8-2001

The accuracy of the FitSense FS-1 speedometer for estimating distance, speed, and energy expenditure

Scott A. Conger

Recommended Citation

Conger, Scott A., "The accuracy of the FitSense FS-1 speedometer for estimating distance, speed, and energy expenditure. " Master's Thesis, University of Tennessee, 2001.
https://trace.tennessee.edu/utk_gradthes/9584

To the Graduate Council:

I am submitting herewith a thesis written by Scott A. Conger entitled "The accuracy of the FitSense FS-1 speedometer for estimating distance, speed, and energy expenditure." I have examined the final electronic copy of this thesis for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Science, with a major in Human Performance and Sport.

David R. Bassett Jr., Major Professor

We have read this thesis and recommend its acceptance:

Dixie L. Thompson, Edward T. Howley

Accepted for the Council:
Carolyn R. Hodges

Vice Provost and Dean of the Graduate School

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

To the Graduate Council:

I am submitting herewith a thesis written by Scott A. Conger entitled "The accuracy of the FitSense FS-1 Speedometer for estimating distance, speed, and energy expenditure." I have examined the final copy of this thesis for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Science, with a major in Human Performance and Sport Studies.

David R. Bassett, Jr.
David R. Bassett, Jr., Major Professor

We have read this thesis
and recommend its acceptance:

Dixie L. Thompson

Edward T. Howley
Edward T. Howley

Accepted for the Council:

Interim Vice Provost and
Dean of The Graduate School

THE ACCURACY OF THE FITSENSE FS-1 SPEEDOMETER FOR ESTIMATING DISTANCE, SPEED, AND ENERGY EXPENDITURE

A Thesis
Presented for the
Master of Science
Degree
The University of Tennessee, Knoxville

Scott A. Conger
August 2001

Dedication

To my wife, Summer Henson-Conger, and my mother, Cindy Conger. Thank you for all your love, support, encouragement, and patience. I love you both very much.

Acknowledgements

I would like to thank all of the subjects who participated in this study. You all did an excellent job and I appreciate your time and effort. I would also like to thank everyone who helped with subject recruitment. Your much-needed help was certainly appreciated. Brian Parr, Ann Swartz, and John Cone, thank you for all your help with testing (and counseling). Thanks to Pam Andrews for logistical assistance and Cary Springer for statistical counseling.

I would especially like to thank Scott Strath. Your contribution to this project was immeasurable. Thank you for your assistance and advice through every step of this process.

Finally, I would like to thank the members of my graduate committee. Thank you Dr. David Bassett for your guidance through this project. Thanks to Dr. Edward Howley and Dr. Dixie Thompson for all of your advice. I have learned a lot form each of you and I appreciate all of the knowledge and guidance you have given me over the past two years.

Abstract

The purpose of this study was to examine the accuracy of the FitSense FS-1 Speedometer for estimating distance, speed, and energy expenditure while walking and running at different speeds and grades. The study was divided into three experiments. Experiment I investigated the accuracy of the FitSense for estimating distance while walking and running at self-selected speeds during repeated 1600 m tests. Experiment II investigated the accuracy of the FitSense for estimating speed (vs. a handheld digital tachometer) and energy expenditure (vs. indirect calorimetry) during treadmill walking (3.0, 4.0, and 5.0 $\text{miles} \cdot \text{hr}^{-1}$) and running (5.0, 6.0, and 7.0 $\text{miles} \cdot \text{hr}^{-1}$) on a level grade. Experiment III investigated the accuracy of the FitSense for estimating energy expenditure (vs. indirect calorimetry) during treadmill walking with an increasing grade (0.0, 2.5, 5.0, 7.5, and 10.0%). Twenty-four subjects (15 male, 9 female) volunteered for Experiment I. A subset of 12 subjects (7 male, 5 female) also volunteered for Experiments II and III. For Experiment I, one-sample t-tests revealed no significant difference between actual distance and the distance estimated by the FitSense during the walking tests. A significant difference was found for distance while running ($p = 0.016$). During Experiment II, a significant difference was found for speed while walking on a level grade. Post-hoc pairwise comparisons found significant stage differences between 3.0 and 5.0 $\text{miles} \cdot \text{hr}^{-1}$ and 4.0 and 5.0 $\text{miles} \cdot \text{hr}^{-1}$. Paired t-tests found no significant differences between the estimated and measured speed for walking speeds of 3.0 and 4.0 $\text{miles} \cdot \text{hr}^{-1}$ or for running speeds of 5.0, 6.0, and 7.0 $\text{miles} \cdot \text{hr}^{-1}$. A significant difference between measured and estimated speed was found while walking at 5.0 $\text{miles} \cdot \text{hr}^{-1}$ (p <

0.001). A repeated measures ANOVA demonstrated significant differences for energy expenditure while walking on a level grade. Post-hoc pairwise comparisons revealed significant differences between each stage while walking. Paired t-tests also found significant differences between measured and estimated energy expenditure while walking at 4.0 and 5.0 $\text{miles} \cdot \text{hr}^{-1}$. No significant differences were found for energy expenditure while running. In Experiment III, a significant difference was found for energy expenditure while walking with an increasing grade. Post-hoc pairwise comparisons revealed significant differences between each grade. Paired t-tests also found significant differences between measured and estimated energy expenditure for each grade. In conclusion, the FitSense FS-1 Speedometer is an accurate tool for estimating distance while walking and running and for estimating speed while walking at 3.0 and 4.0 $\text{miles} \cdot \text{hr}^{-1}$ and running at 6.0 and 7.0 $\text{miles} \cdot \text{hr}^{-1}$ on a level grade. However, the FitSense underestimates energy expenditure while walking and running on a level grade and with an increasing grade.

Table of Contents

Chapter Page

I. INTRODUCTION 1

Purpose 4
Hypotheses 4
Significance 5

II. REVIEW OF LITERATURE 6

Doubly Labeled Water 7
Heart Rate Monitoring 9
Motion Sensors 14
Summary 32

III. METHODS 34

Subjects 34
FitSense FS-1 Speedometer 34
Experiment I: Accuracy of the FitSense for estimating distance during 1600 m track tests 37
Experiment II: Accuracy of the FitSense for estimating speed and energy expenditure at varying treadmill speeds 38
Experiment III: Accuracy of the FitSense for estimating energy expenditure at varying grades 42
Statistical Analysis 43

IV. RESULTS 45

Experiment I: Accuracy of the FitSense for estimating distance during 1600 m track tests 45
Experiment II: Accuracy of the FitSense for estimating speed and energy expenditure at varying treadmill speeds 47
Experiment III: Accuracy of the FitSense for estimating energy expenditure at varying grades 51

V. DISCUSSION 53

Future Research 60
Conclusions 60

REFERENCES 62

APPENDICIES 74

Appendix A – Health History Questionnaire 75
Appendix B – Informed Consent Form (Part I) 78
Appendix C – Informed Consent Form (Parts I-III) 81
Appendix D – $\dot{V}O_{2\,max}$ Data 84
Appendix E – Calibration Values 86
Appendix F – Distance Data 90
Appendix G – Speed Data 94
Appendix H – Energy Expenditure Data 97

VITA 101

List of Figures

FIGURE 1 The FitSense foot pod 35

FIGURE 2 The FitSense wristwatch receiver display 36

FIGURE 3 Mean distances for 1600 m walk and run tests 46

FIGURE 4 Mean data for speed measured by the tachometer and estimated by the FitSense 49

FIGURE 5 Correlation between measured energy expenditure (indirect calorimetry) and estimated energy expenditure (FitSense) while walking and running at 0% grade 49

FIGURE 6 Effects of treadmill speed on measured and estimated energy expenditure while walking and running 50

FIGURE 7 Correlation between measured energy expenditure (indirect calorimetry) and estimated energy expenditure (FitSense) while walking with an increasing grade 52

FIGURE 8 Effects of treadmill grade on measured and estimated energy expenditure while walking at 4.8 km/hr 52

List of Tables

TABLE 1 Subject Characteristics (Experiment I) 45

TABLE 2 Subject Characteristics (Experiments II & III) 47

TABLE 3 Comparison of Measured Speed with Estimated Speed 48

TABLE 4 Within Subject Variability of Calibration Values (CalVals) on Three Different Occasions 56

CHAPTER I

INTRODUCTION

Physical activity has been associated with a reduced risk of a number of chronic diseases such as coronary heart disease, non-insulin-dependent diabetes, hypertension, and obesity (11, 58, 69, 70, 105). In the past, physical activity questionnaires have been used to establish associations between physical activity and health (107, 114). However, in order to fully understand the interaction between physical activity and health-related chronic conditions, a reliable method to accurately quantitate physical activity is needed (113). In recent years, research has focused on various methods of estimating energy expenditure outside of the laboratory setting. One of these methods utilizes motion sensors (pedometers and accelerometers) to measure the quantity and intensity of movement of the whole body or specific body parts. These measurements give an estimation of physical activity, from which energy expenditure can be predicted.

Traditionally, distance during locomotion has been estimated by using the pedometer. The pedometer has been found to be fairly accurate at measuring steps while walking (6). However, pedometers are limited in that they can only accurately measure distance for one preset stride length. Several studies have demonstrated that pedometers can give inaccurate distance estimations during slow or fast walking speeds (6, 49, 80, 108) as well as during running speeds (49, 80, 108). Errors can occur due to a failure to register all footsteps at slow walking speeds and lengthening of the actual stride length at fast walking or running speeds (6). With changes in walking or running speed, there are also changes in stride length. Research has shown that with increases in running speed, stride length increases with very little changes in frequency of steps (40). Because pedometers are limited to one preset stride length, any deviation from this stride length can lead to inaccurate distance measurements (6, 49, 80, 108).

In recent years, motion sensors have been developed that are able to measure the acceleration of the whole body or of individual body parts (i.e., arms or legs) (43, 44, 62, 64, 91). Unlike pedometers, accelerometers such as the Caltrac, the Computer Science and Applications (CSA), and the Tritrac-R3D are capable of detecting changes in speed while walking or running (5, 13, 26, 37, 43, 62, 67, 68, 71, 102). However, they are limited in that they are unable to detect changes in intensity due to increases in grade (26, 43, 62, 64, 67). The display screen of these devices does not allow the user to view any information about current walking or running speed. The Caltrac's display is limited to energy expenditure information. The CSA and the Tritrac do not have a display screen and must be downloaded to a personal computer to access any information about the exercise bout.

Energy expenditure (kcals) is used to quantify physical activity and is an important variable in a weight loss program. In *Physical Activity and Health: A Report of the Surgeon General* (105), it is concluded that "activity leading to an increase in daily expenditure of approximately $150\ \text{kcals}\cdot\text{day}^{-1}$ (equivalent to about $1000\ \text{kcals}\cdot\text{week}^{-1}$) is associated with substantial health benefits." Activities that lead to an average energy expenditure of $1000\ \text{kcals}\cdot\text{week}^{-1}$ include walking briskly ($4\ \text{miles}\cdot\text{hr}^{-1}$) for 30 minutes per day or running for 15 minutes per day at 6 $\text{miles} \cdot \text{hr}^{-1}$ (105). An average of 1000 $\text{kcals} \cdot \text{week}^{-1}$ can also be achieved by running for about 35 minutes at 6 $\text{miles} \cdot \text{hr}^{-1}$ three times per week (105).

There are a number of methods that have been used to estimate energy expenditure. The doubly labeled water technique is generally considered the "gold standard" for measuring energy expenditure in the field setting, but it can only measure energy expenditure over extended periods of time and cannot provide information about a specific exercise bout (1, 35, 82, 107, 114). Also, the isotopes are costly and require expensive and sophisticated measuring equipment. The Caltrac and the Tritrac-R3D accelerometers provide energy expenditure data, but the Caltrac tends to overestimate energy expenditure by 9 to 52% during walking (5, 13, 26, 37, 71) and running (37), while the Tritrac tends to underestimate energy expenditure during walking by 12 to 50% (26, 43).

