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Validation and Comparison of Two Ankle-Mounted and Two Waist-Mounted Electronic Pedometers

Murat Karabulut
University of Tennessee - Knoxville

To the Graduate Council:

I am submitting herewith a thesis written by Murat Karabulut entitled "Validation and Comparison of Two Ankle-Mounted and Two Waist-Mounted Electronic Pedometers." I have examined the final electronic copy of this thesis for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Science, with a major in Exercise Science.

David R. Bassett, Jr., Major Professor

We have read this thesis and recommend its acceptance:

Edward Howley, Dixie Lee Thompson

Accepted for the Council:
Carolyn R. Hodges

Vice Provost and Dean of the Graduate School

(Original signatures are on file with official student records.)

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Anne Mayhew

Vice Chancellor and Dean of Graduate Studies

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Validation and Comparison of Two Ankle-Mounted and Two Waist-Mounted Electronic Pedometers

A Thesis

Presented for the Master of Science

Degree

The University of Tennessee, Knoxville

Murat Karabulut

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Dedication

This thesis dedicated to my mother, Meliha Karabulut, and father, Seyithan Karabulut, who have always believed in me and supported me continuously. I would also like to dedicate this to my son, Ozan, my wife, Ulku, and to my friends.

This is for all of you. I love you.

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I would like to thank the members of my graduate committee. Thank you Dr. David Bassett for your supervision, support, and patience through this project. Thank you Dr. Dixie Lee Thompson and Dr. Edward Howley for all your encouragement and serving as members of my thesis committee. I have learned a lot from each of you, not only how to perform research but also how to solve and deal with the difficulties that I can have. I would also like to thank Scott Crouter. Your help and support were appreciated greatly.

Special thanks are offered to all of the participants in this study. I appreciate your time and effort.

Abstract

The purpose of this study was to validate and compare the accuracy of two ankle-mounted pedometers [StepWatch 3 (SW-3) and Activity Monitoring Pod 331 (AMP)] and two waist-mounted pedometers [New Lifestyles NL-2000 (NL) and Digiwalker SW-701 (DW-701)] under controlled and free-living conditions. The study had three parts: part I: walking on a treadmill at six different speeds, part II: a) evaluation of potential sources of error: leg swinging, heel tapping, and driving a car in city limits, and b) pedaling a stationary cycle ergometer, and part III: wearing pedometers for 24 hours. Ten males and 10 females walked on a motor driven treadmill at various speeds (27, 40, 54, 67, 80, and 107 $m \cdot min^{-1}$). Simultaneously, an investigator determined the actual steps by a hand counter. In a separate trial, participants performed leg swinging, heel tapping, and cycle ergometery to the beat of a metronome. A subset of 10 participants volunteered to drive their cars 6.4 km over a set course in city limits. In part III, a subset of 15 participants volunteered to wear all four pedometers for a 24-hr period. The SW-3 displayed values that were within 1% of actual steps during treadmill walking at all speeds. The other devices underestimated steps at slow speeds but were accurate at 80 $m \cdot min^{-1}$ and above. The SW-3 registered some steps during heel tapping, leg swinging, and cycling, while the AMP was only responsive to leg swinging. For all devices, the number of erroneous steps detected during driving was negligible. Over a 24-hr period the SW-3 recorded higher step counts than the AMP and DW-701 ($P < 0.05$). Ankle-mounted pedometers (especially SW-3) have superior accuracy at slow walking speeds, which could have applications for studying elderly individuals or those with gait impairments. Although waist mounted pedometers have limitations, they have several

advantages that make them suitable for behavioral interventions and large population studies.

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CHAPTER I

INTRODUCTION

Researchers assess physical activity (PA) to describe and evaluate the relationship between physical activity and important health outcomes such as obesity (17), hypertension (5, 28), and glucose tolerance (25, 39). Questionnaires are often used for assessing PA because of their low cost and feasibility, but self-reported PA is limited by the participants' ability to estimate and recall the frequency, intensity and duration of purposeful activity bouts (3, 41). Therefore, there is a need for objective, quantitative, and accurate measures of PA levels to better understand health outcomes and the dose-response relationship.

Pedometers are commonly used and becoming more popular for objective monitoring of PA in research and daily life (9, 34, 35). Due to the increasing use of pedometers it is important that they be accurate since this can have a significant impact in determining the number of $steps \cdot day^{-1}$ that an individual takes. Several studies have examined the accuracy and reliability of these devices under both controlled (2, 9, 22, 35) and free-living conditions (16, 34, 43). The data from previous studies (9, 35) showed that the Yamax Digiwalker SW-701 (DW-701), Kenz Lifecorder (KZ), and New Lifestyles NL-2000 (NL) were the most accurate in counting steps and within 1% of actual steps at speeds of 80 $m \cdot min^{-1}$ and above (9), while at slower speeds there were not as accurate. Schneider et al. (34) also compared 13 pedometer models for measuring steps taken during a 24-hour period and showed that there was significant differences among models. A criterion pedometer was worn on the left side of the body while one of 13 comparison pedometers was worn on the right side of the body for a 24-hour period.

The results showed that the pedometers could range from an underestimation of 25% to an overestimation of 45% over a 24-hour period. As shown in previous studies (9, 35), the Yamax Digiwalker DW-201, DW-701, NL, and KZ were the most accurate. Over the 24-hour period they were all within ± 8%.

Recently two ankle-mounted pedometers have been developed: Activity Monitoring Pod 331 (AMP) (Dynastream Innovation Inc., Cochrane, AB, Canada) and the StepWatch 3 (SW-3) (Cymatech Inc., Seattle, WA). Dynastream Innovations Inc. investigated the accuracy of the AMP at various activity levels. They found that regardless of the activity level the device had mean scores that were within ± 1% of actual steps. They also found that when participants walked five laps around a 200 m track at three different speeds: slow (> 45 $m \cdot min^{-1}$), regular, and fast (< 135 $m \cdot min^{-1}$), the device estimated the mean distance to within ± 3% (13).

The SW-3, which was released in May 2004, is a newer version of the Step Activity Monitor (SAM). To our knowledge there are no published studies on the accuracy of the newer version of the device (SW-3). However, previous versions of the SAM were used in several studies where it was found to be within ± 2% of actual steps (23, 36).

One reason for the step counting discrepancy in pedometers is due to the different mechanisms used. The AMP uses an ankle-mounted accelerometer that measures acceleration of the shank in the horizontal and vertical directions during the gait cycle to count steps. The SW-3 also uses an ankle-mounted accelerometer, which measures directional (horizontal and vertical) acceleration to detect steps. The DW-701 counts the number of steps when a spring-suspended, L-shaped lever arm moves up-and-down, which opens and closes an electrical circuit with each step (9). The NL uses an accelerometer-type mechanism consisting of a horizontal beam and piezoelectric crystal (35).

Due to the new ankle-mounted devices on the market and the need for more accurate devices to measure PA, the purpose of this study was to validate and compare the accuracy of two ankle-mounted pedometers (SW-3 and AMP) and two waist-mounted pedometers (DW-701 and NL) under controlled and free-living conditions: part I: walking on a treadmill at six different speeds, part II: a) evaluation of potential sources of error: leg-swinging, heel-tapping against the floor, and a car-driving in city limits, and b) pedaling a cycle ergometer, and part III: wearing pedometers for 24-hr.

CHAPTER II

REVIEW OF LITERATURE

Walking is one of the most common forms of PA that is performed during exercise and recreational activities (8, 45). Dr. Hatano of Japan has estimated that walking 10,000 steps·day^{-1} is equivalent to expending 336, 382, and 432 kcals during slow (100 steps·min^{-1}), fairly fast (110 steps·min^{-1}), and fast walking (125 steps·min^{-1}), respectively (14). Dr. Hatano suggests that 10,000 steps are reasonably close to the activity needed to maintain good health and prevent cardiovascular disease, because he estimates that for a middle aged Japanese man (60 kg, 165 cm tall), 60 minutes of walking at 88 m·min^{-1} results in 252 kcal energy expenditure (4.2 kcal·min^{-1} x 60 min in 6600 steps). He also believes that walking 10,000 steps·day^{-1} is very functional, because the necessary energy expenditure needed for maintaining fitness of an individual with a large body build should be more than a smaller individual. For example, for an 80 kg man (175 cm tall), the energy expenditure required to walk 60 minutes at 88 m·min^{-1} is 5 kcal·min^{-1}. Instead of calculating the amount of energy expenditure for individuals with different body weights, walking 10,000 steps·day^{-1} will allow every individual to expend the appropriate amount of energy regardless of body size. Thus, because of its simplicity he claimed that 10,000 steps·d^{-1} is very practical and reasonable for preventing cardiovascular diseases as well.

As mentioned earlier, pedometers are important tools that can provide information about the total steps taken and walking distance covered throughout the day. Studies show that there is variability among various pedometer models in their ability to detect steps taken (9, 34, 35). Thus, it is important to investigate the accuracy of pedometers over a range of walking speeds and under various daily life situations to determine whether they are dependable enough to provide accurate information for steps taken and distance traveled.

Validity of Self-Report in Assessing Physical Activity

Many studies have investigated the accuracy of questionnaires or activity logs to assess daily PA (1, 3, 7, 47). Self-reported PA is limited by the participants' ability to estimate and recall the frequency, intensity and duration of activity bouts. Therefore, concern has been raised about the accuracy of self-report measures of PA.

