Chapter 44
Review of Daily Physical Activity Monitoring System Based on Single Triaxial Accelerometer and Portable Data Measurement Unit

Mihee Lee, Jungchae Kim, Sun Ha Jee, and Sun Kook Yoo

Abstract Main objective of this pilot study was to present a method to convenient monitoring of detailed ambulatory movements in daily life, by use of a portable measurement device employing single tri-axial accelerometer. In addition, the purpose of this review article is to provide researchers with a guide to understanding some commonly-used accelerometers in physical activity assessment. Specially, we implemented a small-size wearable data storing system in real time that we used Micro SD-Memory card for convenient and long period habitual physical activity monitoring during daily life. Activity recognition on these features was performed using Fuzzy c means classification algorithm recognized standing, sitting, lying, walking and running with 99.5% accuracy. This study was pilot test for our developed system's feasibilities. Further application of the present technique may be helpful in the health promotion of both young and elderly.

1 Introduction

Over the past two decades, a striking increase in the number of people with the metabolic syndrome worldwide has taken place. This increase is associated with the global epidemic of obesity and diabetes. With the elevated risk not only of diabetes but also of cardiovascular disease from the metabolic syndrome, there is urgent need for strategies to prevent the emerging global epidemic [1, 2]. Although the metabolic syndrome appears to be more common in people who are genetically susceptible, acquired underlying risk factors-being overweight or obese, physical inactivity, and an atherogenic diet-commonly elicit clinical manifestations [3].

M. Lee (✉)
Graduate Programs of Biomedical Engineering, Yonsei University, 262 Seongsanno, Seodaemoon-Ku, Seoul 120-749, Korea
e-mail: leemihee76@yuhs.ac

S.-I. Ao et al. (eds.), *Machine Learning and Systems Engineering*,
Lecture Notes in Electrical Engineering 68,
DOI 10.1007/978-90-481-9419-3_44,

Current guidelines recommend practical, regular, and moderate regimens of physical activity (eq, 30 min moderate-intensity exercise daily) [4]. Regular and sustained physical activity will improve all risk factors of the metabolic syndrome. Sedentary activities in leisure time should be replaced by more active behavior such as brisk walking, jogging, swimming, biking, golfing, and team sports. Combination of weight loss and exercise to reduce the incidence of type 2 diabetes in patients with glucose intolerance should not be dismissed [5].

A variety of methods exist to quantify levels of habitual physical activity during daily life, including objective measures such as heart rate, one- and three-dimensional accelerometer, and pedometer, as well as subjective recall questionnaires like the International Physical Activity Questionnaire and physical activity logbooks [7, 8]. Yet all possess some important limitations. Heart rate monitors have been widely used to quantify physiological stress, but their efficacy at low intensities has been questioned due to the potential interference of environmental conditions and emotional stress [9]. A wide range of self-report activity questionnaires exist that are well suited to large surveillance studies but are limited due to their reliance on subjective recall. Pedometers are an inexpensive form of body motion sensor, yet many fail to measure slow walking speeds or upper body movements, and most are unable to log data to determine changes in exercise intensity [10]. The most common accelerometers used in human activity research measure accelerations either in a vertical plane (uni-axial), or in three planes (tri-axial), with excellent data-logging abilities [1, 10].

Main objective of this study was to present a method to convenient monitoring of detailed ambulatory movements in daily life, by use of a portable measurement device employing single tri-axial accelerometer. In addition, the purpose of this review article is to provide researchers with a guide to understanding some commonly-used accelerometers in physical activity assessment. The literature related to physical activity measurement is reviewed in this paper. For organizational purposes, the literature is presented under the following topics: (a) Measurement of Physical Activity, (b) Behavioral Observation, (c) Pedometers, and (d) Accelerometers.

1.1 Measurement of Physical Activity

Direct measurements of physical activity include behavioral observation and motion sensors (pedometers and accelerometers). An estimate of energy expenditure can be extrapolated from these direct measures of physical activity based on previously validated equations. The ability to examine health in relation to physical activity requires an accurate, precise and reproducible measurement of physical activity. Physical activity measurement tools should provide an objective measure of physical activity, be utilized under normal daily living conditions, have the capacity to record data over a prolonged period of time, and produce minimal discomfort to subjects [11]. Consideration should be given to the number of subjects to be monitored, and size and cost of the measurement tool, and the activity being monitored.

