Comparison of Pedometer and Accelerometer Accuracy under Controlled Conditions

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ABSTRACT

LE MASURIER, G. C., and C. TUDOR-LOCKE. Comparison of Pedometer and Accelerometer Accuracy under Controlled Conditions. *Med. Sci. Sports Exerc.*, Vol. 35, No. 5, pp. 867–871, 2003. **Purpose:** The purpose of this investigation was to compare the concurrent accuracy of the CSA accelerometer and the Yamax pedometer under two conditions: 1) on a treadmill at five different speeds and 2) riding in a motorized vehicle on paved roads. **Methods:** In study 1, motion sensor performance was evaluated against actual steps taken during 5-min bouts at five different treadmill walking speeds (54, 67, 80, 94, and 107 $m \cdot min^{-1}$). In study 2, performance was evaluated during a roundtrip (drive 1 and drive 2) motor vehicle travel on paved roads (total distance traveled was 32.6 km or 20.4 miles). Any steps detected during motor vehicle travel were considered error. **Results:** In study 1, the Yamax pedometer detected significantly ($P < 0.05$) fewer steps than actually taken at the slowest treadmill speed (54 $m \cdot min^{-1}$). Further, the pedometer detected fewer steps than the accelerometer at this speed (75.4% vs 98.9%, $P < 0.05$). There were no differences between instruments compared with actual steps taken at all other walking speeds. In study 2, the CSA detected approximately 17-fold more erroneous steps than the pedometer (approximately 250 vs 15 steps for the total distance traveled, $P < 0.05$). **Conclusions:** The magnitude of the error (for either instrument) is not likely an important threat to the assessment of free-living ambulatory populations but may be a problem for pedometers when monitoring frail older adults with slow gaits. On the other hand, CSA accelerometers erroneously detect more nonsteps than the Yamax pedometer under typical motor vehicle traveling conditions. This threat to validity is likely only problematic when using the accelerometer to assess physical activity in sedentary individuals who travel extensively by motor vehicle. **Key Words:** WALKING, STEPS/DAY, TRANSPORTATION, MOTION SENSORS

Accurate measures of physical activity (PA) are required by researchers interested in describing and evaluating the relationship between PA and important health outcomes (e.g., obesity, hypertension, and glucose tolerance). Advances in technology have generated an increased interest in objective monitoring of PA using body-worn sensors (e.g., accelerometers and pedometers). Recently published journal supplements have reflected this evolution of PA measurement (7,8), and a new PA assessment textbook prominently features chapters on both accelerometry and pedometry (17). A simple search of PubMed using the key words "accelerometer" and "physical activity" elicits 130 studies published between 1990 and 2002. A similar search substituting the term "pedometer" elicits 37 studies. Despite the evidence of increasing utilization of motion sensors for research and practice purposes, the process of objective monitoring is still in its infancy and the threat of measurement bias has not been extensively evaluated. Continued study is necessary to increase our understanding and interpretation of objectively monitored PA.

Pedometers are the least expensive ($10–30 per unit) and most user-friendly (14) of the two motion sensors and therefore are seen as more practical (inexpensive and feasible) for surveillance, screening, program evaluation and intervention through personal feedback (1,4,18,19). The brand that has received the most scientific attention has been the Yamax (Yamax Corporation, Tokyo, Japan) pedometers, perhaps because of an initial brand comparison study that concluded that these instruments were the most accurate of those assessed at the time (2). Since that time, Yamax pedometers have shown strong relationships (r = 0.80–0.90) under laboratory conditions with more expensive accelerometers including CSA model 7164 (MTI Health Services, Fort Walton Beach, FL) (3). Under controlled field conditions, the Yamax pedometer correlated with Tritrac (R3D, Professional Products, Reining Int., Madison, WI) and CSA accelerometers at r = 0.84–0.93 (6). The accumulated evidence indicates that the output of pedometers is highly representative of that produced by accelerometers (13).

