point of view of accuracy. However, the single-monitor method is and may provide a low-burden option that is suitable for some purposes, and that can be employed retrospectively as it uses only data collected from a single activPAL worn in the standard position. Notably, the researcher's purpose may not be to measure all forms of lying but particularly to identify when participants are likely in bed. Currently, a methodological challenge is to differentiate between waking and sleeping during 24-hour monitoring without relying on self-report measures.[4] Estimation of lying down by either the single- or dual-monitor method may provide a possibility to improve algorithms that have estimated time in bed [13,14]. The simple single-monitor method provides a feasible, useful method by which to pursue future development of such algorithms. In addition, an algorithm to detect lying from a single hip-worn accelerometer has recently been published.[15] This could be a feasible alternative for the single- or dual-monitor method when using a different wear positioning and could be tested against the single- or dual-monitor method in future studies regarding distinction of sitting and lying. Whether the algorithm could be modified to work in other wear locations (such as the trunk) as a standalone method to measure sitting, lying, standing and walking could also be explored.

Strengths and limitations

Strengths of the study include the testing of the single-monitor method against a valid reference assessment method (dual-monitor method), in participants performing self-selected behaviors in free-living conditions. Although the comparison with direct observation was too limited in scope to consider the current study as a full validation of either method relative to direct observation, it provided useful insight as to the conditions under which errors occur in each method, and consequently what might produce any disagreement between the two methods. One of the limitations is that the study evaluated a LBP population, based on data availability. This was an appropriate population as they perform large amounts of sitting and lying down. It is unlikely that the accuracy for detecting sitting and lying varies much between this LBP population and other populations, apart from effects arising from how often each form of sitting and lying is performed (which is likely variable across both individuals and populations). Another limitation could be the limited examination timeframe (i.e., shortly after initialization, when synchronization between monitors is optimal). Our estimation of accuracy for the dual-monitor method may be an overstatement of the accuracy occurring towards the end of monitoring, if the two monitors begin to desynchronize. Methods to correct for clock drift and synchronization of the two monitors should be investigated. Accuracy could also decrease over time if participants need to reattach the monitors and fail to do so accurately. When worn on the thigh, the authors use the routine output to screen the data and correct for upside-down wear[16] but it is unclear how this would be performed for a trunk-worn device.

Conclusions

This study showed there was some agreement in overall sitting time and lying time between a low-burden single-monitor method and a valid dual-monitor method, but the two methods did not provide equivalent classifications. The more accurate method is preferable for measuring lying and sitting, for contexts where differentiation of these situations is considered relevant. However, the single-monitor method may provide an acceptable measure when data from a second monitor are unavailable and when extended periods of lying during the day are not anticipated or not of interest. Furthermore, the measure of lying obtained via the single-monitor method could plausibly be used to improve the estimation of time in bed relative to those based on self-report data or classifications derived from standard output of the device.

Perspectives

High levels of sedentary time (i.e., sitting, reclining or lying while awake, expending ≤1.5 metabolic equivalents[17]) have been associated with negative health outcomes (e.g. cardiovascular disease and diabetes). Interestingly, while decreasing sedentary behaviors could be important to establish a healthy lifestyle, sleeping (performed lying down) is typically treated by researchers as beneficial for human health. There is more to sleeping than just posture, however, it is also possible that spending waking hours in a seated posture may have different musculoskeletal and cardio-metabolic consequences than spending this time in a lying posture. Accurate measures are necessary to assess whether this is the case. Our results showed that there was some agreement between a low-burden single-monitor method and valid dual-monitor method in measuring sitting and lying time, but the two did not provide equivalent classifications. The seemingly more accurate dual-monitor method is preferable for contexts where differentiation of sitting and lying especially during waking hours are considered highly relevant. However, the single-monitor method may provide an acceptable measure when data from a second monitor is unavailable and when extended periods of lying during the day and not in bed are not anticipated. Additionally, both methods yield promise for measuring time in bed.

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Conflicts of Interest

One of the authors, Malcolm Granat, is a co-inventor of the activPAL and director of PAL Technologies Ltd that manufactures the activPAL devices used in this study. No funding was provided to this study by PAL Technologies Ltd. For the remaining authors no conflicts of interest were declared. The results of the present study do not constitute endorsement by ACSM. The results of the study are presented clearly, honestly, and without fabrication, falsification, or inappropriate data manipulation.

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Figure captions

Figure 1. Bland-Altman plots of agreement between the single- and dual-monitor methods in total lying time (shown at the left side) and sitting time (shown at the right side) over a 24-hour period.

Figure 2. Activity over a 24-hour period for one of the most discrepant cases as classified by the dual-monitor method (in grey), and the sedentary events which were classified as lying by the single-monitor method (in black).