Utility of a Step Activity Monitor for the Measurement of Daily Ambulatory Activity in Children

Craig M. McDonald, MD, Lana Widman, MS, R. Ted Abresch, MS, Sandra A. Walsh, BS
Denise D. Walsh, MS

ABSTRACT. McDonald CM, Widman L, Abresch RT, Walsh SA, Walsh DD. Utility of a step activity monitor for the measurement of daily ambulatory activity in children. Arch Phys Med Rehabil 2005;86:793-801.

Objectives: To evaluate the reliability and validity of the StepWatch Activity Monitor (SAM) as a reliable and valid measurement tool for assessing ambulatory activity in able-bodied children and to assess the ambulatory activity of able-bodied children.

Design: Descriptive study.

Setting: General community.

Participants: Ninety-seven able-bodied children, aged 6 to 20 years.

Interventions: Not applicable.

Main Outcome Measures: Anthropometric parameters, calibration of a step activity monitor to ensure accuracy, and 3 days of simultaneous heart rate and step activity monitoring.

Results: The SAM had an accuracy of 99.87% compared with the observer-counted steps and was shown to be valid and reliable when compared with heart rate monitoring. The subjects in all age groups (6–10y, 11–15y, 16–20y) spent most of their active time at low step rate but took the fewest steps at this rate. Although the least amount of time was spent at high step rate, it accounted for the most steps. The 6- to 10-year-old group took more total steps per day than any of the other groups. Boys spent significantly more time at high step rate than girls in all age groups (mean for boys, 66±4min/d; girls, 47±4 min/d).

Conclusions: The SAM is an accurate, valid, and useful tool for measuring continuous, time-based step activity during real-world community activity for children and adolescents.

Key Words: Ambulation disorders, neurologic; Monitoring, ambulatory; Rehabilitation; Walking.

PHYSICAL ACTIVITY and ambulation are important in maintaining health and preventing disease. Epidemiologic studies[1,2] with adults suggest that regular physical activity contributes to longevity and decreases the risk of death from a variety of causes. Inactivity has been shown to be the second most significant risk factor for cardiovascular heart disease.[3] However, the consequences of physical inactivity and ambulation on the health, functional ability, and independence among the disabled population has received little research attention.[4] In recent years, the US Centers for Disease Control and Prevention and the American College of Sports Medicine,[5] the US Public Health Service,[6] the National Institutes of Health,[7] and the US Department of Health and Human Services[8] have published recommendations for increased physical activity. Such activity is associated most strongly with the prevention and control of coronary artery disease (CAD),[9] hypertension,[10,11] non–insulin-dependent diabetes mellitus,[12] osteoporosis,[13,14] obesity,[15] and mental health problems.[16,17] More severely disabled populations may be at particular long-term risk for CAD, obesity, osteoporosis, and mental health issues such as anxiety, depression, or reduced self-esteem.[18-24]

Patterns of physical activity in childhood track into adulthood and appear, in part, to determine adult levels of physical activity.[25-27] The Allied Dunbar National Survey of fitness and physical activity,[28] in which 600 people were surveyed, showed that the level of childhood activity was associated with the general level of physical activity in adulthood. Thus, increased physical activity in childhood may have lasting health benefits.

Although ambulation is the major component of physical activity in most people who are able to walk,[29] few studies have assessed the frequency and duration of children's ambulatory activity during free-living conditions. A major reason for the lack of information is that, until recently, no easy-to-use commercial device has been available that accurately and continuously records steps in short time intervals.

Several methods are used to measure either daily physical activity or ambulation, including physical activity questionnaires and diaries, heart rate monitors (HRMs), pedometers, and accelerometers. Diaries and questionnaires, which rely on self-reported physical activity, have been shown to be inaccurate when used with children largely because children are unable to recall details of their daily activity. Baranowski et al[30] reported that children could recall only 55% to 65% of their activities each day. In another study,[31] children 11 to 13 years old could recall only 46% of observed activities from the previous 7 days. Pedometers have been used to measure steps, but commercially available pedometers are generally extremely inaccurate, particularly at slow walking speeds.[32-35] This is particularly relevant when considering the use of these devices in a disabled population with gait disorders.[36] In addition, available pedometers provide information about total steps or distance traveled but no minute-to-minute information about the frequency, duration, or intensity of activity. Accelerometers, including the Caltrac, Tri-Trac3D, Large Scale Integrated Activity Monitor, and the Actigraph have been used to quantitatively measure physical activity. These devices are worn on the waist and simply record 2- and 3-dimensional accelerations over given time periods. Accelerometers are affected by passive movement (eg, riding in an automobile or coasting down-

From the Rehabilitation Research and Training Center in Neuromuscular Diseases, Department of Physical Medicine and Rehabilitation, University of California, Davis, Sacramento, CA.

Supported by the National Institute of Disability and Rehabilitation Research (grant no. H133B980008-99) and the National Institute of Child Health and Human Development (grant no. 5RO1 HD35714-03).

No commercial party having a direct financial interest to the results of the research supporting this article has or will confer a benefit on the author(s) or on any organization with which the author(s) is/are associated.

Reprint requests to Craig M. McDonald, MD, Dept of Physical Medicine and Rehabilitation, 4860 Y St, Ste 3850, Sacramento, CA 95817, e-mail: *cmmcdonald@ucdavis.edu.*

0003-9993/05/8604-9222$30.00/0
doi:10.1016/j.apmr.2004.10.011

Table 1: Anthropometric Characteristics of 83 Subjects Who Completed Self-Report Logs

Age Group (y)	Sex	n	Age (y)	Weight (kg)	Height (cm)
6–10	M	15	8.4±1.2	30.5±8.1	132.7±8.9
	F	15	9.1±1.1	30.0±4.7	134.8±8.5
11–15	M	13	13.8±1.6	52.2±11.2	165.1±12.1
	F	12	13.4±1.6	50.7±12.9	159.3±9.4
16–20	M	13	17.3±1.1	68.8±6.0	178.9±5.8
	F	15	17.3±1.1	65.1±8.9	168.9±6.0

NOTE. Values are mean ± standard deviation.
Abbreviation: F, female; M, male.

hill on a bicycle), which influences the data acquisition. These instruments are problematic for clinical applications because the units of measurement are not well defined with respect to a specific event of clinical interest. Thus, it is difficult to relate the data to recognizable activities such as slow walking, comfortable walking, brisk walking, or running. Long-term heart rate monitoring has been a useful measure of physical activity in disabled children[37,38] and is a well-established quantitative method used to measure community physical activity levels.[39,40] However, this method is labor-intensive, requiring the acquisition of a heart rate–oxygen consumption ($\dot{V}O_2$) calibration curve along with measurement of resting energy expenditure by indirect calorimetry for an accurate estimation of physical activity. This makes the technique impractical for larger clinical studies. In addition, at low activity levels, emotional stress can significantly elevate heart rate independent of any change in $\dot{V}O_2$. Fitness levels also affect heart rate independent of actual levels of physical activity during a testing period.[41] In addition, heart rate, like accelerometry, cannot be directly tied to a specific function such as walking.