In both these studies (6,13), pedometer-determined steps taken were compared with accelerometer-determined activity counts, an output representative of steps taken combined with velocity of movement. A dual-mode CSA accelerometer model 7164-version 2.2 is now available that collects

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TABLE 1. Participant characteristics for study 1 and study 2.

Variable	Study 1 (N = 20) Males (N = 13)	Study 1 (N = 20) Females (N = 7)	Study 2 (N = 20) Males (N = 12)	Study 2 (N = 20) Females (N = 8)
Age (yr)	30.0 ± 6.1 (26.3–33.7)	26.4 ± 3.6 (23.3–29.5)	32.8 ± 11.5 (25.5–40.0)	30.4 ± 10.4 (21.7–39.1)
Height (cm)	183.0 ± 6.4 (179.1–186.9)	168.9 ± 6.2 (163.2–174.7)	183.4 ± 7.0 (179.0–187.9)	168.6 ± 4.8 (164.5–172.6)
Weight (kg)	83.5 ± 9.4 (77.8–89.1)	61.9 ± 6.1 (56.2–67.6)	80.9 ± 5.9 (77.2–84.6)	63.4 ± 3.9 (60.1–66.6)
BMI (kg·m^{-2})	24.9 ± 2.5 (23.4–26.4)	22.0 ± 2.4 (19.7–24.2)	24.1 ± 1.8 (22.9–25.2)	22.3 ± 1.5 (21.0–23.6)

Values are means ± SD (95% CI).

both activity count data and the number of cycles in the signal, which manufacturers claim are representative of the simpler output: steps taken. A recent study examined steps taken as measured by the dual-mode accelerometer and the Yamax pedometer in free-living individuals and determined that, although the correlation between the two instruments was indeed strong (r = 0.86), the accelerometer detected 1,800+ more steps per day than the pedometer (11). This is similar to the difference detected between an ankle-borne accelerometer (Step Activity Monitor, SAM, Prosthetic Research Study, Seattle, WA) and a Sportline pedometer (Campbell, CA) under free-living conditions (10). We hypothesized that the discrepancy between the two instruments was likely due to differences in sensitivity thresholds set to detect vertical accelerations. The CSA accelerometer requires a force ≥ 0.30 *g* to register and record a movement; the corresponding value for the Yamax pedometer is ≥ 0.35 *g* (11). We would therefore expect that some of the discrepancy might be explained by a greater ability of the accelerometer to detect lower forces typical of slower walking speeds. Previous research has shown that the Yamax pedometer underestimates the number of steps taken at slower walking speeds (indicative of lower forces) (2,5). On the other hand, a lower sensitivity threshold may result in the accelerometer erroneously detecting more nonstep movements as steps taken, for example, simple agitation experienced while riding in a motorized vehicle. Therefore, the purpose of this investigation was to compare the concurrent accuracy of the dual-mode CSA accelerometer and the Yamax pedometer to actual steps taken observed under two conditions: 1) on a treadmill at five different speeds and, 2) riding in a motorized vehicle.

METHODS

Participants. Convenience samples of male and female participants between the ages of 20 and 55 yr of age participated in one of two studies: study 1 (N = 20; 13 males, 7 females) or study 2 (N = 20; 12 males, 8 females). Procedures for both studies were reviewed and approved by the Institutional Review Board at Arizona State University. Written informed consent was obtained from all subjects before participation. Age was recorded, and height and weight were measured in light street clothing (without shoes) to the nearest 0.5 cm and 0.1 kg, respectively, using a measuring tape, a framing square, and a standard physician's scale. Because BMI > 30 kg·m^{-2} has been implicated as a source of error when using motion sensors (9), all participants were specifically recruited for a BMI of < 30 kg·m^{-2}. Characteristics of the participants in study 1 and study 2 are presented in Table 1.