Bassett et al. (3) compared values of daily walking distance reported on the College Alumnus Questionnaire (CAQ) and that measured by a Digiwalker DW-500B (DW-500B) pedometer. After participants had completed a CAQ, they were asked to wear the DW-500B pedometer for 7 consecutive days, except when sleeping, showering, and during sports and recreational PA. It was found that men and women under-reported their walking distance on the CAQ, compared with what was estimated by the DW-500B (1.43 ± 1.01 vs. 4.17 ± 1.61 $km \cdot d^{-1}$). The energy expenditure of walking computed from the CAQ was significantly lower than what was estimated from the $steps \cdot day^{-1}$ measured by the DW-500B (555 ± 405 vs. 1608 ± 640 $kcal \cdot wk^{-1}$).

Treuth et al. (41) examined the reliability and validity of motion sensors and self-report instruments in young African American girls (8-9 yr.). Participants attended two clinical visits separated by 4 days. Participants wore a MTI/CSA accelerometer and a Yamax Digiwalker SW-200 (DW-200) pedometer at the same time for four consecutive days. Each girl completed on two different occasions a 24-hr PA checklist of yesterday's activities and usual activities, involving sedentary activities [GEMS (Girls health Enrichment Multi-site Studies) Activity questionnaire (GAQ)] and a 3-d computerized self-report instrument. The MTI/CSA was chosen as a criterion standard because it has been shown to be valid in children (18, 19). The Activitygram score was moderately correlated with the average MTI/CSA counts·min^{-1} (r = 0.43 for the 7 a.m.-12 noon and r = 0.32 for the 6 p.m.-12 p.m. periods), but no significant correlation was seen for the 12 noon – 6 p.m. period. The correlations between the GAQ MET-weighted value obtained from 28 activities and the MTI/CSA average counts·min^{-1} ranged from r = 0.05 to 0.21 (P from 0.078 to 0.864). The overall correlation between the average of the four-day steps·min^{-1} value from the DW-200 and the MTI/CSA monitor counts·min^{-1} was moderate (r = 0.47) and significantly different for day 3 but not for days 1, 2, and 4. It was suggested that the lower validity they observed for the DW-200 compared with the other studies (33, 42) was due to the need to rely on the girl's cooperation and ability to follow the instruction and record the pedometer values. It was also mentioned that self-report instruments for young girls such as those used in the study to evaluate overall activity level was also inadequate in terms of validity and it was concluded that they need further development for better reliability and validity.

Craig et al. (7) developed the International Physical Activity Questionnaire (IPAQ) as an instrument for cross-national monitoring of PA. Criterion validity was determined using the CSA accelerometer, which recorded the total amount of PA. An International Consensus Group developed four short and four long forms of the IPAQ. The agreement between the instruments was fair to moderate; testing long and short forms against the CSA had a median Spearman ρ of 0.33 and 0.30, respectively.

International Physical Activity Questionnaire correlations were about 0.80 for reliability and 0.30 for validity compared to CSA.

Sallis et al. (32) summarized the reliability and validity results for seven self-report PA questionnaires and found that the reliability correlations ranged from 0.34 to 0.89, with a median of about 0.80 and criterion validity correlations ranged from 0.14 to 0.53, with a median of about 0.30. The authors concluded that the IPAQ instruments have suitable assessment properties that are as good as other established self-reports (32).

Accuracy of the Physical Activity Index from the College Alumnus Questionnaire (PAI-CAQ) was investigated by Ainsworth et al. (1). Participants identified the number of flights of stairs climbed and city block walked per day, and the frequency and duration of sports and recreational activities performed during the previous week. Participants were also asked to identify the number of weeks in the past year that each activity was performed and adjustments for sports and recreational activities were made, based on the information provided. Participants recorded all PA for six 48-hour periods. When compared with the PA records, PAI-CAQ significantly underestimated weekly energy cost for overall activity (1270 ± 1086 vs. 3856 ± 1711). The CAQ significantly underestimated walking (416 ± 291 vs. 2131 ± 898 MET·min·wk^{-1}) and stair climbing (222 ± 192 vs. 339 ± 233 MET·min·wk^{-1}) as well as sports and recreational activities (806 ± 916 vs. 1291 ± 1456 MET·min·wk^{-1}). The PAI-CAQ consistency in results was higher when administered over a one-month period (r = 0.31 to 0.88) than over an 8 or 9-month period (r = 0.01 to 0.63).

Validity of Pedometers to Count Steps and Assess Distance

One of the first studies performed to examine the accuracy of a mechanical pedometer and actometer for estimating daily PA was in 1977 by Saris et al. (33). Fifteen participants [9 children (5 – 6 years) and 6 males (21-31 years)] walked and ran at different speeds on a treadmill. Two calibrated pedometers (Russian) were worn on the waist (left and right) and a third one was worn on the left ankle. Participants also wore an actometer on the right ankle and wrist. When the pedometer was worn at the waist, the steps were counted more accurately than when it was worn on the ankle. In addition, the actometer showed agreement in steps taken regardless of location, which was also comparable to what was found with the waist-mounted pedometers. It was found that the pedometer overestimated the actual step rate by 0.1 - 0.3 counts per step during fast walking (100-150 $m \cdot min^{-1}$) and fast running (250 $m \cdot min^{-1}$) and underestimates the actual step rate by 0.2 – 0.7 counts per step during slow walking (17 $m \cdot min^{-1}$). In contrast the actometer's detection of steps increased proportionately with increasing speeds (especially during running), which indicated it had a better mechanism to detect changes in the intensity of the movement.

Kemper et al. (20) also found that mechanical waist-mounted pedometers (Russian and German) overestimated steps at walking speeds above 100 $m \cdot min^{-1}$ in boys (12 -18 years). The German pedometer underestimated steps by 60% at 33 $m \cdot min^{-1}$, while the Russian pedometer underestimated steps at both 33 and 67 $m \cdot min^{-1}$. Both pedometers were within 5% (S.D. ± 9%) of actual steps taken at 133 and 167 $m \cdot min^{-1}$. When walking/running at 100 $m \cdot min^{-1}$ and running at 233 $m \cdot min^{-1}$ there was a mean error of

8.5% (S.D. ± 8%). It was concluded that pedometers did not count steps accurately at slow speeds, but they got better with increasing speed.

Washburn et al. (46) investigated the accuracy of mechanical pedometers for measuring distance during walking and running. Participants performed part I one-mile walks on a treadmill at different speeds (54, 80, and 107 $m \cdot min^{-1}$) and part II two 1-mile walks at their own pace under each of two conditions a) on a 400-meter track, and b) along a one-mile jogging path. The participants also performed two one-mile runs at their own pace over the same jogging path. Four of the same waist-mounted pedometers [Edgemark Digimeter (ED)] were used during the treadmill walking. In general, the pedometers underestimated the mile distance by about 22% when walking at 54 $m \cdot min^{-1}$. Five pedometers [one of ED, two of Schritte Watch (SCHW) (ankle-mounted), and two of Eschenbach (EP) (waist-mounted) were used for the second part of the study. It was found that the pedometers estimated distance accurately while walking the 400-meter track, but on average, the mile distance was underestimated by about 11% when running. Another important finding of this study was that there was inter-subject variation, such that pedometer accuracy for measuring distance was affected by the participants' gait. The authors pointed out that because pedometers record on impact, a negative correlation was expected between stride length and pedometer reading. Based on this finding, it was recommended that future studies should use pedometers that can be adjusted for the stride length to assess distance traveled.

Bassey et al. (4) used a simple mechanical pedometer [Yamasa Digiwalker (model unknown)] to assess walking activity. The study consisted of two parts: part I a bench test, and part II a field study. The bench test showed that the pedometer had a stable sensitivity and linear response with time when exposed to repetitive vertical accelerations. There was some variation in sensitivity between pedometers, so it was mentioned that individual calibration was necessary. The threshold of maximal acceleration was less than 85 $m \cdot min^{-1}$ and the response to increasing acceleration reached a plateau at 120 $m \cdot min^{-1}$. The authors concluded that the pedometers would count the number of steps taken over long periods, because the maximum acceleration of the hip during walking was in this range. The field study consisted of three-sub-parts: part a) participants (5 males and 6 females, 29 ± 9.5 years) wore two pedometers (left and right hip) during waking hours for 5 consecutive days and then the location of the pedometers were switched and the process was repeated for another 5 days. In Part b) a second group consisting of 24 female participants (67 ± 6.4 years) wore two pedometers for six consecutive days without resetting the pedometers each night. In Part c) younger participants (3 males and 5 females, 39 ± 8.5 years) walked for 3.9 km wearing two pedometers and a carbon pad footfall sensor under one heel, and an older group (6 females between the ages of 60 and 70) repeated that protocol over a course of 3.2 km. The relation between the readings from the two pedometers (right and left) was evaluated in ten young subjects for 10 days and in 24 elderly subjects for 6 days. The differences in scores were 0.1 ± 0.4 and – 1.1 ± 0.5 for the first and second week in young subjects, respectively, but the difference of cumulated 6-day scores was higher (3.5 ± 10.4) in older group. It was suggested that a possible reason for the right-left variation was due to asymmetry of gait. The comparison of the number of steps from pedometer and the number of steps from a resistance pad also showed that there was a bigger variation in the older group (0.5 ± 1.08) than the younger group (0.40 ± 0.73) (4).