1.2 Behavioral Observation

Behavioral observation is a seldom utilized, time intensive technique that has primarily be applied when monitoring children and adolescents. This technique requires skilled observers who monitor individuals for a set period of time in an effort to code their behavior to describe overall physical activity patterns and estimate energy expenditure based on published MET values [12].

1.3 Pedometers

The concept of a pedometer was first introduced by Leonardo Da Vinci ~500 years ago. Pedometers are inexpensive tools that measure the number of steps taken by responding to the vertical acceleration of the trunk. Mechanical pedometers have a level arm is triggered when a step is taken and a ratchet within the pedometer that rotates to record the movement [13]. Electronic pedometers have a spring suspended pendulum arm that moves up and down thereby opening and closing an electrical circuit [7]. Output from the pedometer consists of number of steps taken, distance walked (with stride information), and estimated number of calories expended (with body weight considered) [13]. However, it is assumed that a person expends a constant amount of energy per step regardless of the speed (e.g. Yamax pedometer, 0.55 $\text{kcal} \cdot \text{kg}^{-1} \cdot \text{step}^{-1}$) [7].

Vertical acceleration of the hip during walking varies from 0.5 to 8 $\text{m} \cdot \text{s}^{-2}$, however some pedometers do not register movement below 2.5 $\text{m} \cdot \text{s}^{-2}$ or distinguish vertical accelerations above a certain threshold, and therefore are inaccurate at slow or very fast walking speeds and during running [7, 14].

Limitations of the pedometer include insensitivity to: (1) static or sedentary activity, (2) isometric activity, (3) movement occurring with the arms, and (4) slow or fast walking velocities [7, 13, 14]. In addition, they lack internal clocks and data storage capability which makes an analysis of overall physical activity patterns difficult [7]. Pedometers are primarily utilized in health promotion and maintenance and may provide valuable feedback to a participant concerning their level of activity. Advantages of utilizing a pedometer include low cost, size, and compliance of subjects.

1.4 Accelerometers

Accelerometer is based on the assumption that limb movement and body acceleration are theoretically proportional to the muscular forces responsible for the accelerations, and therefore energy expenditure may be estimated by quantifying these accelerations [11, 13]. Interest in monitoring the acceleration of the body started in the 1950s when Broubha and Smith (1958) suggested an association between the integral of vertical acceleration versus time and energy expenditure [15].

Acceleration is the change in velocity over time, and the degree of acceleration detected provides an index of movement intensity. Accelerations increase from the head to the feet and are generally the greatest in the vertical direction. Running produces the greatest vertical direction accelerations (8.1–12 g) at the ankle and up to 5 g at the back [16]. Bouten et al. (1996) recommends that accelerometers should be able to measure accelerations up to ±12 g for measurements occurring in daily living activities and exercise. Processing and filtering is required to identify and include accelerations that are outside the normal acceleration range of human movement.

Low pass filters remove high frequency signals that may occur as a result of external vibrations [17]. Factors which can influence accelerometer output include the acceleration due to body movement and external vibrations (loose straps, transportation) [18]. Most accelerometers are oriented to monitor the vertical plane such that linear acceleration with movement is not recorded [19].

1.4.1 Types of Accelerometer

Accelerometers can be classified based on the process by which acceleration is measured and recorded (piezoelectric versus piezoresistive) or the number of planes of movement it measures. Piezoresistive accelerometers utilize a spring element with strain sensitive gages connected via a Wheatstone bridge. The deflection of the spring element during acceleration causes a deformation of the gages, producing an electrical output in response to the change in resistance [13]. Piezoelectric accelerometers consist of a piezoelectric element and a seismic mass. When movement occurs, the sensor undergoes acceleration which causes deformation of the piezoelectric element (e.g. bending). Conformational changes in the element produce a voltage signal that is proportional to stress, or acceleration of the limb. When the body part to which the accelerometer is attached accelerates a charge is generated that is proportional to the force exerted by the subject. An acceleration-deceleration curve wave is created and the area under the wave is summed to yield the final count value [13, 19]. Ceramic transducers are more reliable than spring mechanisms, sensitive at very low frequencies, and require less power; however, aging of the ceramic may result in a loss of piezoelectric capabilities causing a decreased sensitivity to movement [20].