Instruments. The Yamax SW-200 pedometer and the dual-mode CSA were used in both studies. All instruments were checked for calibration before each individual use. Pedometers were checked using a brief walking test (15), and if the error exceeded 2%, the pedometer was not used in the study. Accelerometers were checked using manufacturer-recommended hardware and software, and calibrated if necessary. All pedometers and accelerometers used in the study met the accuracy and calibration criteria. Accelerometers were initialized to detect steps taken in 30-s epochs (study 1) or 1-min epochs (study 2) and synchronized to the investigator's timing device. Because no detected steps were expected in study 2, a longer epoch was considered sufficient to detect any steps recorded erroneously. Both motion sensors were worn concurrently on the right hip according to the manufacturer's recommendations during all testing. At the end of each test, accelerometer data was downloaded using manufacturer recommended hardware and software. Data reduction focused on accumulated accelerometer steps detected for each epoch between washout periods (defined below), verified with synchronized time records. The final outputs for each motion sensor were recorded as steps taken during each test.

Study 1: impact of walking speed on accelerometer and pedometer accuracy. The purpose of this study was to compare the accuracy of the accelerometer and pedometer to the criterion standard of observed steps taken while walking on a motor-driven treadmill (Quinton model Q55, Seattle, WA) at five different speeds. This study was designed in part to replicate the methods undertaken in a previous evaluation of walking speed and pedometer accuracy (2). Therefore the treadmill speeds used herein were the same used in that earlier study (i.e., 54, 67, 80, 94, and 107 m·min^{-1}). Before testing, the treadmill speed was determined by measuring the belt length (3.2 m) and the time it took to complete 25 revolutions of the treadmill belt. A carpenter's level was used to calibrate the treadmill to a 0% grade according to the manufacturer's instructions. The accuracy of the carpenter's level was checked by turning it horizontally 180° and observing that the bubble was still centered. This calibration method was also used previously (2).

TABLE 2. Comparison of CSA accelerometer and Yamax pedometer steps detected to actual steps taken at five treadmill speeds.

Walking Speed ($m \cdot min^{-1}$)	Actual Steps Taken	Percentage of Actual Steps Detected	
		Accelerometer Steps Detected	Pedometer Steps Detected
54	479 ± 39 (461–497)	98.9 ± 0.9 (98.5–99.3)	75.0 ± 22.1† (64.6–85.3)
67	539 ± 27 (527–552)	99.2 ± 0.8 (98.8–99.6)	96.1 ± 6.4 (93.0–99.0)
80	566 ± 24 (555–577)	99.3 ± 0.5 (99.1–99.5)	99.3 ± 2.4 (98.2–100.5)
94	599 ± 27 (587–612)	99.3 ± 0.6 (99.1–99.6)	100.2 ± 2.2 (99.2–101.3)
107	644 ± 34 (628–660)	99.4 ± 0.5 (99.2–99.7)	100.0 ± 0.6 (99.8–100.3)

Values are means ± SD (95% CI).
† Significantly different from actual steps taken ($P < 0.05$).

Participants walked on the treadmill for 5-min bouts at each of the five walking speeds. Before each bout, participants stood still on the treadmill for a 2-min washout period to ensure that accelerometer steps recorded before the official bout were not entered into the analysis. The 2-min washout period was repeated between each bout and after the last 5-min bout. At the end of each bout, the pedometer steps taken were recorded, and the device was reset to zero before a subsequent bout. The actual number of steps taken was counted by observation and verified by a video recording aimed at the participant's lower extremities.

Study 2: impact of motorized travel on accelerometer and pedometer accuracy. The purpose of study 2 was to compare the accuracy of the accelerometer and pedometer while riding in a motorized vehicle on paved roads. No actual steps were taken under these conditions. Participants were monitored during a roundtrip motor vehicle (2002 Toyota Rav 4) ride on paved roads, split into equal out (drive 1) and back (drive 2) segments (total distance traveled was 32.6 km or 20.4 miles). Participants occupied the front passenger seat, the back seats, and on one occasion the driver seat. Before departure, participants fastened their seat belts, reset their pedometers to zero, and sat still in the vehicle for a 2-min washout period to ensure that any steps taken before the ride were not considered in the analysis of accelerometer data. Another 2-min washout period was implemented between the two driving segments and any pedometer steps detected were recorded at this time. After drive 2, participants sat through a final 2-min washout period before recording any pedometer steps detected.