Bassett et al. (2) examined the accuracy of five waist-mounted electronic pedometers [Freestyle Pacer 798 (FR), Eddie Bauer Compustep II (EB), L.L. Bean (LLB), Yamax Digiwalker DW-500 (DW-500), and Accusplit Fitness Walker (AF)] for measuring distance walked and steps taken. This was a three-part study that consisted of a) assessing the pedometer accuracy while walking a sidewalk course, b) the effects of different surfaces on the accuracy of the pedometers and c) the effects of walking at various speeds on a treadmill. Twenty participants volunteered for part a of the study while a subset of 10 of the original 20 participants were used in part b, and 10 different participants volunteered for part c of the study. While walking a 4.88-km sidewalk course two of the same brand pedometers were worn at the same time (left and right side of the body). The DW-500, FR, and the AF were significantly more accurate than the LLB and EB models. The DW-500 was the most accurate and measured the number of steps and distance to within 1% of actual on the sidewalk course. A subset of 10 of participants walked an additional five trials around a 400-m rubberized outdoor track. There was no effect of the walking surface on the accuracy of the pedometers. For treadmill walking, the DW-500 was found to be more accurate at slow-to-moderate walking speeds (54- 80 $\mathrm{m \cdot min^{-1}}$) than the EB and the FR brands. Pedometers (DW-500, EB, and FP) tended to underestimate the distance at slow speed (e.g., 54 $\mathrm{m \cdot min^{-1}}$) and overestimate the distance at faster speed (e.g., 107 $\mathrm{m \cdot min^{-1}}$). At 107 $\mathrm{m \cdot min^{-1}}$, the EB and FR showed better agreement with the DW-500 pedometer. The distance was significantly higher for the FP worn on the left side of the body than the FP worn on the right side ($P = 0.05$). Bassett et al. (2) concluded that the newer models were more accurate than the older mechanical models and could be useful in epidemiological studies of PA in free-living populations.

Crouter et al. (9) tested the effects of walking speed on the accuracy and reliability of ten pedometers to asses steps taken, distance walked, and energy expenditure. Participants walked on a treadmill at five different speeds for five minutes stages. Consistent with the previous studies, most pedometers underestimated steps at slow walking speed (54 $m \cdot min^{-1}$), but accuracy for step counting improved at faster speeds. At speeds of 80 $m \cdot min^{-1}$ and above, the Yamasa Skeleton (SK), Omron (OM), DW-701, KZ, Walk4Life LS 2525 (LS) and NL were shown to be accurate and gave mean values that were within ± 1% of actual steps. The pedometers that showed the distance traveled assessed mean distance to within ± 10% at 80 $m \cdot min^{-1}$, but overestimated distance covered at slower speeds and underestimated distance covered at faster speeds. The authors concluded that pedometers are most precise for assessing steps, while being less precise for assessing distance and energy expenditure.

Schneider et al. (35) investigated the accuracy and reliability of ten electronic pedometers for measuring steps taken during a 400-meter track walk. Participants wore two pedometers of the same model on the right and left hip while walking 400-m around an outdoor track. Researchers walked with the participants and counted the steps taken with a hand counter. Three Japanese models (KZ, NL, and DW-701) were the most accurate and gave values that were within ± 3% of the actual steps taken. Five models (LS, SK, Sportline 345 (345), Freestyle Pacer Pro (FR), and Oregon Scientific PE316CA (OR)) displayed values that were within ± 19%. The OM and Sportline 330 (330) were the least accurate, displaying mean values within ± 37%. Intra-model reliability was > 0.80 for all pedometers with the exception of the 330, which had a reliability of 0.76. It is suggested that the researchers who use pedometers to evaluate PA need to be concerned with the accuracy and reliability of the pedometers because of the variation among pedometers.

Schneider et al. (34) also compared the steps values of pedometers during free-living PA over a 24-hr period. The DW-200 was the criterion model and was worn on the left side of the body, while one of 13 comparison pedometers was worn on the right side of the body for a 24-hr period. Participants wore the pedometers during their waking hours and recorded the total steps taken before going to bed. This process was repeated for all thirteen pedometers. Five pedometer models significantly underestimated steps taken (FR, Accusplit Alliance 1510, SK, Colorado on the move, and 345) while three models (LS, OM, and OR) overestimated steps taken when compared to the criterion (DW-200). The mean error scores ranged from an underestimation of 25% to an overestimation of 45% between pedometers. This study showed that four Japanese models (KZ, DW-200, DW-701, and NL) had the best agreement and seems to be suitable for research purposes.

Recently, Cyarto et al. (10) examined the accuracy of a DW-200 in nursing home and community-dwelling older adults. Twenty-six residents (79 ± 8.2 yr) and 28 community-dwelling older adults (70 ± 5.5 yr) wore the DW-200 at the waist and completed one walking trial of a 13-m hallway course at each facility at three different self-paced speeds. Particularly, participants were told to walk one length of the course, using usual gait aids, accordingly: 1- walk rather slowly; 2- walk a normal pace; and 3- walk rather fast but without overexerting yourself. The DW-200 underestimated the nursing home residents' steps by 74%, 55%, and 46% at slow (25.2 ± 10.2 $m \cdot min^{-1}$), normal (38.4 ± 16.8 $m \cdot min^{-1}$), and fast (48 ± 21 $m \cdot min^{-1}$) paces, respectively. The scale of error was larger for nursing home vs. seniors' recreation center members, where the DW-200 underestimated steps taken by 25%, 13%, and 7% at slow ($57 \pm 12\ m \cdot min^{-1}$), normal ($76.2 \pm 12\ m \cdot min^{-1}$), and fast ($96.6 \pm 12.6\ m \cdot min^{-1}$) paces, respectively. The authors concluded that pedometers were not very accurate for measuring PA in frail older adults with typically slow walking paces ($< 54\ m \cdot min^{-1}$) and gait impairments.

Comparison and Validation of Accelerometers and Waist-Mounted Pedometers

Hendelman et al. (16) studied the validity of accelerometry in assessing moderate-intensity lifestyle activities in the field and assessed the metabolic cost of various recreational and household activities. Participants performed four bouts of walking at various paces ["leisurely" (bout 1), "comfortable (bout 2), "moderate" (bout 3), and "brisk" (bout 4)], played two holes of golf, and completed indoor (window washing, dusting, vacuuming) and outdoor (lawn mowing, planting shrubs) household tasks. Energy expenditure was assessed by a portable metabolic system (TEEM 100, AeroSport, Inc., Ann Arbor, MI), and activity was recorded by a DW-701 pedometer (walking only), a CSA accelerometer (model 7164, Computer Science and Applications, Inc., Shalimar, FL), and a Tritrac accelerometer (Reining International, Ltd., Madison, WI). The DW-701 step frequency was determined by measuring the time required to complete 10 full strides, which was doubled to get step frequency. At the end of each bout, the step values from the DW-701 were recorded and then divided by the total walking time to get steps per minute. The study found that although the DW-701 underestimated the number of steps taken per minute at lower speeds (bout 1 and 2), accuracy improved at the faster speeds. At the fastest speed (brisk), the difference was not significant. It was mentioned that slow walking may not create enough impact force to be detected by the pedometer, but also it may be slower than the participants' normal walking speeds.

Le Masurier et al. (22) compared the accuracy of a Computer Science Applications (CSA) accelerometer and a DW-200 pedometer under two conditions: a) walking on a treadmill at five different speeds (54, 67, 80, 94, and 107 $m \cdot min^{-1}$) and b) riding in a motorized vehicle on paved roads. The DW-200 pedometer detected fewer steps than the CSA at 54 $m \cdot min^{-1}$ (75.4% vs. 98.9%, $p < 0.05$), but both devices were accurate at all other walking speeds. The CSA detected approximately 17 times more incorrect steps than the pedometer while riding in a motorized vehicle on paved roads. The authors concluded that both instruments were fine to assess the free-living ambulatory populations, but using the DW-200 pedometer to observe frail older adults with slow gaits may be a problem. In contrast, the CSA may also detect more erroneous steps than the DW-200 pedometer during traveling in motorized vehicles and thus may become problematic when using the accelerometer to evaluate PA in sedentary persons who spend a significant time traveling by motor vehicle.

A similar study was performed by Tudor-Locke et al. (44), where they compared the DW-200 pedometer and the CSA under three conditions: a) CSA outputs and DW-200 outputs under free-living conditions, b) the association between pedometer $steps \cdot day^{-1}$ and CSA time spent in inactivity and in light-, moderate-, and vigorous-intensity activities, and c) pedometer $steps \cdot day^{-1}$ that corresponded with a minimum of 30 CSA $min \cdot d^{-1}$ of moderate activity was examined. The data showed a strong correlation between all CSA outputs and pedometer outputs. On average, the CSA recorded 1845 ± 2116 more $steps \cdot day^{-1}$ than the DW-200 ($P < 0.0001$). Activity durations in specific intensity levels for CSA was determined [inactive (0-499 counts·min^{-1}), light (500- 1951 counts·min^{-1}), moderate (1952- 5724 counts·min^{-1}), and vigorous (5725 + counts·min^{-1}) (12, 38). Pedometer-determined PA was described as quartile 1 (≤ 6529 PED-steps·d^{-1}), quartile 2 (6530-9027 PED-steps·d^{-1}), quartile 3 (9,028-12,571 PED-steps·d^{-1}), and quartile 4 (≥ 12,572 PED-steps·d^{-1}). Differences (effect sizes > 0.80) in mean CSA time (min·d^{-1}) spent in moderate and vigorous-intensity activity differed from the increasing pedometer-determined activity quartiles; no differences were seen for inactivity or light activity. The CSA recorded an average of 32.7 ± 14.4 min·d^{-1} of moderate activity for the second quartile of pedometer-assessed activity (8064 ± 766 steps·d^{-1}). The authors concluded that the difference in steps taken was likely due to differences in instrument sensitivity thresholds. It was also suggested that because of the difference in steps·d^{-1} between instruments, one instrument's step data might not be easily substituted for the other.