Recently, Cyma designed the StepWatch Activity Monitor[42] (SAM), a lightweight, unobtrusive ankle-worn instrument[a] that uses a custom accelerometer linked to a microprocessor to detect and store step counts in user-definable time intervals. The SAM counts the number of steps taken by its user at 1-minute intervals for as long as a month at a time. In addition, it uses adjustable electronic filters that are sensitive to the types of movement associated with a wide range of gait styles.

Only a few studies using the SAM as a measure of ambulatory activity have been published, and to our knowledge, none has been published using the SAM in children. Our objectives in this study were (1) to evaluate whether the SAM is an accurate, reliable, and valid measurement tool with which to assess ambulatory activity in able-bodied children; (2) to determine the compliance of able-bodied children during long-term community ambulatory activity monitoring with the SAM; and (3) to show its utility with able-bodied children by measuring their minute-by-minute step rate over extended time periods and by determining the amount of time per day they walk at defined activity levels.

METHODS

Participants

The subject population was a convenience sample of 97 able-bodied children and youths, aged 6 to 20 years, who were recruited from among friends and relatives of University of California (UC) Davis employees and patients in the children's neuromuscular disease clinic at UC Davis. Subjects were also solicited through flyer distribution and an announcement on university-affiliated web sites. Table 1 lists the subjects' physical characteristics in the 3 age groups (6–10y, 11–15y, 16–20). The Institutional Review Board of UC Davis approved the study. All subjects provided a written informed consent, and their parents or legal guardians also provided written informed consent.

Anthropometry

Subjects were weighed in light indoor clothing and without shoes to the nearest 0.2kg; height was measured to the nearest 0.1cm with a wall-mounted stadiometer.

Step Activity Monitoring

Description of the monitor. The StepWatch 2 Activity Monitor[a] is a small device (height, 6.5cm; width, 5cm; thickness, 1.5cm; weight, 65g) that is worn on the ankle at the right lateral malleolus or left medial malleolus; it consists of an accelerometer and a digital counter that records each step or swing of the leg (fig 1). The SAM can be programmed to record data at intervals between 6 seconds and 25 minutes. The duration of data collection depends on the activity of the person

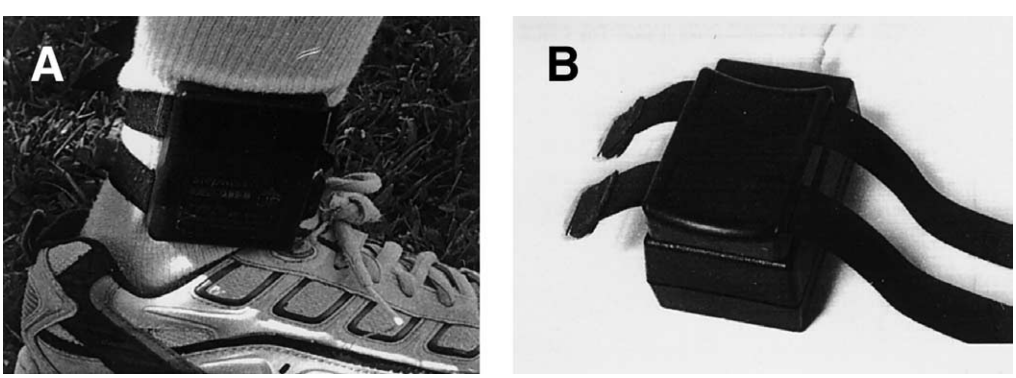

Fig 1. (A) The SAM is attached with 2 elastic straps (left) and is worn on the lateral aspect of the right ankle. (B) Data from the SAM are downloaded to and settings are uploaded from a computer via a dock.

and the sampling interval selected, but in a typical situation, the SAM can conservatively record data continuously at 1-minute intervals for 41 days. It is individualized for each person's gait characteristics by programming it for gait (cadence, motion sensitivity), time interval of data collection, total length of time for data collection, and personal identifying information. This information is entered into a computer using the software supplied by the manufacturer and is uploaded along with the time of day to the SAM through a docking station (fig 1B). The SAM is programmed in the laboratory and then sent home with the subject. Because the time at which data collection will start and stop is a part of the programming, the only task the subject has is to attach the SAM to the appropriate ankle.

Monitor calibration. A SAM was calibrated for each subject according to the manufacturer's recommendations. Estimated values for cadence and sensitivity based on the subject's age and height were initially programmed into the SAM. The subject then walked for 15m at a slow speed and for 15m at a fast speed while wearing the SAM, and an observer counted each step taken by the right leg. The number of steps recorded by the SAM was compared with the manual count. Generally, the recommended settings were accurate. However, if the values differed by 2 or more steps, the SAM's sensitivity and/or cadence were modified by inputting the adjusted values into the computer program. If the manual count was low, the value for the cadence was decreased, and if the count was high, the sensitivity was decreased. The new information was uploaded to the SAM, and the calibration was repeated until the manual count and the SAM values agreed. The SAM was then programmed for start and stop times for the study.

Determination of SAM accuracy. To assess accuracy, 22 subjects of varying ages and walking speeds donned a personally calibrated SAM and walked at a self-selected comfortable pace for 10 continuous minutes up and down a 50-m hallway while 2 observers with tally counters counted the subjects' right-leg steps.

Heart Rate Monitoring

Each subject was provided with a Polar Advantage NV heart rate monitor[b] that consisted of an electrocardiogram transmitter strap worn around the torso at sternal level that communicated heart rate via telemetry to a wristwatch/receiver. HRMs collected data at 1-minute intervals.

