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PHYSICAL ACTIVITY, HEALTH AND EXERCISE

Validation of wearable activity monitors for real-time cadence

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ABSTRACT

The purpose of this study is to establish evidence of validity for wearable activity monitors providing real-time cadence against a criterion measure. Thirty-six healthy adults, aged 18–65 years, participated in the study. Four activity monitors including 2 watch-based monitors and 2 cadence sensors attaching to shoelaces were tested. Each participant completed the study protocol consisting of 2 distinct components: (1) treadmill protocol and (2) overground protocol. Lin's concordance correlation and mean absolute percentage error (MAPE) were calculated for the comparisons between the criterion and measures of the monitors. Bland–Altman analysis was performed to determine the mean bias and 95% limits of agreement. All activity monitors showed high correlations with the criterion measures ($p < .01$). Lower correlations were observed at slow walking speeds in the watch-based monitors. In contrast, consistent and strong correlations were found with both cadence sensors regardless of walking speeds ($p < .01$). Similar patterns were observed in the MAPE scores. Greater than 90% of the participants were able to maintain prescribed walking intensity using real-time cadence. The results suggest that the wearable activity monitors are an acceptable measure of real-time cadence and provide the potential to improve intensity-based prescription of physical activity using the monitors.

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KEYWORDS
Cadence prescription; activity devices; accuracy; compliance

Introduction

Recent public health efforts have focused on the incorporation of moderate-intensity physical activity (i.e., ≥3 metabolic equivalents [METs]) into one's daily routine maintained over the life span. The intensity of physical activity is considered as a central component of the global physical activity recommendations. For maximum health benefits, it is recommended that adult individuals engage in a minimum of 150 min of moderate-intensity physical activity each week (i.e., preferably, spread throughout the week) (U.S. Department of Health and Human Services, 2018; World Health Organization, 2010). In this perspective, cadence (steps min^{-1}), an indicator of intensity of ambulatory activities (e.g., walking, running, dancing, etc.), may have the potential to substantially improve the translation of laboratory findings into public health practice.

Walking is an essential component of everyday life for most people. A recent review reported that walking was one of the most popular physical activities performed by individuals of all ages in 47 different countries (Hulteen et al., 2017). As cadence is a direct reflection of ambulatory movement (e.g., an increase in walking speed as cadence increases), individuals can achieve a minimum of required moderate intensity for optimal health outcomes using the simple metric of cadence. Although further investigations are required to confirm, there has been remarkable consistency for a standardised cadence value (i.e., 100 steps min^{-1}) associated with absolutely defined moderate intensity (i.e., equivalent to 3 METs) (Tudor-Locke et al., 2019, 2018). In order to minimise the individual variation when using this absolutely defined cadence value, other cadence thresholds (e.g., 115 or 125 steps min^{-1}) determined by using relatively determined moderate intensity could be considered to use as the minimal level of moderate intensity (Abt, Bray, Myers, & Benson, 2019, O'Brien et al., 2018).

The utility of wearable activity monitors can provide a better guide to increase compliance with the recommended physical activity levels for health improvement (Marshall et al., 2013). However, due to the practical and technical limitations of their measurement and prescription on describing physical activity intensity, most of the physical activity intervention programmes have focused on achieving specific activity goals that were limited to the volume of physical activity (e.g., frequency and duration). Examples include (1) increasing daily steps (e.g., achieving 10,000 steps day^{-1} or increasing 1,500 steps more than daily baseline), (2) amount of weekly aerobic physical activity (e.g., ≥30 min day^{-1} or ≥150 min week^{-1} of moderate intensity), and (3) number of fitness facility attendance (e.g., 2 to 5 visits per week) (Barte & Wendel-Vos, 2017; Mitchell et al., 2013).

The recent advent of wearable activity monitors to provide physical activity intensity in real time (e.g., real-time cadence) enables researchers and practitioners the ability to measure and prescribe physical activity targeting a specific intensity in real time. However, the validity of real-time estimates from the devices remains unclear, and it is important to examine the accuracy of the devices in detecting real-time cadence performed in various walking speeds before adopting the new technology. Thus, the primary purpose of this study was to

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Supplemental data for this article can be accessed here.

establish evidence of validity for wearable activity monitors providing the values of real-time cadence against a criterion measure (i.e., hand-tally count). Simultaneously, the utility of the devices to prescribe a specific intensity was preliminarily tested to ensure the participants' ability to comply with a given instruction (e.g., walking faster than a cadence of 120 steps min^{-1}) using the devices.

