

Chapter 2

Actigraphy: The Ambulatory Measurement of Physical Activity

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Measurement is as fundamental to modern sport as it is to science. The outcomes of Olympic trials and competitions are sometimes determined by tenths or hundredths of a second. Athletic training typically entails performance measurement in order to guide and enhance training methods. Better performance is often its own reward – that is, observing improvements may strongly motivate competitive athletes.

This chapter has several purposes, and correspondingly two major sections. The first purpose of this chapter is to introduce readers to actigraphy: what it is, available instruments, and basic methodological issues. This is accomplished in the first major section of this chapter. The second purpose of this chapter is to apply this information to sports. In the second section, I begin with circadian issues, since actigraphy can track activity level 24 h per day, seven days per week, 365 days per year. Subsequently, I will discuss nocturnal activity and sleep since athletes need to be properly rested. Following this, I will consider diurnal activity as training occurs during waking hours. This discussion will include high-resolution actigraphy to better understand behavioral topography in sports such as track and field, bowling, golf, skating, gymnastics, and skiing.

Methods of Measuring Human Activity

Indirect Methods

Devices such as sensitive touch pads installed in swimming pools or high-speed video cameras strategically mounted in stadiums and rinks capture human movements for subsequent reviewing, evaluating, informing choices regarding medals, and reviewing decisions made on the field by referees. While these methods enable athletes to move freely, measurement can occur only within the confines of a particular space. Our meaning of ambulatory extends beyond such boundaries. As such, these measurement methods will not be considered further in this chapter.

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Heart Rate

Athletic performances increase heart rate. Montoye, Kemper, Saris, and Washburn (1996, pp. 98–105) discussed the use of heart rate monitoring to track physical activity. Searching for “ambulatory heart rate monitors” on the Internet yields a wide variety of ever-changing equipment models. While it is true that greater activity levels produce higher heart rates, factors other than activity level can also alter heart rate. For instance, the excitement of competition can increase heart rate while the athlete in question observes other athletes prior to their performance. One cannot separate heart rate increases caused by psychological factors from those due to increased exertion except by a carefully kept activity diary that identifies the times of day during which the athlete performed or trained. Because heart rate is an *indirect* measure of activity, I will not discuss it further in this chapter.

Core Body Temperature

O’Brien, Hoyt, Buller, Castellani, and Young (1998) introduced a method of measuring core body temperature based on having participants swallow a pill-sized transducer/transmitter that sends core body temperature to a receiver worn by the person. Because core body temperature is an indirect measure of activity and because body temperature changes lag sufficiently behind activity level changes, I will not discuss it further in this chapter.

Doubly Labeled Water

Montoye et al. (1996, pp. 17–25) discuss a method for measuring energy expenditure in free-living people; in this method, the people drink water laced with stable isotopes of hydrogen and oxygen. The loss of these isotopes over time as assessed from saliva, urine, or blood provides an estimate of energy expenditure, considered a gold standard, that is directly proportional to activity level. Because doubly labeled water is an indirect measure of activity and because it provides only crude temporal resolution, I will not discuss it further in this chapter.

Direct Methods

Pedometers/Digital Step Counters

One of the earliest documented forms of direct measurement of athletic-related behavior comes from Leonardi de Vinci (1452–1519), who invented the pedometer during the midpoint of his life (Gibbs-Smith, 1978). Thomas Jefferson encountered the pedometer during his tour as US ambassador to France between 1785 and 1789 and sent it back to America, along with other items (Wilson & Stanton, 1999). The Japanese introduced the first commercial pedometer under the name of manpo-meter, where “manpo” in Japanese means 10,000 steps. Heel-toe transitions involved in walking move the hips up and down. Putting one foot in front of the other displaces the hips left and right. Together, walking moves the attached sensor

in a spiral trajectory. Old-style pedometers contained a pendulum that moved in response to hip movements associated with walking and related behaviors such as stooping to pick things up from the floor. A distance indicator was connected to the pendulum through a series of gears, one of which was a stride-length setting that could only be crudely set in an effort to make the unit of measure the mile. Stride length was estimated by counting steps while walking a measured distance and dividing. Hence, the unit of measure was crudely estimated. Running would entail a much larger stride than indicated – thus, seriously underestimating distance traversed. Bending to pick up items entails no forward movement, but is counted as a stride – thus, underestimating distance walked to an extent that is directly proportional to frequency of this behavior. Modern step counters digitally convert steps into distance. While a precise stride length can be registered and can be accurately multiplied by the steps registered, the problem of variable stride lengths remains.