Accelerometers can be uni-axial (one plane of movement), tri-axial (three planes of movement) or “omni-directional”, monitoring acceleration in every plane other than that perpendicular to the point of reference. The uni-axial accelerometer is most sensitive to bending in one direction and is typically utilized to monitor acceleration in the vertical plane. An omni-directional accelerometer is most sensitive in one direction (vertical), but has the ability to quantify deformations in other planes (horizontal and lateral). Tri-axial accelerometers quantify acceleration in the vertical, anterior-posterior and medial-lateral plane and provide a measure of counts in each plane as well as an overall vector magnitude [13, 19]. There appears little advantage to using the triaxial accelerometer versus a single axis when the monitored activity is primarily walking [21]. However, activity energy expenditure during sedentary activities, as determined by a tri-axial accelerometer, correlates better with measured energy expenditure when compared to a uni-axial accelerometer [22].

1.4.2 Placement of Monitoring Sensors

Accelerometers are worn while the participant performs different activities and the counts from the monitor are regressed against a criterion measure of energy expenditure (e.g. whole room calorimetry, indirect calorimetry, doubly labeled water, or heart rate). Output from the monitors can be utilized to assess frequency, duration and intensity of physical activity. Energy expenditure is predicted by converting monitor counts into a unit of energy expenditure (MET, $kcal \cdot min^{-1}$, or $kcal \cdot kg \cdot min^{-1}$).

The characteristics of the population being studied and/or the specific activity may affect the accuracy of the motion sensors [23]. The output of the accelerometer will depend on the placement site (e.g. hip, wrist, ankle), the orientation relative to the subject, the posture of the subject, and the activity being performed. Accelerometer output is influenced by the placement of the monitors as body parts are differentially active depending upon the activity. Placing the accelerometer on the limbs while monitoring sedentary and daily living activities may produce more accurate results than hip placement as the limbs are likely to reflect activities which occur in these circumstances. The primary acceleration which occurs during walking or running is in the vertical direction, therefore placing the accelerometer at a site which reflects acceleration at the center of the body mass (e.g. hip) is likely to be more accurate than the limbs. The velocity of movement can also have an effect on the relationship between accelerometer counts and energy expenditure.

1.4.3 Limitations for Physical Activity Monitoring

The disadvantages of utilizing the accelerometer to estimate energy expenditure include subject compliance, altered activity patterns, and a cost of approximately $400 per monitor [13, 24]. One limitation of use is the inability to account for increased energy cost of walking uphill or cost of carrying a load. Accelerometers do not respond to activities where there is minimal movement at the body’s center of gravity (e.g. rowing and cycling) and they are not responsive to isometric work as even thought the limbs are not moving, energy is being expended [25, 26].

However, Westerterp (1999) suggests that the effect of static exercise on the total level of physical activity is negligible. Furthermore, estimates of energy expenditure are derived from equations that were developed within specific populations performing primarily walking activities in the laboratory. Consequently, energy estimation equations may not be applicable to the daily living activities performed within the general population. The primary advantages of utilizing an accelerometer include the ability to respond to both frequency and intensity of movement, its relatively low cost, ability to store large amounts of data over extended periods of time, small size and minimal participant discomfort [27].

These findings indicate that differences between uniaxial, triaxial, and omnidirectional accelerometry devices are minimal and all three provide reasonable measures of physical activity during treadmill walking. Furthermore, the inclusion of stride length in accelerometry based energy expenditure prediction equations significantly improved energy expenditure estimates.

The purpose of this study was to present a method to convenient monitoring of detailed ambulatory movements in daily life, by use of a portable measurement device employing single tri-axial accelerometer. Specially, we implemented a small-size wearable data store system in real time that we used Micro SD-Memory card (Secure Digital memory card) for convenient and long period habitual physical activity monitoring during daily life. In this work, the performance of activity recognition algorithms under conditions akin to those found in real-world settings is assessed. Activity recognition results are based on acceleration data collected from single tri-axial accelerometer placed on subjects' waist under semi-naturalistic conditions for pilot test.

