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Accuracy of Inclinometer Functions of the activPAL and ActiGraph GT3X+: A Focus on Physical Activity

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Abstract

Purpose—The purpose of the study was to examine the accuracy of inclinometer functions of the ActiGraph GT3X+ (AG) (worn on the waist and wrist) and the activPAL (AP) in assessing time spent sitting, standing, and stepping.

Methods—A total of 62 adults (age: 18-40 yrs; male: 37; female: 25) wore three activity monitors (AG waist, and AG wrist, and AP) while completing 15 different types of activities (8 active and 7 sedentary). The 15 activities were classified into 3 different postures (sitting, standing, and stepping) based on the directly observed behaviors. Minutes estimated from the inclinometers of the three monitors were directly compared to those from direct observation (criterion method) using mean absolute percent error (MAPE) values, effect sizes (Cohen's D), and equivalence testing.

Results—The mean of MAPEs were 30.91%, 51.28%, and 13.01% for the waist-worn AG, the wrist-worn AG, and the AP, respectively. All of the three monitors yielded similar levels of MAPEs (<10.00%) for stepping except the activities of climbing stairs and walking 3mph & typing in AG. Equivalence testing indicated that the time measured by the waist-, wrist-worn AG, and AP showed significant equivalence to the time in the equivalence zone (90% confidence interval: 2.7 to 3.3min) for 5, 3, and 7 activities, respectively.

Conclusions—The AP was reasonably accurate for detecting sitting, standing, and stepping, and both the AG and AL were also fairly accurate for classifying stepping. It is expected that the result of the study would contribute to performing movement pattern analyses and health promotion research for classifying activities.

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Keywords

accelerometer; posture classification; inclinometer; activity monitors; physical activity assessment; activity classification

1 Introduction

Contemporary adults spend about 55 to 70% of their waking hours being sedentary [1]. Epidemiological studies have demonstrated that un-interrupted sedentary behaviors have detrimental effects on various health outcomes, including obesity [2, 3], metabolic syndrome [4, 5], type 2 diabetes [2, 3, 6], cardiovascular disease [7], and cancer [8]. Prolonged sitting, as a predominant form of sedentary behavior, has been highly associated with the risk of metabolic syndrome [9] and biomarkers of chronic diseases such as Body Mass Index (BMI), waist circumference, fasting insulin, and C-reactive protein have been linked with sedentary time [10]. Given that sitting is the most prevalent form of sedentary behavior [11] and specified in the definition of sedentary behavior (SB) [12], it is important to test methods to correctly classify sitting from other postures.

Physical activity (PA) monitors have been usually used for estimating PA energy expenditure and classifying different intensities of PA [13]. However, as sedentary behavior has emerged recently as a modifiable risk factor [14], considerable efforts have been placed into utilizing typical accelerometer-based activity monitors as means of differentiating different body postures including sitting, standing, and stepping. Several innovative analytical techniques (e.g. machine learning and artificial neural network) have been proposed to classify different types and/or postures of activities. However, these techniques are in an early phase of development and more importantly, require considerable analytical expertise, which may then limit its widespread use in research. An inclinometer function is a lot easier to use, user-friendly, and already incorporated as a generic analytical option in typical activity monitors. Therefore, it is important to test and compare the accuracy of inclinometer functions of commonly used accelerometers.

The Actigraph GT3X+ (AG) and activPAL (AP), as two widely used accelerometry-based monitors, have incorporated generic inclinometer functions in their respective software programs. This advantage enables researchers without advanced analytical skills to easily use the inclinometer functions to distinguish different body postures (i.e. SB and PA) for various research applications. A few previous studies have investigated the accuracy and utility of inclinometer functions of the AG and AP [15, 16]. However, little is known about the relative accuracy of the inclinometer functions of these monitors relative to a strong reference method. Moreover, no research has investigated the accuracy of inclinometer functions of AG placed on the waist versus wrist. Therefore, the purpose of this present study was to examine the validity of the built-in inclinometer functions of the two activity monitors (AG and AP) in relation to directly observed data.

2 Method

2.1 Participants

Data for the present study were obtained from a larger study focused on evaluating energy expenditure estimates from different activity monitors [17, 18]. A total of sixty-two (males: 37; females: 25) participants between the ages of 18 and 40 volunteered to participate in the study. The inclusion criteria were healthy adults who can perform given activities while wearing the activity monitors. Participant's height and weight were measured and body mass index (BMI) was calculated before data collection. Study protocols and design were approved by the Iowa State University Institutional Review Board and the informed consent was obtained from each participant before participation in the study.

