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Validity of Four Activity Monitors during Controlled and Free-Living Conditions

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The purpose of this study was to examine the step count validity of the pendulum-based Yamax Digiwalker SW-701 pedometer (YX), piezoelectric Omron HJ-720T pedometer (OP), uni-axial Polar Active accelerometer (PAC), and micro electro-mechanical system Actigraph gt3x+ accelerometer (AG) during controlled and free-living conditions. A convenience sample of college-aged students participated in condition 1 (treadmill walking, n = 43; 21 females) and condition 2 (free-living, n = 37; 18 females). During condition 1, subjects performed treadmill walking with the four devices at five speeds for three minutes per stage while a researcher manually counted steps to provide a criterion measure. During condition 2, subjects wore the devices for three days while performing normal daily routines. The YX was utilized as the comparative monitor for condition 2. In condition 1, the OP was within 1.1% of manually counted steps during all speeds, while the PAC underestimated steps at all speeds from -6.7% to -16%. The YX and AG step counts were inaccurate at slow speeds, but became accurate as speed increased. In condition 2, the OP mean percent error ranged from -1.0 to -3.3% daily

compared to the YX. The AG step counts were also accurate compared to the YX (mean percent error between +2.2 and -2.5% daily). The PAC overestimated steps by 44.0% (5,265 steps) per day. This overestimation was observed for each of the three days. When observing each day individually, mean error was between +40.8% and +50.0% per day. In our sample of apparently healthy individuals, the OP and AG provided reliable stepping information when compared to the YX. Caution should be used if selecting the PAC for stepping information. Future studies validating the step count abilities of these monitors in additional populations are warranted.

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DURING CONTROLLED AND

FREE-LIVING CONDITIONS

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This thesis is dedicated to my best friend, Nicholas W. Schmit (5/15/1986 - 6/5/2013). Philippians 1:3 - I thank my God upon every remembrance of you.

J.A.L.

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CHAPTER I

VALIDITY OF FOUR ACTIVITY MONITORS DURING CONTROLLED AND FREE-LIVING CONDITIONS

Introduction

Physical inactivity[1] and exercise-deficit disorder[2] are terms that have been developed to describe the sedentary culture that has evolved in the U.S. It is well-documented that individuals that are sedentary have increased health risks compared to those that are more active.[3] Acknowledging this, many organizations have established activity level recommendations to promote health and well-being in hopes of attenuating the risks of leading a sedentary lifestyle.[4–6] The most common form of activity recommended by health professionals, and practiced by the lay public, is ambulatory activity (i.e. walking and jogging).[7,8] Activity monitors are frequently used in conjunction with recommendations to quantify and prescribe daily activity, most commonly through step counting. Additionally, step counting is often used in interventions because the health-literacy burden is low, making it easier for laypersons to interpret their own activity levels.[9] Pedometers and accelerometers are frequently used as tools to measure activity, specifically in the form of steps. One problem with utilizing these monitors for physical activity assessment is the mass availability of different manufacturers and model. Differences exist in the technological methodology used within these monitors to collect stepping data. For example, the mechanism used inside pedometers often differs from those used in accelerometers. Further, there are differences in technology between models of pedometers (pendulum vs. piezoelectric) and models of accelerometers (piezoelectric vs. micro electro-mechanical systems [MEMS]). The differences in technology between devices may lead to the reporting of dissimilar activity information. Therefore, continued validation of new activity monitors is exigent in order to provide researchers and consumers with data on which monitors are acceptable step counters in all settings.

Validating pedometers and accelerometers in controlled settings (i.e. treadmill walking) is important due to the capability of using a gold-standard step counting criterion (video recording or manually counting steps). However, validating activity monitors in free-living settings is equally imperative because this is where many interventions take place and natural activity/movement occurs. The purpose of this study was to validate and compare the step counting ability of four activity monitors: the pendulum-based Yamax Digiwalker SW-701 pedometer, the piezoelectric Omron HJ-720T pedometer (OP), the Actigraph gt3x+ (MEMS) accelerometer (AG) and the Polar Active (uni-axial) accelerometer (PAC), in controlled and free-living settings.

Methods

Participants

A convenience sample of college-aged males and females participated in condition 1 (treadmill walking, n = 43; 21 females, 22 males) and condition 2 (free-living, n = 37; 18 females, 19 males). Height and weight were measured using a stadiometer (Detecto Prodoc PD300, Webb City, MO) in light clothing and without shoes to the nearest 1.0 cm and 0.1 kg. Demographic characteristics are presented in Table 1. During condition 2, subject loss was experienced due to improperly filling out the step-log, device malfunction and non-compliance to wear protocol (wearing all devices on all days and removing all devices when any device is taken off). Research procedures were reviewed and approved by the Institutional Review Board at Illinois State University. Written informed consent was obtained from all subjects prior to participation in the study.

Instruments

The Yamax Digiwalker SW-701 (YX), Omron HJ-720T (OP), Actigraph gt3x+ (AG) and Polar Active (PAC) were used in both studies. All devices were worn in accordance with manufacturer recommendations. Device wear location was constant for each subject (OP worn on the left hip, YX and AG worn on the right hip and PAC worn on the left wrist).

The YX is a pendulum-based pedometer that employs a lever-arm that is displaced by vertical movement at the hip. The displacement causes the lever-arm to strike a metal surface which opens and closes an electrical circuit, a step is registered for each strike.[10–12]

The OP is a bi-axial, pedometer that utilizes piezoelectric technology. Piezoelectric pedometers contain a cantilever beam with a weight attached to the end. The weight is displaced and the piezoelectric crystal is compressed by acceleration of the body (wearer). The compression generates a voltage proportional to the force of the movement and the voltage oscillations are used to record steps.[10,13,14] The level of voltage generated is proportional to the displacement of the weight, which allows for classifying stepping intensity/rate.

The AG possesses an ADXL335 tri-axial accelerometer (MEMS) that measures steps and movement through the displacement of fixed plates (capacitors). The amount of displacement endured by the weights triggers a proportional electrical output by the capacitors expressing the movement by converting the electrical signal into voltage. A demodulator output then determines the intensity and direction of the movements from the recorded readings.[15–18] This process allows for estimates of steps, activity energy expenditure, activity counts in multiple planes, and minutes of time spent in specific activity intensity zones. Further, the AG offers optional data collection settings including sampling at 30-100 hertz (10 hertz intervals) and normal (NF) or low-frequency extension (LFE) filter options. The present study utilized one-second (condition 1) and one-minute (condition 2) epochs, sampled at 30-hertz (both studies) with the NF filter (both studies).

The PAC employs a proprietary uni-axial accelerometer and is worn on the wrist. The PAC offers information on step counts, energy expenditure and minutes of activity in intensity zones (i.e. light, vigorous, etc). To our knowledge no study has reported on the accuracy of the PAC to estimate step counts in either controlled or free-living conditions, although it has been studied as a weight-loss tool in military personnel.[19]

Condition 1: Treadmill Walking

The purpose of condition 1 was to determine the accuracy of the YX, OP, AG and PAC when compared to manually counted (MC) steps (criterion) during treadmill walking. A researcher hand tallied steps providing for manually counted steps. Subjects walked for three-minutes at speeds of 54, 67, 80, 94 and 107 $m \cdot min^{-1}$ at 0% grade. Between each stage subjects straddled the treadmill and stood motionless for two-minutes while researchers recorded device step counts. This also allowed determination of stage start and end times in the AG data log.

Condition 2: Free-living

The purpose of condition 2 was to compare step counts between the OP, AG and PAC during a 3-day wear period (excluding sleep and water based activities) when compared to the YX, which has been validated elsewhere.[10,12,20] The YX was utilized as the comparative monitor in condition 2 because it has been validated and used as such in similar settings.[10,12,15,20] The monitor wear location was identical to the protocol used in condition 1 and subjects were shown how to wear and handle the monitors prior to putting the devices on. The subjects were also asked to place the monitors on themselves before leaving with the monitors to show that they were familiar with the wear protocol. Due to the inability of the YX to distinguish between days, subjects were asked to record the YX daily step counts on a step-log sheet that was provided. Steps were recorded each night when subjects removed the devices prior to sleeping and subjects were asked to reset the YX each morning when they replaced the devices to wear the next day.

Statistical Analysis

Descriptive characteristics for both studies are presented in Table 1. In condition 1, intra-class correlations (ICC) were used to determine the strength and consistency of the associations between steps recorded by the OP, AG, PAC, YX and MC steps at each treadmill speed. A 5x5 repeated measures ANOVA was used to identify potential differences between the monitors and MC steps across each treadmill speed. Post-hoc least significant difference testing was used to identify the speeds where differences occurred. Standard Error of Measurement (SEM) was computed to provide information about the variation in step counts between manually counted steps and the YX, OP, PAC and AG during each stage.