FitSense (Wellesley Hills, MA), a newcomer to the motion sensor industry, has developed an accelerometer (FS-1 Speedometer) that provides the user with information on distance and speed while walking or running. Accelerometers such as the Caltrac, the CSA, and the Tritrac were all designed to measure the amount of acceleration in the vertical plane. The FitSense was designed to measure the amount of acceleration in the horizontal plane. Haymes and Byrnes (37) suggested that a device measuring acceleration in the horizontal plane could lead to improved accuracy during walking and running. The FitSense manufacturers claim that the use of a shoe mounted, horizontal accelerometer allows the FitSense to more accurately estimate distance and speed than a simple pedometer or a waist-mounted, vertical accelerometer (28). When the user's body weight is entered into the receiver, the FitSense utilizes the acceleration information along with body weight to estimate energy expenditure in kilocalories (kcals) during the exercise session.

Purpose

To date, the accuracy of the FitSense FS-1 Speedometer has not been assessed by an independent research laboratory. The purpose of this study was to examine the accuracy of the FitSense FS-1 Speedometer for estimating distance, speed, and energy expenditure while walking and running at different speeds and grades.

Hypotheses

1. *The FitSense FS-1 Speedometer is an accurate tool for estimating distance while walking or running on a 400-meter outdoor track.* The data estimated by the FitSense accelerometer for distance will not be significantly different than the actual distance during locomotion.
2. *The FitSense FS-1 Speedometer is an accurate tool for estimating speed during treadmill walking or running.* The data recorded by the FitSense accelerometer for speed will not be significantly different than the actual walking or running speed measured by a calibrated handheld digital tachometer.
3. *The FitSense FS-1 Speedometer is an accurate tool for measuring energy expenditure during treadmill walking or running at different speeds and grades.* Predicted energy

expenditure by the FitSense will not be significantly different than the measured energy expenditure obtained via indirect calorimetry.

Significance

The FitSense FS-1 Speedometer could be a useful tool for researchers for monitoring daily and weekly energy expenditure during exercise. For competitive runners and walkers, it could aid in tracking daily and weekly mileage and exercise intensity, thus helping to avoid injury from overtraining. The FitSense could be a useful device not only for the competitive runner, but also for the recreational runner and walker. It could be a valuable source of information on energy expenditure for a person who is trying to lose weight.

CHAPTER II

REVIEW OF LITERATURE

Physical activity has been shown to lower the risks of developing a number of diseases. Regular physical activity has been associated with a decreased risk of cardiovascular disease mortality (56, 69, 70, 116). Regular physical activity is also associated with a decreased risk of high blood pressure (11), colon cancer (92), Type II diabetes (38, 58), osteoporosis (2), and obesity (22, 48, 117). These associations have lead to an increased interest in the development of improved methods for assessing physical activity and energy expenditure in free-living people (1).

Traditionally, physical activity assessment has been done through the use of subjective methods. Subjective methods used to estimate physical activity include physical activity surveys, diaries, questionnaires, and personal interviews (54, 107, 114). Subjective methods are often used in large-scale epidemiological studies because they are inexpensive, easily administered to a large number of people, unobtrusive, and require little effort from the participants (1, 54, 107). These methods are limited in that they all require the subject to accurately recall their activity. This could lead to an under- or overestimation of aspects associated with activity and inactivity.

In recent years, objective methods have been used to estimate physical activity. Objective methods measure movement or physiological parameters that are associated with exercise (1). This review of literature will focus on the objective methods that are most commonly used in field studies: doubly labeled water, heart rate monitoring, and motion sensors.

Doubly Labeled Water

Doubly labeled water is a method for estimating energy expenditure that is applicable to both the laboratory and field settings. Although this technique has existed for years, it has only recently become inexpensive enough to be used in studies involving humans. Doubly labeled water is water containing the nonradioactive isotopes oxygen 18 (^{18}O) and deuterium (^{2}H). A subject drinks a glass of water containing these isotopes and waits 6-12 hours for the water to equilibrate throughout the body (35, 82). During the equilibration period, the subject is free to perform normal activities, but may not eat or drink until a urine sample is collected to determine baseline concentrations of ^{18}O and ^{2}H. Gradually, the ^{18}O and ^{2}H will leave the body as part of the water found in urine, sweat, and vapor loss (35, 82). The ^{18}O will also leave the body when the subject exhales, due to the oxygen that is lost by conversion to carbon dioxide (CO_2) (35, 82). The difference between the actual loss of ^{18}O and the concentration that would have existed had the isotope been lost only through water excretion indicates how much ^{18}O was lost by CO_2 conversion, which is a measure of total energy expenditure (1, 35, 54, 82).

Because of high costs of ^{18}O, early studies using doubly labeled water were only used on animals weighing less than 10 kg. It was estimated that the cost of testing a single adult would have exceeded $5,000 (82). With the development of more sensitive detection equipment, it became possible to get by with less ^{18}O, thus reducing the cost to

$300-500 per subject. The first study using doubly labeled water on humans compared energy expenditure as determined by the doubly labeled water method to energy expenditure by dietary intake (82). Water containing 10 g of ^{18}O and 0.5 g of ^{2}H was orally administered to four subjects. The subjects were maintained on a carefully measured diet to determine caloric (energy) and water intake for 14 days. The total energy expenditure measured by the doubly labeled water method slightly overestimated energy expenditure verses the dietary intake method by an average of 2% (82), though this difference was found to be statistically significant. Similar results were found in other studies when compared with calories from weighed dietary intake (83, 84).

Westerterp et al. (112) compared energy expenditure measured by direct calorimetry and doubly labeled water. Nine subjects were divided into one of two groups: low activity and high activity. The low activity group spent six days in a whole room calorimeter doing deskwork. The high activity group spent 3.5 days in the calorimeter, which included two days of exercise to exhaustion (4-5 hours) on a cycle ergometer. The results showed that the doubly labeled water method was not significantly different from the daily metabolic rate measured by the calorimeter in the low activity group (1.4%) or in the high activity group (-1.0%) (112). Doubly labeled water was also found to be a valid method for estimating total daily energy expenditure when compared with indirect calorimetry (88).

Besides being a very accurate method, there are other reasons why doubly labeled water is the preferred method for measuring energy expenditure in the field. It is does not restrict free-living activity (35, 54, 82, 96), requires minimal cooperation by the subject (54), and is generally acceptable to the subject (54, 82). Despite the advantages of this method, there are also a number of disadvantages associated with doubly labeled water. In order to get an accurate estimate of energy expenditure during free-living activities, it is generally suggested that researchers use a measurement period of one to three weeks (1, 35, 82, 107, 114). Because of the necessity of an extended measurement period, researchers are only able to determine total energy expenditure for the time interval. The doubly labeled water method measures the average energy expenditure per day, but provides no information about day-to-day variations in energy expenditure or any information on types or patterns (frequency, intensity, or duration) of physical activity (12, 18, 25, 43). Also, the cost of the ^{18}O isotope is still much too great for large-scale epidemiological studies. Despite these limitations, doubly labeled water is generally considered the "gold standard" for the validation of field methods of assessing total daily energy expenditure (12, 25, 35, 43, 46, 96, 107, 114).

Heart Rate Monitoring

During exercise, there is a linear relationship between both heart rate and oxygen consumption at intensities above heart rates of 110 $\text{beats} \cdot \text{min}^{-1}$ and below maximal output. Based on this relationship, heart rate has been used as an estimate of energy expenditure. The electrocardiogram (ECG) is accurate for measuring heart rate; but, because of the size and complexity of portable monitors such as the Holter monitor, the ECG is not appropriate for use in the field setting. However, with recent advances in the development of telemetric heart rate monitors, heart rate can now be measured outside of the laboratory setting.

Heart Rate Monitors vs. ECGs

One of the first studies looking at the accuracy of telemetric heart rate monitors compared heart rates from the Polar Sport Tester PE 2000 heart rate monitor with heart rates measured by ECG while exercising (47). This heart rate monitor consisted of a chest strap transmitter and a wristwatch type receiver. Fourteen men and women exercised on a cycle ergometer or on a treadmill. Exercise intensity was increased every four minutes until they reached a maximal level. Heart rate was measured at one-minute intervals during exercise and every 30 seconds during the recovery period. The results showed that during exercise, the heart rates measured by the heart rate monitor were significantly higher than the ECG, but the heart rates differed by at the most only 5 $\text{beats} \cdot \text{min}^{-1}$ (47). The authors attributed the differences to the different methods used to calculate the heart rate measurements.

Treiber et al. (100) tested a similar heart rate monitor (Polar Sport Tester PE 3000) on a group of 10-year-olds while exercising on a cycle ergometer and participating in a variety of play activities (standing, walking, running, hitting a ball, throwing a ball, or playing on a jungle gym). During the cycle ergometer exercise, the results indicated a high correlation at all intensities ($r = 0.97$-0.99) and a standard error of estimate of less than 2 $\text{beats} \cdot \text{min}^{-1}$ at all intensities except for the final intensity, which was less than 4 $\text{beats} \cdot \text{min}^{-1}$ (100). During the play activities, the heart rate monitor and the ECG also showed a high correlation during all activities ($r \geq 0.98$) (100).

Léger et al. (55) tested the validity of 13 commercially available heart rate monitors for measuring heart rate verses ECG readings. Eight men and two women were tested at rest, during two exercise intensities, and during recovery. Exercise tests were completed on a cycle ergometer, treadmill, or during a double step test. The results indicated that most available heart rate monitors are valid and stable. The authors gave highest ratings to the Exersentry, the AMF Quantum XL, the Pacer 2000 H, and the Monark 1 ($r = 0.93$-0.98) (55). Other studies have shown strong correlations between heart rate monitors and ECG readings during graded maximal treadmill tests (89) and during submaximal exercise tests on four different types of fitness equipment (33).

FLEX Heart Rate

It has been suggested that heart rate monitoring is accurate at measuring energy expenditure only during exercise (31, 76). This is because other factors, such as high temperature, high humidity, body position, and emotional stress, can cause increases in heart rate without increases in oxygen uptake (31). Heart rate can also remain elevated after $\dot{V}O_2$ has returned to normal (76). Upper body and lower body exercises also have different effects on heart rate (7). Factors such as age and fitness level can also influence a person's heart rate (7). Because of this, a number of researchers have recommended the use of the FLEX heart rate for longitudinal studies (16, 31, 57, 72).

The FLEX heart rate method is used to separate periods of inactivity from periods of activity. It is defined as the average of the highest heart rate during rest and the lowest heart rate during the lightest possible exercise (16). A regression equation is developed based on the heart rate-$\dot{V}O_2$ calibration curve. FLEX heart rate is determined by calculating the mean heart rate measured during rest activities (measured while in the supine position, sitting and standing) and during light exercise. Anything below the FLEX heart rate is considered to reflect resting energy expenditure (16). For anything above the FLEX heart rate, the calibration curve is used to determine energy expenditure (31). The FLEX heart rate method takes into account variations in the heart rate-$\dot{V}O_2$ relationship due to differences in age, gender, and the person's fitness level (7). Several researchers have recommended that individual heart rate vs. $\dot{V}O_2$ calibration curves be obtained for each subject that is tested (16, 31, 57, 72, 76).

Estimating Energy Expenditure with Heart Rate Monitors

A number of studies have investigated the accuracy of heart rate monitors for estimating energy expenditure. Spurr et al. (95) compared energy expenditure estimated by heart rate recording with energy expenditure measured during whole-body indirect calorimetry. Minute-by-minute heart rate data were collected from 22 men and women who each spent 22 hours in a room calorimeter. The subjects were separated into four groups with different activity requirements ranging from no exercise to six 30-minute exercise bouts. Overall, the authors found no significant difference between energy expenditure estimated from heart rate data by the FLEX heart rate method and energy expenditure measured by indirect calorimetry in any group (95). In a similar study, Ceesay et al. (16) also compared heart rate data with whole-body indirect calorimetry for estimating energy expenditure. Although there was no significant difference between the two methods, energy expenditure estimated by the FLEX heart rate method yielded slightly lower energy expenditure values (16). Similar results have also been found in children (101).