Statistical analysis. Descriptive data for both studies is presented as means ± SD and 95% confidence intervals (CI) for the means. In study 1, steps taken for both motion sensors were expressed as a percentage of the actual number of steps observed for each bout (see Table 2). A repeated measures ANOVA was used to assess significant differences between actual steps taken and those recorded by the two motion sensors. Tukey's honestly significant difference *post hoc* procedure was used to determine where the differences existed.

In study 2, it was assumed that any steps detected by either instrument were indicative of measurement error. Differences in the number of steps detected during both driving segments by the two motion sensors were compared using a Student's *t*-test. An intraclass correlation (ICC) was computed for each motion sensor based on data collected separately for drive 1 and drive 2.

TABLE 3. Steps erroneously detected by the CSA accelerometer and the Yamax pedometer during a motor vehicle ride on paved roads.

Driving Segment	Accelerometer Steps Erroneously Detected	Pedometer Steps Erroneously Detected
Drive 1 (16.3 km)	123 ± 40† (104–141)	6 ± 8 (3–10)
Drive 2 (16.3 km)	145 ± 45† (124–166)	10 ± 9 (5–14)

Values are means ± SD (95% CI).
† Significantly different from corresponding pedometer values ($P < 0.05$).

RESULTS

Study 1. Table 2 presents the motion sensors' performances relative to actual steps taken. Only the Yamax pedometer detected significantly ($P < 0.05$) fewer steps than were actually taken at the slowest treadmill speed (54 $m \cdot min^{-1}$). At the remaining four speeds (67, 80, 94, and 107 $m \cdot min^{-1}$), there were no significant differences between the actual number of steps taken and the number of steps recorded by either instrument, nor did these two motion sensors differ from each other at any of these remaining speeds.

Study 2. Although no actual steps were taken during the motor vehicle travel segments, both motion sensors erroneously detected steps taken. Table 3 displays the performance of the two motion sensors during the two driving segments. On average, the CSA accelerometer detected 17-fold more erroneous steps than the Yamax pedometer ($P < 0.05$). The computed ICC for the two repeated driving segments were 0.79 and 0.88 (both $P < 0.05$), for the accelerometer and the pedometer, respectively.

DISCUSSION

This study replicates and extends an earlier study (2) that examined pedometer accuracy at the same treadmill speeds used in study 1. Both motion sensors performed well at most walking speeds. The Yamax pedometer consistently under recorded steps taken at the slowest walking speed (< 60 $m \cdot min^{-1}$). Such slow speeds of walking are considered much slower than typical normal walking and therefore should not be an important source of error in studies of free-living activity in ambulatory populations (5). Pedometers may not be appropriate measurement devices for assessing the physical activity of frail, institutionalized older adults with characteristically shuffling, slow gaits (20).

The Nationwide Personal Transportation Survey (16) reported that Americans typically drove 39 $miles \cdot d^{-1}$ in 1995, almost twice as far as the total distance evaluated in study 2. The expected corresponding error would be approximately 500 steps for the CSA accelerometer and 30 steps for the Yamax pedometer. Because the average healthy adult takes between 7,000 and 13,000 $steps \cdot d^{-1}$ (15), the magnitude of the error is 4–7% for the accelerometer and less than 1% for the pedometer. The magnitude of the error would become more important when assessing typically sedentary populations (e.g., individuals living with chronic diseases). Such individuals take between 3500 and 5000 steps·d^{-1} (15). The relative magnitude of the error would be 10–14% for the accelerometer and still less than 1% for the pedometer. Measured more directly, erroneous pedometer-detected steps amounted to 2–3% of daily PA levels in a sample of community-dwelling older adults (12). However scrutinized, the magnitude of the error attributed to erroneous objective monitoring of typical motor vehicle travel using either motion sensor is relatively small and likely only a concern when using accelerometers to assess sedentary individuals who primarily use motorized transport.