In condition 2, ICC's were used to determine the magnitude and consistency of associations between the steps recorded by each device for each of the three days the devices were worn. Bland Altman plots were constructed to show the distribution of daily step counts between the devices for each of the three days the monitors were worn across the various quantities of steps taken. A 4x4 repeated measures ANOVA was used to identify potential differences between monitors and daily step counts and also for 3-day step count averages. A post-hoc least significance difference test was ran to identify the days that differences between the YX and the other monitors occurred. SEM was calculated to provide a potential range for step counts for the 3-day average step counts. For both studies, alpha ≤ 0.05 was used to determine statistical significance. All analyses were performed using IBM SPSS statistics version 20 (Somers, NY).

Results

Condition 1

Intra-class correlations were used to determine the strength and consistency of associations between device step counts and MC steps at each speed. The relationship between MC steps and YX steps were significant at all speeds except 54 $m \cdot min^{-1}$. The associations strengthened as speed increased r = 0.281 ($p = 0.141$), 0.528 ($p = 0.008$), 0.715 ($p < 0.001$), 0.974 ($p < 0.001$) and 0.991 ($p < 0.001$) at 54, 67, 80, 94 and 107 $m \cdot min^{-1}$, respectively. The associations between MC steps and OP steps were significant at all speeds and the magnitude of the associations were strong at all speeds ($r = 0.895$, 0.965, 0.993, 0.997 and 0.986; all $p < 0.001$ at 54, 67, 80, 94 and 107 $m \cdot min^{-1}$, respectively). The associations between MC steps and PAC steps were significant at speeds of 67, 80 and 94 $m \cdot min^{-1}$, but not 54 and 107 $m \cdot min^{-1}$. In general, the associations were moderate ($r = 0.392$; $p = 0.053$, 0.469; $p = 0.020$, 0.511; $p = 0.011$, 0.668; $p < 0.001$ and 0.39; $p = 0.050$ at 54, 67, 80, 94 and 107 $m \cdot min^{-1}$, respectively. The relationship between MC steps and AG steps were weak and non-significant during slower speeds ($r = 0.294$; $p = 0.132$ and 0.325; $p = 0.103$ of 54 and 67 $m \cdot min^{-1}$, respectively), moderately-strong at 80 $m \cdot min^{-1}$ ($r = 0.610$; $p = 0.001$) and strong at faster speeds ($r = 0.994$ and 0.993; both $p < 0.001$ at 94 and 107 $m \cdot min^{-1}$ respectively). The results of a 5x5 repeated measures ANOVA showed that differences existed between MC steps and the monitors during each speed. The 95% confidence intervals and SEM are reported in Table 2. SEM was calculated to provide the variation in step counting error by the monitors at each speed. For the YX the SEM decreased as speed increased (71, 36, 14, 3 and 2 at 54, 67, 80, 94, and 107 $m \cdot min^{-1}$, respectively). For the OP the SEM was low during all speeds (8, 4, 2, 1 and 2 at 54, 67, 80, 94, and 107 $m \cdot min^{-1}$, respectively). For the PAC the SEM varied as speed increased (52, 43, 32, 20 and 44 at 54, 67, 80, 94, and 107 $m \cdot min^{-1}$, respectively). For the AG the SEM generally decreased as speed increased (34, 47, 21, 1 and 1 at 54, 67, 80, 94, and 107 $m \cdot min^{-1}$, respectively). The YX and AG steps were different from MC steps at 54 and 67 $m \cdot min^{-1}$ ($p < 0.05$) but similar at the other speeds. The PAC underestimated steps at all speeds ($p < 0.05$). The OP was not different from MC at any speed ($p < 0.05$) and had an average percent difference from MC steps of < 1.1% during all speeds. Figure 1 is a representation of the average device percent difference from MC at each speed during treadmill walking. In general, the YX, PAC and AG step counts became more accurate as speed increased, while the OP was accurate at all speeds. The PAC was the only monitor that the percent difference from MC remained > 6% different for speeds ≥ 80 $m \cdot min^{-1}$.

Condition 2

In free-living, ICC's showed that the strength and consistency of associations between the YX (comparative) and the other monitors step counts were strong when comparing 3-day average step counts. The associations were $r = 0.892$, 0.908 and 0.898 (all $p < 0.001$) for the OP, PAC and AG, respectively. However, a 4x4 repeated measures ANOVA indicated that differences between devices existed when comparing each of the three days individually and the 3-day average step counts. The 95% confidence intervals identified that the PAC overestimated step counts each day when compared to the YX, while the OP and AG were not different from the YX on any day. Table 3 shows daily and 3-day average step counts for each device, along with raw average step counts, step count percent differences for each device from the YX, and the 3-day average SEM. On average, the OP and AG underestimated steps compared to the YX by 301 and 181 steps per day, respectively ($p < 0.05$). In contrast, the PAC overestimated steps by 5,265 steps per day. The 3-day average SEM for each device when compared to the YX was 1,458, 2,018 and 1,392 for the OP, PAC and AG, respectively. Figure 2 identifies a regression equation to adjust for the overestimation of steps by the PAC when compared to the YX ($r^2 = 0.77$, SEE = 977.5). Bland-Altman plots demonstrating the three-day average step counting agreement between the OP, PAC and AG and the YX are reported in Figure 3.

Discussion

Condition 1 examined the accuracy of step counts by the Yamax Digiwalker SW-701 pedometer, Omron HJ-720T pedometer, Polar Active accelerometer and Actigraph gt3x+ accelerometer in controlled conditions when compared to a criterion measure (manually counted steps). With regards to the YX and OP, our findings were similar to previous research concluding that the YX underestimated steps at slower speeds but became more accurate during moderate and brisk walking speeds[10,12,20], and the OP was highly accurate during treadmill walking at all speeds.[14,21,22] The AG displayed the most step counting error at speeds of 54 and 67 $m \cdot min^{-1}$, registering only 59.6% and 87.9% of manually counted steps for each stage, respectively. However, the AG was accurate during moderate and brisk walking speeds registering 96.7% to 99.5% of manually counted steps at these speeds. Our findings during slow walking speeds are comparable to those reported by Webber et al.[23] who showed that the AG was inaccurate while counting steps in a sample of older adults (with and without walking aids) walking 100 meters, recording 52% of steps taken compared to manually counted steps. Based on the present findings, the AG should be considered a viable option for researchers interested in step counts during normal to brisk walking when utilizing comparable device settings (NF filter and 30 hertz sampling rate). The PAC was the only monitor that was not accurate during walking at any treadmill speed, significantly underestimating steps by 16.0% to 6.7% at each speed. Although not a purpose of this study, we examined whether step count differences existed between normal weight subjects and overweight/obese subjects (based on national BMI cut points) and, in general, no differences in step counting accuracy were present in the YX, OP, and AG monitors.

However, the PAC was only different from manually counted steps at 94 $m \cdot min^{-1}$ in normal weight subjects, but inaccurate at all speeds in overweight subjects. Again, although not a purpose of this study, we also examined between-sex differences in the monitor's abilities to accurately estimate steps and no differences were present. Based on our findings, caution is warranted when using the PAC to count steps. To our knowledge this is the first study reporting on the step counting accuracy of the AG in a healthy population, and the PAC in any population within controlled conditions.

Condition 2 investigated the ability of the OP, PAC and AG to count steps during a 3-day free-living wear period when compared to the YX. Although the OP was found to be the most accurate monitor during treadmill walking, the YX was utilized as the comparative monitor because it has been frequently used as such in similar research settings.[10,12,15,20] We found that the OP step count mean percent difference from the YX was -2.5% (-301 steps per day) when observing the 3-day average step counts. The OP percent error ranged from -1.0 to -3.3% daily. These findings are unlike those reported by Silcott et al.[14] who reported that the OP (when worn on the waist) underestimated steps in free-living by 36%, 37% and 48% in normal, overweight and obese individuals, respectively, compared to the StepWatch3 during a 24-hour free-living wear period. It should be noted that they also found the Yamax Digiwalker SW-200 (YX200) step counts to be different from the StepWatch3 although the YX200 has frequently been used as a comparative monitor in free-living studies. Another study by Dondzila et al.[21] reported that the OP underestimated step counts by 13.0% and 6.8% in young and older adults, respectively when compared to a New Lifestyles NL-1000 (NL1000) pedometer during a 24-hour free-living wear period. Both Silcott and Dondzila et al. cited the OP's

4-second step filter as a potential limitation causing the underestimation of steps. Robust differences exist in the step counting ability of the OP reported by this and the aforementioned studies (mean error 1% to 48% per day). One reason these studies may have conflicting findings is the utilization of different comparative monitors. Our study utilized the YX while Silcott et al. and Dondzila et al. utilized a StepWatch3 and a NL1000, respectively. These monitors each utilize different step counting mechanisms and, in the case of the StepWatch3, different wear locations. The utilization of different comparative monitors obfuscates any between-study comparisons. Until a viable criterion measure for step counting during free-living conditions is available, this limitation will persist in this and all free-living validation studies. Further research examining the step count validity of the OP during free-living in various populations is warranted.