Units of measure. The previous section refers to digital step counters since that is the primary mechanism of the modern pedometer. Vertical movements of a small weight increments a digital counter with each movement of the waist activate the counter. In this regard, the step is the unit of measure. Each person's step differs depending upon their height, which makes leg length an important covariate when comparing steps taken across persons of varying heights. However, I submit that such variation is a natural part of human activity and not something that one necessarily wants to control for. Consider the following situation where an adult and a small child cross a street holding hands. The adult strides easily while the child walks rapidly in an effort to keep up. Have they been equally active because they traversed the same curb-to-curb distance? Or has the child been much more active than the adult because their much shorter legs required many more steps to traverse the same distance? I submit that the latter conclusion is valid.

Entering “pedometers” or “step counters” into a search engine will identify many vendors selling a wide variety of instruments that range from high to low quality. One probably gets what one pays for. Assessment of instrument reliability and consistency among devices should be done under laboratory conditions, using some form of bench test (such as a shaker) on which several devices can be mounted simultaneously. Data from devices that over-count or under-count can be adjusted using a conversion factor derived from such a test. For example, if after 100 back and forth movements, Device A counts 115 and Device B counts 95, the conversion factor for Device A would be $100/115 = 0.8696$, with the conversion factor for Device B being $100/95 = 1.0526$.

We shall see below that studies frequently report steps per day. This metric does not control for waking hours and activities for which the pedometer cannot be worn such as swimming. Someone who sleeps late and goes to bed early may get a low step count that day despite being rather active. If that person also went swimming for an hour or two during such a day, their step count for that day would be even lower. However, dividing the steps per day by the minutes that the pedometer was worn might more correctly reflect the person's average activity level. The method I have been using for over 19 continuous years studying my own activity level is as follows. Upon dressing in the morning, I record the date and time I attached my

waist-worn step counter on one line of a 3 × 5 index card. Upon undressing at night, I record the time I took my step counter off using military 24-h designation. I enter a one- or two-word note if I did something unusual that day and then record the step count. If I went swimming that day, then I would record the time off and back on as well. This enables me to record 10 days of data per card. At the time of this writing, I have been using this procedure for almost 24 years. Thus, my personal example demonstrates that longitudinal data collection is both possible and feasible. The point of recording time on and off is to determine the minutes of wearing time so that I can divide steps taken by minutes of wearing time in order to control for time worn as longer wearing times can lead to higher step counts even if activity level is lower. Montoye et al. (1996, pp. 72–75) also discussed the use of pedometers to measure activity level.

An important limitation of standard step counters is that someone must read and record the data at specified intervals. Several models of Actigraph LLC actigraphs have software that converts actigraph data into step counts to simulate pedometer functionality (www.theactigraph.com). This function enables one to change the unit of measure from milli-g to steps. New Lifestyles (<http://new-lifestyles.com/>) retails five models of accelerometer-based step counters with memories in addition to four models of coiled spring pedometers and two models of hair spring pedometers (<http://www.thepedometercompany.com/pedometers.html>).

Actigraphs

Actigraphs are small lightweight computerized accelerometer-based devices worn typically at the waist, wrist, and/or ankle that rapidly and simultaneously digitize movement in one, two, or three dimensions every 15, 30, or 60 s continuously 24 h a day for as many days as memory allows (which typically spans 7–28 days). Further information regarding the term “actigraph” can be found at <http://en.wikipedia.org/wiki/Actigraph>. A list of actigraph vendors and links to most of their products is provided in Table 2.1.

Units of measure. There are no standard units of measurement across actigraphs by various vendors, despite the fact that all of these devices use accelerometers to measure activity level. Velocity, typically understood as speed, is defined as the distance covered per unit time (e.g., miles per hour or meters per second). Acceleration

Table 2.1 Actigraph vendors and devices

Vendor	Device/URL
Actigraph LLC http://www.theactigraph.com	GT1M series http://www.theactigraph.com/productsGT1M.asp ActiTrainer http://www.theactigraph.com/index.php?option=com_virtuemart&page=shop.product_details&flypage=flypage.tpl&product_id=7&26Itemid=87

Table 2.1 (continued)