Several studies have also compared estimated energy expenditure from heart rate data with energy expenditure measured by the doubly labeled water method. Schulz et al. (87) compared energy expenditure measured by doubly labeled water with estimates from energy intake, heart rate, and activity recording in six subjects. The average daily energy expenditure over a two-week period determined by doubly labeled water was compared to energy expenditure estimated by heart rate from two randomly selected days during the two-week period. The energy expenditure measured by doubly labeled water was 1.94 times larger than resting metabolic rate (RMR), while energy expenditure estimated by heart rate was between 1.67 and 2.24 times larger than RMR, depending on the formula used (87). Livingstone et al. (57) also found energy expenditure by doubly labeled water and heart rate monitoring to be similar. Davidson et al. (21) compared doubly labeled water and heart rate monitoring, using the FLEX heart rate technique, over nine days in a group of nine men. The heart rate monitoring method gave slightly higher estimates of energy expenditure (0.8 MJ/d) than the doubly labeled water method (21). Though the differences were small, the authors found them to be statistically significant (21).

Summary

Advances in telemetric heart rate monitoring have made it possible to obtain accurate heart rate data while exercising (33, 47, 55, 89, 100) or at rest (33, 89, 100). Using heart rate monitoring to estimate energy expenditure has also produced promising results when compared to whole-body indirect calorimetry (16, 95, 101) and to doubly labeled water (21, 57, 87). Because heart rate can be influenced by factors other than increases in $\dot{V}O_2$, a number of researchers have recommended the use of the FLEX heart rate technique to account for these factors (16, 31, 57, 72, 76). While heart rate monitoring is sufficient for giving information on general activity, the accuracy of this method is questionable for estimating energy expenditure in the field setting during longitudinal studies (21, 23). However, it can be used to give an accurate measure of energy expenditure during single exercise bouts (31, 76).

Motion Sensors

Physical activity has been described as "any body movement produced by skeletal muscles that results in energy expenditure" (15). This definition implies that physical activity can be assessed by measuring the amount of movement produced by the body. This has been the goal of devices that are used to measure the amount of movement of specific body parts. These motion-sensing devices include pedometers and accelerometers.

Pedometers

Historians have credited Leonardo de Vinci with inventing the pedometer in the 15th century (31, 35, 76). Though it is believed that his idea of a device that could measure how far people walk never got past the design stage, his concept of a lever arm that moved back and forth which rotated a series of gears and counted the number of steps (65) was the basis for the design of the modern pedometer.

Early Pedometer Research

A pedometer is a device that records the quantity of movement in one direction, usually in the vertical direction (80). Early pedometers were mechanical in nature and worked similar to self-winding style watches. A tiny arm was balanced by a delicate spring, which was displaced by slight jolts in the direction of suspension (49, 80). These jolts turned a number of gears and, eventually, an indicator needle on a dial (49, 80, 108). On some pedometers, the display indicated the total number of steps taken. Others were capable of displaying the total distance by calibrating the hand to the length of the user's stride.

Early research on mechanical pedometers focused on their accuracy and reliability for measuring distance and number of steps while walking and running. During treadmill tests, the pedometer tended to underestimate the total number of steps during slow walking and overestimate the total number of steps during fast walking (49, 80, 108). Similar results were found during slow and fast running speeds (80, 108). During a series of one-mile treadmill walks, Gayle et al. (32) found the pedometers to be inconsistent in measuring distance with values ranging from 0.7 to 1.4 miles. It should be noted that a stride length of 66 cm was used for all subjects during this study. Washburn et al. (108) also found these devices to be inaccurate for measuring distance while walking or running on a 400-meter track and along a measured jogging path. Inaccuracies were also found when using mechanical pedometers to measure daily physical activity in children (81). These inaccuracies were mainly due to the fact that the mechanical pedometers could only be calibrated for one stride length. As walking speed increases from slow to moderate to fast, stride length increases (40, 118). Stride length increases even more as one begins to run. Since the pedometer could only be calibrated for one stride length, the stride length during normal walking was usually chosen. Thus, any deviation from this stride length would lead to inaccurate results for measuring distance (49, 80, 108).

Recent Pedometer Research

In recent years, advances in pedometers have led to improvements in their accuracy. Bassey et al. (10) compared steps from a hip mounted mechanical pedometer to foot strikes from a carbon pad footfall sensor worn in the heel of the shoe while walking on a measured outdoor course. The step scores produced by the pedometers compared to the step scores produced by the resistance pad showed reasonable agreement for young subjects, while a group of older subjects showed more variability (10). The authors felt that the variability seen in the older subjects was due to "pottering" in the older subjects rather than walking (10).

The progression from mechanical pedometers to electronic pedometers led to greater accuracy. Electronic pedometers operate on the same principle of an arm balanced by a tiny spring, but the gears are replaced with an electrical contact (6). When the user takes a step, the arm makes an electrical contact and an event is recorded. The accuracy of five brands of electronic pedometers was assessed while walking on a treadmill and over a measured outdoor course (6). Most of the pedometers were found to be reasonably accurate at measuring distance walked and number of steps taken over a measured outdoor course, though some were more accurate than others (6). Three brands in particular (the Yamax Digiwalker DW-500, the Freestyle Pacer 798, and the Accusplit

Fitness Walker) were found to have superior accuracy. The Yamax was more accurate than the other pedometers tested at measuring number of steps while walking at a variety of treadmill speeds (6). However, consistent with earlier studies using mechanical pedometers, all brands tested underestimated distance at very slow speeds and very fast speeds (6). Tryon et al. (104) tested the reliability of electronic pedometers both under controlled laboratory conditions and during repeated half-mile walks. The pedometers showed a 5% error under laboratory conditions and a coefficient of variation of 2.75% during repeated half-mile walks by 39 college students (104).

Pedometer step counts have also been compared to oxygen uptake. Eston et al. (25) compared pedometers with oxygen uptake in children during treadmill walking (4 and 6 $\text{km} \cdot \text{hr}^{-1}$) and jogging (8 and 10 $\text{km} \cdot \text{hr}^{-1}$) and during unregulated play activities. The hip-mounted pedometer showed a strong correlation with scaled $\dot{V}O_2$ for all activities (r = 0.81) and with treadmill (r = 0.78) and unregulated play activities (r = 0.92) (25).

Shoe/Ankle Mounted Pedometers vs. Hip Mounted Pedometers

For a pedometer to provide accurate information, it must be mounted to a body part that will provide enough acceleration to register each step. Most pedometers are worn on the user's belt or waistband. This position assumes that each step will provide enough vertical hip movement to cause the pedometer to register one step. The shoe and ankle have also been used as mounting sites for pedometers. Early studies found that waist pedometers were more reliable than ankle pedometers (49, 80).

A recent study compared the ankle mounted Step Activity Monitor to a hip mounted electronic pedometer. The Step Activity Monitor detects and counts steps for a wide variety of gait styles, ranging from a slow shuffle to a fast run (19). It has been used to monitor adults with and without gait abnormalities, children, and animals (19). Unlike most other pedometers, the Step Activity Monitor also provides minute-by-minute step count information along with total steps taken. Twenty-nine subjects were asked to complete four activities: a brisk 400 meter walk, a slow 10 meter walk, ascend 11 steps, and descend 11 steps. During each of the activities, an investigator followed the subject and counted each stride using a hand-held counter. Overall, the Step Activity Monitor had 2.28% less absolute error than the pedometer (93). The pedometer undercounted more often while the Step Activity Monitor overcounted more often (93). The authors point out that because of the expense of the Step Activity Monitor ($800 plus ~$1,000 in computer equipment vs. $15 for the electronic pedometer), the pedometer is suitable for counting steps in most people (93).

Because most pedometers are dependent on body movement to detect steps, steps are often missed during slow walking (6, 49, 80, 108). Hoodless et al. (41) tested a shoe-mounted pedometer that directly counted the footfalls. A transducer that consists of a force-sensing resistor was placed into the heel of the subject's shoe. Ten young, healthy subjects walked on a treadmill at $4\ \mathrm{km \cdot hr^{-1}}$ for 1500 directly counted steps while wearing the shoe-mounted pedometer and a hip mounted mechanical pedometer. The shoe-mounted pedometer was consistently more accurate than the hip mounted pedometer with a mean error of ± 2.3% (vs. ± 7.7%) (41).

Longitudinal and Epidemiological Research with Pedometers

Since walking is one of the most common forms of physical activity in the United States (20), it could theoretically provide an estimate of daily physical activity. The Centers for Disease Control and the American College of Sports Medicine recommend that adults "accumulate at least 30 minutes of moderate intensity physical activity on most, preferably all, days of the week" (73). In the context of pedometers, Japanese researchers recommend 10,000 steps per day for optimal health (36). This recommendation sets a standard for total physical work (36).

Pedometers have been used in a number of research studies as a way to assess daily physical activity. A study by Bassett et al. (8) compared daily walking distance results from a questionnaire to results from a pedometer. The subjects were 48 men and 48 women between the ages of 25 and 70 years. The subjects completed a questionnaire that included questions about their physical activities, which asked for specifics on total number of city blocks walked daily, the number of flights of stairs climbed, and duration of sports and recreational activities. The subjects were then given a pedometer to wear for seven days. The results showed that both men and women significantly under-reported walking distance on the questionnaire compared with the pedometer values (8). Another study used pedometers to assess physical activity and compared its results with a self-administered questionnaire on their daily physical activity (90). A representative sample of 493 men and women aged 25-74 years wore a pedometer during work and leisure time. The results indicated that the pedometer was able to discriminate between work activity level as indicated by the questionnaire, yielding higher step counts for more active job classifications (90). They also found that steps decreased in both men and women with increases in age (90).

Pedometers have also been used to assess physical activity in specific populations. A pedometer was compared to a triaxial accelerometer and behavioral observations in a group of ten children (50). The pedometer values highly correlated with both the triaxial accelerometer and behavioral observations for moderate to high intensity recreational activity as well as low intensity classroom activity (50). Hoodless et al. (41) looked at activity levels in 18 patients with chronic heart failure verses 10 age-matched healthy control subjects. The results indicated that the patients accumulated less than half as many $\text{steps} \cdot \text{day}^{-1}$ when compared to the control subjects (41). Another study used pedometers to measure daily activity in patients with chronic lung disease (86). Subjects were in one of three groups: 25 patients with stable nonhypercapnic chronic obstructive pulmonary disease (COPD), 25 patients with chronic respiratory failure, and 25 normal healthy subjects. All subjects wore a pedometer for seven days. The median activity level of the healthy subjects was three times greater than in either group of patients (86). The investigators also found that activity counts appeared to complement the questionnaire for estimates of exercise limitations (86).

Summary

There are many advantages to the use of pedometers for measuring physical activity: they are inexpensive (6, 86, 90, 93), relatively easy to use (86), and can provide accurate information on step counts and distance (6, 10, 104). The pedometer can also be a useful tool in epidemiological studies as a way to estimate physical activity (8, 10, 19, 50, 86, 90). However, pedometers do have limitations. They can be inaccurate at measuring distance or number of steps at slow or fast walking speeds (6, 49, 80, 108) or at running speeds (49, 80, 108). Like all motion sensors, they do not recognize changes in grade or resistance encountered while exercising (32). Also, they do not measure any movements made by the upper body.

Accelerometers

While pedometers can provide information on distance walked or number of steps taken, they do not provide feedback on speed while walking. Also, pedometers are limited in that they cannot accurately estimate distance while running. The accelerometer was developed to address these problems by measuring not only the amount of movement, but also the intensity of movement. Although a number of accelerometers have been developed and used in research studies, the three most extensively researched accelerometers are the Caltrac, the Computer Science and Applications, Inc. (CSA), and the Tritrac.