Methods

Participants

Thirty-six healthy adult individuals (18 men and 18 women), aged 18 to 65 years, participated in the study. To identify the minimum number of participants required to achieve sufficient power, we conducted a priori power analysis for correlation using a general stand-alone power analysis program (G*Power 3) (Erdfelder, Faul, & Buchner, 1996). An alpha of 0.05 and power of 0.80 were used with a large expected effect size of 0.5 (Maxwell, Delaney, & Kelley, 2017; Tabachnick & Fidell, 2013). The effect size of 0.5 was used with an expectation based on previous studies showing strong correlations between direct observation and estimated step counts of activity monitors (e.g., $r > 0.5$) (Diaz et al., 2015; Takacs et al., 2014). Based upon results of the power analysis, a minimum sample of 23 participants was suggested. Oversampling of 20% was used to account for participant attrition resulting in a sample size of 28. Participants were recruited using flyers, email advertisements, and word of mouth within the university and the surrounding community. Participants were limited to those who were able to walk and run safely on a treadmill and overground without using a walking aid and those who had no cardiac history. The study protocol was approved by the Oklahoma State University Institutional Review Board. All participants completed a written informed consent form prior to the study.

Instruments

Criterion measure

Cadence performed in each stage was directly observed and counted by a trained researcher (hand-tallied) to be used as the criterion standard. A standard cadence was calculated by dividing total steps accumulated in each bout by the duration of the bout (i.e., 2 min). Each trial was filmed for a reference to the event of staff-disclosed miscounting or any identified ambiguous data during the data processing.

Wearable activity monitors

Two commercially available activity monitors (Garmin Forerunner 235; Garmin Ltd., Olathe, KS and Polar M430; Polar Electro, Kempele, Finland) and a compatible cadence sensor (also known as a stride sensor) with each monitor (Garmin Foot Pod and Polar Stride Sensor Bluetooth Smart, respectively) were tested in this study. Both activity monitors are a running watch with wrist-based heart rate and GPS and use a built-in accelerometer to measure walking/running cadence and show it in real time. In addition, a cadence sensor can be paired with the activity monitors to measure real-time cadence for both indoors and outdoors where the GPS is not available for an accurate measure of real-time cadence. In the current study, an identical model of the activity monitors (Garmin Forerunner 235 for Garmin Foot Pod [software version 2.00] and Polar M430 for Polar Stride Sensor Bluetooth Smart [software version 3.0.2]) were used to pair with the cadence sensors. When using a cadence sensor, cadence is always measured with the sensor instead of using a built-in accelerometer in the activity monitors. The cadence sensors are very small (L × W × H: 35 mm × 25 mm × 7.5 mm for Foot Pod and 119 mm × 76 mm × 30 mm for Stride Sensor) and lightweight (10 g and 90 g, respectively) devices attached to shoelaces. The devices tested herein included: (1) Garmin Forerunner 235 (GM), (2) Polar M430 (PL), (3) Garmin Foot Pod (FP), and (4) Polar Stride Sensor Bluetooth Smart (SS). All devices were attached according to the manufacturer's instructions.

Protocol

After informed consent was obtained, participants wore GM and PL on their wrist of the non-dominant arm in a counterbalanced configuration while attaching a cadence sensor to each foot (e.g., FP on left foot and SS on right foot). The 2 activity monitors paired with the cadence sensors were placed on their dominant wrist. Each participant completed the study protocol consisting of 2 distinct components: (1) treadmill walking/running protocol and (2) overground walking protocol.

Treadmill walking/running protocol

Participants performed a 2-min walking protocol at a fixed speed of 3.2, 4.0, 4.8, 5.6, and 6.4 km h^{-1} and a 2-min running protocol at a speed of 8.0 km h^{-1} on a treadmill (T7xi; Matrix Fitness, Cottage Grove, WI, USA) at 0% incline. For each protocol speed, participants were allowed to walk/run during the initial period of the trial until being familiarised with the given speed, and total steps were counted over the last 2 min at each speed. A 1-min break was provided between the trials. Each treadmill speed was calibrated using a handheld digital tachometer (HT-5500; Ono Sokki Co Ltd, Yokohama, Japan) prior to initiating the protocol and found the errors to be within ± 0.1%.