2 Material and Method

2.1 Portable Data Measurement Unit

Our long-term aim in developing an accelerometry monitoring system was to develop a practical system that could be used to monitor and assess physical activities in free-living subjects. Therefore, we developed a wearable device consisted of Micro SD-Memory card connector (AUTF-08WP01, AUSTONE Electronics, Inc., USA) with mini USB socket (5P, SMT type, SHIH HAN CO., LTD., Russia). Measured acceleration signal was stored on micro SD-Memory card or transmitted wirelessly using Zigbee-compatible 2.4G bandwidth for wireless communication, and CC2420 (Chipcon Co. Ltd., Norway) with a simple interface circuit around the chip. In addition, a ceramic chip antenna TI-AN048 (SMD type, Texas Instruments Co. USA) was applied for stable wireless transmission.

For this we used ADXL330 (Analog Devices, Inc., USA), an acceleration sensor that is composed of a single chip and can detect tri-axis acceleration information, and measured acceleration information of axis X, Y and Z according to the subject's posture and activity. Using the implemented system, we measured change in acceleration signal according to the change of activity pattern. Li-Ionic batteries, micro processor units and micro SD memory card, as shown in Fig. 1. This equipment was small (60 $\times$ 40 $\times$ 20 [mm]) and light enough to carry without and restriction. Sampling frequency was 100 Hz. Data was downloaded via USB, and processed offline by a PC. The equipment was designed to be attached on the waist (see Fig. 1).

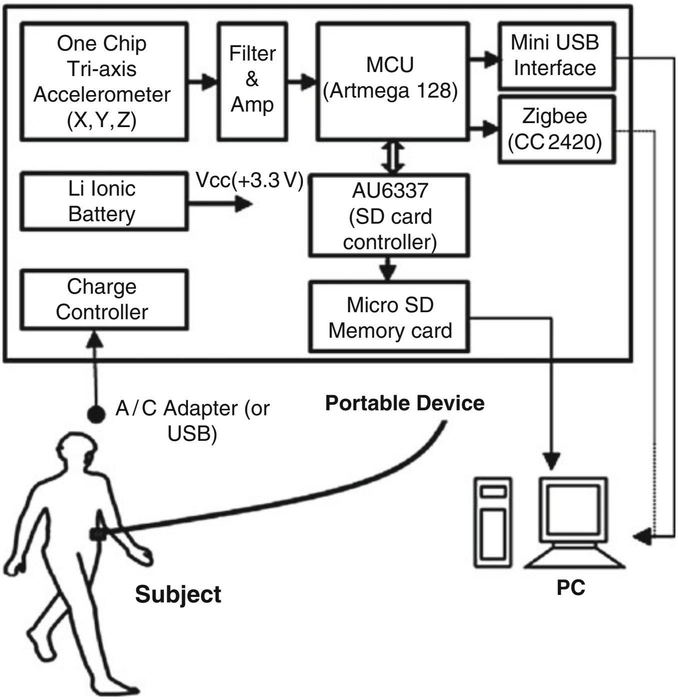

Fig. 1 Architecture of the wearable measurement device

Table 1 Participant characteristics

Case	Gender (M/F)	Age (year)	Height (cm)	Weight (kg)	BMI (kg ◆ m^{-2})
A	M	26	182	76	22.9
B	M	28	179	85	26.5
C	M	28	177	69	22.0
D	F	24	167	55	19.7
E	F	33	160	55	21.5

2.2 Physical Activity Data Collection

The data for these experiments were gathered in an unsupervised pilot study in which healthy young (age 24–33) subjects performed a variety of activities in the three times on outdoor conditions. Characteristics of the participants are presented in Table 1.

We put the acceleration measuring sensor system on the left waist of the subjects, and measured change in acceleration signal according to change in ambulatory movement and physical activities. In the experiment performed in this research, the change of acceleration was measured while the subject was repeating postures such as standing, sitting, lying, walking and running. A representatives set of routine data is shown in Fig. 2.