Caltrac

The Caltrac Personal Activity Computer was developed in the late 1970s by Henry Montoye and John Webster at the University of Wisconsin-Madison. It was the first commercially available accelerometer in the United States (7, 31). The Caltrac (7×7×2 cm, 70 g) is a single-plane accelerometer, typically worn on the hip, that is used to measure the acceleration and deceleration of the trunk in the vertical direction. The transducer is a piezoelectric bender element that is mounted in cantilever fashion (91). The device produces acceleration and deceleration curves that are proportional to the forces exerted. The area under these curves is integrated and summed for the time it is worn (64, 91). The Caltrac is capable of estimating resting energy expenditure by entering the subject's age, gender, height, and weight into the device. The output is displayed as total energy expenditure in kilocalories. The Caltrac's estimate for resting energy expenditure can be negated by entering: age = 99, gender = 0, height = 36, and weight = 25. When programming the device with these variables, it will display raw "activity counts" rather than kilocalories.

There have been a number of studies looking at the validity of the Caltrac. One of the first studies compared the Caltrac's estimation of energy expenditure with energy expenditure measured by indirect calorimetry during 14 exercises (64). The Caltrac correlated well ($r = 0.74$) with $\dot{V}O_2$ for all of the activities, which included treadmill walking and running (64). The major finding that the authors reported was that the Caltrac was unable to detect changes in grade while walking or running (26, 64). Other studies have found that the Caltrac tended to overestimate energy expenditure (9 to 52% difference) during level treadmill walking (5, 13, 26, 37, 71) and during level treadmill running (0.74 to 2.6 $\text{kcal} \cdot \text{min}^{-1}$) (37) and underestimate energy expenditure during stepping exercises (-19% to -28% difference) (26) when compared to indirect calorimetry. In contrast, Melanson and Freedson (62) found no statistical difference between energy expenditure estimated by the Caltrac and energy expenditure measured by indirect calorimetry during treadmill walking and jogging. When compared to heart rate regression equations, the Caltrac was found to overestimate energy expenditure during running (14%) and race walking (19%) and underestimate during stepping (-10%)

(98). Haymes and Byrnes (37) noted that when the Caltrac was programmed to look at activity counts, it was able to detect changes in speed during treadmill walking but unable to detect changes in speed during treadmill running.

Several different methods have been used during free-living activities to validate the Caltrac for estimating energy expenditure with mixed results. Two studies have compared the Caltrac to the doubly labeled water method for measuring energy expenditure. In a group of 31 Caucasian and Native American children who wore a Caltrac for three days, it overestimated total daily energy expenditure by 487.4 $\text{kcal} \cdot \text{day}^{-1}$ versus doubly labeled water (46). Conversely, in a group of 67 men and women between the ages of 45 and 84 years, the Caltrac underestimated total daily energy expenditure by ~50-60% compared with doubly labeled water (96). The Caltrac also underestimated total energy expenditure by 13.3% in 40 girls during 24 hours in a whole-room calorimeter (14). It should be noted that a cycle ergometer was used for all exercise in this study and the Caltrac underestimates energy expenditure during cycling because of the lack of sufficient vertical hip movement during cycling.

The Caltrac has also been compared to direct observation for estimating physical activity. A group of 50 adults were observed for a period of one hour in a multi-purpose fieldhouse. The subjects were told to do whatever activities they desired while a trained researcher observed the subjects' behavior from a balcony. The study was replicated with a group of 30 preschool children in a daycare facility. The results of the study indicated that the Caltrac readings strongly correlated (r = 0.69) with the observed physical activity in the adults, but did not highly correlate (r = 0.35) with the children's values (51). Ballor et al. (3) compared estimates of energy expenditure by Caltrac, video analysis, and heart rate estimation in a high school physical education class. Although all three estimates of energy expenditure were statistically different from each other, the Caltrac did show a strong correlation between both heart rate estimation (r = 0.92) and video analysis (r = 0.95) (3).

Several studies have used the Caltrac to assess physical activity over long periods of time. Sallis et al. (79) had 35 children wear two Caltrac accelerometers and a heart rate monitor for two days. The authors reported that the Caltrac was a highly reliable instrument for estimating energy expenditure compared to heart rate monitoring with correlations of 0.54 and 0.42 for each day of data collection (79). A study by Richardson et al. (74) used the Caltrac to assess physical activity changes over a period of one year. Seventy-eight men and women between the ages of 20 and 59 wore the Caltrac for 48-hours every 26 days (28 total days of monitoring for the year per person). During each monitoring period, the subjects kept a detailed 48-hour activity record and a researcher administered a Four-Week Physical Activity Questionnaire to assess activity levels for the previous four weeks. The results showed a moderate association (r = 0.34-0.51) between the Caltrac and the 48-hour activity record (74). Caltrac accelerometers have also been used to compare various physical activity questionnaires (63, 115), to compare activity levels of normal-weight and overweight women (78), to compare activity levels in children and their parents (29), and to determine the amount of physical activity that is associated with physical therapy (4) and with postal carriers (109).

The development of the Caltrac accelerometer was an improvement on the pedometer. The Caltrac gave researchers the ability to measure not only the amount of activity, but also the intensity of the activity. However, the Caltrac does have a number of limitations. It was designed to be worn only on the hip, thus it is limited to measuring only activities that cause vertical movements of the hips. Energy expenditure during upper body work is underestimated by the Caltrac (35). The Caltrac has limited data storage capabilities and lacks an internal clock. This makes it virtually impossible to study activity patterns in the field setting. There have been a number of studies that have focused on the inaccuracy of the Caltrac for measuring energy expenditure (5, 14, 26, 37, 46, 71, 96, 98). It should be noted that the original regression equations that were developed for the Caltrac utilized 14 different activities that required movement by the upper body and the lower body (35, 64). This was done to take a variety of daily activities into account when estimating energy expenditure. The accuracy of the Caltrac could be improved if regression equations for specific activities could be entered into the Caltrac. However, this would be impractical during every day activities.

Computer Science and Applications (CSA)

The CSA accelerometer is a single plane accelerometer that is smaller (5×4×1.5 cm) and lighter (42g) than the Caltrac. It was designed to be worn not only on the hip, but also on the wrist or ankle. The CSA records accelerations of magnitudes ranging from 0.05 to 2.0 Gs and frequencies of 0.25 to 2.5 Hz. These parameters allow for the device to detect normal body movements and filter out movements not made by the subject. The acceleration signal is digitized and the magnitude is summed over a specified time interval. At the end of each time interval, the movement count is stored and the integrator is reset. This process repeats itself until the memory is filled or the device is reset. The CSA has large data storage capabilities, allowing for data to be stored in time intervals from 1 second to several minutes for up to 22 days, allowing for information on minute-by-minute movement activity to be collected. The CSA output can then be downloaded to a personal computer.

The validity of the CSA accelerometer was initially investigated during treadmill walking and jogging. Twenty-eight subjects walked at 4.8 and 6.4 $\text{km} \cdot \text{hr}^{-1}$ and jogged at 8.1 $\text{km} \cdot \text{hr}^{-1}$ mph during three laboratory sessions (62). During each session, data was collected at 0%, 3%, and 6% grades for 8 minutes each. CSA accelerometers were secured to the hip, ankle, and wrist. CSA activity counts significantly increased with increased speed at all three sites (62). But, the CSA did not show higher activity counts with increases in treadmill grade (62).

Nichols et al. (68) investigated the validity and inter-instrument reliability of the CSA in the laboratory and in the field setting. Wearing a CSA on the right and left hip, 60 men and women walked and jogged on a treadmill at 3.2, 6.4, and 9.7 $\text{km} \cdot \text{hr}^{-1}$ at 0% grade and 6.4 $\text{km} \cdot \text{hr}^{-1}$ at 5% grade. Using a different group of 30 men and women, the CSA was also evaluated while walking and jogging on a 400-meter track. The results of the study indicated that the CSA was highly sensitive to increases in speed but had low sensitivity to increases in treadmill grade (68). The device also showed high inter-instrument reliability (left vs. right hip) at 6.4 $\text{km} \cdot \text{hr}^{-1}$ at 0% grade ($r = 0.89$) 6.4 $\text{km} \cdot \text{hr}^{-1}$ at 5% grade ($r = 0.91$) and 9.7 $\text{km} \cdot \text{hr}^{-1}$ ($r = 0.73$) but only moderate inter-instrument reliability at 3.2 $km \cdot hr^{-1}$ ($r = 0.55$) (68). In the field study, the CSA was able to detect changes in exercise intensity as velocity increased (68). The authors noted that prediction equations developed during treadmill exercise might not be appropriate to estimate intensity during outdoor physical activity (68). Eston et al. (25) found that the CSA correlated well with oxygen uptake ($r = 0.78$) in children during treadmill and unregulated play activities. The CSA has also been found to be a valid indicator of physical activity in children during treadmill walking and jogging (102).

A number of studies have attempted to develop regression equations to predict the energy cost of activities using CSA accelerometers. Freedson et al. (30) used treadmill walking and jogging to establish activity count ranges that could classify intensity levels using the CSA accelerometer. Hendelman et al. (39) developed a regression equation for several every day activities using activity counts from a CSA worn on the hip. Swartz et al. (99) tested 70 subjects in activities ranging from housework to recreational activities. The results of this study indicated that using the combination of hip and wrist accelerometers provided more accurate estimations of energy expenditure (99).

CSA accelerometers have also been used to assess daily physical activity in children. Thirty-one children wore a CSA accelerometer and a heart rate monitor for three consecutive days. The researchers found moderate to high correlation coefficients ($r = 0.50$-0.74) between accelerometry and heart rate monitoring (44). Janz et al. (45) compared CSA activity counts to physical activity questionnaires in children. They found that self-report questionnaires were poorly to moderately correlated ($r = -0.03$-0.51) to CSA activity counts (45). They also found that CSA accelerometers could be used to measure physical activity intensity levels in children during extended periods of monitoring (45). A study by Trost et al. (103) used CSA accelerometers to establish the minimal number of days needed to assess physical activity in children when using accelerometers. The authors concluded that a seven-day monitoring period provides reliable estimates of physical activity in children and adolescents (103).

The CSA accelerometer addresses several of the limitations that are associated with the Caltrac. The CSA has much larger data storage capabilities and features an internal clock that allows researchers to assess activity patterns. It was designed to be worn at several different points on the body, thus allowing researchers to gain information on energy expenditure during upper body as well as lower body activities. This makes it an ideal choice for research studies. Because it was intended to be used for research, requiring extra computer equipment and technical expertise to interpret the data, it is unsuitable for use by the general public. And, like other single-plane accelerometers, it is unable to detect changes in grade while walking or jogging (62, 68).

Tritrac-R3D

Rarely is physical activity limited to movement in only one direction. Because single-plane accelerometers are only able to measure movement in one direction, they neglect the amount of energy that is expended for movements in other directions. The Tritrac-R3D triaxial accelerometer uses three accelerometers to measure movement in three directions: vertical, horizontal, and lateral. The three accelerometers are oriented at right angles to one another, each having a frequency response of 0.1 to 16 Hz (97). The Tritrac's output is measured in three dimensions: medio-lateral (x), anterior-posterior (y), and vertical (z). The Tritrac also measures a composite movement score for all three directions called the "vector magnitude" ($\sqrt{x^2+y^2+z^2}$) (67, 97). The vector magnitude movement count is used to calculate estimated energy expenditure for each minute of data. Because of the added accelerometers, the Tritrac is much larger (11.1×6.7×3.2 cm) and heavier (170 g) than both the Caltrac and the CSA. Like the Caltrac, the Tritrac was designed to be worn at waist level. Similar to the CSA, the Tritrac's sampling intervals can be programmed for 1-15 minutes, with a maximum of 14 days of data collection when the interval is set at one minute. The Tritrac uses technology similar to the Caltrac for estimating resting energy expenditure when the subject's age, gender, height, and weight are entered. Data from the Tritrac is downloaded to a personal computer where information on minute-by-minute energy expenditure, total energy expenditure, and activity counts from the vector magnitude, as well as each individual dimension (x, y, and z), is available to the user.