Overground walking protocol

Overground walking protocol consisted of 2 main sections including (1) self-determined walking trials and (2) researcher-prescribed walking trials. For both trials, participants were asked to continuously walk a 13-m oval track (i.e., marked using 2 cones) in an indoor gymnasium for 2 min for each trial followed by a 1-min break. For the self-determined walking trials, participants walked at self-determined slow, normal, and fast walking paces. Each pace was described as: (1) slow pace: a speed that the participant would walk if they were in grocery shopping or texting while walking, (2) normal pace: typically normal everyday walking speed in free-living, and (3) fast pace: a speed that the participant would walk if they were in a hurry to get somewhere, but not as fast as power-walking. The first trial was always at the normal walking pace. The remaining sets (slow and fast) were counter-balanced. Extra time was provided at the beginning of each trial for the participants to reach their self-determined walking speed. For the researcher-prescribed walking test, participants were instructed to walk faster than 120 $stepsmin^{-1}$ using each activity monitor (i.e., GM, PL, FP, and SS: 4 trials in a counter-balanced order) providing a feedback on their cadence in real-time. Same as self-determined walking trials, the participants were given an extra time to reach above 120 stepsmin^{-1} and asked to maintain the intensity for 2 min using the real-time cadence feedback as needed. The cadence of 120 stepsmin^{-1} was selected to ensure that participants walked briskly (i.e., above 3 METs) (Pillay, Kolbe-Alexander, Proper, van Mechelen, & Lambert, 2014, Rowe, Kang, Sutherland, Holbrook, & Barreira, 2013).

Data processing

BMI was calculated by dividing weight in kilograms by height in metres squared. The recorded second-by-second data from the Polar monitors were obtained directly through the manufacturer web service called Polar Flow. Stride rate, a measure of the Polar devices, was converted to cadence (e.g., multiplied by 2). Second-by-second measures from the Garmin monitors were accessed through the publically available software, Golden Cheetah (Version 3.4). For all activity monitors, any seconds of zero (0) real-time cadence recorded during the measurement period throughout the protocol were manually counted and removed from the analyses.

Data analysis

Descriptive statistics were used to summarise participant characteristics. Lin's concordance correlation coefficient for each monitor was calculated to quantify the relationship between criterion measures and device-determined real-time cadences. To determine the extent of monitor accuracy in measuring real-time cadence, mean absolute percentage error (MAPE) scores were obtained for criterion versus measures from the monitors:

$$MAPE = \frac{1}{n}\sum\nolimits_{t=1}^{n} \frac{|Device\ Measure - Criterion|}{Criterion} \times 100$$

A 2 one-sided test (TOST) was used to evaluate the equivalence between criterion measures and device-determined real-time cadences. Since no guidelines are currently available for the determination of the equivalence margin, the equivalence margin of 10% was used for TOST (Bai et al., 2016). Bland–Altman analysis was additionally performed to determine the mean bias and 95% limits of agreement between the criterion and the measures of activity monitors (Bai, Hibbing, Mantis, & Welk, 2018; Bland & Altman, 1986). Briefly, the differences in criterion and the monitor-determined real-time cadence were plotted against the mean of the differences. All statistical analysis was conducted using IBM SPSS 25 for Windows.

Results

The mean age and BMI were 21.2 ± 4.5 years and 24.8 ± 3.4 kg m^{-2}, respectively. The majority of participants were White (72.2%), followed by Asian, African American, and Other race/ethnicity (8.3% of the equal proportions). The number of participants in a few trials varied, ranging from 30 to 36. This variation was mainly due to a number of occasions of device malfunction (n = 13) and the participants' failure of walking at 6.4 km h^{-1} (n = 9).