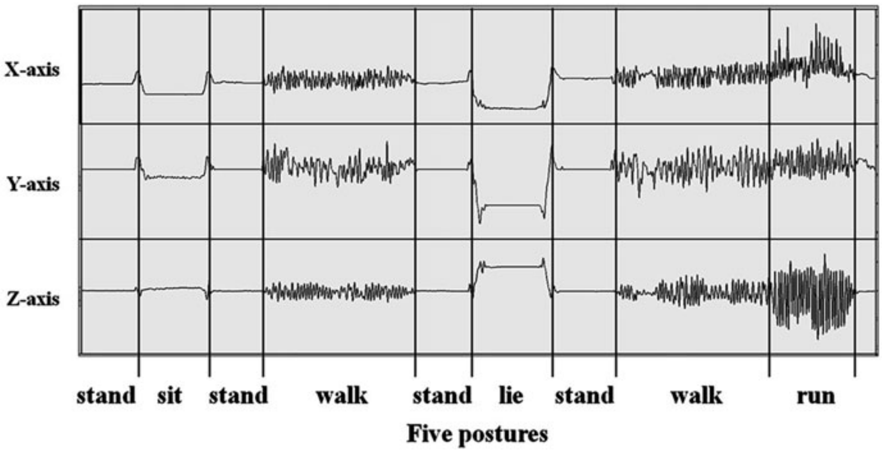

Fig. 2 Representative data from the daily routine for each of the three axes of the tri-axial device

While the movements and postures contained within the routine are by no means a complete set of all possible activities that a given person might perform, they do form a basic set of simple activities which form an underlying structure to a person's daily life, and are likely to provide a great deal of information in terms of the person's balance, gait and activity levels if they can be accurately identified.

2.3 Feature Extraction

Features were computed on 512 sample windows of acceleration data with 256 samples overlapping between consecutive windows. At a sampling frequency of 100 Hz, each window represents 5.2 s. Maximum acceleration, mean and standard deviation of acceleration channels were computed over sliding windows with 50% overlap has demonstrated success in past works. The 512 sample window size enabled fast computation of FFTs used for some of the features. The DC feature for normalization is the mean acceleration value of the signal over the window. Use of mean of maximum acceleration features has been shown to result in accurate recognition of certain postures and activities.

3 Results

This section describes the experiments and experimental results of the human posture recognition system. In the pilot test, a subject continuous posture change including standing, sitting, lying, walking and running. In the experiment, each posture was recognized third.

Table 2 Clustering results of different posture in a continuous motion

Parameters and real posture	Jaccard score	Purity	Efficiency
Standing	0.99	0.99	1
Sitting	1	1	1
Lying	1	1	1
Walking	0.99	1	0.99
Running	1	1	1
Average	0.98	0.99	0.99

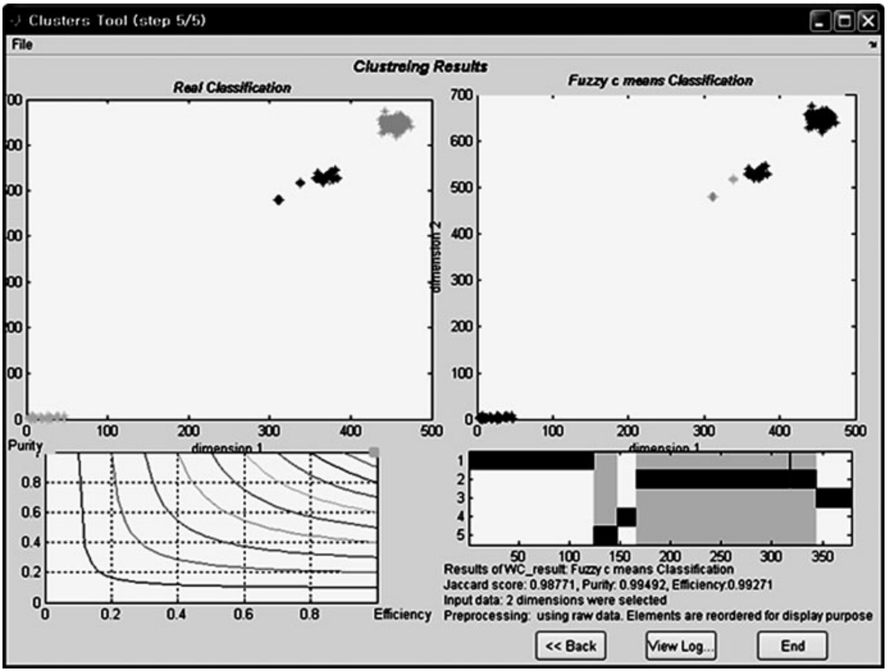

Fig. 3 Activity recognition result using Fuzzy c means classification algorithm

Mean and standard deviation of acceleration and correlation features were extracted from acceleration data. Activity recognition on these features was performed using Fuzzy c means classification algorithm recognized standing, sitting, lying, walking and running with 99.5% accuracy as shown in Table 2 and Fig. 3.