Waist-Mounted Pedometers Versus Ankle-Mounted Pedometers

Waist-mounted pedometers are worn at the belt line and respond to vertical accelerations of the hip. Thus, it is hypothesized that they might not sense small steps or shuffling movements of the lower extremities and likely undercount the total steps taken during a 24-hour period. Therefore, ankle-mounted pedometers have been used and compared with waist-mounted pedometers to determine if they are a better assessment technique.

Shepherd et al. (36) compared the accuracy of an ankle-mounted pedometer [Step Activity Monitor (SAM)] with a digital waist-mounted pedometer (Sportline 345). Participants briskly walked 400 m, slowly walked 10 m, and ascended and descended a flight of stairs. Overall the SAM had less error then the Sportline 345 during all activities. The SAM had an absolute mean error of 0.5%, which was independent of body weight; however the Sportline 345 had an absolute mean error of 2.8%. The difference was more distinct in obese participants (BMI > 30), with an absolute mean error of 0.48% for the SAM and 6.12% for the Sportline 345. The authors concluded that the SAM is a more accurate tool to evaluate walking activity than the Sportline 345, especially in obese individuals.

Macko et al. (23) examined the accuracy and reliability of a mechanical waist-mounted pedometer (Elexis Trainer, Model 3FM-180 (3FM-180), International Microtech, Miami, FL) vs. a microprocessor-based step activity monitoring (SAM) in stroke patients. Participants walked replicate sets of two 1-min floor walks at self-selected and fastest comfortable pace and performed two 6-min walks on separate days. The SAM total step counts were more accurate than the 3FM-180 during the 1-min walks at self-selected pace (99 ±1 vs. 87 ±11.3%, $P < 0.01$); fast pace (98±2.3 vs. 85 ±15%, $P < 0.01$); and repeated 6-min walks (99 ±1 vs. 89 ±12%, $P < 0.01$). The authors concluded that the SAM gives accurate and reliable assessments of cadence and total steps in stroke patients versus the 3FM-180.

Silva et al. (37) used a pedometer (Sportline, Campell, CA) and a SAM to examine activities of daily living (ADL) in patients with total hip arthroplasty (THA). The participants wore both devices during waking hours for 4 consecutive days. In this review of literature, the cycles were converted to steps and presented as $steps \cdot d^{-1}$. The SAM recorded an average of 10,438 $steps \cdot day^{-1}$, while the Sportline recorded on average 3,560 $steps \cdot d^{-1}$ less than the SAM. The correlation between the Sportline pedometer and

SAM in men was 0.82 ($P = 0.009$), while in women the correlation was 0.58 ($P = 0.009$). Further analysis showed that patients with a BMI < 27 $kg \cdot m^{-2}$ had a correlation between the Sportline and SAM of 0.77 ($P = 0.001$), while those with a BMI ≥ 27 $kg \cdot m^{-2}$ had a correlation of 0.56 ($P = 0.03$). Specifically, there was a significant difference in women for the percent difference between the Sportline and SAM for those with a BMI < 27 $kg \cdot m^{-2}$ and those with a BMI ≥ 27 $kg \cdot m^{-2}$ (27.8% vs. 53.7%, $P = .04$), while there was 2% difference in males based on BMI (for BMI < 27 and BMI ≥ 27). For cycles per day, the SAM was accurate regardless of body weight, while the Sportline pedometer reported 54% fewer cycles per day in women with a BMI ≥ 27 and 30% fewer cycles per day in men with BMI ≥ 27. The authors concluded that the SAM was more accurate and reliable than the Sportline pedometer in stroke patients.

Comparison of Physical Activity Recommendations

Several studies verify that PA can have positive effects on a variety of health conditions by decreasing the risk of hypertension (5, 28), reducing blood pressure of people with hypertension (11), decreasing the risk of heart disease (26, 29), reducing insulin resistance in people with type 2 diabetes (15, 24), and lessening depression and anxiety (21, 40). The most recent PA recommendations have shifted from the vigorous intensity activity (for improving VO_{2max}) to moderate intensity activity, which has been shown to improve health outcomes. The American College of Sports Medicine (ACSM) and the Centers for Disease Control and Prevention (CDC) joint summary statement, recommends that every American adult should accumulate at least 30 minutes of moderate-intensity PA on most, preferably all, days of the week (27).

An alternative suggestion by Dr. Hatano of Japan is to take 10,000 steps$\cdot$day^{-1} (14). Dr. Hatano suggests that 10,000 steps are reasonably close to the activity needed to maintain good health and prevent cardiovascular disease, because he estimates that for a middle aged Japanese man (60 kg, 165 cm tall), 60 minutes walking at 88 m$\cdot$min^{-1} resulted in 252 kcal (4.2 kcal$\cdot$min^{-1} x 60 min in 6600 steps). He also believes that walking 10,000 steps$\cdot$day^{-1} is very functional, because the necessary energy expenditure needed for maintaining fitness of an individual with a large body build should be more than a smaller individual. For example, for an 80 kg man (175 cm tall), the energy expenditure required to walk 60 minutes at 88 m$\cdot$min^{-1} is 5 kcal$\cdot$min^{-1}. Instead of calculating the amount of energy expenditure for individuals with different body weights, walking 10,000 steps$\cdot$day^{-1} will allow every individual to expend the appropriate amount of energy regardless of body size. Thus, he indicated that 10,000 steps$\cdot$d^{-1} is reasonable to prevent cardiovascular diseases and practical as well.

Two recent studies indicate that walking 10,000 steps$\cdot$day^{-1} results in improvements in cardiovascular disease risk factors in sedentary populations (25, 39). Swartz et al. (39) investigated whether a recommendation to accumulate 10,000 steps$\cdot$d^{-1} for 8 weeks was effective at improving glucose tolerance in overweight women. Eighteen women (53.3 ± 7.0 yr, 35.0 ± 5.1 kg$\cdot$m^{-2}) who had a family history of type-2 diabetes accomplished a four-week control period followed by an eight-week walking program with no changes in diet. The walking intervention was monitored with a DW-200 pedometer. On average the women increased their daily walking from 4972 steps$\cdot$d^{-1} to 9213 steps$\cdot$d^{-1}. The data showed that a 10,000 steps$\cdot$d^{-1} recommendation resulted in improved glucose tolerance and a reduction in systolic and diastolic blood pressure in overweight women at risk for type-2 diabetes without a concurrent loss in body weight.

Moreau et al. (25) investigated the effectiveness of the ACSM/CDC recommendation (30 min of daily activity) in lowering blood pressure (BP) in hypertensives females. Fifteen women were randomized to the exercise group (EX) and nine to a control group (CON). The EX increased their daily walking by 4300 steps (3 $km \cdot d^{-1}$) and averaged a total of 9700 ± 400 $steps \cdot d^{-1}$ during the walking program. After 24 weeks, it was found that increasing the daily walking by 4300 $steps \cdot d^{-1}$ resulted in a decrease in systolic BP in postmenopausal women with borderline to stage 1 hypertension. The EX also decreased their body mass by 1.3 kg ($P < 0.005$, vs. baseline), while there was no change in the CON. In addition the decrease in systolic BP was independent of the weight loss.

It is proposed if you take a sedentary individual who walks approximately 6,000 $steps \cdot day^{-1}$ and increase that to 10,000 $steps \cdot day^{-1}$, this would be similar to the ACSM/CDC recommendation of 30 minutes of moderate intensity activity. This is based on the calculation that walking one mile at 3 mph is equivalent to approximately 2000 steps and takes 20 minutes. If healthy older adults accumulate 6000 - 8500 $steps \cdot d^{-1}$ (45) walk 20 - 40 minutes at 3 mph, they will accumulate extra 2000 - 4000 steps, which will satisfy Hatano's PA recommendation.

In support of the 10,000 $steps \cdot day^{-1}$ and the ACSM/CDC recommendation being similar is a study performed by Wilde et al. (48) which determined daily baseline steps counts for sedentary women and whether baseline step counts, plus step counts in 30 minutes of brisk walking, would total 10,000 steps. Participants wore a DW-200 to determine the steps taken throughout the day for four consecutive days and were asked to perform a 30-min walk for two of the four days. Mean step counts for the two walking days differed from the 2 nonwalking days by 3,104 steps. This indicating that a 30-min walk was approximatelly 3,100 steps for a sedentary women. It was mentioned that lower mean daily free living step counts were available in the literature for sedentary people. Thus the authors believed that 10,000 steps would be more challenging for sedentary people who have lower baseline step counts. It was suggested that lower or higher step count targets might be essential based on baseline step counts.

Conclusion

Walking is one of the most common forms of leisure time PA (8, 14, 45). Pedometers provide a low-cost method of measuring PA, especially in situations where the major activity is walking (2). The limitations of self-reported PA are widely documented in the literature (1, 3, 7, 17, 41). Besides, variation in the accuracy in the pedometers (9, 35) and the need for a better methods to get objective, quantitative, and accurate measures of PA make the assessment of pedometer accuracy both necessary and critical.