Daily community activity measurement. All subjects and their parents were given written instructions and a demonstration of the proper wearing and operation of both the SAM and HRM. All subjects were instructed to wear both monitors for 3 complete days (2 weekdays, 1 weekend day) while they went about their normal daily routines. They were instructed in the proper placement of the monitors and were told to attach them immediately on waking and to leave them on until going to bed. They were asked not to wear the monitors on days that were atypical because of illness, vacation, or other unusual activities. The time of day set in the HRM watch and SAM internal clock were synchronized. Subjects were also asked to keep a log of the time they awoke, the time they went to bed, and their daily activities on the days the monitors were worn.

Data Analysis

Data from each monitor were downloaded and merged into a single file for data analysis. Based on previous definitions used by the developers of the SAM,[42] step activity levels were defined as zero step rate (ZSR) (0 steps), low step rate (LSR) (1–15 steps/min); medium step rate (MSR) (16–30 steps/min), and high step rate (HSR) (>30 steps/min). Each minute was

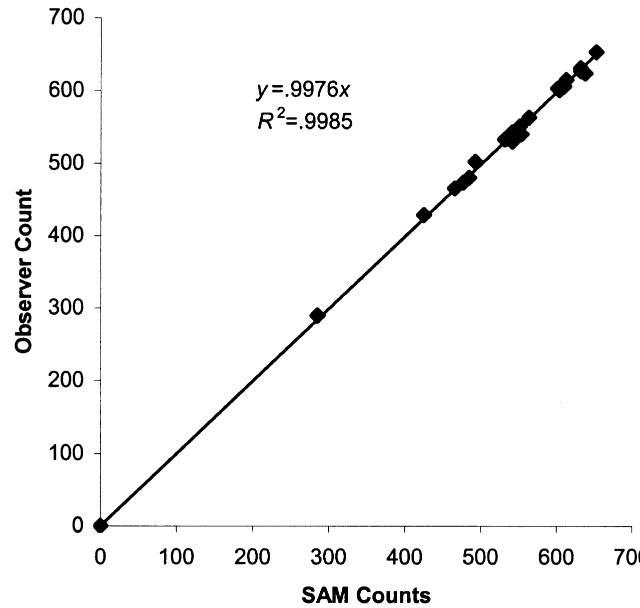

Fig 2. The number of steps counted visually versus the number of steps counted by the SAM during a 10-minute walk at a subject-selected pace.

labeled for its activity level using the SAM data to identify ZSR, LSR, MSR, or HSR. For each subject, the time in minutes spent at each activity level (including ZSR minutes) and the number of steps taken at each activity level were calculated for each of the 3 days. The mean of the 3 days was calculated for each person and used for statistical analysis.

A mean heart rate was determined for each of the step activity levels. Because there was dropout of data in the HRM because of electric interference, only minutes with heart rate values greater than 40 beats per minute were analyzed for heart rate.

Statistics

We used Systat, version 9.0,[c] for statistical analysis. Means ± standard errors (SEs) were calculated for each of the output measures. We used Pearson product-moment correlations to assess the concurrent validity of the heart rates and step rates on a minute-by-minute basis. Mean correlations were computed from subjects who had at least 800 minutes of simultaneous HRM and SAM monitoring. These correlations had undergone a Fisher z transformation because the sampling distribution of the Pearson r did not approximate a normal distribution.[43] Linear regression analysis was used to examine the relation between the HRM and SAM monitoring. Two-way analysis of variance (ANOVA) was used to make comparisons by age group and sex. Significance was accepted at P less than .05 for all tests.

RESULTS

SAM Accuracy

Figure 2 shows the observer-counted steps plotted against the SAM-counted steps for 22 subjects for the 10-minute continuous walk. The SAM had an accuracy of 99.87% as compared with the observer-counted steps. The greatest discrepancy in any of the subjects was an undercount by the SAM of 2.4%.

Table 2: Subject Compliance

Days With Complete Data	SAM		HRM	
	Subjects (n)	Days	Subjects (n)	Days
3	58	174	25	75
2	17	34	32	64
1	9	9	19	19
0	13	0	21	0
Total time data acquired, (h)		217d (3104)		158d (2474)
Data collected, (%)		75% (271/291)		54% (158/291)

Subject Compliance

To examine whether the pediatric subjects properly used the monitors, the number of minutes of data acquired from the SAM and from the HRM were compared with the amount of expected data for 3 days of continuous monitoring (table 2). Originally, 97 pediatric subjects were asked to wear the monitors for 3 days. A complete day of data collection was determined by examining the output from the SAM—the first recorded steps of each day determined the beginning of the day and the last recorded steps each night determined the end of the day. This time interval was compared with the self-report logs. The SAM data were used as an indicator because the SAM did not require any action from the subject other than donning it properly. Of the original 97 subjects, 84 (87%) had at least 1 complete day of SAM data and 76 (78%) had at least 1 complete day of HRM data. Twelve subjects either refused to wear the SAM or did not keep the monitor on for complete days. One subject lost both the SAM and HRM. No subject wore the HRM without the SAM. There were 3 main reasons why 8 subjects obtained fewer HRM data than SAM data. Some subjects refused to wear the HRM chest strap because it was uncomfortable. Others wore it incorrectly and thus no signal was obtained; still others ignored instructions not to alter the watch settings. This caused lost data because of incorrect recording mode or inadequate memory on the receiver. There were no differences in age, sex, or sociodemographic characteristics of children with missing data compared with those with complete data. Eighty-three subjects completed self-report logs of the time they got up and the time they went to bed.

SAM and HRM Equipment Reliability

With all subjects, once the SAM started recording there was no interruption in the recorded data. For 2 subjects, the SAMs were incorrectly programmed to start after the subjects began wearing them. The first day of data for those subjects was discarded. Data from 1 subject was lost because of a communication malfunction during downloading of the data to the computer. Daily data collection by the SAM averaged 14.2 hours, whereas data from the HRMs averaged only 11.25 hours a day. There were significant problems with HRM data dropout because of environmental interference in the acquisition of the telemetry signal (eg, from home computers, riding in cars) or from equipment malfunction. As a result, the HRM data were sporadic, and more than 14% of the expected heart rate data (based on the quantity of SAM data) were not acquired.