4 Discussion and Conclusion

This paper proposes an ambulatory movement's recognition system in daily life. A portable acceleration sensor module has been designed and implemented to measure human body motion. A small portable device utilizing single tri-axis accelerometer was developed, which detects features of ambulatory movements including vertical position shifts. The classification method based on Fuzzy c means classification algorithm, recognition accuracy of over 99% on a five activities (standing, sitting, lying, walking and running). These results are competitive with prior activity recognition results that only used laboratory data. However, several limitations are also observed for the system. Firstly, collected data was from younger (age 24–33) subjects. Secondly, single accelerometer of placed on body waist typically do not measure ascending and descending stairs walking.

Accelerometers are preferable to detect frequency and intensity of vibrational human motion [28]. Many studies have demonstrated the usefulness of accelerometer for the evaluation of physical activity, mostly focusing on the detection of level walking or active/rest discrimination [29–31].

This study was pilot test for our developed system's feasibilities. Further application of the present technique may be helpful in the health promotion of both young and elderly, and in the management of obese, diabetic, hyperlipidemic and cardiac patients. Efforts are being directed to make the device smaller and allow data collection for longer time periods. Implementation of real-time processing firmware and encapsulation of the hardware are our future studies.

Acknowledgments This study was supported by a grant of the Seoul R&BD Program, Republic of Korea (10526) and the Ministry of Knowledge Economy (MKE) and Korea Industrial Technology Foundation (KOTEF) through the Human Resource Training Project for Strategic Technology.

References

1. P. Zimmet, K.G. Alberti, J. Shaw, Global and societal implications of the diabetes epidemic. Nature **414**, 782–787 (2001)
2. S.M. Grundy, B. Hansen, S.C. Smith Jr, J.I. Cleeman, R.A. Kahn, Clinical management of metabolic syndrome: report of the American Heart Association/National Heart, Lung, and Blood Institute/American Diabetes Association conference on scientific issues related to management. Circulation **109**, 551–556 (2004)
3. R.H. Eckel, S.M. Grundy, P.Z. Zimmet, The metabolic syndrome. Lancet **365**, 1415–28
4. P.D. Thompson, D. Buchner, I.L. Pina, et al., Exercise and physical activity in the prevention and treatment of atherosclerotic cardiovascular disease: a statement from the Council on Clinical Cardiology (Subcommittee on Exercise, Rehabilitation, and Prevention) and the Council on Nutrition, Physical Activity, and Metabolism (Subcommittee on Physical Activity). Circulation **107**, 3109–3116 (2003)
5. J. Tuomilehto, J. Lindstrom, J.G. Eriksson, et al., Prevention of type 2 diabetes mellitus by changes in lifestyle among subjects with impaired glucose tolerance. N. Engl. J. Med. **344**, 1343–1350 (2001)
6. Y. Ohtaki, M. Susumago, A. Suzuki, et al., Automatic classification of ambulatory movements and evaluation of energy consumptions utilizing accelerometers and a barometer. Microsyst. Technol. **11**, 1034–1040 (2005)
7. D.R. Bassett Jr. Validity and reliability issues in objective monitoring of physical activity. Res. Q Exerc. Sport **71**, S30–S36 (2000)