CHAPTER III

MANUSCRIPT

Abstract

Purpose: The purpose of this study was to validate and compare the accuracy of two ankle-mounted pedometers [StepWatch 3 (SW-3) and Activity Monitoring Pod 331 (AMP)] and two waist-mounted pedometers [New Lifestyles NL-2000 (NL) and Digiwalker SW-701 (DW-701)] under controlled and free-living conditions. The study had three parts: part I: walking on a treadmill at six different speeds, part II: a) evaluation of potential sources of error: leg swinging, heel tapping, and driving a car in city limits, and b) pedaling a stationary cycle ergometer, and part III: wearing pedometers for 24 hours. **Methods:** Ten males and 10 females walked on a motor driven treadmill at various speeds (27, 40, 54, 67, 80, and 107 $m \cdot min^{-1}$). Simultaneously, an investigator determined the actual steps by a hand counter. In a separate trial, participants performed leg swinging, heel tapping, and cycle ergometery to the beat of a metronome. A subset of 10 participants volunteered to drive their cars 6.4 km over a set course in city limits. In part III, a subset of 15 participants volunteered to wear all four pedometers for a 24-hr period. **Results:** The SW-3 displayed values that were within 1% of actual steps during treadmill walking at all speeds. The other devices underestimated steps at slow speeds but were accurate at 80 $m \cdot min^{-1}$ and above. The SW-3 registered some steps during heel tapping, leg swinging, and cycling, while the AMP was only responsive to leg swinging. For all devices, the number of erroneous steps detected during driving was negligible. Over a 24-hr period the SW-3 recorded higher step counts than the AMP and DW-701 ($P < 0.05$). **Conclusion:** Ankle-mounted pedometers (especially SW-3) have superior

accuracy at slow walking speeds, which could have applications for studying elderly individuals or those with gait impairments. Although waist mounted pedometers have limitations, they have several advantages that make them suitable for behavioral interventions and large population studies.

Key Words: WALKING, STEP COUNTER, PHYSICAL ACTIVITY, AND EXERCISE

Introduction

Many investigators assess physical activity (PA) to describe and evaluate its relationship to important health outcomes, such as obesity (17), hypertension (5, 28), and glucose tolerance (25, 39). Questionnaires are often used for this purpose because of their low cost and feasibility, but some limitations of self-report and recall are documented (3, 41). Since self-reported PA is limited by the participants' ability to estimate and recall the frequency, intensity and duration of purposeful activity bouts, there is a need for objective, quantitative, and accurate measures of PA levels to better understand health outcomes and the dose-response relationship.

Pedometers are commonly used and becoming increasingly popular for the purpose of objective monitoring of PA levels in research and in daily life (9, 34, 35). It is important that they be accurate since this can affect the number of $steps \cdot day^{-1}$. Several studies have examined the accuracy and reliability of pedometers under controlled (2, 9, 22, 35) and free-living conditions (16, 34, 43). Two studies showed that three pedometers [(Yamax Digiwalker SW-701 (DW-701), Kenz Lifecorder (KZ), and New Lifestyles 2000 (NL)] were very accurate in counting steps (9, 35), but even the most accurate waist-mounted pedometers fail to record some steps taken at slower speeds ($<67\ m \cdot min^{-1}$) (9, 10). Schneider et al. (34) compared 13 pedometer models for measuring steps taken in 24-hr and found that there can be significant differences between models. A comparison (on the right side of the body) and a criterion (on the left side of the body) pedometer were worn for 24-hr. The errors ranged from a 25% underestimation to a 45% overestimation compared to a criterion pedometer.

Recently two ankle-mounted pedometers have been developed: AMP 331 (AMP) (Dyna-streams Innovation Inc., Cochrane, AB, Canada) and the StepWatch 3 (SW-3) (Cymatech Inc., Seattle, WA). Dynastream validated their device by having participants walk a prescribed number of steps (155) at different activity levels. They found that during all walking trials the device gave mean values that were within ± 1% of actual steps. Participants also walked around a 200 m track five times at three different speeds, slow (> 45 $m \cdot min^{-1}$), regular, and fast (< 135 $m \cdot min^{-1}$) to test the accuracy of the distance computation, the device estimated the mean distance to within ± 3% (13).

The StepWatch 3 (SW-3) is a new version of the Step Activity Monitor (SAM), which was released in May 2004. To our knowledge there are no published studies on the accuracy of this new device (SW-3). However, a previous version (i.e., SAM) was used in several studies, and was found to be more accurate than a waist-mounted pedometer (23, 36).

Differences in pedometer mechanisms can affect their accuracy. The AMP uses two ankle-mounted accelerometers that measure acceleration of the shank in the horizontal and vertical directions throughout the gait cycle to count steps. The SW-3 also uses an ankle-mounted accelerometer, which measures directional (horizontal and vertical) acceleration to detect steps. In contrast, the waist-mounted Yamax Digiwalker SW-701 has a spring-suspended lever arm that moves up-and-down in response to vertical acceleration of the hip. This opens and closes an electrical circuit with each step (9). The NL is a waist-mounted pedometer that uses an accelerometer-type mechanism to record steps (35).

Due to the new ankle-mounted pedometers that have the potential to be more accurate, particularly at slow walking speeds, the purpose of this study was to validate and compare the accuracy of two ankle-mounted pedometers (SW-3 and AMP) and two waist-mounted pedometers (DW-701 and NL). This was a three-part study: part I: walking on a treadmill at six different speeds, part II: a) evaluation of potential sources of error: leg swinging, heel tapping, and driving a car in city limits, and b) pedaling a stationary cycle ergometer, and part III: wearing pedometers for 24-hr.

Methods

Participants

Ten males (28 ± 3.7 yr) and ten females (28 ± 3.9 yr), with a BMI ranging from 19.6-39.9 $kg \cdot m^{-2}$ were recruited from the UT staff/student body, and surrounding community. Prior to participation in the study the participants were asked to read and sign an informed consent form approved by the University of Tennessee's Institutional Review Board. They were also asked to fill out a Physical Activity Readiness Questionnaire (PAR-Q) (6) regarding their health status and if they reported any contraindications, they were not tested. The physical and demographic features of the participants are shown in Table 1.

Anthropometric Measurements

Participants had their height and mass measured (in light clothing, without shoes) using a stadiometer (Seca Corp., Columbia, Maryland) and a physician's scale (Health-o-meter, Inc. Bridgeview, Illinois), respectively. Body Mass Index was calculated by dividing body weight (kg) by height (m^2). Waist circumference was

Table 1. Physical characteristics of participants [mean ± SD]

	Men (N=10)	Women (N=10)	All participants (N=20)
Age	28 ± 3.7	28 ± 3.9	28 ± 3.7
Height (cm)	179 ± 5.9	165 ± 6.0	172 ± 9.3
Weight (kg)	92 ± 23.2	63 ± 7.2	77 ± 22.6
BMI ($kg \cdot m^{-2}$)	28.9 ± 7.5	23.0 ± 2.0	26.0 ± 6.1
Waist (cm)	95 ± 15.9	74 ± 4.9	84 ± 15.6
Hip (cm)	110 ± 13.4	98 ± 9.1	104 ± 12.6
WHR	0.86 ± 0.1	0.74 ± 0.04	0.80 ± 0.08
Stride Length (cm)	70 ± 6.4	72 ± 5.7	71± 5.9

BMI, body mass index; WHR, waist-to-hip ratio

measured at the narrowest part of the torso (above the umbilicus and below the xiphoid process) and hip circumference was measured at the maximal circumference of the hips or buttocks region, (above the gluteal fold). Waist-to-hip ratio was computed by dividing waist circumference (cm) by hip circumference (cm).

To determine stride length the participants were asked to take 20 steps at their normal walking speed. The participants performed two trials and an average was taken. Average stride length was computed by dividing the total distance by 20.

Part I- Treadmill Walking

Before walking on the treadmill the DW-701 was programmed with the participant's stride length. The SW-3 was programmed with the participants' height and the default response (normal) was used for questions about "walking speed", "range of speeds", and "leg motion". The pedometers were then placed on the participant according to the manufacturer's instructions. Specifically, the NL and DW-701 were placed on the left and right waistline, respectively, and the SW-3 and AMP were placed on the left and right ankle, respectively.

Participants walked on the treadmill (Quinton, Medtrack ST Control, Bothell, Washington) at speeds of 27, 40, 54, 67, 80 and 107 $m \cdot min^{-1}$ for 3 minutes at each speed, while wearing the pedometers. Before testing, treadmill speed and grade were calibrated according to manufacturer's instruction and speed was verified by using a hand-held digital tachometer (Nidec-Shimpo America Corp. Model DT-107, Itasca, Illinois) that had been calibrated to an accuracy of within $\pm$ 0.1%. An investigator counted the number of steps taken using a hand-tally counter. Both ankle-mounted pedometers recorded data in one-minute epochs. The total steps for SW-3 were computed by multiplying by two, since it records the steps taken with one leg. The total walking distance was determined from the calibrated treadmill speed and bout duration. Only two pedometers (DW-701 and SW-3) estimated the distance traveled.

Part II- Heel Tapping, Leg Swinging, Car Driving, and Cycle Ergometry

For the heel-tapping trial the participants tapped both heels lightly against the floor for three minutes at a rate of 120 $times \cdot min^{-1}$ in beat with a metronome. For the leg swinging trial the participants sat on a table and swung both legs to the metronome beat for three minutes. On the cycle ergometer the participants used the metronome beat to ride at a cadence of 60 RPM for three minutes.

Ten out of 20 participants volunteered to drive their car while wearing all four pedometers. The driving took place over a 6.4 km course within city limits and the principal investigator accompanied the participants during that time. Just before starting out around the driving loop, the waist-mounted pedometers were reset to 0 and the starting time was recorded. When the driving loop was completed, the values from the waist-mounted pedometers were noted, and the ending time was recorded. After the trials, data from the ankle-mounted pedometers were downloaded to computer, and the number of steps recorded during each activity was noted.