Several studies have looked at the validity of the Tritrac accelerometer in laboratory studies. The accuracy of the Tritrac for estimating energy expenditure was investigated during five different exercises (43). The Tritrac was compared to indirect calorimetry during treadmill walking (3.0 mph at 0, 5.0, and 10.0% grade), treadmill running ($5.0\ \text{miles} \cdot \text{hr}^{-1}$ at 0 and 5.0% grade), cycling (1.5 kg of resistance at 50 $\text{rev} \cdot \text{min}^{-1}$ and 65 $\text{rev} \cdot \text{min}^{-1}$), stepping (8 inch step at 20 and 30 $\text{steps} \cdot \text{min}^{-1}$) and slideboard (160 cm slide at 17 and 21 $\text{cycles} \cdot \text{min}^{-1}$). The Tritrac correlated well with indirect calorimetry for estimating energy expenditure during all exercises with correlation coefficients ranging from 0.63 to 0.96 (43). However, the Tritrac significantly underestimated energy expenditure during all exercises (-29.8% to -89.1% difference) except for treadmill running (43). The Tritrac was unable to detect changes in treadmill grade during treadmill walking and running (43).

Nichols et al. (67) looked at the ability of the Tritrac to detect changes in grade during treadmill walking and running by examining the vector magnitudes. While the Tritrac was able to detect changes in treadmill speed, it was unable to detect changes in grade (26, 67). Fehling et al. (26) found that the Tritrac underestimated energy expenditure versus indirect calorimetry during treadmill walking (-12% to -37% difference) and during stepping (-58% to -60% difference) in older adults. In contrast, Sherman et al. (94) found no difference between energy expenditure measured by indirect calorimetry during treadmill walking and jogging. They also noted that energy expenditure estimated by the Tritrac during 10 minutes of rest did not differ from actual energy expenditure (94). Eston et al. (25) found that the Tritrac correlated significantly better than CSA accelerometers, pedometers, or heart rate when compared to oxygen uptake (r = 0.891) in children during treadmill and unregulated play activities.

The Tritrac has been used in a number of studies to estimate energy expenditure during daily living. A group of 125 men and women spent two 24-hour periods in a whole-room calorimeter while wearing the Tritrac to assess the accelerometer's accuracy for estimating energy expenditure (17). During one 24-hour stay, the subjects were asked to structure their activity patterns as close to normal as possible. The other stay included structured exercise bouts. The Tritrac was found to significantly underestimate energy expenditure during both the normal day (0.12 to 1.16 MJ difference) and the exercise day

(0.21 to 1.24 MJ difference) (17). This underestimation was seen at all intensities except for sleeping, which was significantly overestimated (0.20 MJ difference) (17).

Studies comparing the Tritrac to self-reported physical activity have shown mixed results. Epstein et al. (24) compared energy expenditure estimated by the Tritrac and by self-report in children and found that the self-report estimates were almost 43% higher than the Tritrac estimates. This was also seen in a group of adults when compared to two physical activity questionnaires (59). Matthews et al. (59) also showed that Tritrac overestimated resting energy expenditure by ~100 $\text{kcal} \cdot \text{day}^{-1}$. In contrast, McMurray et al. (61) found that the Tritrac significantly overestimated energy expenditure versus a computerized activity recall (1941 kcal vs. 1576 kcal) in 45 middle-school students.

The Tritrac has been shown to correlate better with heart rate measurements in the field setting than with self reported physical activity in obese children (18). Welk and Corbin (111) compared the Tritrac to a heart rate monitor and the Caltrac activity monitor. The correlations between the Tritrac and the heart rate monitor (r = 0.58) were not significantly higher than the correlations between the Caltrac and the heart rate monitor (r = 0.52) suggesting that the triaxial accelerometer did not significantly improve its validity over a uniaxial accelerometer as a measure of physical activity in the field (111). Other studies have shown that the Tritrac is a stable and reliable instrument to estimate energy expenditure over time in the elderly (52) and in COPD patients (97).

The idea that a triaxial accelerometer could improve on the measurements of physical activity and energy expenditure made by a single-plane accelerometer is a logical extension to the motion sensor theory. But, research has shown that the Tritrac-

R3D has not achieved this goal. Compared to indirect calorimetry, the Tritrac has been shown to underestimate (26, 43, 67) energy expenditure more often than not (94). It has also been found to underestimate energy expenditure versus whole-room calorimetry (17). Studies comparing the Tritrac to questionnaires have yielded mixed results (24, 59, 61). Like other single-plane accelerometers, the Tritrac is unable to detect changes in grade while walking (26, 67). The additional size of the Tritrac along with the fact that it does not improve on single-plane accelerometers for estimating physical activity make it a questionable choice for use over other available accelerometers.

Summary

There are advantages and disadvantages to each of the objective methods that are used in the field setting. The doubly labeled water method gives a very accurate measure of energy expenditure for a given time period. Because the time period must be at least one week long, this method does not give any information on day-to-day activity or the types or patterns of activity. Heart rate monitors are very accurate at measuring heart rate and can be used to give a good estimation on energy expenditure. But, a number of factors other than exercise can cause heart rate to be elevated, thus leading to an overestimation of physical activity energy expenditure. Pedometers can be useful in measuring the amount of walking activity, but they have questionable accuracy for other activities. Accelerometers are able to measure not only the amount of activity, but also the intensity of activity. But, most are limited to measuring movements of only the upper body or the lower body and neglect to measure any other movements. Similar to pedometers, accelerometers are also unable to detect increases in intensity due to factors other than increases in the speed of movement, such as change in grade or carrying a heavy load. While there have been a number of advances in recent years in the objective measurement of physical activity in the field setting, the lack of a method that can accurately measure all of the components of physical activity, yet are socially acceptable and do not inhibit movement, remains.

CHAPTER III

METHODS

Subjects

Twenty-four subjects (15 male, 9 female) between the ages of 18 and 45 years were recruited from the Knoxville, Tennessee community to participate in Experiment I of this study. A subset of 12 (7 male, 5 female) of the original 24 subjects also volunteered for Experiments II and III. Subjects who volunteered for Experiments II and III completed each of the four tests on different days. Subjects were eligible for this study if they were moderately active and had no apparent contraindications to exercise. Prior to participating in the study, each subject completed a health history questionnaire (Appendix A) and an informed consent form (Appendices B and C) approved by the University of Tennessee's Institutional Review Board. All testing was completed at the Applied Physiology Laboratory in the Health, Physical Education and Recreation building and at the Tom Black Athletic Track on the University of Tennessee campus.

FitSense FS-1 Speedometer

The FitSense FS-1 Speedometer utilizes a small (5.0×4.0×1.5 cm, 19.3 g), horizontally mounted, uniaxial accelerometer (foot pod) (Figure 1) that is attached to the user's shoe at the shoelaces. Data is telemetrically transmitted from the foot pod to a wristwatch receiver (5.0×5.2×1.4 cm, 48.6 g). The FitSense measures distance while

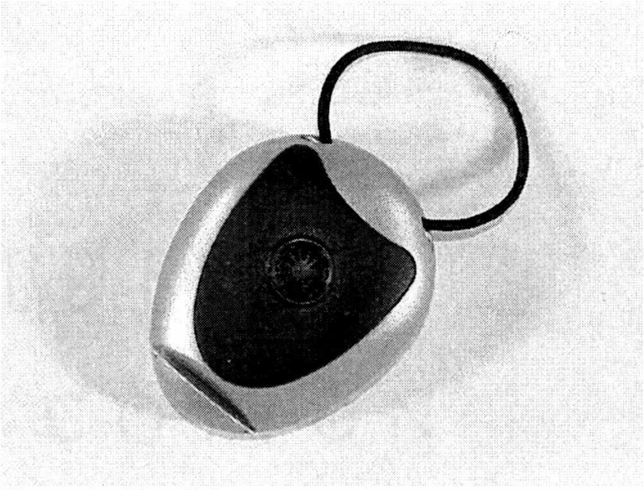

Figure 1 – The FitSense foot pod

walking and running by measuring the acceleration of each step and adjusting for changes in stride length. The acceleration and stride length information are integrated together to get a more accurate estimation of distance. When the user's weight is entered into the receiver, the device uses the acceleration information along with body weight to estimate energy expenditure in kilocalories (kcals) during the exercise session. The FitSense estimates energy expenditure by utilizing a formula which is based on the theory that the metabolic cost of locomotion is primarily determined by the cost of supporting total body weight and the rate at which force is generated (42, 53). This formula (body weight divided by foot contact time) allows the FitSense to estimate energy expenditure during locomotion. Thus, it is able to estimate energy expenditure during two of the most frequently reported leisure-time physical activities, walking and running (20). With the addition of the FitSense heart rate monitor and chest strap, heart rate data is also viewable on the receiver's display. Heart rate gives the user valuable information on exercise intensity, which may be important for training purposes.

Figure 2 – The FitSense wristwatch receiver display. *Top row*: speed ($\text{miles} \cdot \text{hr}^{-1}$) and distance (miles); *Bottom row*: heart rate ($\text{beats} \cdot \text{min}^{-1}$) and total exercise time.

The FitSense accelerometer calculates walking or running speed from distance ÷ time. This can be viewed on the receiver as speed ($\text{miles} \cdot \text{hr}^{-1}$) or as pace ($\text{min} \cdot \text{mile}^{-1}$) while walking or running. A number of variables, including exercise time, distance (miles), speed ($\text{miles} \cdot \text{hr}^{-1}$), heart rate ($\text{beats} \cdot \text{min}^{-1}$), current pace ($\text{min} \cdot \text{mile}^{-1}$), average pace ($\text{min} \cdot \text{mile}^{-1}$), and calories, are viewable while exercising. The FitSense can display four variables at one time (Figure 2), giving the user several pieces of information while walking or running. During each exercise bout, the device automatically records and saves the time (splits) for each mile. The user can also manually save splits at any time. The FitSense has a data storage capacity of the latest 75 splits and 28 exercise bouts. Data can be downloaded to a personal computer and stored on a personal web page on the FitSense website. Information on speed, distance, and heart rate is accessible and displayed graphically on the web page. The web page can also display information on daily, weekly, monthly, and yearly exercise time and distance.

Experiment I: Accuracy of the FitSense for estimating distance during 1600 m track tests

The accuracy of the FitSense for estimating distance was tested during two, 1600 m walking tests and two, 1600 m running tests on a 400 m rubberized athletic track. Prior to testing, the subject's weight was measured with a standard physician's scale (Health-o-meter, Inc., Bridgeview, IL) and height was measured with a stadiometer (SECA Corp., Columbia, MD).

FitSense Calibration on the Track

The FitSense was calibrated to each individual according to the manufacturer's instructions for track calibration before beginning testing (28). Subjects were instructed to warm-up and stretch prior to beginning the calibration procedures. The foot pod was attached to the subject's right shoe by lacing the attached elastic cord through the shoelaces. The wristwatch receiver unit was worn on the right wrist of the subject. Using lane one of the track, a start/finish line was established. The subject was instructed to move back about 20 feet from the starting line. The subject began walking and pressed the "Start" button on the receiver as he/she crossed the starting line. The subjects were not instructed to walk at any standard speed or pace; they were only instructed to maintain an even and natural pace for one lap. As the subject crossed the finish line, he/she pressed the "Stop" button to complete the walking calibration procedure. Lap time was recorded and the watch was prepared for the running calibration. The entire procedure was repeated while running. After completing both the walking and running calibration, the calibration values (CalVal) determined by the FitSense were recorded.