Vendor	Device/URL
Ambulatory Monitoring, Inc. http://www.ambulatory-monitoring.com/	MotionLogger http://www.ambulatory-monitoring.com/motionlogger.html MicroMini-Motionlogger and family of sensors http://www.ambulatory-monitoring.com/micro_sensors.html Motionlogger Buzz Bee http://www.ambulatory-monitoring.com/buzz_bee.html
Body Media, Inc. SenseWear http://www.sensewear.com/	SenseWear BMS http://www.sensewear.com/BMS/solutions_bms.php
Cambridge neurotechnology limited http://www.camntech.com/	Actiwatch http://www.camntech.com/
IM Systems http://www.imsystems.net/	ActiTrac http://www.imsystems.net/actitrac/actitrac.htm DigiTrac (12 bit A/D Triaxial, 40 Hz) http://www.imsystems.net/actitrac/actitrac.htm BioTrainer-Pro http://www.imsystems.net/btpro/btpro.htm BioTrainer II http://www.imsystems.net/bt2/bt2.htm BedMate http://www.imsystems.net/bedmate/bedmate.htm SleepCheck http://www.imsystems.net/sleepcheck/sleepcheck.htm
Mini mitter http://www.minimitter.com/	Actiwatch http://ribn.respironics.com/
New Lifestyles http://new-lifestyles.com/	Pedometers http://new-lifestyles.com/content.php?p=100 http://www.thepedometercompany.com/pedometers.html
Nokia http://www.nokiausa.com/	N95, N95 8GB, N82, N93i, 6210, N79, N85, N96 Phones http://betalabs.nokia.com/apps/nokia-step-counter
Cellphone actigraphy PAL Technologies Ltd http://www.paltechnologies.com/	ActivPAL http://www.paltech.plus.com/products.htm#activpal
Philips directlife activity monitor http://exercise.about.com/od/productreviews/fr/philipsactivitymonitor.htm	Activity monitor http://exercise.about.com/gi/o.htm?zi=1/XJ&zTi=1&sdn=exercise&cdn=health&tm=91&gps=123_265_1020_517&f=10&su=p284.9.336.ip_p674.7.336.ip_tt=6&bt=1&bts=1&st=24&zu=http%3A/www.directlife.philips.com/how_it_works/advanced_activity_monitor/
Polar http://www.polarusa.com/us-en	Activity monitors http://www.polarusa.com/us-en/products/get_active Polar AW200 activity monitor http://www.dickssportinggoods.com/product/index.jsp?productId=2715949&CAWELAID=110638143
Stayhealthy http://www.stayhealthy.com/en_us/main/	RT3 http://www.stayhealthy.com/en_us/main/research_activity_monitor

is defined as the change in velocity per unit time; typically meters/second/second. Acceleration is frequently measured in units of “g” for gravity, where 1 g equals the rate with which bodies freely fall to Earth, which is 9.80616 m/s/second at sea level at 45° latitude and mean sea level.

The problem begins with the material used to make the accelerometer. Piezoceramic accelerometers emit a voltage only while they are undergoing positive or negative acceleration. The charge bleeds off to zero when acceleration is constant, which includes the absence of movement. This is understandable as no movement should be measured as zero, and the fact that limbs are jointed and attached to the torso means that they cannot accelerate at a constant rate in a single direction for very long. All changes in direction produce acceleration. This rate of angular movement, measured in Hertz, modifies the actual acceleration value. Because actigraphs do not measure these frequencies, it is impossible to accurately report in units of g. However, because most actigraphs bandpass filter movement frequency from approximately 0.1–3.6 Hz in order to preclude artifact from being recorded as human movement, one could use the midpoint of this frequency range to convert accelerometer voltages to g units. The technical specifications of each vendor should be consulted regarding this issue.

Some actigraphs contain analog-to-digital (A/D) converters that divide a g-force range into parts. For example, one actigraph used an 8-bit A/D converter to divide a –2.13 g to +2.13 g maximum range into $2^8 = 256$ levels of acceleration (cf. Tryon & Williams, 1996). Dividing 4.26 g by 256 gives 0.01664 g/s/count on the A/D converter. This actigraph makes 10 measurements per second resulting in a sampling period of 0.1 s. Integrating over this interval corresponds to multiplying 0.01664 g/s/count by 0.1 s resulting in 0.001664 g/count = 1.664 milli-g/count. Other actigraphs integrate the area under the curve created by the time varying voltage from the accelerometer. The resulting volt-second units are not standard.

Methodological Issues

The reader should be aware of the following four methodological issues when considering actigraphy: (1) site of attachment, (2) instrument reliability, (3) clinical repeatability, and (4) instrument validity. The following three sections address these issues.

Site of Attachment

Activity level is commonly considered to be something akin to a personality trait (i.e., a rather stable feature of the person). This conceptualization is incorrect in two major ways. First, activity is measured by placing a sensor on a body part such as the wrist, waist, or ankle. The instrument actually responds to its own movement, which corresponds to movements of the site of attachment only. Placing instruments at multiple body sites provides information about those sites, but only about those sites. While walking and running move all body sites, these behaviors move them differently. Sitting in a chair reading a magazine immobilizes the waist and ankles,

but not the arms and hands, which are involved in turning pages and perhaps writing notes. Securely attaching actigraphs to a belt or waist band places it relatively close to the body's center of gravity. Vertical movements of this site are directly proportional to energy expenditure.

One should therefore think in terms of the site of attachment that most reflects the behavior of interest. For example, the wrist is the most active site in waking people and, therefore, the site of interest when assessing sleep. All computer sleep-scoring algorithms assume that the data are from the wrist. It does not seem to matter whether one measures the left or right wrist in left- or right-handed people.