Part III – 24-hr Study

A subset of 15 participants volunteered to wear all pedometers for a 24-hr period. They were instructed to record what time the devices were put on and taken off, and to record the number of steps displayed by the waist-mounted pedometers at the end of the day. Participants were shown on how to correctly position the pedometers and to wear them for 24-hr except when sleeping, bathing, and swimming. They were encouraged to go about their normal activities, and not to alter their daily routine.

Statistical Analysis

The data were analyzed using SPSS 11.5.0 for Windows (SPSS Inc., Chicago, IL). For all analyses, an alpha of 0.05 was used to indicate statistical significance. Two-way repeated measures ANOVA (pedometer x speed) were used to compare actual step counts and distance with that measured by each pedometer for all speeds. One-way repeated measures ANOVA were used to determine if the pedometers recorded steps during heel tapping, leg swinging, and car driving, as well as if they were able to record the correct cadence during cycling. A repeated measures ANOVA (1 x 4) were used to compare differences in 24-hr step counts between the pedometers. Where appropriate, post-hoc analyses were performed using Bonferoni corrections.

Results

Figure 1 shows percentage of actual steps at each speed. The SW-3 was the only pedometer that gave mean step counts within 1% of actual at all speeds. The other pedometers tended to underestimate actual steps at the slowest speeds, but accuracy

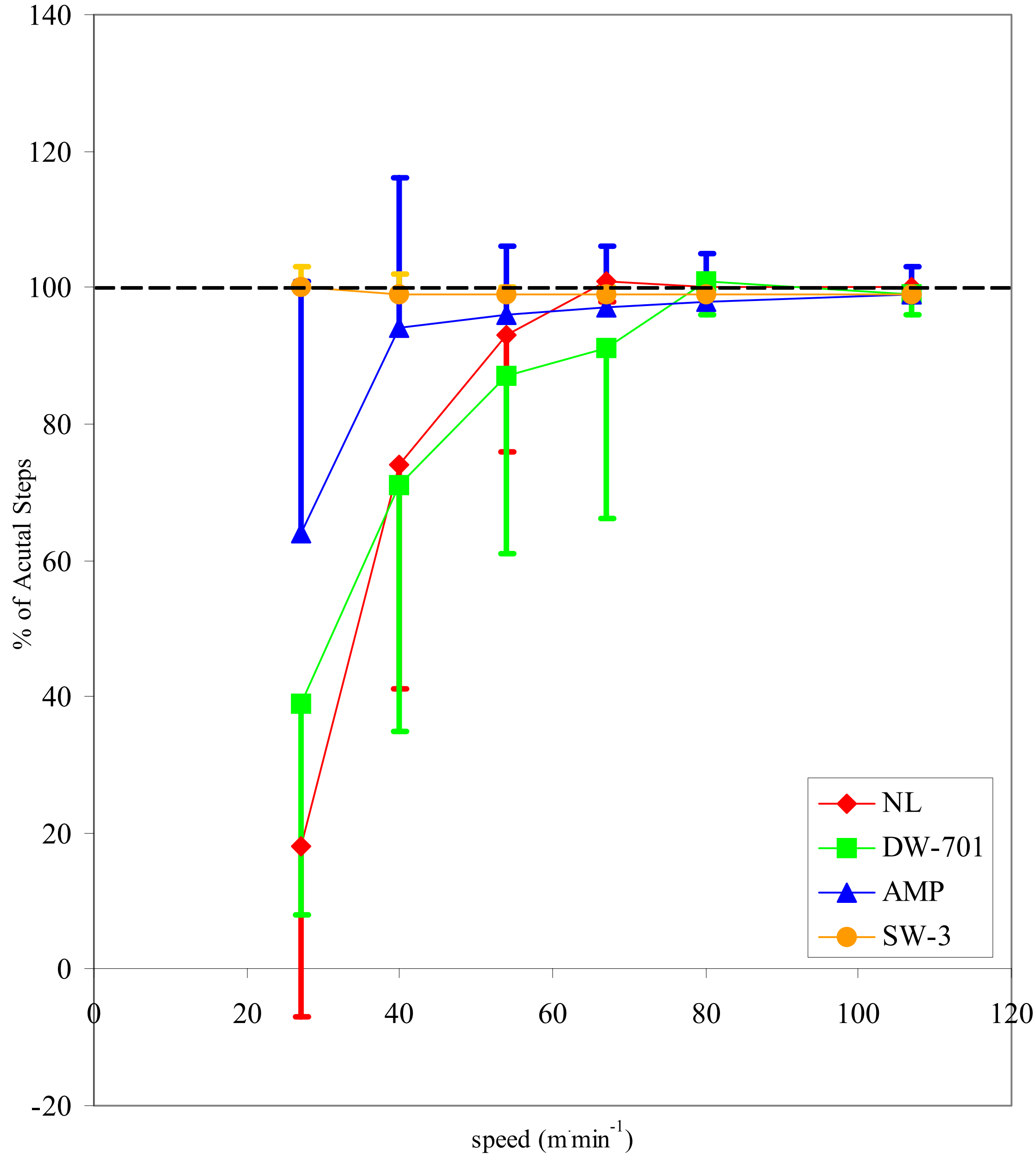


Figure 1. Effect of walking speed on pedometer accuracy for counting steps during treadmill walking (N=20).

improved as the speed increased. The AMP and NL were within 3% of actual steps at 67 $m \cdot min^{-1}$ and faster, while the DW was within 1% of actual steps at 80 $m \cdot min^{-1}$ and faster.

Two pedometers [DW-701 and AMP] displayed the distance traveled. Figure 2 shows the percentage of actual distance traveled at each speed. The AMP underestimated distance traveled at all speeds. At speeds of 40 $m \cdot min^{-1}$ and above the AMP provided mean estimates that were within 11% of actual distance traveled. The DW-701 underestimated distance traveled at all speeds except 40 and 54 $m \cdot min^{-1}$. For speeds between 40 and 80 $m \cdot min^{-1}$ the DW-701 was within 7% of actual distance.

Table 2 shows the mean steps detected during the heel tapping, leg swinging, cycle ergometry and car driving. In general, the waist-mounted pedometers (NL and DW-701) recorded very little artifact with these activities. The SW-3 was responsive to heel tapping, leg swinging and cycling, while the AMP was only responsive to leg swinging.

For the 24-hr data (Figure 3), the recorded averages of steps for each of the pedometers were: NL, 11,087 ± 970.2, DW-701, 10,611 ± 960.3, AMP, 10,269 ± 854.7, and SW-3, 12,454 ± 986.2. The mean value of steps counted by DW-701 and AMP was significantly lower than that of SW-3 ($P < 0.05$).

Discussion

This study showed that waist-mounted pedometers underestimated steps at slow speeds (< 80 $m \cdot min^{-1}$), but were more accurate at faster speeds (≥ 80 $m \cdot min^{-1}$). This is in agreement with previous studies (2, 9, 10, 23). The Japanese Industrial Standard have set the maximum acceptable error of miscounting steps at 3% (14). Interestingly, the data from previous studies (2, 9, 35) showed that the pedometers made by Japanese companies