Distance Test

After completing the calibration procedures, all testing procedures were explained to the subjects. The first two, 1600 m tests were at self-selected walking speeds. Each subject started and stopped at the same predetermined point. The subjects were instructed to walk four laps in the middle of lane one at a self-selected speed. At the end of each lap, distance was recorded and heart rate was monitored. At the completion of the fourth lap, the subjects were instructed to stop on the finish line. Total distance and time were recorded, the receiver was reset, and the subject was given 2-5 minutes to rest, if needed. The walking procedure was then repeated for a second 1600 m test. Following the completion of the two, 1600 m walking tests, the entire procedure was repeated during two, 1600 m tests at self-selected running speeds. Distance data from the FitSense was then converted from miles to meters.

Experiment II: Accuracy of the FitSense for estimating speed and energy expenditure at varying treadmill speeds

The accuracy of the FitSense for estimating speed and energy expenditure were determined while walking and running on a level grade. Prior to testing, the subject's body composition was determined by using whole body plethysmography (Bod Pod®, Life Measurement Instruments, Concord, CA) (34, 60).

Maximal Testing

Each subject who volunteered for Experiments II and III completed a maximal, graded treadmill test to determine maximal oxygen uptake ($\dot{V}O_{2\ \mathrm{max}}$). Subjects were asked to abstain from exercise, alcoholic beverages, and caffeine the day of the test and to abstain from eating 4-6 hours prior to testing. Subjects were asked to warm-up for five minutes on the treadmill (Quinton Q65, Quinton Instrument Co., Bothell, WA). After the warm-up, subjects were given a brief rest period to stretch the appropriate muscle groups.

During the maximal treadmill test, expired gases were collected and analyzed to calculate ventilation, oxygen consumption, and carbon dioxide production using a ParvoMedics TrueMax 2400 Metabolic Measurement System (Consentius Technologies, Sandy, UT) (9). A mouthpiece was attached to a Hans Rudolph (Kansas City, MO) two-way non-rebreathing valve (2700 series, large). The non-rebreathing valve was attached to two tubes: one for inspired and one for expired air. The Hans Rudolph 3813 heated pneumotachometer (Kansas City, MO) was calibrated before each use with a 3.00 L syringe and the gas analyzers were calibrated against concentrations of known gases previously analyzed using the Scholander technique (85). The metabolic cart was configured to compute $\dot{V}O_2$, respiratory exchange ratio (RER), and heart rate every 30 seconds. A speed was selected that elicited a heart rate that was approximately equal to 70-80% of his/her age-predicted maximal heart rate. This speed remained constant throughout the test. The test protocol began with the subject running at the predetermined speed and a grade of 0%. The grade was increased 1% every minute until the subject signaled that he/she could not continue. Subjects were verbally encouraged to continue throughout the test. At the end of each minute, the subject's rating of perceived exertion was recorded. After volitional exhaustion was signaled, the subject continued walking on the treadmill for three minutes at a comfortable pace. After three minutes, a

100 μl blood sample was obtained from the subject's fingertip, using a sterile lancet to break the skin. This sample was analyzed for lactate content using the YSI-2300 STAT Plus automated blood analysis machine (Yellow Springs Instrumentation Company, Inc., Yellow Springs, OH). Maximal oxygen uptake was defined as the highest oxygen uptake attained and was further validated using additional criteria (RER ≥ 1.10, post-test lactate $> 8.0\ \text{mmol} \cdot \text{L}^{-1}$, and maximal heart rate within ten $\text{beats} \cdot \text{min}^{-1}$ of the age predicted max).

FitSense Calibration on the Treadmill

The FitSense was calibrated to each individual according to the manufacturer's instructions for treadmill calibration before beginning testing (28). Subjects were instructed to warm-up and stretch before beginning the calibration procedure. The calibration procedure consisted of treadmill walking at 3.5 $\text{miles} \cdot \text{hr}^{-1}$ ($5.6\ \text{km} \cdot \text{hr}^{-1}$) and running at 6.5 $\text{miles} \cdot \text{hr}^{-1}$ ($10.5\ \text{km} \cdot \text{hr}^{-1}$) with the foot pod attached to the subject's right shoe as previously described. All subjects were experienced and comfortable with treadmill exercise and were given 2-3 minutes to become accustomed to the speed before the walking and the running calibration began. After the 2-3 minute period, the calibration process was started on the watch. After 30-60 seconds, the watch beeped signaling that the calibration process was completed. Following the completion of both the walking and running calibrations, the CalVals determined by the FitSense were recorded.

Treadmill Speed Test

Each subject exercised for six 5-minute stages, for a total of 30 minutes, with progressive increases in intensity at each stage. The first three stages were at walking speeds of 3.0, 4.0, and 5.0 $\text{miles} \cdot \text{hr}^{-1}$ (4.8, 6.4, and 8.0 $\text{km} \cdot \text{hr}^{-1}$) followed by three stages at running speeds of 5.0, 6.0, and 7.0 $\text{miles} \cdot \text{hr}^{-1}$ (8.0, 9.6, and 11.2 $\text{km} \cdot \text{hr}^{-1}$). The treadmill grade was set at 0.0% for each stage. The speed estimated by the FitSense was compared to the speed measured by a Shimpo DT-107 handheld digital tachometer (Nidec-Shimpo America Corp., Itasca, IL). The tachometer operates by placing the attached wheel against the belt of the treadmill while the belt is moving. The measured speed by the tachometer and the estimated speed by the FitSense were recorded at the mid-point of each minute and averaged for the entire 5-minute stage to get an average speed measured by both methods.

During this experiment, the FitSense was also evaluated for its accuracy for estimating energy expenditure. Energy expenditure was measured using the aforementioned metabolic testing procedures. The subjects were allowed three minutes of each stage to reach steady state before measurements were recorded. Oxygen uptake ($\dot{V}O_2$) and carbon dioxide expired ($\dot{V}CO_2$) were recorded each minute and were averaged for minutes four and five of each stage. Energy expenditure was recorded by the FitSense for minutes four and five of each stage, after which the watch was reset for the next measurement period. Energy expenditure from the metabolic cart was determined by using the Weir equation (110). In order to determine net energy expenditure of the exercise bout, resting metabolic rate was estimated based on gender, height, weight, and age using the revised Harris-Benedict equations (77). Net energy expenditure was calculated by subtracting resting energy expenditure from the measured gross energy expenditure.

The treadmill was calibrated according to manufacturer's instructions for speed (by measuring belt length and determining the time needed for 20 revolutions at several speeds) and grade (by using a carpenter's level and a carpenter's square to measure the rise-over-run at several grades) before, periodically during, and after the completion of all test sessions. The calibrations were further verified with the digital tachometer. The tachometer was calibrated to an accuracy of ± 0.1 RPM by the manufacturer according to standards set by the National Institute of Standards and Technology (NIST) (calibration certificate #K202023).

Experiment III: Accuracy of the FitSense for estimating energy expenditure at varying grades

The accuracy of the FitSense for estimating energy expenditure was also determined while walking at 3.0 $\text{miles} \cdot \text{hr}^{-1}$ at different grades. The FitSense was calibrated using the previously described treadmill calibration procedures prior to beginning testing.

Treadmill Grade Test

The treadmill grade test consisted of treadmill walking at 3.0 $\text{miles} \cdot \text{hr}^{-1}$ (4.8 $\text{km} \cdot \text{hr}^{-1}$) with a progressive increase in grade. The test consisted of five 5-minutes stages with increasing grades of 0.0, 2.5, 5.0, 7.5, and 10.0%. Testing was completed using the procedures for energy expenditure described in Experiment II.

Statistical Analysis

In general, repeated measures ANOVA showed no gender differences in distance, speed or energy expenditure. Thus, statistics were run on males and females as a combined group.

In Experiment I of this study, the distances estimated by the FitSense for the two walking tests were averaged and the distances estimated by the FitSense for the two running tests were averaged for each subject to give an *average walking distance* and an *average running distance*. One-sample t-tests (2-tailed) were used to compare the estimated walking distance to the actual distance and the estimated running distance to the actual distance. The overall significance level was set at $\alpha = 0.05$.

In Experiment II, the difference scores were used in a 2 × 3 repeated measures ANOVA to compare the differences between the two methods for measuring speed and energy expenditure during each mode of exercise (walking and running). When appropriate, post-hoc testing was performed using pairwise comparisons with the Bonferroni adjustment to locate significant differences. Paired t-tests were used to compare the within-stage differences by comparing the measured and the estimated values for speed and energy expenditure using the Bonferroni adjustment factor. Correlations were also performed to determine the relationship between measured and estimated values for energy expenditure.

In Experiment III, the difference scores were used in a 2 × 5 repeated measures ANOVA to compare the differences between the two methods for measuring energy expenditure while walking with an increasing grade. When appropriate, post-hoc testing was performed using pairwise comparisons with the Bonferroni adjustment to locate significant differences. Paired t-tests were used to compare the within-stage differences by comparing the measured and the estimated values for energy expenditure using the Bonferroni adjustment factor. Correlations were also performed to determine the relationship between measured and estimated values for energy expenditure.

CHAPTER IV

RESULTS

The purpose of this study was to examine the accuracy of the FitSense FS-1 Speedometer for estimating distance, speed, and energy expenditure while walking and running.

Experiment I: Accuracy of the FitSense for estimating distance during 1600 m track tests

The subjects' physical characteristics for Experiment I are shown in Table 1. Each subject completed two, 1600 m walks and two, 1600 m runs. The average walking distance and the average running distance were computed for each subject. The mean distance estimated by the FitSense while walking was 1575 ± 100 m. The mean distance estimated by the FitSense while running was 1543 ± 107 m. The measured average speed

TABLE 1 – Subject Characteristics (Experiment I)

	Males (N = 15)	**Females (N = 9)**	**Total (N = 24)**
Age (yr)	28.1 ± 5.9 (20-42)	25.8 ± 5.5 (20-39)	27.2 ± 5.7 (20-42)
Height (cm)	181.4 ± 4.0 (174-190)	164.1 ± 5.0 (158-172)	174.9 ± 9.6 (158-190)
Mass (kg)	76.6 ± 7.7 (63.0-88.9)	59.1 ± 3.2 (51.7-61.9)	70.0 ± 10.7 (51.7-88.9)
BMI[1] ($kg \cdot m^{-2}$)	23.2 ± 2.1 (19.3-26.8)	22.0 ± 0.9 (20.8-23.1)	22.8 ± 1.8 (19.3-26.8)

Values are mean ± SD (range)

[1] Body Mass Index

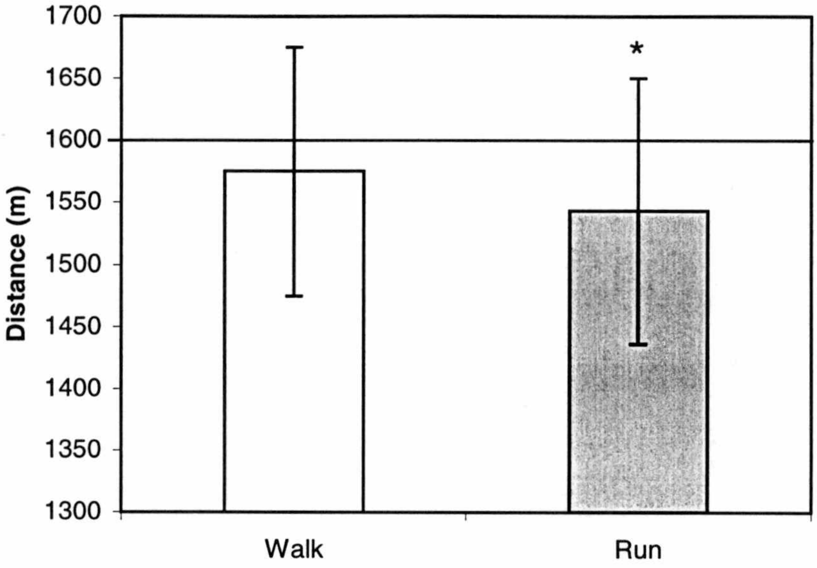

Figure 3 – Mean distances for 1600 m walk and run tests (mean ± SD)
*** Significant difference between actual distance and estimated distance ($p < 0.05$).**

was 4.18 ± 0.45 miles·hr^{-1} (6.73 ± 0.72 km·hr^{-1}) for the walk tests and 8.18 ± 1.33 miles·hr^{-1} (13.16 ± 2.14 km·hr^{-1}) for the run tests. Figure 3 shows the mean walking and running distance for all subjects. For the walk tests, the mean distance estimated by the FitSense was not significantly different than the measured distance ($p = 0.230$). The FitSense was found to significantly underestimate distance while running ($p = 0.016$).