SAM Validity

There was a moderate (.49) correlation between the SAM and the HRM in the 68 subjects who had more than 800 minutes of simultaneous SAM and HRM data. The mean regression line indicated that for every 1 step per minute increase recorded by the SAM, the heart rate increased by .79 beats/min. The slope of the regression line was not significantly affected by sex or age. However, the mean heart rate when inactive (ZSR) was 97.9±1.9 beats/min for the 6- to 10-year age group, 88.7±2.0 beats/min for the 11- to 15-year age group, and 85.7±1.6 beats/min for the 16- to 20-year age group. Thus, factors that could in part influence the overall relation between heart rate and step rate include maturational influences.

To determine if the step activity levels chosen to discriminate difference between various levels of activity were meaningful, we compared the mean heart rates at the ZSRs, LSRs, MSRs, and HSRs (fig 3). A 1-way ANOVA indicated that for each subject group, the mean heart rate at each step rate differed significantly ($P<.001$) from each of the other step rates. There was no difference in mean heart rate between boys and girls in the two younger age groups, but the 16- to 21-year-old women had significantly higher mean heart rate than did their male counterparts at all activity levels, including ZSR (fig 3).

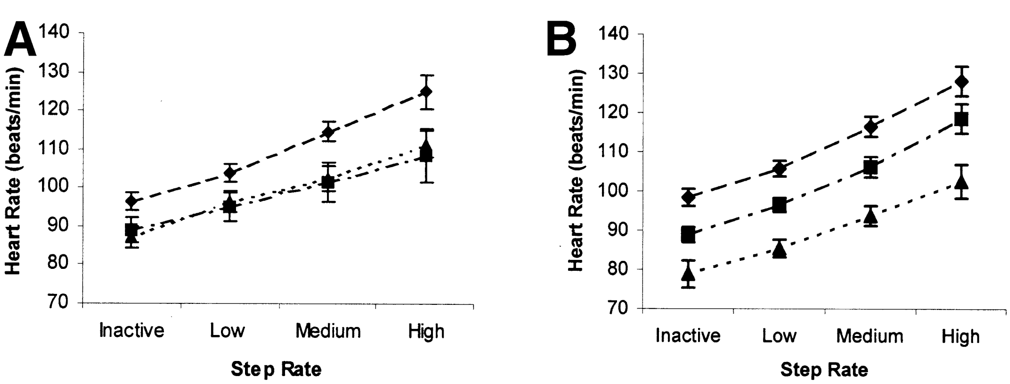

Fig 3. Mean heart rate at each step rate for (A) girls and (B) boys. Legend: ♦, ages 6 to 10 years; ■, ages 11 to 15 years; ▲, ages 16 to 20 years. Values are mean ± SE.

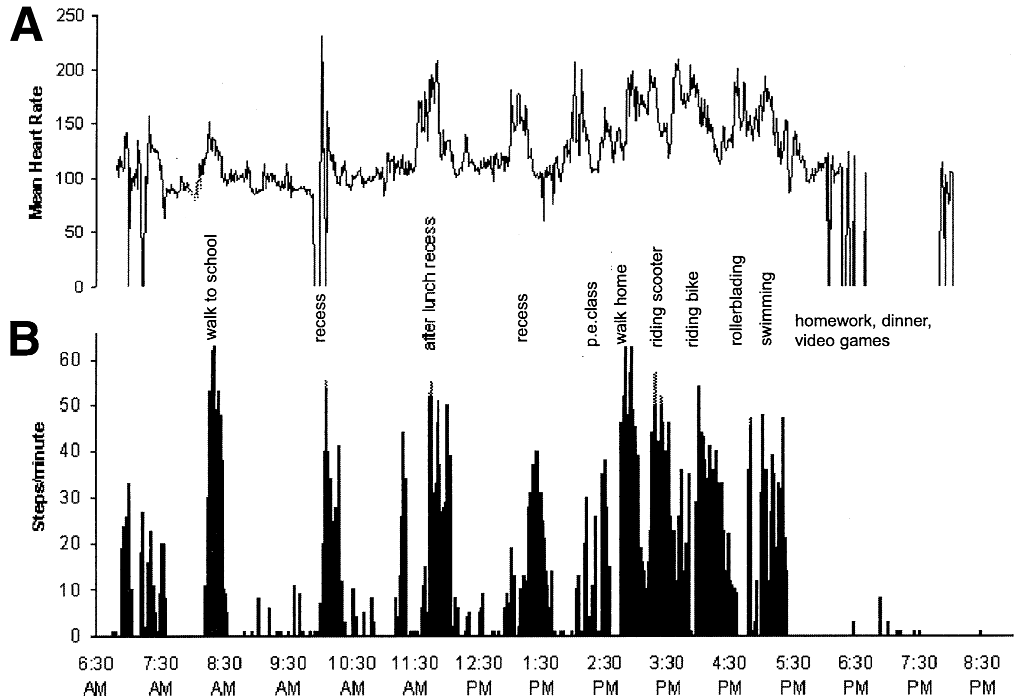

Fig 4. Sample output showing 1 day of simultaneous heart rate and SAM data for a 7-year-old boy. (A) The average heart rate at 1-minute intervals. (B) The number of steps taken in each minute. The portions of the heart rate trace that read zero represent times when environmental conditions interfered with the telemetry. Abbreviation: p.e., physical education.

Daily Community Ambulation

Figure 4 represents simultaneous heart rate and SAM data for 1 day for a 7-year-old boy. The figure shows the utility of using SAM data for observing various functional activities and their corresponding step rates. The correlation between heart rate and step rate for this entire day was *r* equal to .55. The figure also shows that there is significant dropout of data collection with the HRM when the computer is being used.

Step Analysis

The number of steps per day at each step rate is shown in figure 5A, and the number of minutes per day spent at each step rate is shown in figure 5B. The figures illustrate that all subjects spent the majority of their active time at LSR but took the fewest steps at this rate. Although the least amount of time was spent at HSR, it accounted for the most steps in all groups. At the MSR, both the time and step rate were intermediate between the LSR and HSR.