The second problem is that activity level is not constant over time, but varies in two substantial and important ways. Autocorrelation is the first characteristic of how activity level varies over time when behavior is measured in one-min or 30-s epochs. If one is walking through a given minute, it is rather probable that one will also be walking during the next minute as it usually takes more than one min to walk anywhere. If one is sitting through a given minute, it is rather probable that one will be sitting during the next minute also. Autocorrelation violates the common assumption of independence made by most statistical methods such as t-tests and analysis of variance (ANOVA), thus precluding their use. Aggregating activity level over sufficiently long blocks of time such as 15, 30, 45, or 60 min tends to reduce autocorrelation. The second characteristic of repeated activity measurements is that at the one-min epoch of temporal resolution, activity level tends to form a Poisson distribution where the standard deviation equals the mean. Most observations lie within 1 standard deviation of the Poisson mean versus ± 3 standard deviations in a normal distribution. A graph of activity vs. time using one-min epochs reveals that the magnitude of activity level changes radically from one min to the next, thereby creating enormous variability. Attempting to normalize this integral feature of activity level is *not* recommended for at least two reasons. The first, and perhaps the most persuasive, reason is that one is ignoring a central feature of activity level. The second reason is that all transformations complicate interpretation. For example, how should one interpret the square root or the logarithm (natural or base 10) of activity level or, worse yet, the square root of the logarithm of activity level?

Instrument Reliability

Physical instruments and psychological tests differ in fundamental ways that influence how one assesses their reliability and validity. Psychological tests must be given to people in order to obtain data from which to compute reliability and validity coefficients. The sample studied can markedly influence the obtained results, which is why informed psychometricians understand that tests are reliable and valid only for some samples and some purposes, but not others. In short, reliability and validity are not entirely about the test, *per se*. This limitation does not pertain to instruments whose functional properties can be studied in the laboratory with machines capable of accurately reproducing specific movements.

The concept of reliability requires that the same phenomenon be measured at least twice, and preferably multiple times, to see if the same value is returned. The

source of movement used to study the reliability of an instrument should vary as little as possible; preferably variation should be negligible so that it can be assumed to be effectively zero. Then, all observed variation over repeated measurements can be entirely attributed to the unreliability of the device. However, more commonly, investigators have people repeatedly perform the same behavior and attribute all observed variability to the unreliability of the device. This assumes that the people have precisely repeated the requested behaviors – I submit that this is rarely, if ever, true. For example, participants are asked to repeatedly walk a measured distance or repeatedly climb a set of stairs, or repeatedly perform a task such as hammering a nail. Attributing all observed variation to measurement unreliability assumes that human variability is negligible, when in fact it is both measurable and substantial. Hence, the variability of instruments should always be established under laboratory conditions, and never with people performing specific behaviors as this concerns clinical repeatability, which is discussed below.

The standard methods by which psychometricians calculate the reliability of psychological tests are inappropriate when measuring the reliability of instruments for methodological and statistical reasons. The typical method for psychological tests is to administer them to a group of people on one occasion and to compute Cronbach's alpha using commercially available software to determine the test's reliability, which is a measure of internal consistency. When possible, psychologists administer the test to a group of people on two occasions to determine test-retest temporal stability. Here the reliability coefficient is the correlation coefficient between the test and retest scores. The time interval must be carefully chosen: long enough so that participants do not clearly recall their prior answers but short enough so that real change does not occur. Both methods assume substantial variation across people.

Instruments are typically constructed to a physical standard to minimize inter-device variability and then calibrated to remove as much remaining interdevice variability as possible. The resulting homogeneity artificially reduces traditional psychometric indices of reliability in direct proportion to the extent to which devices perform the same way. This is the reverse of what one wants. A solution I have recommended is to compute the coefficient of variation (CV) on a set of repeated measurements taken from a machine such as a pendulum or shaker (cf. Tryon & Williams, 1996; Tryon, 2005). This is done by dividing the standard deviation (SD) of the repeated measurements for a single device by the mean of those measurements and multiplying by 100 to yield a percentage. The more close one measurement is to another, the smaller is its SD and CV. This method enables one to determine a reliability coefficient for each device.

When an investigator has multiple devices, they may observe that the means used to compute the CAs are not identical. One can compute a correction coefficient for each device as follows. Compute the grand mean, the mean of all the means across devices. The correction coefficient for each device is the difference between its mean and grand mean, i.e., the number that must be added to or subtracted from the instrument's mean in order to obtain the grand mean; i.e., some correction values are negative and others positive. This correction constant is then added to every measurement made with that instrument. This will minimize any systematic differences

across instruments. This issue is avoided for individuals when the same instrument is used at the same body site for the same person across time. However, this issue occurs when two or more instruments are used to compare the behavior of two or more individuals.