Table 1 presents the means of cadence (95% CI) for each walking speed and pace as measured by the criterion and the 4 activity monitors in both treadmill and overground protocols. In addition, the numbers of zero (0), indicating a second of zero (0) real-time cadence detected, which occurred during the measurement period (i.e., 2 min) were reported. Overall, cadence increased as walking speed increased (Supplementary Material 1). GM and PL showed considerable numbers of zero real-time cadence at slow walking speeds (3.2 km h^{-1} and slow pace). FP and SS showed identical values to the criterion without zero real-time cadence except at the slow walking pace in the overground protocol; however, the values were negligible averaging less than 1% for each.

Correlations between the criterion and the measures of the activity monitors for both the treadmill protocol and overground protocol are described in Table 2. In the treadmill protocol, SS had,

Table 1. Measures of cadence determined by criterion and activity monitors.

	Hand count	FP		GM		SS		PL	
Speed	Mean ± SD (steps min^{-1})	Mean ± SD (steps min^{-1})	#No. of Zero (%)	Mean ± SD (steps min^{-1})	#No. of Zero (%)	Mean ± SD (steps min^{-1})	#No. of Zero (%)	Mean ± SD (steps min^{-1})	#No. of Zero (%)
Treadmill									
3.2 km h^{-1}	98.1 ± 6.2	98.2 ± 6.3	0 (0%)	111.7 ± 9.6	57.5 ± 36.2 (47.9%)	98.3 ± 6.4	0 (0%)	89.8 ± 14.1	50.0 ± 49.4 (41.7%)
4.0	106.0 ± 5.5	106.4 ± 5.7	0 (0%)	109.5 ± 7.0	22.1 ± 31.3 (18.4%)	106.3 ± 5.5	0 (0%)	100.1 ± 14.7	23.5 ± 37.3 (19.6%)
4.8	113.5 ± 5.3	114.0 ± 5.4	0 (0%)	113.8 ± 5.3	1.3 ± 3.3 (1.0%)	113.6 ± 5.2	0 (0%)	111.7 ± 8.8	6.4 ± 15.9 (5.3%)
5.6	121.0 ± 5.7	121.4 ± 5.6	0 (0%)	121.0 ± 6.0	0.9 ± 2.6 (0.7%)	121.1 ± 5.4	0 (0%)	120.5 ± 6.8	0.8 ± 3.0 (0.7%)
6.4	128.6 ± 6.4	129.2 ± 6.4	0 (0%)	128.2 ± 5.6	1.8 ± 6.8 (1.5%)	128.8 ± 6.4	0 (0%)	129.0 ± 6.4	0 (0%)
8.0	157.3 ± 6.7	158.5 ± 7.1	0 (0%)	157.0 ± 6.8	0 (0%)	157.4 ± 6.8	0 (0%)	157.1 ± 8.0	0 (0%)
Overground									
Slow	95.5 ± 9.7	95.6 ± 10.0	0.6 ± 3.4 (0.5%)	110.5 ± 10.2	56.4 ± 36.3 (47.0%)	95.5 ± 10.0	0.4 ± 2.1 (0.4%)	90.6 ± 19.1	40.3 ± 46.6 (33.6%)
Normal	108.6 ± 9.4	108.9 ± 9.5	0 (0%)	111.8 ± 7.7	18.0 ± 27.3 (15.0%)	108.9 ± 9.2	0 (0%)	105.4 ± 14.3	12.2 ± 26.5 (10.1%)
Fast	120.3 ± 10.4	120.6 ± 10.7	0 (0%)	120.6 ± 8.5	4.3 ± 10.1 (3.6%)	120.7 ± 10.3	0 (0%)	119.2 ± 10.6	3.6 ± 11.5 (3.0%)

Note: FP, Garmin Foot Pod; GM, Garmin Forerunner 235; PL, Polar M430; SD, standard deviation; SS, Polar Stride Sensor Bluetooth Smart.
Number of zeros indicates an average of time in second appeared as a zero (0) real-time cadence on the screen and the percentage out of 120 s.

Table 2. MAPE, correlation and TOST between the criterion and measures of activity monitors.