Although our groups were small, the SAM data showed significant differences in the steps taken at each of the step rates (table 3) and in the time spent at these rates for children of different ages and sex (table 4). A 2-way ANOVA showed that the 6- to 10-year-old group took significantly more total steps per day than the other groups ($F=4.84$, $P=.01$), and there was a slight, but significant, overall sex effect ($F=4.29$, $P=.042$). The data show that the SAM can be used to differentiate changes in everyday moderate-intensity lifestyle activities, which until now have been difficult to quantify. There were significant age group differences in the time spent at ZSRs, MSR, and HSR. The 6- to 10-year-old children spent

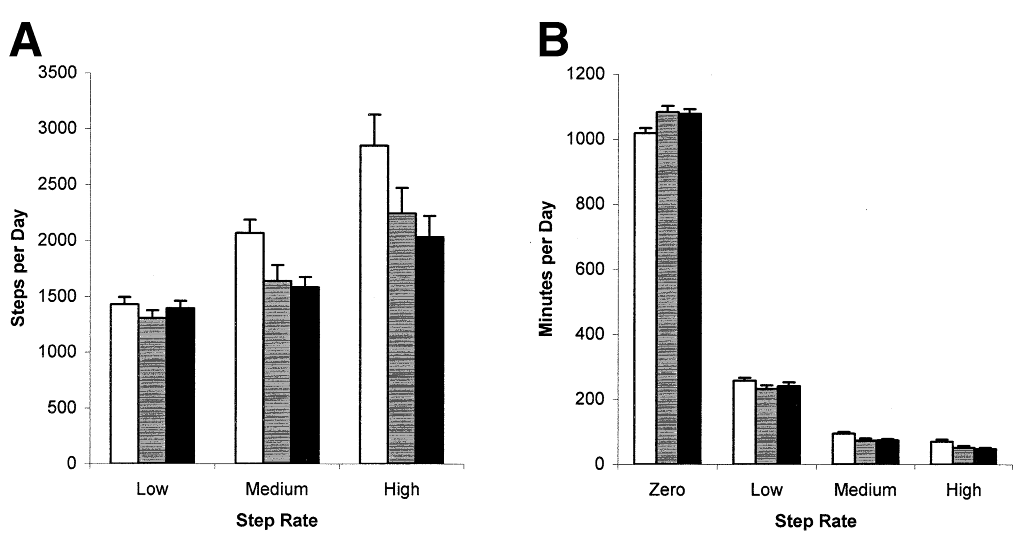

Fig 5. (A) Total steps per day at each step rate. (B) Minutes per day spent inactive and at each step rate. Legend: □, ages 6 to 10 years; ▤, ages 11 to 15 years; ■, ages 16 to 20 years. Values are mean ± SE.

Table 3: Steps per Day at Each Step Rate

Age Group (y)	Sex	Low	Medium	High	Total
6–10	M	1430±93	2210±157	3362±455	7001±580
	F	1431±94	1930±175	2342±271	5703±464
11–15	M	1257±109	1797±241	2301±307	5354±566
	F	1359±92	1471±130	2184±356	5014±525
16–20	M	1299±113	1622±152	2473±297	5394±480
	F	1387±80	1430±75	1718±234	4534±292

NOTE. Values are mean ± SE.

significantly more time at the MSRs and HSRs than did the other 2 groups, and they spent less time at ZSR. A 2-way ANOVA showed that the boys spent significantly more time at HSR than the girls (mean for boys, 66±4min/d; girls, 47±4min/d; F=7.48, P=.008), regardless of age, because there was no age and sex interaction. Consequently, the 6- to 10-year-old boys spent approximately 25 to 40 more minutes at HSR than the other groups.

DISCUSSION

This study shoes the accuracy, validity, ease-of-use, and utility of the SAM in quantifying daily ambulatory activity in able-bodied children from 6 to 20 years of age.

Accuracy

Analysis comparing the SAM with visual hand counting found the SAM to be extremely accurate in counting the number of steps taken by the able-bodied subjects during a 10-minute continuous walk (99.9%). It has also been reported that the SAM has a 96% step-counting accuracy in older adults,[44] and a 99% accuracy in hemiparetic stroke patients walking at a self-selected pace and a 98% accuracy at a fast pace.[45] Factors likely to account for the higher accuracy in our study are that (1) the cadence and motion sensitivity settings of the SAM were optimized for each subject at his/her self-selected pace, (2) the subjects were tested at a self-selected walking pace and a sprinting pace but not through a wide range of paces, and (3) they may have had a faster and more uniform gait than either the older adults or the hemiparetic stroke patients. Nevertheless, all of these reports show that the SAM is accurate when used with a variety of subjects of all ages at both slow- and fast-comfortable walking speeds and across a broad range of gait types.

Validity

The SAM provides a valid measure of physical activity intensity as shown by the comparison of step data and heart rate on a minute-by-minute basis over 3 days of monitoring. The moderate correlations between the HRM and SAM (r=.49) are similar to the correlations reported in other studies using HRMs and other accelerometry-based measurement devices. For example, Welk and Corbin[46] found that the correlation between HRM and the 3-dimensional Tritrac accelerometer was .58, whereas Sallis et al[47] reported that the correlation between HRM and the unidimensional Caltrac accelerometer was .52.

The step rate ranges chosen to define intensities of activity produced significant concurrent validity with heart rate at the increasing step rates, and there were significant differences between the increasing step rates. A first-order repeated-measures ANOVA showed a significant linear increment in mean heart rate at each investigator-defined step activity rate in all 3 age groups and in both sexes. Using Bonferroni adjusted t tests, the heart rates at the HSR differed significantly from the heart rates at the other step activity levels.

The average step rate for the 10-minute walk was 60±5 right steps per minute over all ages (range, 40–66 steps/min). Given that the nature of children's behavior consists of sporadic bursts of activity,[48] these data suggest that the HSR (step rate, >30 steps/min) equated to continuous comfortable walking for at least half a minute or running for a portion of the minute. The step counts at MSR (15–30 steps/min) represented periods when the subject was awake and moving around intermittently but with a significantly lower heart rate than at HSR. Step counts at LSR (1–15 steps/min) represent intermittent steps taken during activities of daily living, class time, and/or moving about the house. Step counts at ZSR indicated the subject was engaged in sedentary or stationary activities such as sleeping, doing homework, playing video games, and watching television.