2.2 Instrument

Participants were asked to wear two different types of activity monitors (i.e., AP and AG while performing a given set of activities (for approximately 90 minutes). Each participant wore two AGs (one on the wrist and one on the waist) and one AP on the right thigh. ActiLife (version 6.5.3) and activPAL Research Edition (version 6.4.1) were used to initialize AG and AP, respectively, according to the manufacturers' instructions. AGs were set at a sampling rate of 80Hz and data were obtained at 1-second epoch.

2.2.1 The ActiGraph GT3X+ (ActiGraph Corp, Pensacola, FL, USA) (AG)—The AG is the most widely used in research and clinical settings [13]. The AG is a small (4.6cm × 3.3cm × 1.5cm and 19g), tri-axial, and solid-state accelerometer. It has a full-speed of USB 2.0 port for connection with a computer, and lasts about 30 days with the built-in battery (when fully charged). In addition, an integrated ambient light sensor, called a lux, is built in the AG, which allows for differentiating indoor versus outdoor conditions [19]. The accelerometer of the AG produces an inclinometer information, based on the data collected from the accelerometer, which is capable of classifying an individual's posture such as sitting, standing, and lying and 'off' (non-wear) [20, 21].

2.2.2 The activPAL (PAL Technologies Ltd, Glasgow, UK) (AP)—The AP is a small (5.3cm × 3.5cm × 0.7cm and 15g) and capacitance-based accelerometer. The monitor is equipped with a memory of 16MB and a battery lasting about 10days. The AP is designed to be worn on the thigh. It can be waterproof by being wrapped with medical covering such as 3M Tegaderm or S&N Opsite flexifix. The AP has the inclinometer function to detect limb positions and activity. Specifically, it has the ability to distinguish three different activities; sitting, standing, and stepping [22].

2.3 Study Protocol

Participants' height and weight were measured at the beginning of the data collection. The height was measured to the nearest 0.1cm by Harpenden stadiometer (Harpenden, London, UK), and the weight was measured to the nearest to 0.1kg by SeCa 770 digital flat scale (SeCa, Chino, USA). Participants' BMI was calculated as weight (kg)/height squared (m²).

After initialization, the AGs were placed on the participants' wrist and waist, and APs were attached to their right thigh with the PAL stickie. The participants were asked to complete an activity protocol designed to simulate true free-living activities. The testing protocol included 15 activities, and the 15 activities were classified in to 3 activity categorizes: 1) Sitting: supine resting, sitting reading a book, sitting typing at a computer, and sitting fidgeting, 2) Standing: standing reading a book, standing typing at a computer, and standing fidgeting, 3) Stepping: climbing stairs, throwing/catching a ball, stationary biking, walking at 2.0 mph, walking at 3.0 mph, walking at 3.0 mph typing at trekDesk, running at 4.5 mph, and running at 5.5 mph. Each activity lasted 5 minutes and participants had 1-minute resting periods between them. This directly observed data served as a criterion measure and was temporarily aligned with the monitor data.

The AP's inclinometer function is capable of quantifying sitting, standing, and stepping time. However, the inclinometer function of the AG can distinguish lying, sitting, and standing time. Since the inclinometer of the AG does not measure any stepping activity, in order to make a direct comparison between the AP and AG for estimating 'stepping' time, a new 'stepping' variable for both waist- and wrist-worn AG was generated as follows: if a step count from the AG over a 1min period / [standing time (sec) + sitting time (sec) + lying time (sec) over the same 1min period] is greater than 1, the activity was classified as 'stepping'. If a step count collected over a 1min period / [standing time (sec) + sitting time (sec) + lying time (sec)] is less than 1, the activity was categorized as a non-stepping activity. Activities that were originally classified as standing or sitting, but that had a value (from the above calculation) greater than 1, were reclassified as 'stepping'. This formula was developed based on assuming the participant walk when he or she made more than 1 step per second. The stepping time determined by the formula was compared to the direct observation data to examine the accuracy of the calculation for the inclinometer function of AG.

2.4 Data Analysis

The three monitors all provided second-by-second inclinometer data, which were then aggregated for every minute. Minute by minute inclinometer data from all the three monitors were directly compared to the direct observation (criterion method) using equivalence testing, which is a novel statistical approach to test for equivalence (rather than zero differences) between different measures [23]. All 1-minute transitioning intervals between different activities as well as the first and the last minute of each 5-minute activity trial were excluded to remove data noise. So, only the three middle minutes of each activity were used for data analyses. Mean absolute percent error (MAPE) was calculated by averaging the absolute difference between each monitor and the direct observation value divided by the direct observation value, then multiplying by 100. Cohen's D was calculated, and used as an index to examine the effect sizes of differences. In this study, smaller effect sizes represented smaller differences between activity monitors and direct observation: therefore, better agreement of activity monitors relative to direct observation. All statistical analyses were performed in SAS 9.4 (SAS Institute Inc., Cary, North Carolina, USA).