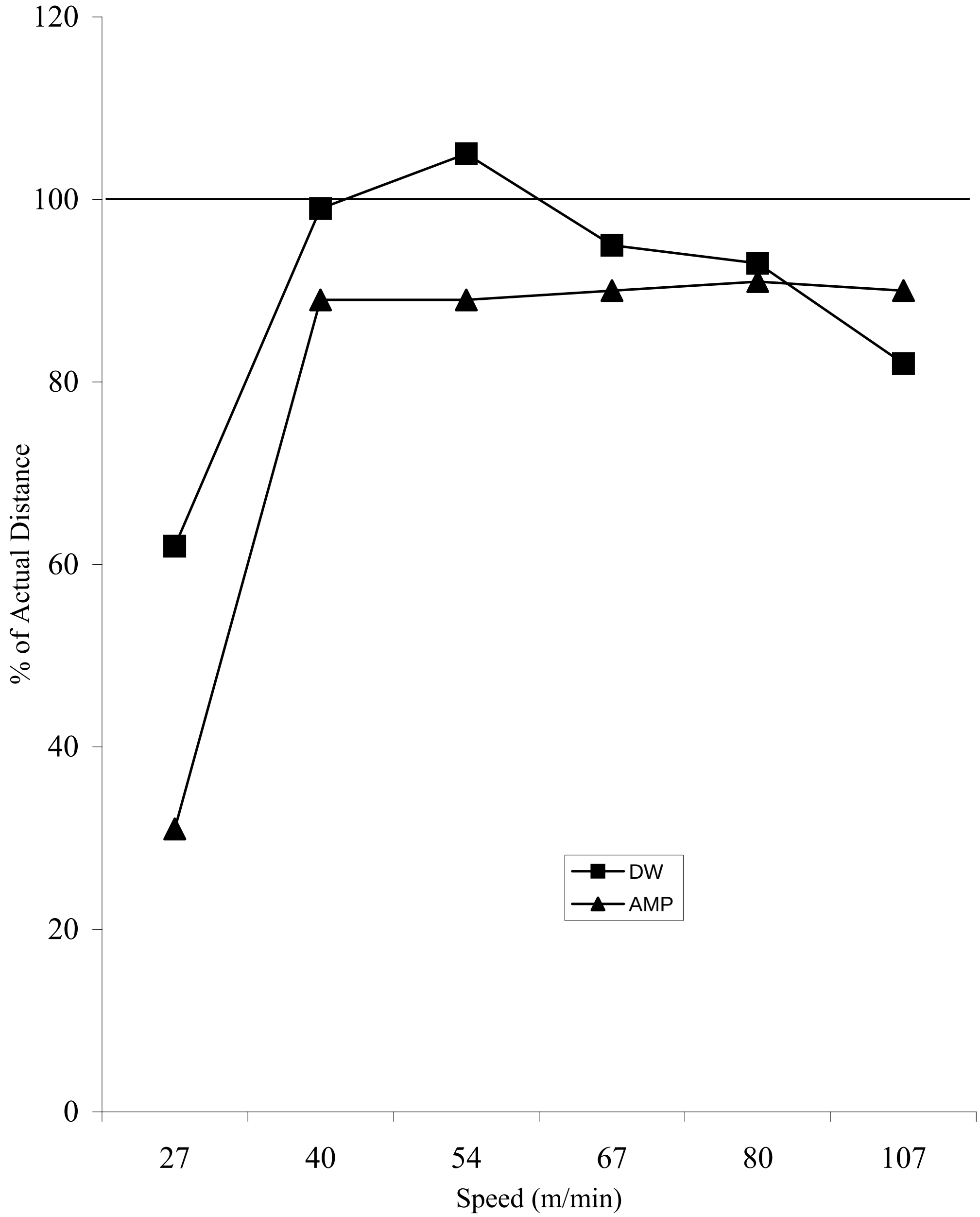
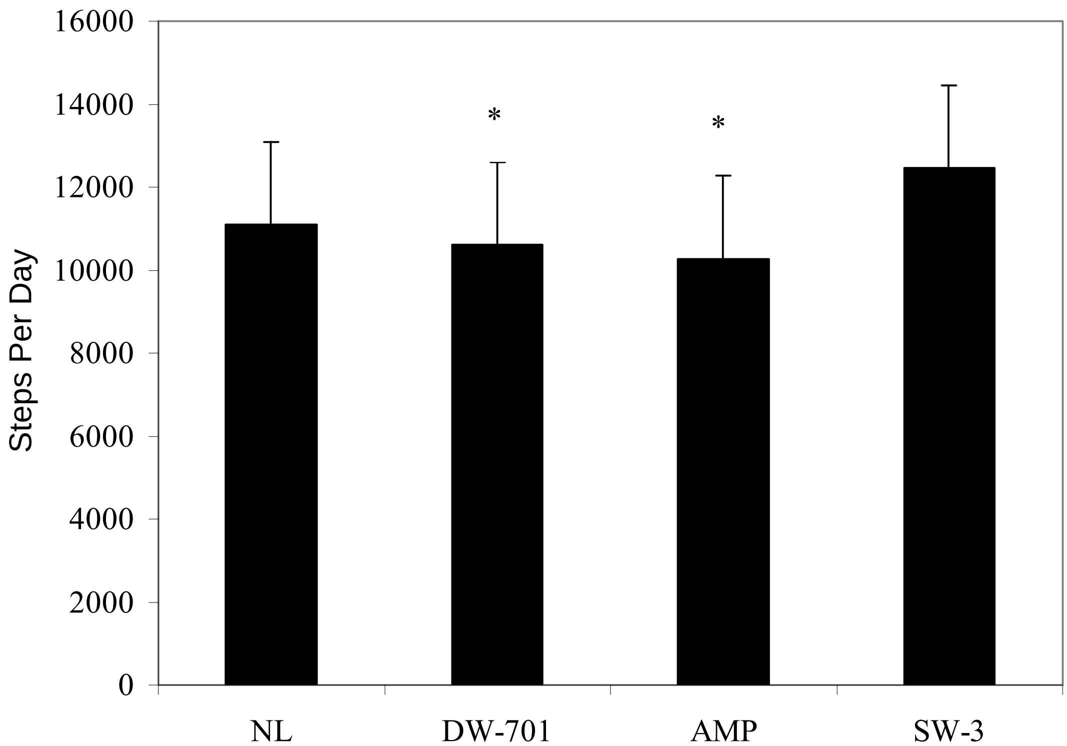


Figure 2. Effects of walking speed on pedometer estimates of distance traveled during treadmill walking (N=20).

Table 2. Mean steps detected during heel tapping, leg swinging, car driving, and cycle ergometry.

	Heel Tapping (N=20)	Leg Swinging (N=20)	Cycle Ergometry (N=20)	Car Driving (N=10)
NL	0.35 ± 0.18	0.38 ± 0.17*	5.9 ± 3.8$^{\#}$	7.6 ± 1.5*
DW-701	0.27 ± 0.11	0.17 ± 0.08	3.3 ± 1.3$^{\#}$	3.1 ± 1.5
AMP	0.0 ± 0.0	63.7 ± 12.6*	5.0 ± 2.6$^{\#}$	0.0 ± 0.0
SW-3	28.7 ± 6.4*	118.2 ± 0.75*	120.2 ± .41	0.0 ± 0.0

* = Significant detection of erroneous steps ($P < 0.05$)
\# = Significant underestimation of cycles·min^{-1} ($P < 0.05$)



* = significantly different From SW-3

Figure 3. Mean daily step counts recorded by two waist-mounted (New Lifestyles NL-2000 and Digiwalker SW-701) and two ankle-mounted (Activity Monitoring Pod 331 and StepWatch 3) (N=15).

met this recommendation at 80 m·min^{-1} and above, and some met this standard at 67 m·min^{-1} and above.

An important finding of the study is that two new, ankle-mounted pedometers provide superior accuracy at slower speeds. Specifically, the SW-3 had mean step counts within 1% of actual, at all speeds measured. Consequently, ankle-mounted pedometers such as the SW-3 may be a better choice when working with elderly people or those with an abnormal gait. For example, Cyarto et al. (10) investigated the impact of walking speed and gait disorders on the accuracy of waist-mounted pedometers (Yamax Digiwalker DW-200) in older adults. The DW-200 underestimated steps by 74%, 55%, and 46% at slow (25.2 ± 10.2 m·min^{-1}), normal (38.4 ± 16.8 m·min^{-1}), and fast (48 ± 21 m·min^{-1}) paces in the nursing home residents, and by 25%, 13%, and 7% at slow (57 ± 12 m·min^{-1}), normal (76.2 ± 12 m·min^{-1}), and fast (96.6 ± 12.6 m·min^{-1}) paces in seniors' recreation center members, respectively. Similarly, Macko et al. (23) investigated the effects of gait disorders on the accuracy of an ankle-mounted accelerometer (SAM) and a waist-mounted pedometer (Elexis Trainer, Model 3FM-180, International Microtech, Miami, FL) in stroke patients. The SAM recorded 98.5% of actual steps, while the Elexis Trainer pedometer missed approximately 13% of actual steps during a 1-min floor walk at the self-selected paces (average cadence 46 steps·min^{-1}). Both of these studies, as well as the current study, provide evidence of the superior accuracy of ankle-mounted pedometers at slow walking speeds.

Two of the pedometers (DW-701 and AMP) estimated distance traveled. The AMP consistently underestimated distance by about 10% at 40 m·min^{-1} and above. This error is greater than that reported by the manufacturer, but it could be due to differences in test protocol. The present study examined treadmill walking and the pod was secured in a neoprene sleeve, while the manufacturer's testing was done on a track and used athletic tape to secure the pod over the Achilles tendon. It is possible that over ground versus treadmill differences, or the tendency of the AMP to rotate around the ankle could have affected the accuracy in the present trial. The DW-701 underestimated the distance by more than 10% for the slowest and fastest speed, but it provided mean estimates that were within ± 10% of the actual distance at the other speeds. This indicates that these pedometers might be suitable for use in research to determine distance walked at speeds of 40 $m \cdot min^{-1}$ and above.

There are some habitual movements such as heel tapping and leg swinging that could result in an overestimation of steps. The placement and the mechanism of the device are important in determining whether they detect steps in these types of movements. As expected, the waist-mounted pedometers detected virtually no steps during heel tapping and leg swinging, while the ankle-mounted pedometers recorded some erroneous steps. The SW-3 recorded 29 erroneous steps during heel tapping ($P < 0.05$) and 118 erroneous steps during leg swinging ($P < 0.05$), while the AMP recorded 64 erroneous steps during leg swinging ($P < 0.05$), but not heel tapping.

The SW-3 detected 100% of cycle pedal revolutions, while the AMP, NL, and DW-701 recorded only a few steps. The ability of the SW-3 to detect bicycling activity could be advantageous in assessing PA in those who walk and bicycle. In this case, the SW-3 would be used to detect locomotion (walking, jogging, cycling) rather than steps, per se. This may have a practical application in European countries where a high percentage of trips are taken by bicycle. For example, in the Netherlands and Denmark they take 28% and 20% of trips by bicycle, respectively (30). In contrast, Americans take only 1% of trips by bicycle (30).

Even though the NL recorded a statistically significant number of steps (8 steps) during car driving, from a practical standpoint this source of error would have a minimal impact. Since Americans drive an average of 39 miles$\cdot$d^{-1} (31), the expected erroneous steps detection by the NL would be approximately 78 steps$\cdot$d^{-1} . Since healthy adults take between 7,000 and 13,000 (45), the number of the erroneous steps would be less than 1% of their daily total.