Taken together, potential error due to slow walking (missing steps taken) and to typical motor vehicle travel (detecting nonsteps) begins to explain the ≈1800 steps·d^{-1} difference between the these two types of motion sensors used to monitor PA in a free-living population (10,11). In addition, compared with the pedometer, the accelerometer is likely more sensitive to other nonambulatory movements (e.g., weight-shifting, twisting, fidgeting, bending, etc.). These incidental movements taken throughout the day would widen the gap between steps taken and steps detected by the two instruments. A similar sensitivity threshold (e.g., 35 *g*) might remedy the measurement discrepancy. However, any set sensitivity threshold must take into consideration the inevitable specificity/sensitivity trade-off; if greater sensitivity (i.e., ability to detect low force stepping) is expected, then the researcher must be willing to accept decreased specificity (i.e., ability to discriminate movements, including external agitation, that are not ambulatory in nature).

This investigation comprised controlled studies of motion sensor performance under a limited array of situations. Self-selected walking speeds on a variety of real-world surfaces were not evaluated. Similarly, a single motor vehicle was used on a paved road. It is likely that results will vary with different vehicles and conditions including suspension systems, road surfaces, and the stop-and-go motion of typical vehicle travel. Our results may underestimate the error of the pedometer and CSA accelerometer during motorized travel. Regardless, it is abundantly apparent that the two instruments detect the actual number of steps taken differently and in a manner consistent with their intended design.

In summary, both CSA accelerometers and Yamax pedometers are useful instruments for objectively assessing PA as steps taken over a defined unit of time (e.g., hour, during physical education class, or day). Accelerometers also detect the velocity of the movement, which can be used to infer intensity, and can record movement in even smaller units of time (e.g., 30-s epochs). The pedometer does not discriminate intensity of movement nor reflect the amount of time spent in specific intensity categories of activity. Pedometers detect fewer steps taken during very slow walking speeds (e.g., < 60 m·min^{-1}). The magnitude of the error (for either instrument) is not likely an important threat to the assessment of free-living ambulatory populations but may be a problem when monitoring frail older adults with slow gaits. CSA accelerometers erroneously detect more nonsteps than the Yamax pedometer under typical motor vehicle traveling conditions. This threat to validity is likely only problematic when using the accelerometer to assess PA in sedentary individuals who travel extensively by motor vehicle. A correction factor should be considered when comparing steps taken between studies of free-living individuals monitored with these two instruments. Although a difference of ≈1800 steps·d^{-1} between accelerometers and pedometers has been previously identified (10,11), it is premature at this point to specify an absolute correction factor. Additional studies of a confirmatory nature are warranted.

The authors do not have a professional relationship with companies or manufacturers who may benefit from the results of the present study. The results of the present study do not constitute endorsement of the products by the authors or the ACSM.