Pedometers. Bassett et al. (1996) reported that the “manpo” pedometers initially introduced by the Japanese were subject to large measurement errors, but that the next generation of electronic pedometers (i.e., step counters) is reasonably accurate for assessing walking-related activities. Modern pedometers, especially those using the “KS10 and JW200 pedometer engines, are quite accurate. Vincent and Sidman (2003) tested 24 Yamax MLS-2000 digital pedometers using a shake test. The average deviation over 100 shakes was $0.39 \text{ steps} \pm 0.29$, before what they characterize as heavy use in a large study, and 0.60 ± 0.62 steps after the study was completed. All pedometers were within 5% of nominal values, i.e., within 5 steps of the programmed 100 shakes. The authors also reported results for a standard walking where the mean was 2.26 and the standard deviation was 0.80 before the study. The walking test was repeated after the study ended, when the mean was 1.71 and the standard deviation was 0.88. The authors reported that the walking test produced significantly more error ($F(1, 46) = 109.04, p < 0.01$). Note that the walking test mean of 2.26 is 5.79 times as large as the shake test mean of 0.39 before the study began, and the mean of 1.71 was 2.85 times as large as the shake test of 0.60 after the study ended. Hence, we can conclude that walking tests overestimate pedometer error from approximately 300 to 600% – thus supporting the recommendation made above to restrict assessments of the reliability of activity monitors to laboratory studies.

Actigraphs. The reliability and validity of actigraphs has also been studied under laboratory conditions where known physical forces can be repeatedly applied with considerable precision. Tryon and Williams (1996) studied the reliability and validity of 40 CSA Model 7164 actigraphs using a spinner and a 5 feet 7 inch pendulum. They reported reliability coefficients between 97.5 and 99.4%. Validity was established by comparing the observed performance with expectation during pendulum decay and spinning. Tryon (2005) repeatedly tests four MotionLogger™ and four BuzzBee™ actigraphs 10 times on a precision pendulum. He reported reliability coefficients of 0.98 and validity coefficients of 0.99.

Clinical Repeatability

It is important to know how much variability is associated with efforts that people make to reproduce behaviors in the same way, because this level of variability limits our ability to detect change such as improvements due to training. All instrumented measures of human activity level in applied contexts such as sports necessarily confound instrument unreliability with human biomechanical, neural, and psychological limits and will necessarily be more variable than instrument reliability suggests. It is important for trainers and athletes to repeatedly measure performances that they feel are the same and compare them with measurements of behaviors that they feel are different.

Aggregates of behavior are more repeatable than are single measurements of behavior. Hourly measures are more repeatable than are minute-by-minute measures. Weekly measures are more repeatable than are daily measures. Epstein (1979, 1980, 1983, 1986) clearly demonstrated that aggregation improves test–retest reliability including good agreement. He also demonstrated that the Spearman–Brown prophecy formula enables one to accurately estimate reliability from the number of repeated measurements taken.

Instrument Validity

Instruments are designed and constructed to measure specific quantities. For example, the accelerometers in modern actigraphs measure acceleration, and little else, as long as they are operated within specified temperature extremes and not dropped, i.e., exposed to extreme accelerations that might damage them. Nevertheless, it is important to establish their operating characteristics, which is best done under laboratory conditions for all of the reasons discussed above concerning reliability. Tryon and Williams (1996) used both a large 5 foot 7 inch pendulum and a spinner device to assess both reliability and validity.

Application to Sports

I now turn to the question of what can be done to enhance sport performance with pedometers and actigraphs. I separate this discussion into two parts because the possible applications differ by virtue of the different technical capabilities of pedometers and actigraphs.

Pedometers

General Fitness Using Pedometers

Athletes must be generally fit in order to benefit from specialized training. The President's Council on Physical Fitness and Sports (2001) identified physical inactivity as important to a healthy life style and made recommendations for using pedometers to improve general fitness.

Normative data. Bohannon (2007) reported a meta-analysis of the average and 95% confidence interval for the number of steps taken by 6,199 participants in 42 studies. The overall average was 9,448 with a 95% confidence interval of 8,899–9,996 steps. Participants below the age of 65 took an average of 9,797 steps per day with a 95% confidence interval of 9,216–10,377 steps. Participants 65 and older took an average of 6,565 steps per day with a 95% confidence interval of 4,897–8,233 steps.