Over a 24-hr period, the DW-701 and AMP gave lower step counts than the SW-3. The NL was not significantly different from the SW-3, but it still underestimated total steps by 11%, which is less than the error seen in the DW-701 (15%) and the AMP (18%). Even though the SW-3 detected more steps during a 24-hr period, this may not be of practical significance. We found that the SW-3 detected a small, yet significant number of erroneous steps during activities such as leg swinging and heel tapping, which could contribute to the differences seen between the devices. It could also be argued that the other pedometers undercount small steps taken during very slow walking. However, these small steps do not require a great deal of energy and it could be argued that they should not count towards a specified daily step goal. In the frail elderly, on the other hand, it is very important to measure slow walking and the SW-3 would be the most suitable device.

Ankle- and waist-mounted pedometers each have advantages and disadvantages. The ankle-mounted pedometers have better accuracy for step counting at slow speeds (especially the SW-3). However, the SW-3 and AMP are quite expensive. The SW-3 costs $500, plus an additional $1500 for the computer software and docking station. The AMP costs $450 per device, plus an additional $750 for the computer software and docking station. Both of these ankle-mounted devices can store step data in one-minute epochs, which is an advantage in looking at the pattern of activity bouts throughout the day. They also provide information on the amount of time spent in different activity categories.

On the other hand, the waist-mounted pedometers (NL and DW-701) will continue to be good choices for measuring PA in healthy, free-living adults. Waist-mounted pedometers are inexpensive (DW-701, $25; NL, $50). Although they underestimate steps at slow speeds, most healthy adults walk at around 80 $m \cdot min^{-1}$. Using waist-mounted pedometers also enhances comparability with previous studies, because most studies used the Yamax Digiwalker SW-200. In addition waist-mounted pedometers are more user friendly and provide immediate feedback to the user, which is a good motivational tool.

In conclusion, careful consideration needs to be taken when choosing a suitable device for assessing ambulatory PA. Although the ankle-mounted pedometers have superior accuracy at slower speeds, they are expensive, which makes them impractical to use in large studies. However they could be very useful for those working with the elderly or gait impaired. Waist-mounted pedometers are inexpensive and have acceptable accuracy at normal walking speeds, making them a suitable choice for behavioral interventions and large epidemiological studies.

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APPENDICES

Appendix A

Informed Consent

INFORMED CONSENT FORM

Validation and Comparison of Two Ankle-Mounted and Three Waist-Mounted Electronic Pedometers

Investigator: Murat Karabulut
Address:
Applied Physiology Laboratory
The University of Tennessee
Department of Health and Exercise Science
1914 Andy Holt Ave.
Knoxville, TN 37996
Telephone: 865-974-8768

Purpose

You are invited to participate in a research study. The purpose of this study is to validate and compare the accuracy of ankle-mounted and waist-mounted pedometers under controlled laboratory conditions and free-living environment. Before exercising, you will be given a brief questionnaire to determine your health status.

Procedures

1. Height and weight will be measured.
2. Girth measurements will be taken around your hips and waist using a nylon tape measure.

You will be asked to participate **only** in the parts of the study that are checked below:

☐ 1. You will be asked to walk on a treadmill at 1.0, 1.5, 2.0, 2.5, 3.0, and 4.0 mph, for three minutes at each speed. The total amount of walking time will be 18 minutes. The Yamax Digiwalker SW-701 and NL-2000 will be worn on the right and left side of the belt, respectively. The AMP 331 and StepWatch 3 (ankle-mounted pedometers) will be worn on the right and left ankles, respectively. You will be asked to tap and swing your heel (right and left) and to cycle the cycle ergometer at 60 rpm, after you are done with the walking on the treadmill. Each exercise will be done for three minutes. The anthropometric measurements, treadmill and other testing will take place during one visit to the Applied Physiology Laboratory and will require about **60** minutes of your time.

☐ 2. You may be asked to drive your car for four miles in the city while wearing the two ankle-mounted pedometers on your right ankle and three waist-mounted pedometers on your waist. The principal investigator will accompany you during this time. Total time commitment of you for this part of the study will be **15** minutes.

☐ 3. You may be asked to wear three pedometers on the waist and two pedometers on the ankles (left and right) for 24-hours and record the number of steps taken at the end of the day. You will not be asked to perform any activities out of your normal routine. You will be given instructions on proper placement site and how to work the devices. You will be asked to return the devices to the Applied Physiology lab (Murat Karabulut) the day after you are finished.

Your total time commitment for the study will be **75** minutes, if you are asked to participate treadmill and driving study. If you are also asked to perform 24-h data collection, then total time commitment will be **75** minutes plus the **24**-hours that you will be wearing the devices.

Risks and Benefits

There are few risks associated with moderate exercise. The risks include abnormal blood pressure responses and heart rhythm disturbances. The risks of participating in this study are equivalent to the risks of activities requiring moderate exertion (yard work, light sport activities, etc.) that you engage in during everyday activities. The benefits to participation include exposure to devices that may provide accurate information about steps taken, and in some cases distance traveled. You will also find out your body mass index and waist-to-hip circumference, which are used to assess your risk of obesity-related diseases. In the unlikely event that physical injury occurs as a result of participating in this study, financial compensation is not automatically available and medical treatment will not be provided free of charge. If a physical injury should occur over the course of the study, immediately notify the primary investigator, Murat Karabulut.

Confidentiality

The information obtained from these tests will be treated as privileged and confidential and will consequently not be released to any person without your consent. However, the information will be used in research reports or presentations, but your name and other identity will not be disclosed.

Contact Information

If you have questions at any time about the study or the procedures, (or you experience adverse effects as a result of participating in this study,) you may contact the Principal Investigator, Murat Karabulut. If you have questions about your rights as a participant, contact Research Compliance Services of the Office of Research at (865) 974-3466.

Right to Ask Questions and to Withdraw

You are free to decide whether or not to participate in this study and are free to withdraw from the study at any time.

Before you sign this form, please ask questions about any aspects of the study, which are unclear to you.

Consent

By signing this paper, I am indicating that I understand and agree to take part in this research study.

______________________________ ____________________
Your signature Date

______________________________ ____________________
Researcher's signature Date

Appendix B

Pedometer Data Sheet

Pedometer Data Sheet

Subject Name & number: ________________________________ Gender: **M / F** Date of Birth: ___/___/_____ Date:

Height: ______cm _____in Weight:_______ lb _______ kg BMI:________ kg·m^{-2}

Waist: _______ cm Hip: ______ cm Waist/hip Ratio:______ Stride Length: ________ft

Device #: #: #: #:

Start &End Time	Treadmill Speed	Actual Steps (Hand Counter)	NL 2000	Yamax Digiwalker SW-701	AMP 331	StepWatch 3	Actual Distance (m·min^{-1})	Yamax Digiwalker Distance Mile = meter/3 (m·min^{-1})	AMP 331 Distance (m·min^{-1})
-	1 mph	(______X 2)/3 =	______/ 3 =	______/ 3 =		______X 2 =	26.8 m·min^{-1}	=	
-	1.5 mph	(______X 2)/3 =	______/ 3 =	______/ 3 =		______X 2 =	40.2 m·min^{-1}	=	
-	2 mph	(______X 2)/3 =	______/ 3 =	______/ 3 =		______X 2 =	53.6 m·min^{-1}	=	
-	2.5 mph	(______X 2)/3 =	______/ 3 =	______/ 3 =		______X 2 =	67 m·min^{-1}	=	
-	3 mph	(______X 2)/3 =	______/ 3 =	______/ 3 =		______X 2 =	80.4 m·min^{-1}	=	
-	4 mph	(______X 2)/3 =	______/ 3 =	______/ 3 =		______X 2 =	107.2 m·min^{-1}	=	

Start &End Time		Actual Steps (Hand Counter)	NL 2000	Yamax Digiwalker SW-701	AMP 331	StepWatch 3
-	Heel tapping	0				X 2 =
-	Leg Swinging	0				X 2 =
-	Cycling	0				X 2 =
-	Car Driving	0				

Brand name of the car: ___________________________ Automatic / Shift gear

Appendix C
Physical Activity Questionnaire
(PAR-Q)

Physical Activity Questionnaire
(PAR-Q)

Yes	No	
___	___	1. Has your doctor ever said you have heart trouble?
___	___	2. Do you frequently have pains in your heart and chest?
___	___	3. Do you often feel faint or have spells of severe dizziness?
___	___	4. Has a doctor ever said your blood pressure is high?
___	___	5. Has a doctor ever told you that you have a bone or joint problem such as arthritis that has been aggravated by exercise, or might be made worse with exercise?
___	___	6. Is there a good physical reason not mentioned here why you should not follow an activity program even if you wanted to?
___	___	7. Are you over age 65 and not accustomed to vigorous exercise?

If you accurately answered no to all questions, you have reasonable assurance of your present suitability for a graduated exercise program. If you answered yes to or more questions; if you have not done so recently, consult with your personal physician by telephone or in person BEFORE increasing your physical activity and/or taking part in this course. Tell your physician what questions you answered yes to on the PAR-Q. (Adopted from the British Columbia Ministry of Health)

Signature ____________________ Date ________________________

Vita

Murat Karabulut was born in Turkey on December 4, 1971 to Meliha and Seyithan Karabulut. He earned his Bachelor of Science degree in Physical Education and Sports from Middle East Technical University in Turkey. He was working as a PE teacher while in Turkey. He worked as a graduate teaching assistant in the Physical Education Activity Program, while pursuing his Master's degree in Exercise Science at The University of Tennessee, Knoxville. He also assisted in the physiology research laboratory and contributed to one pedometer study. He received a Master of Science degree with an emphasis in Exercise Physiology.