Additionally during condition 2, we found the AG to be accurate at estimating steps when compared to the YX. When considering the 3-day average step counts, the AG mean step count percent error was -1.5% (-181 steps per day). When observing each day individually, the AG mean percent error was between +2.2 and -2.5% daily. The 2003-04 and 2005-06 National Health Examination and Survey (NHANES) utilized a previous Actigraph accelerometer (model 7164) to collect physical activity information, and from this numerous studies have reported nationally representative stepping information.[24–26] The 2011-14 NHANES is presently utilizing the Actigraph gt3x to collect physical activity data, though the monitor will be worn on the wrist. It is exigent to continue validating devices being used to collect data that will eventually be used to establish national recommendations and activity levels. Barreira et al.[27] investigated the validity of the AG step counts during a 7-day free-living data collection in a sample of older adults (aged 61-82 years) utilizing both filter options the AG offers (NF and LFE). They reported that when utilizing the NF filter option the AG step counts were significantly different from the comparative monitor (NL1000) and that the absolute percent difference in step counts was 16.0%. When utilizing the LFE filter option the step counts recorded were again significantly different and the absolute percent difference was 121.9% (+8,140 steps per day). Although the correlations for step counts utilizing both the NF (r = 0.80) and LFE (r = 0.90) filter options were moderately-strong to strong, the actual step counts recorded were not accurate. Additional research by Barreira et al.[15] examined the step count validity of a previous Actigraph accelerometer (model gt3x, which employs the same internal mechanism for recording data as the AG) utilizing a sample of overweight and obese adults (mean age 52.6 years). Subjects wore the Actigraph gt3x (gt3x) along with a YX200 (comparative monitor) for 7-days during free-living conditions. They found that there was a significant difference in the absolute percent difference of step counts recorded of 23.9% between the gt3x and YX200. Further analysis indicated that there was no consistent reporting of steps per day by the gt3x with 52.7%, 24.7% and 22.6% of days being under, acceptable and over reported, respectively. It should be noted that spring-levered pedometers have been shown to be inaccurate when worn by overweight and obese subjects due to an altered tilt angle.[13] Potential reasons for the discrepancy in the reporting of steps between the studies observing AG step counts include the differences in comparative monitors utilized and the difference in weight status of the participants. As noted previously, the AG has not been found to be accurate at reporting steps in subjects that walk slowly. Also, the utilization of a spring-levered pedometer as a comparative monitor when utilizing overweight and/or obese subjects or slow or impaired walking populations could influence results. The present study supports the use of the AG for stepping data in free-living settings when utilizing apparently healthy populations.

Similar to condition 1, the PAC performed poorly during free-living. We found that the PAC overestimated steps each day by 40.8% to 50.0% when compared to the YX. The mean percent error was +44.0% (+5,265 steps per day). One reason the PAC may tend to overestimate steps during free-living could be because it is worn on the wrist. Wrist-worn accelerometers may record steps during hand movement (e.g. writing, eating, weight-lifting, etc) when steps are not being taken. Also, adding a second axis to the monitor may allow for more accurate classification of steps and reduce the tendency to overestimate steps in free-living. Similar to condition 1, we compared step counting accuracy by BMI status and no differences were found. However, when comparing differences between sexes, the PAC was not significantly different from YX step counts on any day or for the three-day average step counts in females. In males, step counts were different on each day and for the three-day average step counts. Caution should be used when utilizing the PAC for step counting information.

There are limitations to the current study. The majority of our subjects were young and perceived to be active and fit, therefor, further research examining additional populations is necessary. Also, there is no feasible criterion measure available for step counting in free-living conditions. The use of a criterion measure in condition 1 is a strength of this study. Utilizing a 3-day wear period during condition 2 was another strength of this study as it allowed for the observation of consistent over, under, and/or acceptable step count information across multiple days.

In summary, in controlled conditions the YX, OP and AG performed well during moderate and brisk walking speeds providing step counts within 3.3% of manually counted steps at 80 $m \cdot min^{-1}$, and within 0.6% at speeds of 94 and 107 $m \cdot min^{-1}$. In contrast, the PAC performed poorly at all speeds (6.7% to 16.0% error in step counting). During free-living, both the OP and AG were accurate step counting monitors in an apparently healthy population when compared to the YX. Considering this, the OP and AG could be considered acceptable for use in research and intervention settings when stepping information in apparently healthy populations is the goal. The PAC showed poor validity in step counting during free-living overestimating steps by an average of 44.0% per day. Caution is warranted when utilizing the PAC to report stepping information. Future research investigating the step counting validity of each of these monitors in more diverse populations is desirable.

TABLE 1. Participant Demographics for Condition 1 and Condition 2.

	Condition 1 (Treadmill Walking)	
Variables	**Males (N = 22)**	**Females (N = 21)**
Age (yr)	20.9 (1.9)	20.9 (2.1)
Height (cm)	175.6 (4.7)	165.8 (5.8)
Weight (kg)	78.5 (9.0)	63.8 (10.3)
BMI ($kg \cdot m^{-2}$)	25.5 (2.7)	23.1 (2.9)

	Condition 2 (Free- Living)	
Variables	**Males (N = 19)**	**Females (N = 18)**
Age (yr)	21.6 (2.8)	21.1 (2.5)
Height (cm)	175.6 (4.9)	165.5 (1.2)
Weight (kg)	78.8 (9.2)	63.5 (6.2)
BMI ($kg \cdot m^{-2}$)	25.5 (2.6)	23.2 (2.3)

*Values are mean (SD).

TABLE 2. Comparison of Step Counts Between Manual Count and Yamax, Omron, Polar Active, and Actigraph during Treadmill Walking.

Walking Speed ($m \cdot min^{-1}$)	Manual Count	Yamax	Omron	Polar Active	Actigraph
54	282 (276-288)	191[M] (167-216)	279 (271-287)	237[M] (217-258)	168[M] (156-180)
67	313 (308-319)	287[M] (272-302)	313 (307-318)	280[M] (262-299)	275[M] (257-292)
80	334 (329-340)	324 (316-332)	334 (329-340)	306[M] (292-320)	323 (312-334)
94	356 (351-361)	356 (351-361)	356 (351-361)	332[M] (322-343)	354 (349-359)
107	378 (373-383)	379 (374-384)	377 (372-382)	348[M] (330-366)	376 (371-381)

		Standard Error of Measurement			
Walking Speed ($m \cdot min^{-1}$)	Manual Count	- Yamax	- Omron	- Polar Active	- Actigraph
54	Referent	71	8	52	34
67	Referent	36	4	43	47
80	Referent	14	2	32	21
94	Referent	3	1	20	1
107	Referent	2	2	44	1

*Values are mean (95% Confidence Intervals).

[M]Indicates steps were significantly different from Manual Count (criterion).

TABLE 3. Comparison of Daily and Average 3-Day Step Counts Between Yamax, Omron, Polar Active, and Actigraph.

Variable	Yamax	Omron	Polar Active	Actigraph
Day 1 Steps	13,319 (11,363-15,275)	12,910 (11,265-14,555)	18,756[Y] (16,548-20,964)	12,986 (11,382-14,589)
Day 2 Steps	10,809 (8,988-12,631)	10,703 (8,891-12,631)	15,861[Y] (13,525-18,198)	11,042 (9,276-12,807)
Day 3 Steps	11,782 (9,916-13,648)	11,394 (9,563-13,225)	17,089[Y] (14,628-19,549)	11,338 (9,630-13,046)
Average Daily Steps	11,970 (10,317-13,623)	11,669 (10,146-13,192)	17,235[Y] (15,197-19,273)	11,789 (10,325-13,252)
Average Step Difference from Yamax	Referent	-301	+5,265	-181
Average % Difference from Yamax	Referent	-2.5%	+44.0%	-1.5%
Standard Error of Measurement	Referent	1,458	2,018	1,392

*Values are mean (95% Confidence Interval).

[Y]Indicates significantly different from Yamax (referent).

- Indicates underestimated steps compared to Yamax.

+ Indicates overestimated steps compared to Yamax.