3 Results

Table 1 presents descriptive statistics of the sample population. The participants' age (mean $\pm$ SD) were 25.1 ± 5.6 years (male) and 22.4 ± 4.1 years (female), ranged from 18 to 40 years. The average of BMI (mean $\pm$ SD) was 24.7 ± 3.1 kg·m⁻² for male and 21.4 ± 3.1 kg·m⁻² for female participants.

The MAPE values in Table 2 show the overall accuracy of the three inclinometer functions for estimates of time across 15 different activities. The AP was more accurate than the AG in both sitting and standing activities except the activity of stationary biking. The MAPE of AP was 9.40% for sitting reading book, 5.54% for sitting typing, 21.46% for sitting fidgeting, 0.25% for standing reading book, 0.04% for standing typing, 19.41% for standing fidgeting, and 12.86% for throwing ball. The MAPEs of waist- and wrist-worn AG were 52.23% and 79.01% for sitting reading book, 46.67% and 86.19% for sitting typing, 43.94% and 79.76% for sitting fidgeting, 78.90% and 88.41% for stationary biking, 44.35% and 90.44% for standing reading book, 44.67% and 92.46% for standing typing, 39.45% and 84.31% for standing fidgeting, and 25.24% and 9.31% for throwing ball. All of the three monitors yielded similar levels of MAPEs (<10.00%) for stepping except the activities of climbing stairs (AG waist: 55.49, and AG wrist: 22.34%) and walking 3mph & typing activity (AG wrist: 58.31%). The Cohen's D values in Table 2 revealed that the effect sizes ranged from 0.00 (walking 3mph & typing) to 3.55 (stationary biking) for the AG waist, 0.19 (running 4.5mph) to 10.52 (standing typing) for the AG wrist, and 0.19 (walking 3mph) to 0.93 (standing fidgeting) for the AP.

Equivalence testing revealed that the AG waist was significantly equivalent to directly observed data for 5 treadmill activities: walking 2 mph, walking 3 mph, walking 3 mph & typing, running 4.5 mph, and running 5.5 mph activities. Estimates of time assessed by the AG wrist were within the time in the equivalence zone (90% confidence interval: 2.7 to 3.3 min of equivalence zone) for 3 treadmill activities: walking 3 mph, running 4.5 mph, and running 5.5 mph. The AP produced equivalent estimates of time relative to direct observation for 7 activities: standing reading book, standing typing, walking 2mph, walking 3mph, walking 3mph & typing, running 4.5 mph, running 5.5 mph. All of the results from equivalence testing are described in Figures 1, 2, and 3.

4 Discussion

In the current study, we systematically examined the inclinometer functions of different types of accelerometers (i.e. AP and AG) in terms of distinguishing 15 different activities based on sitting, standing, and stepping. We also investigated whether there are any differences in accuracy between AG placed on the waist versus wrist. With respect to sitting activities (sitting reading book, sitting typing, sitting fidgeting, and stationary biking), none of the monitors showed any good agreement relative to direct observation.

All of the monitors showed good agreement to direct observation for treadmill activities (walking 2mph, 3mph, 3mph & typing, running 4.5mph and 5.5mph) except climbing stairs. It can be inferred that the AP is accurate for detecting stepping activity in both lab and free-

living condition. The stepping time determined by the AG is more accurate in treadmill activities.

Although the time calculated by the formula was used for stepping activity in the AG, almost perfect agreement was observed for running 4.5mph (MAPE: 0.02% and 0.00%) and running 5.5mph (MAPE: 0.02% and 0.09%) in both waist- and wrist-worn AG. This calculated metric helped to correctly classify many of the treadmill activities, but both wrist-worn and hip-worn AG produced relatively large errors for sedentary activities. In this regard, an interesting observation was the wrist-worn AG produced a substantial error (58.3%) for one of the treadmill activities that included a sedentary component (e.g., walking 3mph & typing); the error value was 0 with the hip-worn AG produced (and 0.42 with the AP). This larger error with the wrist-worn AG might have occurred since the participants' wrist being placed on the standing desk for computer typing was generally static (i.e. analogous to the other true sedentary activities) even if the participants were actually walking on the treadmill. Several intervention studies have been using standing desks to minimize sedentary time and increase PA time at work [24, 25], but researchers should be cognizant of the potential misclassification that might occur when evaluating activity outcomes with the wrist-worn AG.