		FP			GM			SS			PL		
Type	Speed	MAPE (%)	Correlation (CI)	TOST	MAPE (%)	Correlation (CI)	TOST	MAPE (%)	Correlation (CI)	TOST	MAPE (%)	Correlation (CI)	TOST
Treadmill	3.2 km h^{-1}	0.4 ± 0.4	0.996** (0.993, 0.998)	<.001	14.3 ± 10.7	0.093 (-0.044, 0.226)	.984*	0.3 ± 0.4	0.996** (0.992, 0.998)	<.001	9.9 ± 12.9	0.179 (-0.027, 0.370)	.426*
	4.0	0.5 ± 0.4	0.993** (0.986, 0.996)	<.001	4.2 ± 5.3	0.480** (0.225, 0.673)	<.001	0.4 ± 0.3	0.996** (0.992, 0.998)	<.001	7.0 ± 11.8	0.256** (0.062, 0.432)	.026*
	4.8	0.5 ± 0.3	0.991** (0.983, 0.995)	<.001	1.2 ± 1.2	0.939** (0.881, 0.969)	<.001	0.3 ± 0.4	0.994** (0.989, 0.997)	<.001	3.1 ± 5.5	0.531** (0.298, 0.704)	<.001
	5.6	0.5 ± 0.4	0.991** (0.982, 0.995)	<.001	0.9 ± 0.6	0.976** (0.953, 0.988)	<.001	0.3 ± 0.5	0.993** (0.986, 0.996)	<.001	1.5 ± 2.6	0.836** (0.706, 0.912)	<.001
	6.4	0.6 ± 0.7	0.982** (0.959, 0.992)	<.001	1.0 ± 1.2	0.934** (0.864, 0.969)	<.001	0.2 ± 0.2	0.999** (0.997, 1.000)	<.001	0.5 ± 0.5	0.990** (0.977, 0.996)	<.001
	8.0	0.8 ± 0.4	0.977** (0.958, 0.987)	<.001	0.3 ± 0.3	0.994** (0.988, 0.997)	<.001	0.2 ± 0.3	0.997** (0.994, 0.999)	<.001	0.9 ± 2.4	0.848** (0.720, 0.920)	<.001
Total		**0.6 ± 0.4**	**0.999** (0.999, 0.999)**	**<.001**	**3.7 ± 7.0**	**0.919** (0.896, 0.937)**	**<.001**	**0.3 ± 0.4**	**1.000** (1.000, 1.000)**	**<.001**	**3.8 ± 8.2**	**0.908** (0.883, 0.928)**	**<.001**
Over-ground	Slow	0.6 ± 0.5	0.997** (0.994, 0.999)	<.001	16.6 ± 18.6	-0.072 (-0.237, 0.097)	.969*	1.0 ± 1.4	0.986** (0.973, 0.993)	<.001	12.9 ± 17.4	0.229 (-0.023, 0.453)	.151*
	Normal	0.5 ± 0.4	0.997** (0.994, 0.999)	<.001	4.5 ± 7.0	0.560** (0.304, 0.740)	<.001	0.6 ± 0.5	0.996** (0.992, 0.998)	<.001	4.7 ± 7.2	0.765** (0.630, 0.855)	<.001
	Fast	0.5 ± 0.3	0.998** (0.996, 0.999)	<.001	2.0 ± 2.8	0.912** (0.844, 0.951)	<.001	0.4 ± 0.4	0.998** (0.996, 0.999)	<.001	2.4 ± 4.4	0.811** (0.654, 0.901)	<.001
Total		**0.5 ± 0.4**	**0.999** (0.998, 0.999)**	**<.001**	**7.6 ± 13.1**	**0.484** (0.351, 0.599)**	**<.001**	**0.6 ± 0.9**	**0.997** (0.995, 0.998)**	**<.001**	**6.4 ± 11.6**	**0.723** (0.631, 0.795)**	**<.001**

Note: CI, confidence interval; FP, Garmin Foot Pod; GM, Garmin Forerunner 235; MAPE, mean absolute percentage error; PL, Polar M430; SS: Polar Stride Sensor Bluetooth Smart; TOST, 2 one-sided test. * indicates no equivalence in TOST, $p > .05$. ** Correlation is significant at the 0.01 level (two-tailed).

overall, the highest correlation (r = 1.000), followed by FP (r = 0.999), GM (r = 0.937), and PL (r = 0.932) ($p < .01$). The correlations ranged from 0.093 (GM) ($p > .01$) to 0.999 (SS) ($p < .01$) across the different treadmill speeds. In general, lower correlations were observed at slow walking speeds, i.e., 3.2 and 4.0 km h^{-1}, when using the watch-based activity monitors (both GM and PL), whereas both cadence sensors (FP and SS) remained in high correlations regardless of the treadmill speeds. Similar trends occurred in the overground protocol. The correlations ranged from −0.072 (GM) ($p > .01$) to 0.998 (FP and SS) ($p < .01$) and were lower at the self-determined slow walking pace compared to normal and fast walking paces for both GM and PL. Consistent and strong correlations were observed with both cadence sensors (overall, 0.999 for FP and 0.997 for SS; $p < .01$) in all walking speeds.