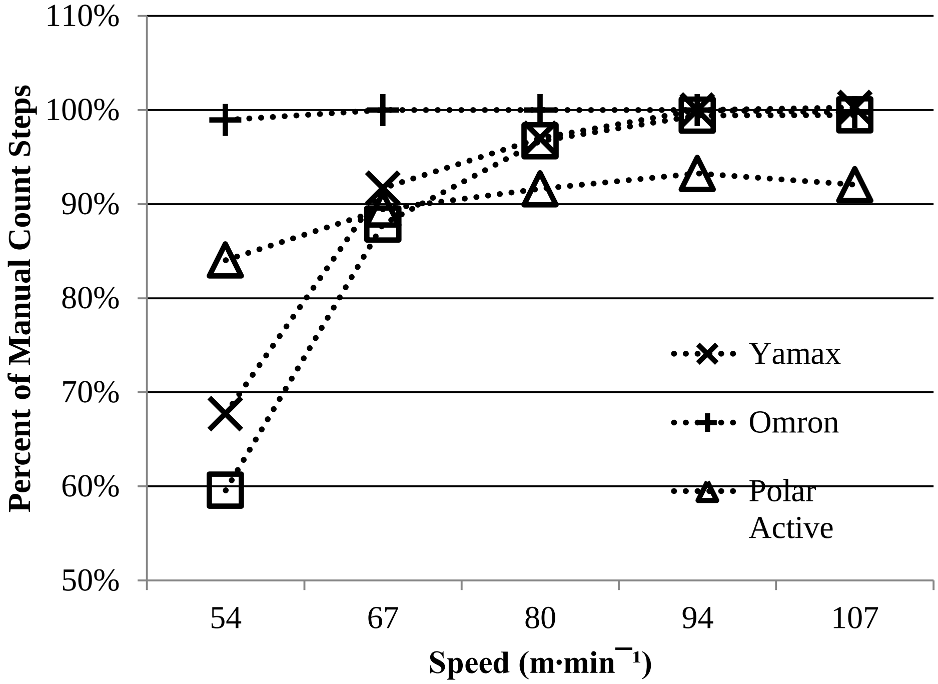

FIGURE 1. Effect of Speed on Monitor Accuracy during Treadmill Walking.

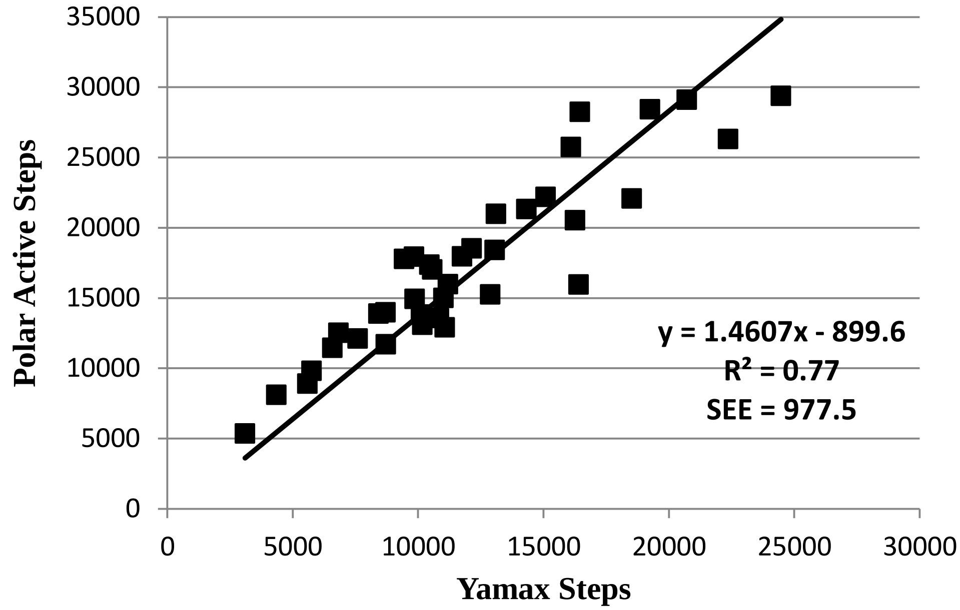

FIGURE 2. Regression Equation to Predict Polar Active Daily Step Counts from Yamax Step Counts during Free-Living.

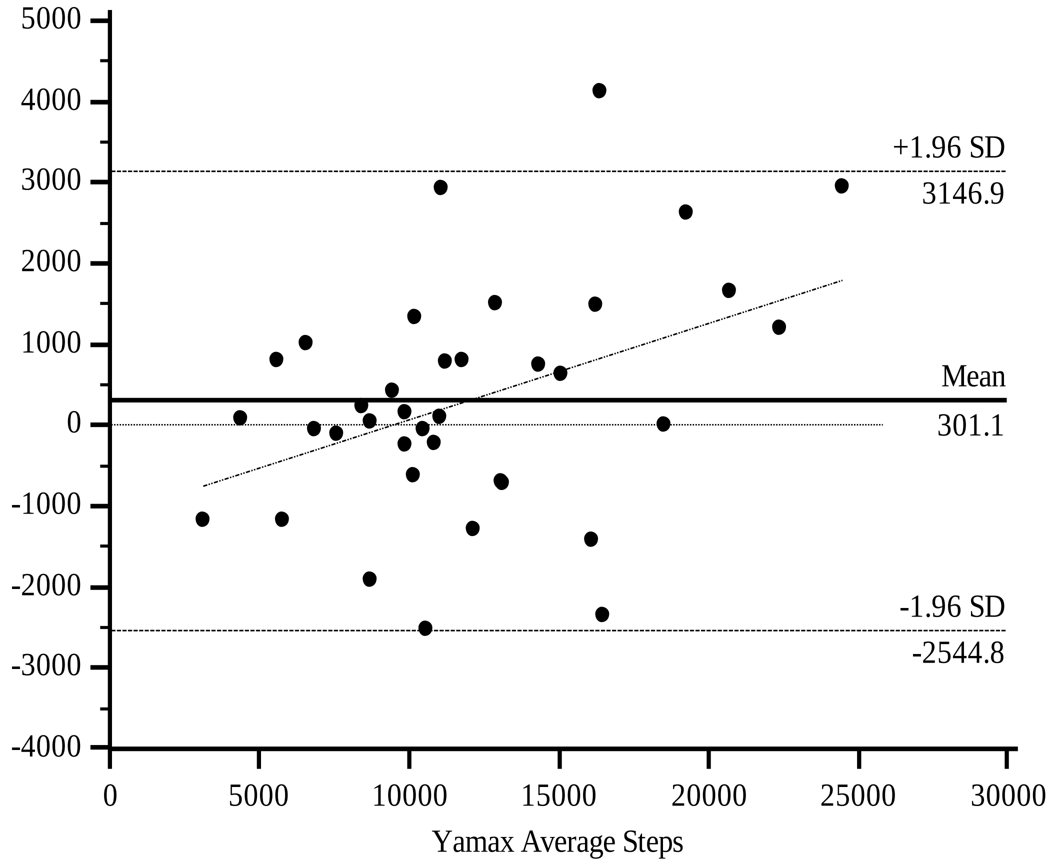

FIGURE 3. Distribution of 3-Day Average Step Counts Between the Yamax and Omron Pedometer Across the Various Quantities of Steps Taken.