The time measured for stationary biking showed the worst accuracy in all of the three monitors. This is because participants were pedaling on the bike, generating movement of a lower body, despite of the sitting posture. The AG worn on the wrist of three monitors showed the worst performance on sitting activities because participants might be moving their arms or hands even though they were performing sedentary activities in the seated position. Only the AP showed overlapped parts to the equivalence zone in 'sitting reading book' and 'sitting typing' activity.

For standing activities (standing reading book, standing typing, and standing fidgeting), both waist- and wrist-worn AG did not show any favorable agreement, but the AP was significantly equivalent to the direct observation for 'standing reading book' and 'standing typing' activity. This result corresponds to the studies by Kozey-Keadle et al. [22] and Steeves et al. [16] that reported that the AP was more accurate in detecting time spent on standing as well as sitting activities. Kozey-Keadle et al. used the AP and the AG to assess sedentary time, and compared them to direct observation. They found that the AP showed better agreement (i.e., the correlation between the AP and direct observation, $R^2 = 0.94$) than the AG (i.e., the correlation between the AP and direct observation $R^2 = 0.39$) in assessing sedentary activity [22]. Steeves et al. [16] studied the accuracy of the inclinometer functions of the AP and the AG by placing them on the same attachment site (i.e. thigh). They reported the different algorithms of each monitor may cause the difference in detecting postures, showing the sitting time measured by the AG was more sensitive than the time measured by the AP under free-living conditions [16].

Several large epidemiological studies (i.e. UK Biobank, NHANES) have begun to place accelerometers on the wrist rather than the waist, which is a historical attachment site. This methodological shift has motivated researchers not only to develop new processing techniques for wrist placement but also to understand relative advantages of the wrist over

the waist, but it still remains controversial [26]. Rosenberger et al. [27] used Wockets accelerometer (open source device for mobile phones) to estimate energy expenditure and sedentary time and found out that the AG worn on the hip exhibited better performance than the wrist-worn AG (A higher area under the curve, AUC: 0.917 for hip and 0.737 for wrist, $P < 0.001$). However, several studies demonstrated both wrist- and waist-worn accelerometer showed comparable agreement on measuring energy expenditure, sedentary time, and recognition of activities [28–30]. Recently, Tudor-Locke et al. [26] reported wrist- and waist-worn accelerometer cannot be comparable for step measurement, demonstrating the data from waist-worn accelerometer were more accurate on step counts. Collectively, waist-worn accelerometers may be more accurate than or as accurate as wrist-worn accelerometers in quantifying activity outcomes. However, this has not been extensively investigated under free-living conditions, and particularly, more research is clearly needed to examine the inclinometer functions for wrist versus waist placement. Moreover, one of the major rationales for using the wrist approach is better participant's compliance with study protocols [27], in particular in field-based studies requiring extended wearing time periods. Future research is warranted to further determine and improve the accuracy of built-in inclinometers for wrist and waist placement so that they can serve as feasible, accurate methods for various research and clinical applications.

4.1 Limitations and Applications

There are a few limitations that need to be considered when interpreting the results of this research. Only three activity categories (sitting, standing, and stepping) were tested for activity classification, but contemporary inclinometer functions can capture only these three types of body posture. Participants' physical characteristics (e.g., wrist-, waist-, thigh-circumference, and leg length) were not controlled in the present study. Since the inclinometer of the AG does not measure any stepping activity, the formula was developed and used for assessing stepping activity with both waist- and wrist-worn AG. Further research is warranted to detect more variable body postures, determine the optimal placement of monitors, and examine the effect of physical characteristics on the inclinometer functions.

5 Conclusion

In conclusion, we examined the accuracy of the inclinometer functions of the AP and the AG (waist and wrist) monitors. Although inclinometer functions are increasingly used in various types of PA research using accelerometers, efforts to validate the inclinometer functions are lacking. This study is the first empirical investigation to determine the relative accuracy of the inclinometers of the AP and the AG for 15 different activities based on sitting, standing, and stepping activities. As a result, the AP was reasonably accurate for detecting sitting, standing and stepping, and both AG and the AP were also fairly accurate for classifying stepping. Therefore, both the AG and the AP have a potential to be utilized in PA research aimed at correctly assessing stepping behavior. It is expected that the result of the study would contribute to performing movement pattern analyses and health promotion research for classifying activities.