Compliance

One of the most difficult aspects of quantifying normal physical activity in the community is determining a subject's compliance with the measurement protocol; this is particularly true with small children. Ours is the first study using the SAM with children, and it shows good compliance among children when used for community-based monitoring of ambulatory activity. The subjects had higher compliance using the SAM than they did with the HRM, for which tolerance was more problematic. Nevertheless, 70% of all subjects provided at least 13 hours of simultaneous heart rate and step activity monitoring. Of the 97 subjects in the study, 84 (86.6%) had at least 1 complete day of step activity monitoring.

The small, unobtrusive size of the SAM assures that the device does not interfere with normal activity, and the computerized activation with no user intervention necessary ensures proper operation of the device. Many subjects reported that they forgot they were wearing the device while they went about their daily routine. The monitor also provides no real-time feedback to the subject, which minimizes the influence of the monitoring paradigm on subject behavior. This leads to better subject compliance and more valid data concerning real-world levels of community ambulation.

A possible concern in these uncontrolled nonlaboratory conditions is that equipment may not function properly. SAM data were missing because of subject noncompliance or investigator error in SAM programming, whereas the gaps in the heart rate record were most often caused by technical considerations (telemetry interference) or lack of compliance (subject tampering with the watch, incorrect wearing of the chest belt, refusal to continuously wear the monitor).

Utility

This study shows that the SAM provides a practical, objective way to record daily physical activity patterns, to determine

Table 4: Minutes per Day at Each Step Rate

Age Group (y)	Sex	Inactive	Low	Medium	High
6–10	M	999.3±17.4	254.6±9.8	102.0±5.4	84.1±10.1
	F	1038.1±24.8	259.5±16.2	86.9±7.6	55.5±6.5
11–15	M	1091.2±28.8	216.3±15.1	78.6±10.2	53.7±7.3
	F	1073.6±26.6	249.0±16.1	68.2±6.1	49.2±8.0
16–20	M	1077.7±28.7	231.6±21.1	74.2±6.9	56.5±6.4
	F	1092.8±15.9	239.0±12.5	68.2±2.9	40.0±4.5

NOTE. Values are mean ± SE.

the proportion of time spent at various intensities of activity, and to provide a quantitative profile of minute-by-minute real-world community mobility. Little training (≤2h) is necessary for the technical personnel to calibrate the SAM for each user or to retrieve the data. Moreover, the user simply has to attach the SAM to the appropriate ankle with the arrow on the SAM pointing up. The research and clinical uses of this monitor are important because lower-intensity activities such as walking and housework tend to be less reliably reported than higher-intensity exercises when measured with physical activity questionnaires,[49,50] and it is harder to recall less structured activities on self-report instruments.[5]

Because the step, the natural unit of ambulation, is a major component of most physical activities and is a functionally relevant parameter, a step monitor has greater clinical implications for rehabilitation than physical activity monitors that measure heart rate or a vector magnitude of acceleration. The step activity data are readily quantifiable and can be standardized and compared across groups, unlike total energy expenditure data, which are influenced by multiple factors—for example, a person's metabolism, age, sex, body composition, ethnicity, or health status. Estimating total daily energy expenditure is a labor-intensive parameter. Thus, the ease of data acquisition with the SAM makes possible research into the physical activity levels of larger, more diverse populations. The flexibility of the SAM also lets researchers focus on very specific functional activities such as running, idle time, or continuous walking versus intermittent walking. Although the SAM can theoretically provide an estimate of energy expenditure, such estimates necessitate more labor-intensive calibrations with the determination of step rate–oxygen uptake relationships. It is more likely that the SAM will be used to quantitatively evaluate the daily ambulatory function of specific population groups rather than to determine of energy expenditure.

Many orthopedic and rehabilitation interventions have the objective of improving ambulatory function in the community. Mobility proficiency and ambulatory activity in the community are important measures of functional status and provide outcome measures with which to evaluate interventions in people with physical impairment, including children with spinal cord injury, cerebral palsy, spina bifida, progressive neuromuscular diseases, lower-extremity amputations, and severe joint disease. Objective measures of ambulatory activity are important functional outcome measures in mobility-impaired populations. Currently, objective measures of actual ambulatory activity are lacking and, too frequently, rely on patient or parental reports of mobility levels or, alternatively, subjective clinician impressions. For example, measured distances traveled by physician-determined "community ambulators" may never exceed 1 city block for some disabled children.[51,52] Such children have been labeled "community ambulators" despite the fact that most of their day is spent in a wheelchair. The number of steps that a person actually takes during the day is critical in determining his/her level of "community ambulation."

There has been the need for a technique that quantitatively and reliably measures continuously the actual or real-world physical activity of able-bodied and disabled people over an extended time period in an unobtrusive manner. The functional mobility of able-bodied and disabled populations can be evaluated and expressed in 2 ways: what a person is capable of doing over brief time intervals using objective and standardized testing protocols in laboratory settings or what the person actually does over extended periods in his/her own real-world community. Ideally, objective information about physical activity patterns in disabled and nondisabled subjects includes the following: (1) when, in a given day or series of days, is a person engaged in active physical activity or community locomotion and when are they relatively sedentary; (2) what is the magnitude of peak activity during this period; (3) what is the average total daily physical activity over an extended sample time that may be several days or several weeks; and (4) what is the proportion of time spent at various investigator-defined physical activity intensities. The SAM is an easily applied activity-monitoring device that provides objective assessments of patterns of physical activity in the real-world community over extended time periods. In addition to the use shown here with healthy children, step activity monitoring could become an extremely meaningful and valuable outcome tool to assess the impact of therapeutic interventions (medical treatments, orthopedic surgeries, new prosthetics or orthotics, therapeutic exercise) on ambulation.

Age and Sex as Determinants of Activity Levels

Our study was not designed to develop widely applicable normative data about the step activity levels of healthy children. Such a normative study will necessitate large samples from widely diverse geographic areas and an appropriate representation of diverse ethnic groups. In addition, other variables that potentially influence ambulatory behavior (eg, climate, geographical region, school or workday vs nonschool or nonwork day, season) will need to be systematically studied. In the future, normative information will be valuable, not only in measuring the degree and normal range of physical activity of able-bodied, healthy children but also in determining the degree of abnormality in physical activity among disabled children and adults.