In both treadmill and overground protocols, generally larger differences between the criterion measures and those measured by GM and PL were found at the slow walking speeds (i.e., 3.2 & 4.0 km h^{-1} and self-determined slow pace) compared to faster speeds (Table 2). Average MAPE score was 3.7% and 3.8% for GM and PL, respectively, in the treadmill protocol whereas a higher average MAPE score (7.6% vs. 6.4% for GM and PL, respectively) was observed in the overground protocol. Less than 1% of the MAPE scores occurred with the measures of both cadence sensors (FP and SS) throughout the entire protocol.

Bland–Altman plots indicate the proportional bias of cadence measured for each device (Figure 1). The difference of 95% limits agreement was calculated for FP (mean = 0.5; ±1.96 SD = 1.9, −1.0), GM (3.9; 21.4, −13.6), SS (0.2; 1.7, −1.3) and PL (−3.1; 16.6, −22.8) regardless of the study protocols. The smallest difference of 95% limits agreement was found in the FP indicating the best agreement between the criterion and the device measures. Comparatively, the largest difference of 95% limits agreement was observed with the PL.

Lastly, the participants' ability to comply with a given prescription using real-time cadence was found while using each activity monitor. The majority participants (100%, 91.7%, 97.1%, and 97.2%) adhered to the prescription (i.e., walking faster than 120 steps min^{-1}), when using FP, GM, SS, and PL, respectively.

Discussion

The current study investigated the accuracy of commercially available activity monitors providing a real-time cadence and examined the potential of utilising the real-time cadence to prescribe the intensity of physical activity for optimal health benefits. In general, the results demonstrated that the measures of real-time cadence estimated from the wearable activity monitors were highly accurate at various walking speeds on a treadmill and overground. The most accurate measures appeared to be with both cadence sensors (e.g., ≤1% of the MAPE regardless of performed walking speeds). The findings also indicated that most of the participants (e.g., ≥90%) were able to easily achieve and maintain the prescribed intensity of walking (i.e., >120 steps min^{-1}) using real-time cadence during the specified time.

This is the first study to evaluate the accuracy of real-time cadence in wearable activity monitors. A novel finding of the study is the high accuracy of the cadence sensors (FP and SS) to estimate a real-time cadence regardless of the varied walking speeds. Due to an inherent limitation of most accelerometer-based activity monitors (Feito, Bassett, & Thompson, 2012), a reduced accuracy of the devices in detecting steps is often