REFERENCES

1. Bassett, D. R. Validity and reliability issues in objective monitoring of physical activity. *Res. Q. Exerc. Sport* 71:30–36, 2000.
2. Bassett, D. R., B. E. Ainsworth, S. R. Leggett, et al. Accuracy of five electronic pedometers for measuring distance walked. *Med. Sci. Sports Exerc.* 28:1071–1077, 1996.
3. Bassett, D. R., B. E. Ainsworth, A. M. Swartz, S. J. Strath, W. L. O'Brien, and G. A. King. Validity of four motion sensors in measuring moderate intensity physical activity. *Med. Sci. Sports Exerc.* 32:S471–S480, 2000.
4. Freedson, P. S., and K. Miller. Objective monitoring of physical activity using motion sensors and heart rate. *Res. Q. Exerc. Sport.* 71:21–29, 2000.
5. Hendelman, D., K. Miller, C. Baggett, E. Debold, and P. Freedson. Validity of accelerometry for the assessment of moderate intensity physical activity in the field. *Med. Sci. Sports Exerc.* 32:S442–S450, 2000.
6. Leenders, N. Y. J. M., W. M. Sherman, and H. N. Nagaraja. Comparisons of four methods of estimating physical activity in adult women. *Med. Sci. Sports Exerc.* 32:1320–1326, 2000.
7. Mahar, M. T., and B. E. Ainsworth. Measurement of physical activity: the Cooper Institute Conference Series. *Res. Q. Exerc. Sport.* 71:S1–S158, 2000.
8. Raven, P. B., A. W. Perrel, D. M. Robertson, H. W. Kohl, D. L. Kibbe, and S. Trost. Measurement of moderate physical activity: advances in assessment techniques. *Med. Sci. Sports Exerc.* 33: S439–S516, 2000.
9. Shepherd, E. F., E. Toloza, C. D. Mcclung, and T. P. Schmalzried. Step activity monitor: increased accuracy in quantifying ambulatory activity. *J. Orthop. Res.* 17:703–708, 1999.
10. Silva, M., E. F. Shepherd, W. O. Jackson, F. J. Dorey, and T. P. Schmalzried. Average patient walking activity approaches 2 million cycles per year: pedometers under-record walking activity. *J. Arthroplasty* 17:693–697, 2002.
11. Tudor-Locke, C., B. E. Ainsworth, R. W. Thompson, and C. E. Matthews. Comparison of pedometer and accelerometer measures of free-living physical activity. *Med. Sci. Sports Exerc.* 34:2045–2051, 2002.
12. Tudor-Locke, C., G. R. Jones, A. M. Myers, D. H. Paterson, and N. A. Ecclestone. Contribution of structured exercise class participation and informal walking for exercise to daily physical activity in community-dwelling older adults. *Res. Q. Exerc. Sport.* 73:350–356, 2002.
13. Tudor-Locke, C., J. E. Williams, J. P. Reis, and D. Pluto. Utility of pedometers for assessing physical activity: Convergent validity. *Sports Med.* 32:795–808, 2002.

14. TUDOR-LOCKE, C. E., and A. M. MYERS. Challenges and opportunities for measuring physical activity in sedentary adults. *Sports Med.* 31:91–100, 2001.
15. TUDOR-LOCKE, C. E., and A. M. MYERS. Methodological considerations for researchers and practitioners using pedometers to measure physical (ambulatory) activity. *Res. Q. Exerc. Sport.* 72:1–12, 2001.
16. U.S. DEPARTMENT OF TRANSPORTATION. Proceedings from the Nationwide Personal Transportation Survey Symposium, October 29–31, 1997. In: *Nationwide Personal Transportation Survey Symposium*. Bethesda, MD: Federal Highway Administration, 1999.
17. WELK, G. J. (Ed.). *Physical Activity Assessments for Health-Related Research*. Champaign, IL: Human Kinetics, 2002, pp. 125–140, 163–175.
18. WELK, G. J., C. B. CORBIN, and D. DALE. Measurement issues in the assessment of physical activity in children. *Res. Q. Exerc. Sport.* 71:59–73, 2000.
19. WELK, G. J., J. A. DIFFERDING, R. W. THOMPSON, S. N. BLAIR, J. DZIURA, and P. HART. The utility of the Digi-walker step counter to assess daily physical activity patterns. *Med. Sci. Sports Exerc.* 32:S481–S488, 2000.
20. WILCOX, S., C. E. TUDOR-LOCKE, and B. E. AINSWORTH. Physical activity patterns, assessment, and motivation in older adults. In: *Gender, Physical Activity and Aging*. R. J. Shephard (Ed.). Boca Raton, FL: CRC Press, 2002, pp. 13–39.