For the entire pool of 1600 m tests (96 tests), the mean distance estimated by the FitSense while walking or running was 1559 ± 108 m.

TABLE 2 – Subject Characteristics (Experiments II & III)

	Males (N = 7)	Females (N = 5)	Total (N = 12)
Age (yr)	29.4 ± 4.7	27.0 ± 7.1	28.4 ± 5.6
	(25-38)	(21-39)	(21-39)
Height (cm)	180.9 ± 3.6	165.9 ± 4.0	174.7 ± 8.5
	(174-185)	(161-172)	(161-185)
Mass (kg)	75.6 ± 6.5	60.8 ± 1.3	69.5 ± 9.0
	(65.8-86.4)	(59.4-61.9)	(59.4-86.4)
BMI[1] ($kg \cdot m^{-2}$)	23.1 ± 1.5	22.1 ± 0.8	22.7 ± 1.3
	(21.7-25.9)	(21.0-23.1)	(21.0 25.9)
% Body Fat	15.1 ± 5.6	23.5 ± 4.8	18.6 ± 6.6
	(6.2-23.5)	(16.6-30.0)	(6.2-30.0)
$\dot{V}O_2$ max ($ml \cdot kg^{-1} \cdot min^{-1}$)	57.1 ± 4.4	51.4 ± 4.9	54.7 ± 5.3
	(48.3-62.9)	(46.6-58.9)	(46.6-62.9)
Est. RMR[2] ($kcal \cdot hr^{-1}$)	75.1 ± 5.0	58.6 ± 1.9	68.2 ± 9.3
	(66.2-82.5)	(55.7-60.4)	(55.7-82.5)

Values are mean ± SD (range)

[1] Body Mass Index

[2] Estimated Resting Metabolic Rate

Experiment II: Accuracy of the FitSense for estimating speed and energy expenditure at varying treadmill speeds

The subjects' physical characteristics for Experiments II and III are shown in Table 2. The measured and estimated speeds for each stage are shown in Table 3. A repeated measures ANOVA was run on the differences between the tachometer and the FitSense for measuring speed while walking and while running. For the between-stage differences, repeated measures ANOVA demonstrated a significant difference ($p < 0.001$) for the walking speeds, meaning that the FitSense estimates for walking speed were not consistent at each speed. Post-hoc analysis revealed no significant stage differences between the 4.8 and 6.4 $km \cdot hr^{-1}$ walking speeds ($p = 0.246$). Significant stage differences were found between the 4.8 and 8.0 $km \cdot hr^{-1}$ walking speeds ($p < 0.001$) and the 6.4 and 8.0 $km \cdot hr^{-1}$ walking speeds ($p < 0.001$). For the within-stage differences,

TABLE 3 – Comparison of Measured Speed with Estimated Speed

TM Speed ($\mathrm{km \cdot hr^{-1}}$)	Tach Speed ($\mathrm{km \cdot hr^{-1}}$)	FitSense Speed ($\mathrm{km \cdot hr^{-1}}$)	Δ Speed	Δ %
4.8	4.88 ± 0.08	5.09 ± 0.45	-0.21 ± 0.44	-4.36 ± 9.09
6.4	6.49 ± 0.02	6.54 ± 0.21	-0.05 ± 0.21	-0.79 ± 3.29
8.0	8.13 ± 0.02	10.19 ± 1.13	-2.06 ± 1.14	-25.32 ± 14.05 *
8.0	8.14 ± 0.02	8.99 ± 1.90	-0.85 ± 1.89	-10.39 ± 23.27
9.7	9.88 ± 0.05	9.92 ± 0.32	-0.04 ± 0.34	-0.39 ± 3.41
11.3	11.43 ± 0.05	11.36 ± 0.89	0.06 ± 0.92	0.54 ± 8.13

Values are mean ± SD; Δ Speed = measured speed – estimated speed; Δ % = [(measured speed – estimated speed)/measured speed] × 100; * Significant difference from zero ($p < 0.001$).

paired t-tests revealed no significant differences between mean measured and estimated speed for the 4.8 $\mathrm{km \cdot hr^{-1}}$ ($p = 0.122$) and the 6.4 $\mathrm{km \cdot hr^{-1}}$ ($p = 0.426$) walking speeds. A significant difference was found between the measured and estimated speeds for the 8.0 $\mathrm{km \cdot hr^{-1}}$ walking speed ($p < 0.001$). For the between-stage differences during the running stages, repeated measures ANOVA found no statistical differences ($p = 0.215$) for the running speeds. For the within-stage differences, paired t-tests revealed no statistical differences between the mean estimated and the measured running speeds. Figure 4 depicts the measured and the estimated values for speed.

The FitSense was compared to indirect calorimetry to determine the accuracy of the FitSense for estimating net energy expenditure. Energy expenditure was measured and estimated while walking and running on a level grade. A significant correlation ($r = 0.804$) between measured and estimated energy expenditure was demonstrated during walking and running at a 0.0% grade (Figure 5). Figure 6 shows the measured vs. estimated energy expenditure for each walking and running stage. A repeated measures ANOVA was run on the differences between the two methods. For the between-stage interactions, repeated measures ANOVA demonstrated a significant differences for

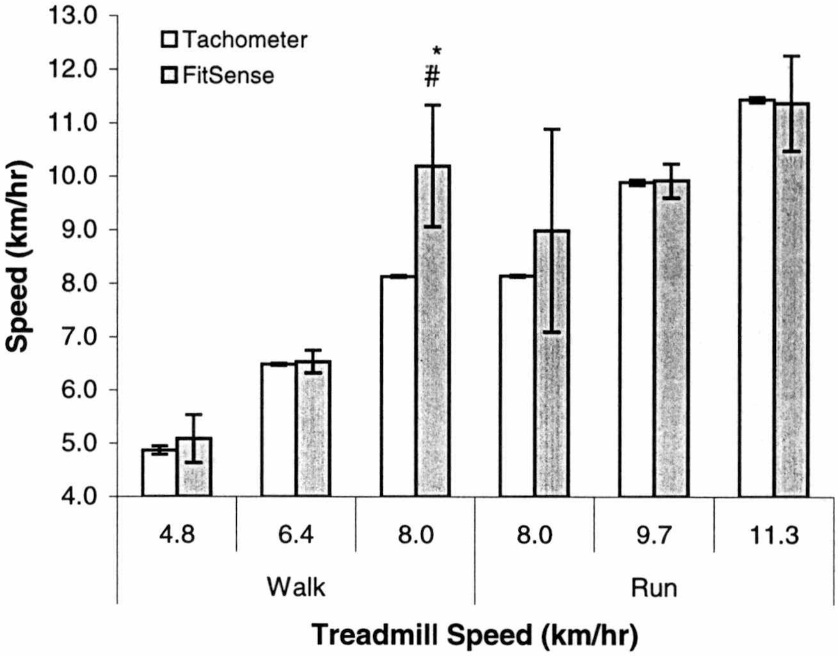

Figure 4 – Mean data for speed measured by the tachometer and estimated by the FitSense (mean ± SD). # Significant stage differences between 4.8 and 8.0 km/hr speeds and 6.4 and 8.0 km/hr speeds ($p < 0.001$); * Significant difference between measured and estimated speed ($p < 0.001$).

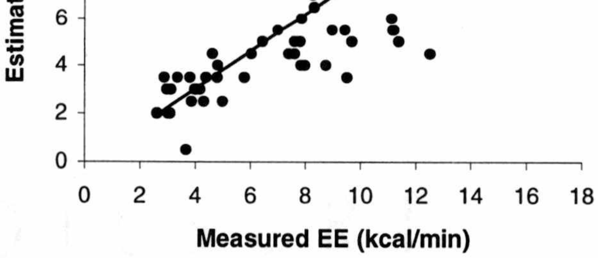

Figure 5 – Correlation between measured energy expenditure (indirect calorimetry) and estimated energy expenditure (FitSense) while walking and running at 0% grade.

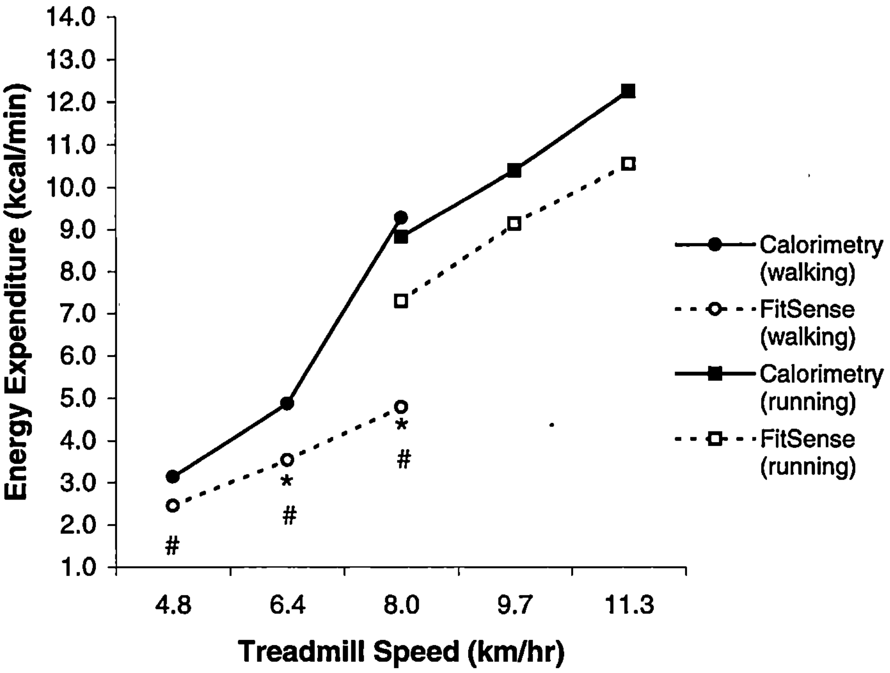

Figure 6 – Effects of treadmill speed on measured and estimated energy expenditure while walking and running; # Significant stage differences (p < 0.01) * Significant difference between measured and estimated energy expenditure (p < 0.001).

energy expenditure during the walking stages ($p < 0.001$), meaning that the differences between the measured and estimated energy expenditure were not consistent for each walking speed. Post-hoc analysis revealed significant differences between the 4.8 and 6.4 $km \cdot hr^{-1}$ ($p = 0.007$), the 6.4 and 8.0 $km \cdot hr^{-1}$ ($p < 0.001$), and the 4.8 and 8.0 $km \cdot hr^{-1}$ ($p < 0.001$) walking speeds. For the within-stage differences, paired t-tests using the Bonferroni adjustment factor revealed significant differences between measured and estimated energy expenditure during the 6.4 $km \cdot hr^{-1}$ ($p < 0.001$) and 8.0 $km \cdot hr^{-1}$ ($p < 0.001$) walking speeds. No significant difference was found between measured and estimated energy expenditure during the 4.8 $km \cdot hr^{-1}$ ($p = 0.031$) walking speed. For the between-stage interactions, repeated measures ANOVA demonstrated no significant differences for energy expenditure during the running stages ($p = 0.067$). For the within-stage differences, paired t-tests using the Bonferroni adjustment factor demonstrated no significant differences between measured vs. estimated energy expenditure for the 8.0 $\text{km}\cdot\text{hr}^{-1}$ ($p = 0.033$), 9.7 $\text{km}\cdot\text{hr}^{-1}$ ($p = 0.054$) and 11.3 $\text{km}\cdot\text{hr}^{-1}$ ($p = 0.040$) running speeds.