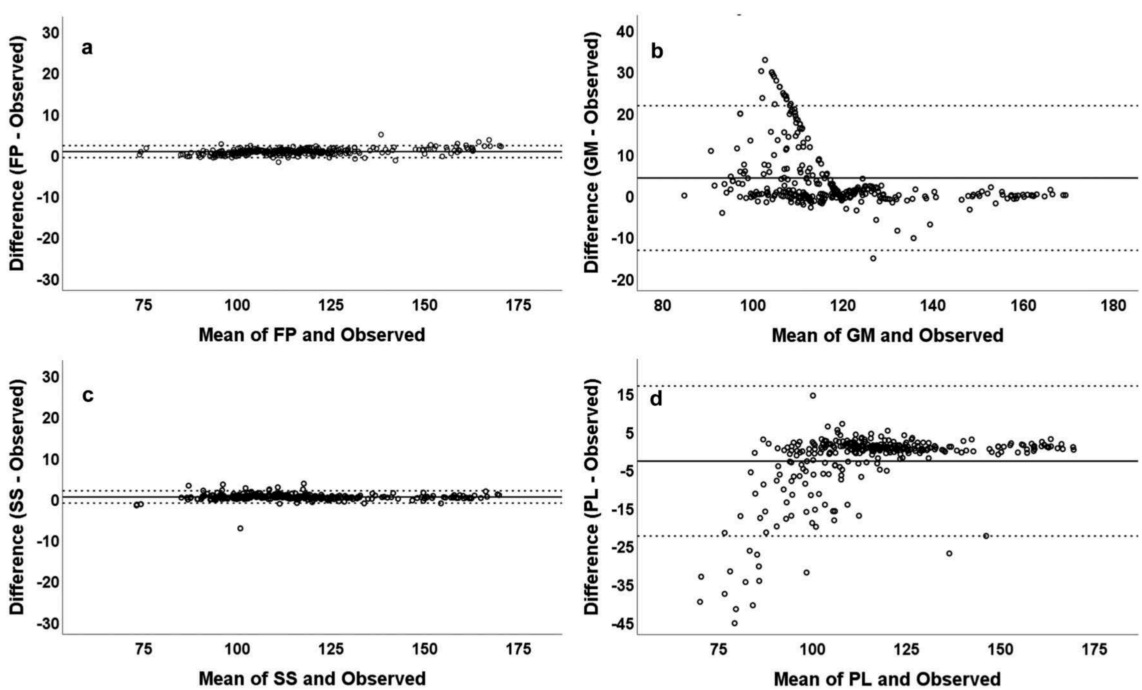

Figure 1. Bland–Altman plot for each monitor: FP (a), GM (b), SS (c), and PL (d). Two participants [(97.0, 44.4), (108.65, 69.3)] from B and 3 participants [(74.5, −65.0), (79.2, −45.6), (99.5, 51.0)] from D were removed for relative comparison. The solid line indicates the mean of the difference between cadences measured from the device and observed. Dotted line indicates 95% limits of agreement of differences. FP, Foot Pod; GM, Garmin Forerunner 235; MAPE, mean absolute percentage error; PL, Polar M430; SS, Polar Stride Sensor Bluetooth Smart.

observed at the slower walking speeds (e.g., ≤4.0 km h^{-1}) (Fokkema, KOOIMAN, KRIJNEN, van der Schans, & de Groot, 2017). The correlations between the criterion and the measures from the sensors were very strong, ranging r = 0.987–1.000, and the differences between the 2 measures were substantially small (less than 1% of the overall MAPE values) at all walking speeds in the protocol. The constant capability of the sensors in estimating accurate real-time cadence at the slower speeds highlights the substantial potential to advance the utilisation of these sensors for a special population (e.g., elderly people or those with limited motor abilities who were characterised by slow walking) in physical activity interventions. Not surprisingly, the wrist-based running watches (GM and PL) demonstrated reduced accuracy during slow walking at a speed of 3.2 and 4.0 km h^{-1} on a treadmill and at self-determined slow walking pace on the overground protocols. These findings concur with consistent evidence of reduced accuracy of activity monitors at slow walking speeds (Tudor-Locke, Williams, Reis, & Pluto, 2002) that could be explained by instrumental threshold sensitivity originally designed to detect normal walking (Feito et al., 2012). The lower intensity (i.e., slow) walking may produce insufficient vertical accelerations to exceed the threshold, and thus underestimation of step detection typically occurs at slow walking speeds from most activity monitors as illustrated herein the Bland–Altman plot (Figure 1(d)). Thus, analysing the data excluding any seconds of undetected real-time cadence (i.e., zero (0) cadence), especially observed in the wrist-based running watches at slow walking speeds, makes the results of this study more reliable. An interesting finding in the present study is the performance of the GM at slow walking speeds. The monitor appeared to overestimate a real-time cadence at slow walking speeds (Figure 1(b)). This finding is in contrast to the aforementioned typical performance of activity monitors during slow walking. This can empirically be explained by the fact that the GM frequently showed a random cadence of '119' on the screen for multiple seconds while performing a number of trials at slow walking speeds. The manufacturer algorithms used internally in the monitor are not publicly disclosed so that it is unclear how the random cadence appeared. Despite the reduced accuracy of the activity monitors at slow walking speeds, both wrist-based monitors demonstrated comparable performances at normal and fast walking speeds (e.g., ≥4.8 km h^{-1}) to the criterion. Thus, the monitors should be acceptable to use for promoting active lifestyles in general populations.