Despite this limitation, our study showed that the 6- to 10-year-old boys and girls were more active than the older participants. Although one may argue that younger children have a shorter stride and therefore take more steps to cover the same distance than a taller child or an adult, these children also spent more time at each activity level. When height was entered as a covariate to remove the effect of shorter stature, the young group still took significantly more steps than the older age groups. Maturational trends and sex differences in the amount of physical activity have been previously observed in children. Overall, boys have been shown to be 15% to 25% more active than girls and a consistent decline in physical activity through school age and adolescent years has been measured in both sexes.[53] A recent study[54] that used self-reported data from thousands of school-age and adolescent children showed declines in physical activity among teenagers, particularly girls, similar to those we have documented.[54]

Implications for Physical Activity Interventions Among Adolescents

There has been increasing awareness of obesity as a complex and escalating problem among children and adults in the United States.[55] Successful intervention programs in able-bodied, obese children have combined nutritional modifications to reduce energy intake with interventions to increase physical activity over baseline levels. Knowledge gained from the SAM about ambulatory activity patterns can provide important information about the degree to which simple modifications in ambulatory activity may produce significant changes in overall physical activity. For example, the low levels of activity and brief durations spent at the high step rate that we found among teenagers have implications for simple exercise interventions to increase physical activity. A simple exercise intervention for nondisabled teenagers, such as an additional 20-minute walk per day, could increase daily physical activity at the high intensity level by 42% and total steps per day by 20% to 25%.

CONCLUSIONS

This study shows that with the SAM it is possible to accurately and reliably monitor ambulatory activity in children. Subject compliance was better with the SAM than with HRMs and was superior to compliance in keeping very simple diaries. The programmability of the SAM in terms of gait cadence, motion sensitivity, time, and time interval of data collection makes it a useful device for real-world, community activity monitoring in children with different gait deviations. The SAM is effective in determining the number of steps taken at investigator-defined step rates, the amount of time spent at each of the defined step rates, the total steps taken during the day, and the time spent during the day that in ambulatory activity in the real-world community environment.

Acknowledgment: We appreciate the valuable contributions of Kim Coleman, MS, for her technical assistance with the SAM and for editorial comments on this manuscript.

References

1. Leon AS, Connett J, Jacobs DR Jr, Rauramaa R. Leisure-time physical activity levels and risk of coronary heart disease and death. The Multiple Risk Factor Intervention Trial. JAMA 1987;258:2388-95.
2. Paffenbarger RS Jr, Hyde RT, Wing AL, Hsieh CC. Physical activity, all-cause mortality, and longevity of college alumni. N Engl J Med 1996;314:605-13.
3. Hahn RA, Teutsch SM, Rothenberg RB, Marks JS. Excess deaths from nine chronic diseases in the United States. JAMA 1990;264:2654-9.
4. Fernhall B, Unnithan VB. Physical activity, metabolic issues, and assessment. Phys Med Rehabil Clin N Am 2002;13(4):925-47.
5. Pate RR, Pratt M, Blair SN, et al. Physical activity and public health. A recommendation from the Centers for Disease Control and Prevention and the American College of Sports Medicine. JAMA 1995;273:402-7.
6. Public Health Service, Department of Health and Human Services. Healthy People 2000.. Washington (DC): DHHS; 2000. Pub No. PHS 91-50212.
7. NIH Consensus Development Panel on Physical Activity and Cardiovascular Health. Physical activity and cardiovascular health. JAMA 1996;276:241-6.
8. Department of Health and Human Services, Centers for Disease Control and Prevention, National Center for Chronic Disease Prevention and Health Promotion, The President's Council on Physical Fitness and Sports. Physical activity health: a report of the Surgeon General. Executive summery. Washington (DC): DHHS; 1996.
9. Powell KE, Thompson PD, Caspersen CJ, Kendrick JS. Physical activity and the incidence of coronary heart disease. Annu Rev Public Health 1987;8:253-87.
10. Blair SN, Goodyear NN, Gibbons LW, Cooper KH. Physical fitness and incidence of hypertension in healthy normotensive men and women. JAMA 1984;252:487-90.
11. Paffenbarger RS Jr, Wing AL, Hyde RT, Jung DL. Physical activity and incidence of hypertension in college alumni. Am J Epidemiol 1983;117:245-57.
12. Taylor R, Ram P, Zimmet P, Raper LR, Ringrose H. Physical activity and prevalence of diabetes in Melanesian and Indian men in Fiji. Diabetologia 1984;27:578-82.
13. Recker RR, Davies KM, Hinders SM, Heaney RP, Stegman MR, Kimmel DB. Bone gain in young adult women. JAMA 1992;268:2403-8.
14. Dalen N, Olsson KE. Bone mineral content and physical activity. Acta Orthop Scand 1974;45:170-4.
15. Thompson JK, Jarvie GJ, Lahey BB, Cureton KJ. Exercise and obesity: etiology, physiology, and intervention. Psychol Bull 1982;91:55-79.
16. Folkins CH, Sime WE. Physical fitness training and mental health. Am Psychol 1981;36:373-89.
17. Brown DR, Wang Y. The relationships among exercise training, aerobic capacity, and psychological well-being in the general population. Med Exerc Nutr Health 1992;1:125-42.
18. Brenes G, Dearwater S, Shapera R, LaPorte RE, Collins E. High density lipoprotein cholesterol concentrations in physically active and sedentary spinal cord injured patients. Arch Phys Med Rehabil 1986;67:445-50.
19. Dallmeijer AJ, Hopman MT, van As HH, van der Woude LH. Physical capacity and physical strain in persons with tetraplegia; the role of sport activity. Spinal Cord 1996;34:729-35.
20. Huonker M, Schmid A, Sorichter S, Schmidt-Trucksab A, Mrosek P, Keul J. Cardiovascular differences between sedentary and wheelchair-trained subjects with paraplegia. Med Sci Sports Exerc 1998;30:609-13.
21. Olle MM, Pivarnik JM, Klish WJ, Morrow JR Jr. Body composition of sedentary and physically active spinal cord injured individuals estimated from total body electrical conductivity. Arch Phys Med Rehabil 1993;74:706-10.
22. Hoffman MD. Cardiorespiratory fitness and training in quadriplegics and paraplegics. Sports Med 1986;3:312-30.
23. Davis GM, Shephard RJ, Jackson RW. Cardio-respiratory fitness and muscular strength in the lower-limb disabled. Can J Appl Sport Sci 1981;6(4):159-65.
24. Dearwater SR, LaPorte RE, Robertson RJ, Brenes G, Adams LL, Becker D. Activity in the spinal cord-injured patient: an epidemiologic analysis of metabolic parameters. Med Sci Sports Exerc 1986;18:541-4.
25. Powell KE, Dysinger W. Childhood participation in organized school sports and physical education as precursors of adult physical activity. Am J Prev Med 1987;3:276-81.
26. Rowland TW. Influence of physical activity and fitness on coronary risk factors in children: how strong an argument? Pediatr Exerc Sci 1991;3:189-91.
27. Carnethon MR, Gidding SS, Nehgme R, Sidney S, Jacobs DR Jr, Liu K. Cardiorespiratory fitness in young adulthood and the de-