8. C.L. Craig, A.L. Marshall, M. Sjostrom, A.E. Bauman, et al., International physical activity questionnaire: 12-country reliability and validity. Med. Sci. Sports Exerc. **35**, 1381–1395 (2003)
9. K.M. Allor, J.M. Pivarnik, Stability and convergent validity of three physical activity assessments. Med. Sci. Sports Exerc. **33**, 671–676 (2001)
10. M.J. LaMonte, B.E. Ainsworth, C. Tudor-Locke, Assessment of physical activity and energy expenditure, in *Obesity: Etiology, Assessment, Treatment and Prevention*, ed. by R.E. Andersen (Human Kinetics, Champaign, IL, 2003), pp. 111–117
11. C.V.C. Bouten, W.P.H.G. Verboeket-Van Venne, et al., Daily physical activity assessment: comparison between movement registration and doubly labeled water. J. Appl. Physiol. **81**, 1019–1026 (1996)
12. U.S. Department of Health & Human Services, *Physical Activity and Health: A Report of the Surgeon General* (U.S. 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, Atlanta, GA, 1996)
13. P.S. Freedson, K. Miller Objective monitoring of physical activity using motion sensors and heart rate. Res. Quart. Exerc. Sport **71**, 2129 (2000)
14. H.J. Montoye, H.C.G. Kemper, W.H.M. Saris, R.A. Washburn, *Measuring Physical Activity and Energy Expenditure* (Human Kinetics, Campaign, IL, 1996)
15. R.K. Dishman, R.A. Washburn, D.A. Schoeller, Measurement of physical activity. Quest. **53**, 295–309 (2001)
16. A. Bhattacharya, E.P. McCutcheon, E. Shvartz, J.E. Greenleaf, Body acceleration distribution and O2 uptake in humans during running and jumping. J. Appl. Physiol. **49**, 881–887 (1980)
17. G.J. Welk, *Physical Activity Assessments for Health-Related Research* (Human Kinetics, Champaign, IL, 2002)
18. C.V.C. Bouten, A.A.H.J. Sauren, M. Verduin, J.D. Janssen, Effects of placement and orientation of body-fixed accelerometers on the assessment of energy expenditure during walking. Med. Biol. Eng. Comput. **35**, 50–56 (1997)
19. K.Y. Chen, D.R. Bassett, The technology of accelerometry-based activity monitors: current and future. Med. Sci. Sport Exerc. **37**(11), S490–S500 (2005)
20. E.L. Melanson, P.S. Freedson Physical activity assessment: a review of methods. Crit. Rev. Food Sci. Nutr. **36**, 385–396 (1996)
21. T.G. Ayen, H.J. Montoye Estimation of energy expenditure with a simulated threedimensional accelerometer. J. Ambul. Monit. **1**(4), 293–301 (1988)
22. K.R. Westerterp, Physical activity assessment with accelerometers. Int. J. Obes. **23**(Suppl 3), S45–S49 (1999)
23. B.G. Steele, B. Belza, K. Cain, C. Warms, J. Coopersmith, J. Howard, Bodies in motion: monitoring daily activity and exercise with motion sensors in people with chronic pulmonary disease. J. Rehabil. Res. Dev. **40**(Suppl 2) 45–58 (2003)
24. M.J. Lamonte, B.E. Ainsworth, Quantifying energy expenditure and physical activity in the context of dose response. Med. Sci. Sports Exerc. **33**, S370–S378 (2001)
25. R.K. Dishman, R.A. Washburn, D.A. Schoeller, Measurement of physical activity. Quest. **53**, 295–309 (2001)
26. K.R. Westerterp, Physical activity assessment with accelerometers. Int. J. Obes. **23**(Suppl 3), S45–S49 (1999)
27. M.J. Mathie, A.C.F. Coster, N.H. Lovell, B.G. Celler, Accelerometry: providing an integrated, practical method for long-term, ambulatory monitoring of human movement. Physiol. Meas. **25**, R1–R20 (2004)
28. C.V.C. Bouten, K.T.M. Koekkoek, M. Verduin, R. Kodde, J.D. Janssen, A triaxial accelerometer and portable data processing unit for the assessment of daily physical activity. IEEE Trans. Biomed. Eng. **44***(3)*:136–147 (1997)

29. A.K. Nakahara, E.E. Sabelman, D.L. Jaffe, Development of a second generation wearable accelerometric motion analysis system. *Proceedings of the first joint EMBS/BMES conference*, 1999, p. 630
30. K. Aminian, P. Robert, E.E. Buchser, B. Rutschmann, D. Hayoz, M. Depairon, Physical activity monitoring based on accelerometry. Med. Biol. Eng. Comput. **37**, 304–308 (1999)
31. M.J. Mathie, N.H. Lovell, C.F. Coster, B.G. Celler, Determining activity using a triaxial accelerometer, in *Proceedings of the Second Joint EMBS/BMES Conference*, 2002, pp. 2481–2482