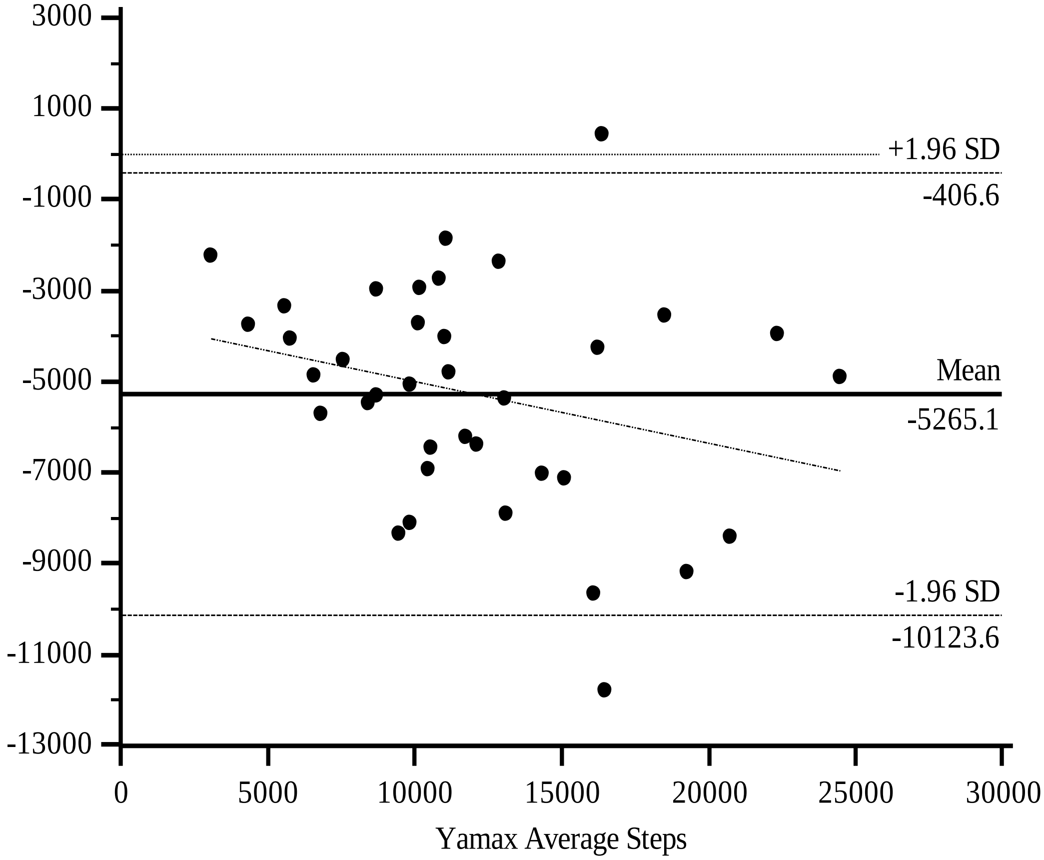

FIGURE 4. Distribution of 3-Day Average Step Counts Between the Yamax and Polar Active Across the Various Quantities of Steps Taken.

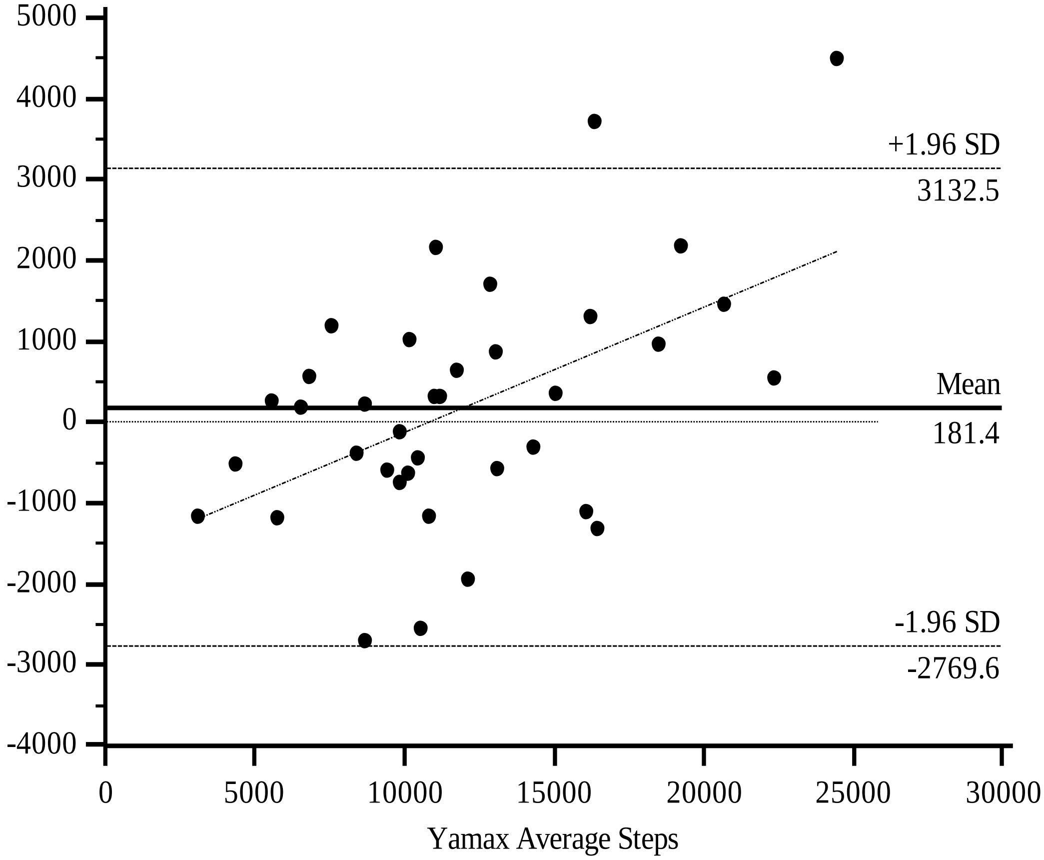

FIGURE 5. Distribution of 3-Day Average Step Counts Between the Yamax and Actigraph Accelerometer Across the Various Quantities of Steps Taken.

CHAPTER II

EXTENDED LITEREATURE REVIEW

Introduction

Terms such as physical inactivity (PIA)[1] and exercise-deficit disorder (EDD)[2] have been developed to highlight the sedentary culture that has developed in the U.S. A robust amount of research is available identifying that inactive individuals have increased health risks compared to their more active counterparts.[3] Acknowledging this, many organizations have established health-related activity level recommendations, such as accumulating 10,000 steps per day, to promote health and wellbeing and to attenuate potential health risks of a sedentary lifestyle.[4–6] The most common form of activity recommended by health professionals and practiced by individuals is ambulatory activity (i.e. walking and jogging).[7,8] Physical activity monitors are often used in conjunction with these recommendations to quantify individual’s activity levels each day, most commonly through step counting. Considering this, it is essential to validate activity monitors to provide physicians and consumers information on the step count accuracy each monitor provides.

Although numerous metrics are available to assess activity, such as minutes of moderate to vigorous physical activity (MVPA) and energy expenditure (EE), step counts are frequently utilized because high levels of health literacy are not required to understand step count recommendations and implement step count goals.[9] Additionally, step count outputs are easily interpretable. Coupled with user-friendliness, an additional benefit of using step counts is that most activity monitors estimate step counts in some fashion. The purpose of this review is to observe the accuracy of four activity monitors to estimate step counts in controlled and free-living conditions.

Monitor Step Counting Mechanisms

Even though many activity monitors assess step counts, devices use different methods for counting steps, for example, pedometers estimate steps in a different manner than accelerometers. Further, the mechanism used to count steps varies between different manufacturers and/or models of the same types of devices (e.g. piezoelectric vs. pendulum-based pedometers, waist- vs. wrist-worn accelerometers, and piezoelectric vs. micro electro-mechanical systems accelerometers). The use of different mechanisms to estimate steps within different activity monitors further supports the need to validate activity monitors as the technology implemented continues to progress.

It is important to identify the differences that exist within each type of monitor (e.g. comparing mechanisms used to estimate steps between pedometers) and between different types of activity monitors (e.g. comparing step counts between pedometers and accelerometers). Pendulum-based pedometers, also referred to as spring-levered, are worn on the hip and employ a lever-arm that is displaced when there is vertical movement at the hip. The displacement causes the lever-arm to strike a metal surface which opens and closes an electrical circuit, a step is registered for each strike.[10,12,28] The Yamax Digiwalker is a commonly used pendulum-based pedometer that has been found to be inaccurate at counting steps among overweight and obese populations (due to an altered tilt angle)[13] and during slow walking (i.e. 54-67 $m \cdot min^{-1}$), but is considerably more accurate during moderate and brisk walking.[10,12,20]

Piezoelectric pedometers are a common alternative to pendulum-based monitors. Piezoelectric pedometers contain a cantilever beam with a weight attached to the end. When acceleration is sensed, the weight is displaced and the piezoelectric crystal is compressed. The compression generates a voltage proportional to the force of the movement/displacement and the voltage oscillations are used to record steps.[10,11,13,14] The level of voltage generated is proportional to the displacement of the weight, which allows devices that employ piezoelectric technology (such as the Omron HJ-720T pedometer) to distinguish between step intensities, allowing for classification of step and activity intensity rates. Piezoelectric pedometers can be uni-, dual/bi- or tri-axial, enabling piezoelectric pedometers to record in horizontal, horizontal and vertical, or horizontal, vertical, and flat conditions, respectively. Piezoelectric pedometers have been found to be accurate during all walking speeds and across all BMI statuses.[13,14,22,29]

Accelerometers are a more recent addition to the realm of quantifying physical activity, specifically in the form of steps. In general, accelerometers estimate activity by utilizing internal mechanisms that are sensitive to acceleration (movement) and converting accelerations into voltages that are expressed as specific intensities of movements (i.e. light, moderate, vigorous), steps and activity EE. However, accelerometers quantify these metrics differently depending on the internal mechanism used (i.e. piezoelectricity or micro electro-mechanical systems [MEMS]). Actigraph accelerometers are the most commonly used accelerometers in research settings, most notably used in the 2003-2006 National Health and Nutrition Examination Survey (NHANES) data collection.[30,31] The most recent model of the Actigraph accelerometer (gt3x+) possesses an ADXL335 tri-axial accelerometer, more commonly referred to as a MEMS accelerometer. This accelerometer measures steps and movement through the displacement of fixed plates (capacitors) in relation to one another. The amount of displacement endured by the plates triggers a proportional electrical output by the capacitors. The movement is expressed when the electrical signals are converted into voltages. A demodulator then determines the intensity and direction of movements from the recorded voltage readings and quantifies the data in a user-friendly output .[15–18] This process allows for estimates of steps, activity energy expenditure, activity counts in multiple planes, and minutes of time spent in specific activity intensity zones. Additionally, many accelerometers are designed to be worn on either the waist or the wrist (e.g. Actigraph accelerometers), but some accelerometers are designed to be worn in a specified location, such as on the wrist in the instance of the Polar Active accelerometer.