Tudor-Locke and Myers (2001) compiled normative results from 32 studies and reported that activity level decreases with age; they also noted a sex effect. Healthy 8–10-year-old children take between 12,000 and 16,000 steps per day, boys being

more active than girls. Vincent and Pangrazi (2002) studied more than 700 children aged 6–12 years old and reported that boys took between 12,300 and 13,989 steps per day whereas girls took between 10,479 and 11,274 steps per day. Wilde (2002) studied more than 600 adolescents aged 14–16 years old and reported between 11,000 and 12,000 steps per day, boys being more active than girls. Rowlands, Eston, and Ingledew (1999) reported that 8–10-year-old UK children take between 12,000 and 16,000 steps per day.

Tudor-Locke and Myers (2001) reported that healthy young adults take between 7,000 and 13,000 steps per day, men being more active than women, whereas healthy older adults take between 6,000 and 8,500 steps per day with men again being more active than women. Individuals living with disabilities and chronic diseases can be expected to take between 3,500 and 5,500 steps per day.

Suzuki et al. (1991) reported that children and adults aged 3–22 years took an average of 14,500 steps per day if they were intellectually disabled, 12,700 steps per day if blind, 17,400 steps per day if deaf, and 8,050 steps per day if physically handicapped.

How active should we be? Initial recommendations by Japanese investigators were for 10,000 steps per day to achieve general fitness (Hatano, 1993; Yamanouchi et al., 1995), which corresponds to approximately 300–400 calories per day (Hatano, 1997) depending upon walking speed, sex, age, and body size. This is at least double the amount of activity (150 kcal/day) recommended by the U.S. Surgeon General (U.S. Department of Health and Human Services, 1996). The American College of Sports Medicine (ACSM: www.acsm.org) has endorsed the following categorization of activity levels. Taking less than 5,000 steps per day is termed “Sedentary.” Taking between 5,000 and 7,499 steps per day is termed “Low Active.” Taking between 7,500 and 9,999 steps per day is termed “Somewhat Active.” Taking between 10,000 and 12,500 steps per day is termed “Active.” Taking more than 12,500 steps per day is termed “Highly Active.” The President’s Council on Physical Fitness and Sports (2001) recommended that children take at least 11,000 steps per day, at least five days per week, as a standard healthy base. The more recent ACSM recommended daily activity level for children is between 12,000 and 16,000 steps per day. Leermakers, Dunn, and Blair (2000) suggested that at least 15,000 steps per day may be necessary to achieve weight loss goals.

Effects of body composition. Overweight adults take fewer steps than do normal-weight adults (McClung, Zahiri, Higa, Amstutz, & Schmalzried, 2000; Tryon, Pinto, & Morrison, 1991; Tudor-Locke & Myers, 2001; Tudor-Locke, Jones, Myers, Paterson, & Ecclestone, 2002). The same relationship holds for children (Rowlands et al., 1999). Tudor-Locke and Myers (2001) have shown that people who take more than 9,000 steps per day frequently have a normal body mass index (BMI), whereas individuals who take less than 5,000 steps per day frequently are considered obese by BMI standards. However, physicists define work as mass times distance. Multiplying body weight by steps taken frequently reveals that overweight people expend more energy than do normal weight people (Tudor-Locke & Myers, 2001).

Using pedometers to promote activity. Sidman (2002) has reported at book length about promoting activity in sedentary women using pedometers. However, I am

aware of no studies that used pedometers to enhance athletic performance in healthy people even in such likely journals as *Sports Medicine*, *Research Quarterly for Exercise and Sport*, and *Medicine and Science in Sports and Exercise*. The focus of research with pedometers is on sedentary people and/or sedentary people with health issues such as obesity, diabetes, and hypertension.

Richardson et al. (2008) reported a meta-analysis of studies designed to promote activity level. Their inclusion criteria were extensive. Each study had to use pedometers as a motivational tool including setting a step-count goal. The study was a controlled trial or had a pre-post design. The study did not use concurrent dietary intervention. Participants were both sedentary at baseline and overweight or obese. Intervention lasted at least four weeks. The following databases were searched: CINAHL, EMBASE, MEDLINE, PsycINFO, SportDiscus, and the Web of Science. The authors identified 9 studies covering 307 participants in programs lasting from four weeks to one year. Results indicated that participants' average activity level increased by 3,656 steps.

Bravata et al. (2007) also conducted a meta-analysis of pedometer-based activity promoting programs. They searched for all English-language articles in the MEDLINE, EMBASE, Sport Discus, PsychINFO, Cochrane Library, Thompson Scientific (previously known as Thompson ISI), and ERIC databases from 1966 through 2007, and retrieved 2,246 citations. Of these 26 studies, 8 randomized controlled trials (RCTs) and 18 observational studies met the following inclusion criteria. Studies had to include more than five participants; studied participants in naturalistic settings; counseled participants relative to activity goals; measured BMI, glycemic control, serum lipid levels, and blood pressure; and expressed baseline activity as steps per day using a pedometer. As noted above, the steps per day metric fails to control for length of waking day and for activities such as swimming during which the pedometer would be removed. Participants were 49 years old on average ($SD = 9$), although five studies concerned people whose age was greater than 60 years on average. Nine studies exclusively enrolled women. Overall, men accounted for just 15% of the samples. When race and ethnicity were reported, 93% were white, on average. Most participants were obese by BMI standards, but had relatively normal serum lipid levels.