A wide variety of activity monitors are currently available for both the lay public and professionals to estimate and monitor their daily physical activity. In spite of the progressions of the technologies, most wearable activity monitors provide the estimates of energy expenditure, global positioning system (GPS), step counts, and heart rate; however, none of these estimates are a direct indicator of physical activity intensity. A unique feature of the current study is to highlight a new function of the wearable activity monitors; the capability of tracking real-time cadence. Cadence is often explained as the number of steps accumulated in a minute. Previously available technologies providing step-based feedbacks (i.e., recording minute-by-minute step accumulations) did not allow individuals to track the intensity of physical activity. The global physical activity recommendations emphasize the intensity of physical activity to gain substantial health benefits (e.g., greater than moderate intensity), and other essential components of the recommendations (i.e., frequency and duration of physical activity recommended for major health outcomes) also rely on the performed intensity of physical activity (U.S. Department of Health and Human Services, 2018). As a number of recent studies have suggested some possible thresholds ranging 100 to 125 stepsmin^{-1} as a proxy measure of moderate intensity (Abel, Hannon, Mullineaux, & Beighle, 2011; Abt et al., 2019; Rowe et al., 2011; Tudor-Locke et al., 2019), using the real-time cadence will enable individuals to sustain recommended intensity of physical activity for their health improvement while engaging in physical activity, particularly ambulatory activities.

The strengths of this study include an extended investigation examining the capability of activity monitors to provide stable and accurate real-time cadence values for adhering to prescribed intensity of physical activity. In addition to the traditional validation protocols, the current study tested whether the monitors enable individuals to consistently maintain a prescribed intensity of physical activity during a given time, which is required for the individuals to obtain substantial health benefits. Overall, greater than 90% of the participants showed their abilities to maintain the prescribed intensity using the real-time cadence values provided by the activity monitors. Although some participants failed to comply with the prescription, their average walking intensity was slightly lower (e.g., 119 steps min^{-1}) than the target (i.e., >120 steps min^{-1}). The target cadence is comparable to brisk walking indicating a typical example of moderate-intensity physical activity (Ainsworth et al., 2011). Such a high accuracy and extensive compliance level indicate that the activity monitors may be a promising intervention tool for intensity prescription of physical activity. When using these activity monitors for promoting physical activity in a practical setting, the participants' ability to utilise the monitors has to be confirmed prior to implementing an intervention programme in order to improve the effectiveness of the programme (Lee, Kim, & Welk, 2014, Maher, Ryan, Ambrosi, & Edney, 2017).

Several study limitations should be acknowledged. Although the recruitment process was targeting a general adult population, only young individuals (18–42 years) within the normal range of BMI participated in the present study. Some caution should be exercised when generalising the findings to specific populations such as the elderly and overweight/obese individuals. In addition, the study tested a single cadence cut-point (>120 steps min^{-1}) to examine the utility of real-time cadence for prescribing the recommended intensity of physical activity. Prescribing a different intensity or a range of intensities may result in different consequences. Further research targeting multiple intensities is warranted. It is also possible that wearing 2 wrist-based devices on the same wrist simultaneously might influence the validity of real-time cadence measurement. However, the counterbalanced configuration used in the current study might minimise any possible bias caused by the simultaneous placement of the 2 devices. Lastly, only one slow running trial was included to determine the running validity. The monitors may perform differently during faster running speeds.

In conclusion, the current study provides evidence of validity for real-time cadence derived from commercially available activity monitors. Highly accurate measures were produced from the cadence sensors (FP and SS) attached to shoelaces and transmitted to a compatible activity monitor. An impressive finding with the sensors was the constant accuracy in estimating real-time cadence regardless of walking speeds. Although both watch-based monitors (GM and PL) showed a reduced accuracy during slow walking, their performances were also adequate for prescribing moderate- to vigorous-intensity ambulatory activities. Overall, all activity monitors included in this study are highly valid. Additionally, the real-time cadence appears to be a useful strategy to prescribe a recommended physical activity intensity for substantial health benefits.

Disclosure statement

No potential conflict of interest was reported by the authors.

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