Validity of Step Counting Monitors

Validation of activity monitors typically takes place in two settings, controlled and free-living. Controlled conditions are carried out on a treadmill or pre-measured distance (commonly a flat surface or track). Often, subjects perform stages of walking or running at varying speeds while wearing activity monitors with researchers employing a criterion measure (i.e. hand-counting steps and/or video recording devices) to count steps. Free-living validation studies are performed to compare step counts between monitors utilizing a previously validated device as the criterion. Free-living studies require subjects to wear devices in their normal environments and carry-out their typical daily routines while wearing the monitors. To date, there is no feasible gold standard activity monitor for step counting in free-living conditions. Both controlled and free-living studies are necessary, however free-living studies possess greater practical implications for intervention and consumer purposes. Limited literature exists observing the step count accuracy of the Actigraph gt3x+ accelerometer and Omron HJ-720T pedometer (OP720), and to our knowledge, no study has examined the Polar Active wrist-worn accelerometer's ability to estimate steps in controlled or free-living conditions.

Yamax Digiwalker SW-701 Pedometer

Crouter et al.[12] observed the accuracy and reliability of the Yamax Digiwalker SW-701 (YX) and nine other pedometers from varying manufacturers to count steps, distance traveled, and EE during treadmill walking. Five male and five female subjects were asked to complete five, five-minute stages of walking at speeds of 54, 67, 80, 94 and 107 $m \cdot min^{-1}$ while wearing a pedometer of each brand on the left and right side of their body at the midline of their thigh. After each stage subjects straddled the treadmill and stood motionless while researchers recorded the step counts from each pedometer. The step count criterion measure was hand tallied steps. Indirect calorimetry was used during the last two-minutes of each stage to assess EE during steady state. The two-minute measurement was averaged and multiplied by five for comparison across the pedometers. Also, resting metabolic rate (RMR) was assessed for each subject prior to testing. Each subject was asked to perform an overnight fast and to avoid stimulants and intense physical activity prior to testing. The RMR measurement allowed researchers to calculate activity energy expenditure (energy expenditure above RMR) from indirect calorimetry to compare against pedometers. Finally, distance was calculated by multiplying time by pace.

The key finding from the study was that, the YX step counts were not significantly different from hand counted steps at any speed. Additionally, the YX was within ±1% of hand counted steps at speeds ≥ 80 $m \cdot min^{-1}$. The authors also concluded that the YX could be worn on the right or left side of the body (correlation coefficient = .98). In general, it was reported that pedometers should not be used to estimate distance or EE. The researchers indicated that pedometer selection should be made based on what variable was most important to their study. With regards to steps, the YX was highly accurate during controlled conditions and recommended. Although these results were promising, further studies investigating alternative testing conditions were necessary.

A study by Schneider et al.[10] observed the step count validity of the YX and nine other pedometers while walking on a 400-meter outdoor track. Subjects included ten males and ten females between the ages of 22 and 69 years. Subjects walked a single lap at a self-selected pace around the track while wearing two pedometers of the same model on their left and right sides per the manufacturer's recommendations. A researcher walked behind the subjects counting their steps with a hand counter as the criterion measure. This process was repeated for each make of pedometer. The testing was completed over a one to four day period and subjects wore the same pair of shoes for all trials. Similar to the previous study, the YX was found to be highly accurate at counting steps (±3%, 95% of the time) and was able to do so accurately on both the left and right sides. Additionally, the intra-model reliability of the YX was > 0.99. Considering the accuracy of the YX in multiple walking conditions, testing in free-living conditions with natural and less structured movements was encouraged.

To build on previous research, Schneider et al.[20] considered the accuracy of pedometers to estimate steps during free-living conditions. For this study the Yamax Digi-walker SW-200 (YX200) was considered as the referent monitor because of the Yamax SW series' (which all utilize the same step counting mechanism) consistent success in controlled laboratory conditions when assessing steps. Ten male and ten female subjects with a mean age of 41 agreed to take part in the study. Subjects wore a YX200 on their left side and a second pedometer to compare to the YX200 on their right side for a one-day period. In total, twelve monitors were tested including a day wearing a YX200 on both sides to test left and right side differences. The order of pedometer wear was randomized for each subject. Taking into consideration the literature supporting the notion that considerably less steps are taken on Sunday's compared to other days, subjects were asked not to wear the devices on Sunday's.[32] Subjects put the devices on upon waking and were instructed to only remove them for showering and swimming. Subjects removed the devices prior to going to bed and recorded step counts for each device on a log sheet.

The results from the study revealed that only five of the twelve pedometers were not statistically different from the referent and seven of the twelve pedometers were within ±10% of steps recorded by the referent and deemed acceptable. The YX was among the devices that were not statistically different from the reference. As such, the researchers recommended the YX as an acceptable tool for quantifying step counts in free-living conditions.

In summary, the literature supports the YX as a highly accurate pedometer for use in research settings. Due to the significant portion of literature that supports the YX as a valid step counting monitor, it is frequently used in research settings as a comparative monitor. However, advances in technology have made new devices available for this purpose, containing alternative mechanisms used to count steps. These devices also assess metrics that pedometers are not capable of accurately quantifying, such as activity EE and MVPA. One such aforementioned mechanism is piezoelectricity, which is used in both pedometers and accelerometers.

Omron HJ-720T Pedometer

In contrast to spring-levered pedometers, pedometers possessing piezoelectric mechanisms are more sensitive to movement through requiring a lower peak vertical acceleration when estimating steps. Due to the difference in sensitivity, it was theorized that piezoelectric pedometers would be more accurate when estimating steps at slower speeds and more accurate in overweight and obese subjects (due to decreasing the impact of pedometer tilt angle on step counting) when compared to pendulum-based pedometers. In a study by Giannakidou et al.[33] two Omron pedometers, HJ-113 (OP113) and HJ-720T (OP720) (both employing bi-axial piezoelectric mechanisms), were tested in controlled conditions for their accuracy to estimate steps, distance traveled, and EE at five treadmill speeds, along with validating a YX200 (steps only) in a sample of healthy adults. Twenty-four male and eighteen female subjects participated in the study. Anthropometrics were assessed and programmed into the pedometers (height, weight, and stride length). Subjects were asked to walk at speeds of 54, 67, 80, 94 and 107 $m \cdot min^{-1}$ for five-minutes per stage. Two investigators hand tallied steps providing the criterion measure. Distance was assessed by multiplying speed by time and EE was assessed via open-circuit spirometry (Oxycon Champion IEC 601-1).

Both the OP113 and OP720 provided step counts that were ±1.5% of actual steps taken at all speeds. The YX200 provided accurate step counts at all speeds excluding 54 $m \cdot min^{-1}$. Similar to previous studies exploring the utility of pedometers to assess distance and EE, this study reported that the pedometers observed were not accurate at estimating these variables. However, the main finding was that both of the piezoelectric Omron pedometers were highly accurate at counting steps independent of speed. But the conditions of this study were controlled and the generalizability was limited to treadmill walking. Further studies utilizing more natural settings were recommended to build upon these findings.

In a study by Holbrooke et al.[22] the validity of two piezoelectric Omron pedometers during prescribed- and self-paced walking on an outdoor track was investigated. In addition, the validity of different wear locations was also considered. Forty-seven student volunteers took part in the study (24 males and 23 females). Subjects were verbally prompted to walk at slow, moderate, and very brisk paces with no other cues. Researchers were hopeful that the verbal cues would elicit speeds of 2, 3, and 4 mph for slow, moderate, and very brisk stages, respectfully. Subjects speed was recorded using a Speedtrap-2 timing system and steps were hand tallied by a study investigator serving as the criterion measure. Each subject performed one trial at each pace wearing the Omron HJ-151 (OP151) and one trial at each pace with the OP720. The wear protocol consisted of placing both the OP151 and OP720 pedometers on the left and right hip and at the midline of the back. For the OP720 additional wear locations were tested including the left and right pockets and in a backpack worn over the shoulders. The self-selected walking required subjects to walk a 1-mile course (once for each model) that included flat concrete walking, stair climbing and decent, grass-walking and road crossings.