Interventions took from 3 to 104 weeks, with an average and standard deviation of 18 and 24, respectively. Five of the interventions took place at work. Counseling sessions ranged from 0 to 104 with a mean and standard deviation of 7 and 19, respectively. The average steps per day during baseline were 7,473 with a standard deviation of 1,385 and a range of 2,140–12,371 steps per day. The 155 participants across the 8 RCTs that actively used pedometers to increase activity took an average of 2,491 more steps per day than did the 122 control participants. The 95% confidence interval ranged from 1,098 to 3,885 steps per day. Participants in the 18 observational studies who used pedometers to increase activity level took an average of 2,183 more steps per day. The 95% confidence interval ranged from 1,571 to 2,796 steps per day. When combined, using a pedometer with an activity goal such as 10,000 steps per day resulted in an average activity increase of 26.9%. This change was associated with an average BMI reduction of 0.38 with a 95%

confidence interval ranging from -0.05 to -0.72 . Systolic blood pressure decreased by 3.8 mmHg with the 95% confidence interval ranging from -1.7 to -5.9 mmHg. These changes were more pronounced in participants who had a higher initial blood pressure and who took more steps per day suggesting a dose-response relationship between activity and health benefits.

Conclusions. Pedometers provide numerical evidence of activity level that can be incorporated into a planned regimen favoring greater activity and corresponding improvements in fitness. The existing literature shows that even unathletic people can increase their activity level and improve fitness. It therefore seems reasonable that athletes should be able to do as well or better at achieving similar goals. However, pedometers cannot be used to measure activity while swimming, and while pedometers can be worn while bike riding and weight training, they will not accurately measure caloric expenditure during these activities. Hence, pedometers pertain to general fitness that derives from ambulation.

Actigraphs

Actigraphs offer two important advantages over even the best accelerometer-based pedometers: (1) proportionality and (2) time-locked repeated measurements. Whereas the earliest actigraphs registered presence of movement but not intensity, modern actigraphs respond in direct proportion to the intensity of activity. While this information can be reduced to “steps,” much information is lost in doing so because actigraphs measure activity level at least 10 times per second, and then average over a user-defined epoch (typically one min, i.e., 600 measurements/min). Measuring activity level so intensively and reporting and storing results at one-min time slices provide a much more detailed record of activity level – this therefore enables more applications than pedometers.

Sleep

It is important that athletes get proper sleep in order to give their best performance. Polysomnography (PSG) is the gold standard for measuring sleep, but requires one to sleep in a sleep lab, which would be prohibitively expensive for continuous use. Home PSG is possible, but its use is also restricted to diagnosing sleep disorders rather than as a training resource for athletes. Actigraphy provides an alternative instrumented method for studying sleep. The American Academy of Sleep Medicine updated its Practice Parameters for the use of actigraphy to assess sleep (Morgenthaler et al., 2007). These Practice Parameters are also available on the American Academy of Sleep Medicine Web page (<http://www.aasmnet.org/PracticeParameters.aspx?cid=-1>) and on the National guideline Clearinghouse Web page (http://www.ngc.gov/summary/summary.aspx?doc_id=10779). A PubMed search for “actigraphy, sleep” returned 720 articles on April 18, 2010, indicating that a substantial body of research supports these guidelines.

Actigraphy and PSG differ with regard to sleep measures for primarily two reasons (cf. Tryon, 2004): (1) PSG is a multichannel physiological (e.g., EEG, EMG,

respiration) monitoring system; actigraphy is a single-channel behavior-monitoring system, and (2) PSG and actigraphy key on different parts of the sleep-onset spectrum. PSG sleep scoring continues to be based on the Rechtschaffen and Kales (1968) sleep scoring criteria for humans that score wake and then various stages of sleep. However, it is now clear that sleep onset entails several systematic changes and is not a discrete event. Tryon (2004) described the following three phases of sleep onset: (1) People become inactive for a period of time that actigraphy considers characteristic of sleep onset. People with insomnia are noted for their ability to remain awake but motionless. Good sleepers complete this phase of sleep onset much more rapidly. (2) The beginning of the second stage of sleep onset is marked by muscle relaxation resulting in dropping handheld objects. This was the gold standard criterion of sleep onset that was used to validate the onset of PSG-based sleep and consequently continues to mark the point when PSG marks sleep onset. An empty spool of thread held between the thumb and the forefinger was typically used to determine this point of muscle relaxation. (3) The beginning of the third stage of sleep onset is marked by an elevation of the auditory threshold, i.e., when awareness of one's surroundings is lost. This is the point of subjective sleep onset and corresponds to sleep onset times recorded in sleep logs. Waking up rapidly reverses the three stages of sleep onset. Actigraphy cannot measure all that PSG can, but Tryon (1996) has shown that actigraphic measures of four sleep parameters are highly correlated with PSG measures of the same parameters. For example, validity correlations for total sleep time ranged from $r(19) = 0.72$ to $r(3) = 0.98$. Validity correlations for percent sleep ranged from $r(19) = 0.82$ to $r(2) = 0.96$. Validity correlations for sleep efficiency ranged from $r(23) = 0.63$ to $r(11) = 0.91$. Validity correlations for wake after sleep onset ranged from $r(37) = 0.56$ to $r(67) = 0.87$.