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Research Highlights

The activPAL was reasonably accurate for detecting sitting, standing and stepping activity.

The activPAL was more accurate than the ActiGraph GT3X+ in both sitting and standing activities except the activity of stationary biking.

Both ActiGraph GT3X+ and the activPAL were also fairly accurate for classifying stepping activity.

It is expected that the result of the study would contribute to performing movement pattern analyses and health promotion research for posture classification.

Figure1. Equivalence testing for ActiGraph worn the waist

*Within the 10% equivalence zone.

Dashed lines indicate proposed equivalence zone ($\pm 10\%$ of the mean). Black bars indicated the 90% confidence for a mean of the time measured.

· The formula for stepping time

If a step count from the Actigraph over a 1min period / [standing time (sec) + sitting time (sec) + lying time (sec) over the same 1min period] is greater than 1, the activity was classified as 'stepping'. If a step count collected over a 1min period / [standing time (sec) + sitting time (sec) + lying time (sec)] is less than 1, the activity was categorized as a non-stepping activity

Figure2. Equivalence testing for ActiGraph worn the wrist

*Within the 10% equivalence zone.

Dashed lines indicate proposed equivalence zone ($\pm 10\%$ of the mean). Black bars indicated the 90% confidence for a mean of the time measured.

· The formula for stepping time

If a step count from the Actigraph over a 1min period / [standing time (sec) + sitting time (sec) + lying time (sec) over the same 1min period] is greater than 1, the activity was classified as 'stepping'. If a step count collected over a 1min period / [standing time (sec) +

sitting time (sec) + lying time (sec)] is less than 1, the activity was categorized as a non-stepping activity

Figure3. Equivalence testing for activPAL worn the thigh

*Within the 10% equivalence zone.

Dashed lines indicate proposed equivalence zone ($\pm 10\%$ of the mean). Black bars indicated the 90% confidence for a mean of the time measured.

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Table 1
Physical Characteristics of male (n = 37) and female (n = 25) participants.

	Male		Female	
	Mean $\pm$ SD	Range	Mean $\pm$ SD	Range
Age (yr)	25.1 $\pm$ 5.6	18.0 – 40.0	22.4 $\pm$ 4.1	18.0 – 34.0
Height (cm)	179.5 $\pm$ 7.2	167.5 – 190.6	165.9 $\pm$ 7.9	148.6 – 184.0
Weight (kg)	79.8 $\pm$ 11.7	59.4 – 107.3	58.9 $\pm$ 9.8	41.3 – 78.9
BMI (kg·m ⁻²)	24.7 $\pm$ 3.1	19.2 – 31.2	21.4 $\pm$ 3.1	16.6 – 30.7

* BMI, Body Mass Index; SD, Standard Deviation

Table 2
Mean absolute percent error (MAPE) and effect size for each activity

Activity	MAPE (%)			Effect Size		
	ActiGraph Waist	ActiGraph Wrist	activPAL	ActiGraph Waist	ActiGraph Wrist	activPAL
Lying Down	30.62	63.21	N/A *	1.16	2.29	N/A *
Sitting Reading Book	52.23	79.01	9.40	1.59	3.24	0.46
Sitting Typing	46.67	86.19	5.54	1.38	3.99	0.35
Sitting Fidgeting	43.94	79.76	21.46	1.35	3.34	0.78
Stationery Biking	78.90	88.41	100.00	3.55	5.27	N/A **
Standing Reading Book	44.35	90.44	0.25	1.41	9.42	0.27
Standing Typing	44.67	92.46	0.04	1.43	10.52	0.19
Standing Fidgeting	39.45	84.31	19.41	1.19	4.99	0.93
Throwing Ball	25.24	9.31	12.86	1.11	0.63	0.86
Climbing Stairs	55.49	22.34	6.32	1.74	0.89	0.61
Walking 2MPH	1.99	9.54	1.49	0.29	0.66	0.36
Walking 3MPH	0.01	5.74	0.41	0.18	0.47	0.19
Walking 3MPH & Typing	0.00	58.31	0.42	0.00	2.40	0.20
Running 4.5MPH	0.02	0.02	2.80	0.26	0.19	0.28
Running 5.5MPH	0.00	0.09	1.98	0.27	0.28	0.28
Average	30.91	51.28	13.03	1.13	3.24	0.44

N/A*: activPAL is not capable of detecting lying activities only (it can only detect sitting plus lying).

N/A**: activPAL captured 0 minutes for 'stationery biking' (sitting activity) because the participants' legs were moving for pedaling. So it was not possible to calculate an effect size value for this activity since the denominator was 0 in the calculation.