velopment of cardiovascular disease risk factors. JAMA 2003;290:3092-100.
28. Activity and Health Research. Allied Dunbar National Fitness Survey, 1992. London: Health Education Authority/Sports Council; 1992.
29. Crespo CJ, Keteyian SJ, Heath GW, Sempos CT. Leisure-time physical activity among US adults. Results from the Third National Health and Nutrition Examination Survey. Arch Intern Med 1996;156:93-8.
30. Baranowski T, Dworkin RJ, Cieslik CJ, et al. Reliability and validity of self-report of aerobic activity: Family Health Project. Res Q Exerc Sport 1984;55:309-17.
31. Sallis JF, Buono MJ, Roby JJ, Micale FG, Nelson JA. Seven-day recall and other physical activity self-reports in children and adolescents. Med Sci Sports Exerc 1993;25:99-108.
32. Gayle R, Montoye HJ, Philpot J. Accuracy of pedometers for measuring distance walked. Res Q 1977;48:632-6.
33. Rowlands AV, Eston RG, Ingledew DK. Measurement of physical activity in children with particular reference to the use of heart rate and pedometry. Sports Med 1997;24:258-72.
34. Washburn R, Chin MK, Montoye HJ. Accuracy of pedometer in walking and running. Res Q Exerc Sport 1980;51:695-702.
35. Crouter SE, Schneider PL, Karabulut M, Bassett DR Jr. Validity of 10 electronic pedometers for measuring steps, distance, and energy cost. Med Sci Sports Exerc 2003;35:1455-60.
36. Kochersberger G, McConnell E, Kuchibhatla MN, Pieper C. The reliability, validity, and stability of a measure of physical activity in the elderly. Arch Phys Med Rehabil 1996;77:793-5.
37. Van den Berg-Emons RJ, Saris WH, Westerterp KR, van Baak MA. Heart rate monitoring to assess energy expenditure in children with reduced physical activity. Med Sci Sports Exerc 1996; 28:496-501.
38. Van den Berg-Emons HJ, Saris WH, de Barbanson DC, Westerterp KR, Huson A, van Baak MA. Daily physical activity of schoolchildren with spastic diplegia and of healthy control subjects. J Pediatr 1995;127:578-84.
39. Ekelund U, Poortvliet E, Yngve A, Hurtig-Wennlov A, Nilsson A, Sjostrom M. Heart rate as an indicator of the intensity of physical activity in human adolescents. Eur J Appl Physiol 2001;85:244-9.
40. Trost SG, Kerr LM, Ward DS, Pate RR. Physical activity and determinants of physical activity in obese and non-obese children. Int J Obes Relat Metab Disord 2001;25:822-9.
41. Saris WH, Binkhorst RA, Cramwinckel AB, et al. The relationship between working performance, daily physical activity, fatness, blood lipids and nutrition in school children. In: Berg K, Eriksson BO, editors. Children and exercise: IX. Baltimore: University Park Pr; 1980. p 166-74.
42. Coleman KL, Smith DG, Boone DA, Joseph AW, del Aguila MA. Step Activity Monitor: long-term, continuous recording of ambulatory function. J Rehabil Res Dev 1999;36:8-18.
43. Glass G, Hopkins K. Statistical methods in education and psychology. Englewood Cliffs: Prentice-HSRl; 1984.
44. Resnick B, Nahm ES, Orwig D, Zimmerman SS, Magaziner J. Measurement of activity in older adults: reliability and validity of the Step Activity Monitor. J Nurs Meas 2001;9:275–90.
45. Macko RF, Haeuber E, Shaughnessy M, et al. Microprocessor-based ambulatory activity monitoring in stroke patients. Med Sci Sports Exerc 2002;34:394-9.
46. Welk GJ, Corbin CB. The validity of the Tritrac-R3D Activity Monitor for the assessment of physical activity in children. Res Q Exerc Sport 1995;66:202-9.
47. Sallis JF, Buono MJ, Roby JJ, Carlson D, Nelson JA. The Caltrac accelerometer as a physical activity monitor for school-age children. Med Sci Sports Exerc 1990;22:698-703.
48. Bailey R, Olson J, Pepper S, Porszasz J, Barstow TJ, Cooper DM. The level and tempo of children's physical activities: an observational study. Med Sci Sports Exerc 1994;27:1033-41.
49. Kriska A. Ethnic and cultural issues in assessing physical activity. Res Q Exerc Sport 2000;71(2 Suppl):S47-53.
50. Sallis JF, Haskell WL, Wood PD, et al. Physical activity assessment methodology in the Five-City Project. Am J Epidemiol 1985;121:91-106.
51. Findley TW, Agre JC, Habeck RV, Schmalz R, Birkebak RR, McNally MC. Ambulation in the adolescent with myelomeningocele. I: early childhood predictors. Arch Phys Med Rehabil 1987; 68:518-22.
52. Findley TW, Agre JC. Ambulation in the adolescent with spina bifida. II. Oxygen cost of mobility. Arch Phys Med Rehabil 1988;69:855-61.
53. Sallis JF. Epidemiology of physical activity and fitness in children and adolescents. Crit Rev Food Sci Nutr 1993;33:403-8.
54. Troiano RP. Physical inactivity among young people. N Engl J Med 2002;347:706-7.
55. Flegal KM. The obesity epidemic in children and adults: current evidence and research issues. Med Sci Sports Exerc 1999;31 (11 Suppl):S509-14.

Suppliers

a. Cyma, 8515 35th Ave NE, Ste C, Seattle, WA 98115.
b. Polar Electro Inc, 34740 Carl Ave, Zephyrhills, FL 33541.
c. Systat Software Inc, 501 Canal Blvd, Ste C, Point Richmond, CA 94804-2028.