The results indicated that the absolute percent error for the OP720 was 2.3%. When worn at the waistline the error ranged from 1.0 - 2.6%. Wearing the device in the pocket or backpack reduced accuracy. Although the OP720 was found to be accurate at slow, moderate and very brisk speeds, it should be noted that the mean pace for each stage exceeded the researchers targeted prescribed speed (slow, moderate, and very brisk = 2.7, 3.3, and 4.1 mph, respectively). This study was not without error and further research was warranted in both controlled and free-living conditions to verify these results.

To progress on previous research, Silcott et al.[14] compared the OP720 to the StepWatch3 (SW3) and the YX200 during free-living conditions. A second focus of this research was to observe the reliability of multiple wear locations of the OP720 including along the waistline, in a pant pocket, and around the neck on a string. Sixty-two volunteers aged 18-69 (31 males and 31 females) participated in the study. A phone interview was used to screen out individuals with abnormal gait patterns (e.g. Are you pregnant? Do you walk with assistance?). Each subject's anthropometrics were assessed in lab which included the following assessments: height, weight, hip and waist circumference, body composition (via bioelectrical impedance) and stride length. The day after attaining subject's anthropometrics, subjects wore each of the devices from the time they woke up until the time they went to bed. They were encouraged to perform normal daily activities and to avoid non-ambulatory activities such as cycling, lifting weights and using an elliptical. Subjects were asked to log the YX200 step counts after removing the devices at night because it has no internal memory to record daily step counts, but the OP720 and SW3 were capable of storing daily step counts.

For data analysis, subjects were separated into normal (n = 19), overweight (n = 23) and obese (n = 20) categories. The results showed that the OP720 underestimated step counts compared to the SW3 within all BMI categories, regardless of wear location. When worn around the neck the OP720 underestimated steps in normal, overweight and obese individuals by 37%, 37% and 57%, respectively. The same observation for the OP720 pocket wear location resulted in similar underestimations of steps by 32%, 30% and 35% in normal, overweight and obese classes, respectively. Finally, for the OP720 waist wear location, underestimations of 36%, 37% and 48% were seen in normal, overweight and obese categories, respectively. To explain part of the underestimation of steps by the OP720 the authors referenced the 4-second step filter that the OP720 utilizes. The 4-s step filter was implemented by the manufacturers to prevent the OP720 from overestimating steps by not counting steps in a sequence that lasts less than 4-seconds. The filter was utilized to eliminate incidental steps that take place from being registered (e.g. adjusting one's posture when seated, crossing one's legs or intermittent steps). The OP720, although very accurate in bouts of continuous walking, was found to be less suitable then the YX200 in free-living conditions with regards to normal and overweight individuals (both were unsuitable for obese subjects) when compared to the SW3.

Further research by Dondzila et al.[21] assessed the OP720 during treadmill walking, over-ground walking and free-living conditions in a convenience group of community dwelling young (aged 20-49 years, n = 53) and old adults (aged 50-80 years, n = 49). During the subject's first visit to the lab, anthropometrics including height, weight, waist circumference and stride length were assessed and the treadmill walking protocol was completed. The treadmill walking protocol consisted of walking at speeds of 53.6, 67.0, 80.4, 93.8 and 107.2 m·min^{-1} for five-minutes or until 85% of age-predicted max heart rate was reached. Subjects wore two devices during treadmill walking, the OP720 and the Kenz Lifecorder EX pedometer (LC). Between each walking stage subjects straddled the treadmill so that steps could be recorded from each device. The criterion measure for treadmill walking was hand tallied steps by a researcher. On a separate day participants returned to complete the over-ground walking protocol while wearing the OP720 and LC. During the visit, subjects were asked to walk three laps around an indoor track at three paces, a normal pace, a less than normal pace, and a faster than normal pace while a researcher followed them hand-counting their steps (criterion). A random subset of twenty (out of 103) subjects were selected and agreed to participate in two 1-day free-living data collection sessions with the OP720 and LC against a comparative measure (New Lifestyles NL-1000 pedometer [NL]). For these twenty subjects their third visit included instructions on how to wear the devices and to remove the devices before water-based activities (i.e. swimming and bathing). For the first day subjects wore the LC on a belt at their right waistline and the NL on their left waistline, this day was followed by a day of wearing the OP720 on a belt at the right waistline with the NL again on the left waistline. Subjects were given a step log sheet and asked to write down starting daily steps for each device and ending daily steps for each device each day. The subject's final visit was to return the monitors and step logs.

During treadmill walking the OP720 was accurate at each of the five speeds in both the young and old adult groups, while the LC was different from hand-tallied steps in both groups at 53.6 m·min^{-1} and also at speeds of 67.0 and 80.4 m·min^{-1} in older adults.

When considering the over-ground walking protocol the OP720 was again accurate in both young and old adults at each of the three speeds while the LC was inaccurate at counting steps in younger adults walking at a "less than normal" pace. As for free-living conditions, the OP720 underestimated steps when compared to the NL by 949.1 (13.0%) and 612.9 (6.8%) steps per day in young and old adults, respectively. Likewise to Silcott et al., the 4-second step filter was cited as being the most likely contributor to the underestimation of steps by the OP720 during free-living conditions. The current study noted important limitations including the lack of a true gold standard for counting steps in free-living conditions. Further, the subject pool was generally healthy with mean BMI classifications slightly above normal and mean waist circumference measures categorized as low health risk. Therefore generalizing to populations other than this should be done with caution.

Although limited research observing the step count abilities of the OP720 exist, generalizing the limited findings indicates that the OP720 is highly accurate during continuous walking, but inaccurate during free-living conditions (regardless of BMI and wear location). Further research is necessary utilizing alternative criterion measures, different populations, and longer wear periods in hopes of encapsulating normalized routines as opposed to 24-hour wear periods. Utilizing such a small window of time for data collection may lead to the inclusion of enhanced levels of abnormal activities or activity levels (i.e. reactivity). Reactivity to pedometers in adult populations has been said to last between 3 and 7 days.[34,35] If subjects are performing activities that they do not perform on a normal basis, such as running, they may lack the skill to perform the movement appropriately which could lead to errors in registering steps by pedometers.

As a method in attempting to reduce reactivity, some researchers utilize accelerometers that do not provide immediate feedback on activity, such as the Actigraph accelerometers, along with manipulation (i.e. telling subjects that the monitors are something other than an activity monitor) in free-living data collection settings.

Actigraph gt3x+ Accelerometer

Due to its recent release in (September 2010), limited research is available on the Actigraph gt3x+ accelerometer model. However, it uses the same MEMS accelerometer as the two models released before it, the Actigraph gt1m and gt3x. The gt3x+ measures and records accelerations ranging in magnitude from ±6g (opposed to 0.05 - 2.0 and 0.05 - 2.5g by the gt1m and gt3x, respectively) and the acceleration output can be digitized by a converter at rates ranging from 30 - 100 hertz in 10 hertz increments (opposed to the standardized 30 hertz sampling rate used by the gt1m and gt3x). Although these differences exist, Robusto et al.[18] compared the three aforementioned accelerometers in children and adolescents (aged 7 - 18) during two 45 - 60 minute activity sessions. Each session ranged in activities from sedentary (e.g. lying down) to moderate (e.g. over-ground walking) to vigorous (e.g. running) and each activity was performed for five-minutes. Their focus was on the vertical axis counts, vector magnitude counts and MVPA metrics. Their findings demonstrated that the three models demonstrated strong agreement and that the monitors could be used interchangeably. Considering this, and the limited amount of research available on the gt3x+ (AG), the present review included studies that utilized the Actigraph gt3x (gt3x) and the AG to assess step counts in various settings.

Connolly et al.[29] compared the step count validity of four activity monitors during treadmill walking in pregnant women. Women were at least 18 years old and between 20 - 34 weeks pregnant. The subjects walked at four speeds (54, 67,80 and 94 $m \cdot min^{-1}$) for two-minutes per stage while wearing all four monitors. The monitors worn were a gt3x, a SW200, a New Lifestyles NL-2000 (NL), and an OP720. A researcher hand-tallied steps, which was the criterion measure. Interestingly, the OP720 wear-location was in the front right pocket.