Athletes sometimes fly long distances before competing, and that can result in jet lag, which can interfere with athletic performance. Montaruli, Roveda, Calogiuri, La Torre, and Carandente (2009) reported results from an actigraph-based study demonstrating how jet lag can be minimized and sleep can be improved. They used actigraphs to measure the sleep of 18 athletes who flew from Milan to New York, where 12 of them ran the 2007 New York City Marathon. They divided these 12 athletes into two groups of six: a morning training group (MTG) who trained in Milan from 7 a.m. until 9 a.m. for one month and an evening training group (ETG) who trained in Milan from 7 p.m. to 9 p.m. for one month. The remaining six athletes served as a control group (CG); they did not train and did not run the marathon. In New York, the MTG and ETG groups both trained in the morning from 7 a.m. to 9 a.m. Their results showed that the transatlantic flight fragmented the sleep of the ETG and CG significantly more than that of the MTG and that morning workouts repaired this problem.

Circadian Applications

Circadian rhythms are those biological functions that wax and wane over an approximately 24-h period. Fit individuals typically have robust circadian rhythms. Activity

level is normally characterized by a circadian rhythm in that it should be much higher during waking hours than during sleep. While it is possible to assess circadian rhythm over a single 24-h period, a much more accurate assessment results when evaluated over a week or month. The average activity level over a 24-h period or multiple periods is called the *measor*. The time at which peak activity level occurs is called *acrophase*. Cosinor software can be used to determine the best-fitting cosine wave and deduce acrophase from its peak. Amplitude refers to the height of the fitted cosine function. The suprachiasmatic nucleus (SCN) is believed to be the biological clock in mammals that regulates circadian rhythms. Zeitgebers are environmental cues that entrain, i.e., regulate, circadian rhythms. The solar light/dark cycle is a prominent zeitgeber that can be disrupted by long jet flights where the light/dark cycle of the destination differs substantially from that of the point of departure. The study reviewed above by Montaruli et al. (2009) shows how physical training during morning hours can help return circadian rhythms to normal.

Improving Sleep

Monitoring sleep during training is practical and feasible using sleep logs and actigraphy. Sleep logs provide a rough estimate of sleep as they primarily contain the time the person started trying to sleep and the time that they awoke. Actigraphy can provide additional objective information, such as the time that the person went to sleep and the time that they awoke with an accuracy of one-min. The athlete needs to wear only a wristwatch-size actigraph to bed every night. Data need to be downloaded only once each week and sleep scoring has been simplified to a menu selection. The Zeo is a new sleep-monitoring system that can be used to monitor sleep (<http://www.myzeo.com/>). Data are archived on a website in order to keep track of sleep quality over time. Bedtime, alcohol consumption, and diet can all be modified as necessary to keep sleep scores up.

Diurnal Activity

Low resolution. Actigraphs normally measure from 10 to 30 times per second and average over one-min epochs. This level of temporal resolution is much more detailed than pedometer data and frequently adequately characterizes the duration and intensity of ambulation-based workouts that include running or walking. The Fitbit system (<http://www.fitbit.com/>) uses a triaxial accelerometer to track activity level throughout the day. The Nike+ system (<http://www.apple.com/ipod/nike/>, http://nikerunning.nike.com/nikeos/p/nikeplus/en_US/) creates a personal fitness trainer by wirelessly connecting a sensor placed in the heel of running shoes with an iPhone or iPod to collect data while exercising that is then sent to a server for further processing.

High resolution. Sometimes greater temporal resolution is helpful in quantifying athletic performance. The RT3 sold by StayHealthy has a one-second recording epoch, which gives 60 times better temporal resolution than a one-min recording epoch. The ActiTrainer Solution Package sold by Actigraph LLC measures and records activity level at 30 Hz (30 times per second), and their GT3X model

can sample and record at 80 Hz, which should be sufficient to track a golf swing or a bowling approach. I could not find published applications of high-resolution actigraphs for these purposes.

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