The piezoelectric pedometers (OP720 and NL) provided the most accurate stepping information at the slowest speed (54 $m \cdot min^{-1}$) which was 103.2% and 94.6% of hand-tallied steps for the NL and OP720, respectively. Considering total step counts for all stages, the OP720 step count performance (97.7%) was superior to the other three monitors (gt3x - 86.9%, NL - 103.3%, and SW200 - 78.6%). The gt3x underestimated the total number of steps during testing by 13.1%. Additionally, the gt3x was outperformed by the piezoelectric pedometers during treadmill walking and the piezoelectric pedometers (NL and OP720) were encouraged for use in populations of pregnant women.

To progress upon previous research, Barreira et al.[15] compared free-living steps counts between the gt3x and SW200 in a sample of 23 (18 females and 5 males) overweight and obese adults with a mean age of 54 years. Participants wore both a gt3x and SW200 for seven days only removing them at night to sleep and during water-based activities.

The findings showed that the gt3x under-counted daily steps when compared to the SW200 on 53% of days, over-counted steps on 23% of days, and was found to be acceptable on 25% of days. Although the correlation between these monitors was strong (r = 0.87), there were clear differences in step counts. There was no systemic classification of steps based on BMI, for example, subjects with varying BMI levels had days in each of the three classification (under, acceptable and over estimations of steps by the gt3x compared to the SW200) eliminating the possibility that BMI or tilt angle affected the outcome. It has been previously reported that tilt angle can impact pendulum-based pedometer's step counts[13], but if this were the case in the present study, the SW200 would have consistently under estimated steps when compared to the gt3x, which was not the case. Because no true criterion is feasible for step counts in free-living conditions, suggesting that one monitor was superior to the other based solely on these results would be inappropriate.

The newer models of Actigraph accelerometers employing the MEMS technology require higher accelerations to register counts compared to the previous piezoelectric models (7164 and prior). However, in response to the recent interest in investigating sedentary activities, Actigraph has incorporated a low frequency extension filter (LFE) that is more sensitive to light movement in the gt3x+ (AG).

Multiple studies have observed the differences between variables, such as step counts and activity EE, when comparing the data collected via the normal and LFE filters. In general, the LFE filter tends to attenuate differences between new and old versions of Actigraph accelerometers making data across studies comparable. It should be noted that utilizing the LFE filter creates bias in reporting moderate activity.[16,36] With regards to stepping data, Cain et al.[36] observed step counts in a healthy adult population wearing two Actigraph's (model 7164, AG NF and LFE filter) for three days in free-living conditions. Subjects included 13 females and 12 males with a mean age of 33 years. The AG provides a raw data output that can then be processed through both filter options (i.e. LFE and NF) for comparisons. With regards to stepping data, the 7164 model, which has been found to be acceptable for estimating steps[37], reported 9,384 steps per day. Comparatively, the AG NF had mean daily step counts of 7,343. This finding was statistically significant, but considering higher accelerations are required for the AG NF to register counts, lower step counts would be expected. Conversely, the AG LFE reported a mean daily step count of 12,981, also significantly different from the comparative monitor. These findings highlight the importance of selecting the proper frequency output dependent upon the variable of interest to each study. Additionally, researchers utilizing these monitors should report the filter option used in order for proper across-study comparisons to be made.

To further validate AG steps, Barreira et al.[27] observed the step counts between the NL piezoelectric pedometer and the AG NF and LFE filters in a sample of older adults. The NL was selected as the referent model due to its ability to count steps at slower speeds which may be present in older adults. The subjects were 15 older adults (7 men, mean age 73 years; 8 women, mean age 67 years). The protocol for the study required subjects to wear the AG 24-hours per day for seven days excluding during bathing along with the NL for seven days excluding during bathing and sleeping. Subjects were provided a log to document when they removed the devices for bathing and sleeping and to write down NL step counts upon removing the device for bed.

The results were analyzed by day (n = 86 valid days). The correlation between the NL and AG LFE (r = 0.90) was stronger than correlation between the NL and AG NF (r = 0.80). However, the magnitude of the difference in actual steps taken between the

NL and AG NF was 769 steps/day, while the difference between the NL and AG LFE was 8,140 steps/day. The AG NF tended to underestimate daily steps while all of the observations by the AG LFE overestimated daily steps. These findings were similar to those reported in the previous study by Cain et al. One limitation to comparing the two studies, however, is that Cain et al. failed to report the hertz interval that data was collected at. Barreira et al. indicated that their data was collected at a sampling rate of 80 hertz while the standard data collection setting is 30 hertz (a higher bandwidth/hertz setting increases the frequency of readings registered by the accelerometer). Future studies should provide information on the filter option used and the hertz setting selected for the study. Reporting this information will allow for relevant between-study comparisons of data and offer clarity on whether the hertz setting implemented has an impact on data collected by the AG. If this information is not presented, it may obfuscate the utility of between study comparisons. Barreira et al. concluded that the AG was not a good predictor of step counts when compared to the NL utilizing either filter with an 80 hertz sampling frequency.

Although Actigraph accelerometers are commonly used in research settings, limited information on the more recent models (i.e. gt3x and gt3x+) step count validity exists, in either controlled or free-living conditions. To complicate this, both have NF and LFE filter options in need of further validation. It appears that researchers interested in stepping information may benefit from using the NF filter option to receive more precise and comparative data, as long as sedentary behavior is not of significance to the study. Researchers interested in activity intensity classifications, allowing for the documented bias in the reporting of moderate activity, may be best suited to utilize the

LFE filter option. Although accelerometers offer information about higher level metrics, such as MVPA, activity EE and sedentary time, their validity in counting steps has been questioned. Although step counts may be considered a lower level metric, they provide clinicians with a practical variable to assign laypersons needing to attain more activity to preserve or improve their health, while further providing physicians with data pertaining to numerous physiological variables to evaluate a patient's health. With the constant production of newer technologies, it is important to validate these devices under each of their data collection options (NF vs. LFE) and also each wear location (waist vs. wrist) prior to their use in settings that may influence national health related recommendations and cutpoints.

Polar Active Accelerometer

The Polar Active wrist-worn accelerometer is a uni-axial activity monitor that offers step counts, EE and minutes of activity in intensity zones (i.e. light, vigorous, etc). This accelerometer is comparable to the Polar FA20 wrist-worn accelerometer that provides immediate feedback in the form of an animated person mimicking basic movements being performed by the wearer (i.e. sitting, standing, walking, jogging, and running) along with a bar that fills up across the day as minutes of MVPA are accumulated. These watches have not been validated to our knowledge; however they are sold to schools and employed in classrooms across the world. In addition, these devices have emerged in research settings as a potential weight-loss tool in military personnel.[19] The need to validate these devices to confirm that they are providing wearers with accurate activity data is crucial, specifically if they are being used in schools and weight-loss settings. If activity monitors being used in weight-loss settings are providing inaccurate information, patients could suffer through additional weight gain if EE is being overestimated or malnutrition if EE is being underestimated. The same could be true if step count goals are being recommended by physicians and the same under- or over-estimation of steps is taking place, or if step counts are included in the proprietary algorithm for EE.

Summary and Conclusions

It appears that bi-axial piezoelectric technology is the most consistent at estimating steps in controlled settings across multiple speeds and populations varying in BMI. However, the pendulum-based YX offers accurate stepping data in normal BMI subjects during controlled conditions at moderate to brisk walking speeds. Although accelerometers offer information on higher level metrics, they appear to consistently report inaccurate step counts during controlled conditions. If errors exist in step counting, it may be that errors occur when classifying activity zones and activity EE as well. In free-living conditions it is important to provide information on accelerometer settings/filter use when reporting on steps and other metrics in order to allow for more confident and consistent between study comparisons, and inevitably to accumulate data on which settings provide valid information across each variable measured.

Providing activity monitors that accurately quantify steps is imperative for research considering step counts are estimated by most activity monitors. Monitor step counts need to be validated prior to being used in research settings that can influence national standards. For example, the National Health and Nutrition Examination Survey (NHANES) conducted by the Centers for Disease Control and Prevention, will be providing nationally representative information based on data collected utilizing the

Actigraph gt3x accelerometer worn on the wrist although limited data validating step counts with this wear protocol exist. Tudor-locke et al. has provided target step count recommendations for specific populations based on the data collected during the 2003-06 NHANES data collection.[26,38] It is possible that these recommendations may be impacted by the method that steps were estimated (i.e. wrist-worn Actigraph accelerometer 7164). It may be beneficial to validate each metric activity monitors estimate, concurrently or individually, in multiple settings prior to their use in setting national or clinical guidelines. Providing this information will permit more confident interpretation of the data received from devices and potentially more precise national activity- and health-related recommendations.

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