Experiment III: Accuracy of the FitSense for estimating energy expenditure at varying grades

The FitSense was also evaluated for estimating energy expenditure during walking with an increasing grade. The correlation between measured and estimated energy expenditure while walking with an increasing grade was not significant ($r = -0.104$) (Figure 7). For the between-stage differences, repeated measures ANOVA revealed a significant difference ($p < 0.001$) for estimating energy expenditure while walking with an increasing grade. Post-hoc analysis demonstrated significant stage differences between every grade ($p < 0.001$). For the within-stage differences, paired t-tests found significant differences between the measured and estimated energy expenditure values while walking at 0% ($p = 0.002$), 2.5% ($p < 0.001$), 5.0% ($p < 0.001$), 7.5% ($p < 0.001$), and 10.0% ($p < 0.001$) grade (Figure 8).

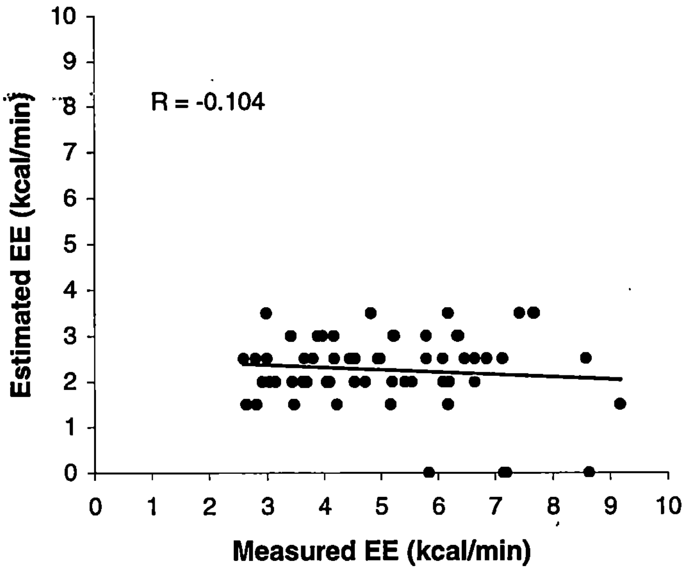

Figure 7 – Correlation between measured energy expenditure (indirect calorimetry) and estimated energy expenditure (FitSense) while walking with an increasing grade.

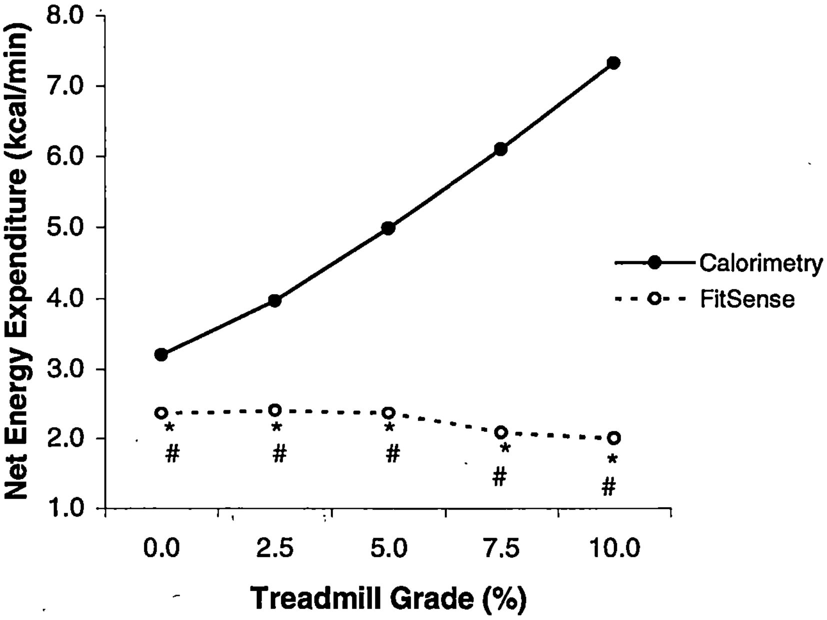

Figure 8 – Effects of treadmill grade on measured and estimated energy expenditure while walking at 4.8 km/hr; # Significant stage differences (p < 0.001); * Significant difference between measured and estimated energy expenditure (p < 0.01).

CHAPTER V

DISCUSSION

The results of this study indicate that the FitSense is fairly accurate for estimating distance while walking or running during repeated 1600 m track tests. There was no significant difference between the actual walking distance and that estimated by the FitSense. Although the FitSense was found to statistically underestimate distance while running, the difference only amounted to a 3.5% underestimation. The FitSense manufacturers state that the FitSense is 98% accurate for measuring distance while walking or running (28). For the entire pool of 1600 m walking and running tests (96 tests) from this study, the FitSense was 97.4% accurate for estimating distance.

Traditionally, distance while walking has been measured by the belt-mounted pedometer. A study by Bassett et al. (6) found that electronic pedometers are reasonably accurate for estimating distance walked. The mean values for all five pedometer brands tested recorded within 0.53 km for the 4.88 km course (11% difference), with the most accurate brand (Yamax) differing by 0.05 km for the 4.88 km course (1% difference) (6). The FitSense results for walking distance compare favorably to distance estimated by belt-mounted pedometers. The mean distance estimated by the FitSense differed by 25 m for the 1600 m walks (1.6% difference). There are a limited number of studies that have used pedometers to measure distance while running. Washburn et al. (108) found that pedometers tend to underestimate running distance by, on average, 11% during repeated

1-mile trail runs. The FitSense also underestimated distance during 1600 m runs, but the underestimation was only 3.5%. This is a large improvement in accuracy of estimating distance by the FitSense over the belt-mounted pedometer.

The FitSense manufacturers have developed an adjustment factor for inaccurate distance estimations. This adjustment factor is available on the FitSense website. The website's "CalVal Calculator" can calculate a new calibration value based on information provided by the user without having to recalibrate the accelerometer by the conventional method. The website calculates the new value based on the previous calibration value, the actual walking or running distance, and the provided under- or overestimated distance estimated by the FitSense. Although the FitSense developers claim that it is only necessary to calibrate the device once (28), it may be beneficial to recalibrate the device periodically and check for any substantial variations in the new CalVals.

This study's results indicate that the FitSense performs well for estimating speed while walking at 3.0 and 4.0 $\text{miles}\cdot\text{hr}^{-1}$ (4.8 and 6.4 $\text{km}\cdot\text{hr}^{-1}$) and while running at 6.0 and 7.0 $\text{miles}\cdot\text{hr}^{-1}$ (9.6 and 11.2 $\text{km}\cdot\text{hr}^{-1}$) (Figure 2). In contrast, the Caltrac activity counts do not increase at running speeds above 5.0 $\text{miles}\cdot\text{hr}^{-1}$ (37). Haymes and Byrnes (37) suggested that a device measuring acceleration in the horizontal plane could lead to improved accuracy. The FitSense, which measures acceleration in the horizontal plane, is accurate at estimating specific speeds, and it is able to detect changes in acceleration and stride length that occur with increases in speed (40, 118).

Studies using pedometers have demonstrated that pedometers are most accurate for estimating distance and steps during normal walking speeds (4.8 $\text{km}\cdot\text{hr}^{-1}$). Bassett et al. (6) found that pedometers tend to underestimate distance at very slow (3.2 $\mathrm{km \cdot hr^{-1}}$) and at very fast (6.4 $\mathrm{km \cdot hr^{-1}}$) walking speeds. Other studies also found that pedometers are inaccurate at running speeds (49, 80, 108). These inaccuracies are due to the fact that pedometers are preset for one stride length and this cannot be adjusted during exercise. Hogberg et al. (40) found that during running speeds between 9.0 and 19.0 $\mathrm{km \cdot hr^{-1}}$ (5.6 to 11.9 $\mathrm{miles \cdot hr^{-1}}$), runners increase their speed by increasing stride length with very little increases in stride frequency. Thus, pedometers would be expected to underestimate distance while running. The FitSense is an improvement over the pedometer for estimating distance in that it is able to detect changes in speed while walking and running.

The FitSense appeared to have trouble estimating speed during fast walking and slow running speeds (8.0 $\mathrm{km \cdot hr^{-1}}$). During this transition zone between walking and running, the FitSense tended to overestimate walking speed by an average of 25.3%. Although the FitSense's estimation of speed while running at 8.0 $\mathrm{km \cdot hr^{-1}}$ was not statistically different from the actual speed, the device tended to overestimate speed by 10.4%. There was a great deal of variability during this speed with average speeds ranging from 7.53 to 13.71 $\mathrm{km \cdot hr^{-1}}$ (4.68 to 8.52 $\mathrm{miles \cdot hr^{-1}}$). The FitSense is, in general, able to differentiate whether the user is walking or running by requiring separate calibrations for each mode of ambulation. However, during this study, the FitSense apparently had difficulty estimating speed during this transition zone of 8.0 $\mathrm{km \cdot hr^{-1}}$.

Prior to beginning each test, the FitSense was calibrated for each individual (calibration values can be seen in Appendix E). During our testing, subjects who participated in all three parts of the study repeated the calibration procedure on three different occasions (two treadmill calibrations and one track calibration). Table 4 lists the mean calibration values for each subject who participated in Parts I-III. The calibrations were all individualized, thus the mean values cannot be compared between individuals or between walking and running tests. The standard deviation of each individual's calibration values indicates the amount of variation between calibrations. The within-subject variability can differ from test to test, but FitSense developers state that the variability should not vary by more than 5 to 10 points, regardless of which calibration procedure is used (personal communication, 2001). Although the CalVals were consistent for most of our subjects, large amount of inter-subject variability was observed in the CalVals for a few subjects. For example, the large standard deviations for the walking CalVals in subjects 1 and 5 and in the running CalVals in subjects 2, 6, and 7 indicate a large amount of CalVal variability for these subjects. This variability

TABLE 4 – Within Subject Variability of Calibration Values (CalVals) on Three Different Occasions

Subject	Walking	Running
1	116.0 ± 19.9	80.7 ± 2.9
2	86.0 ± 3.5	87.0 ± 21.6
3	58.3 ± 1.2	42.0 ± 1.7
4	58.3 ± 4.0	74.7 ± 6.0
5	125.0 ± 41.6	50.3 ± 1.2
6	99.7 ± 10.7	111.0 ± 18.0
7	63.7 ± 6.5	83.0 ± 24.8
8	63.3 ± 2.5	49.7 ± 6.0
9	105.3 ± 3.2	83.0 ± 3.6
10	87.3 ± 3.1	98.7 ± 4.6
11	110.0 ± 5.6	81.3 ± 6.8
12	95.0 ± 6.6	105.3 ± 6.0

Values are mean ± SD

could be due to the differences in walking/running speed during the track calibration vs. the treadmill calibration. During the treadmill calibration, standardized walking and running speeds (3.5 and 6.5 $\text{miles} \cdot \text{hr}^{-1}$) were used (28). The track calibration does not require the subject to maintain any set speed, only to walk/run a set distance. For some of our subjects, the self-selected speeds during the track calibration were much greater than the standardized speeds used during the treadmill calibration.

The results of this study indicate that the FitSense underestimates energy expenditure while walking and running on a level grade (Figure 6). The FitSense was unable to detect the increases in energy expenditure that occur while walking up an increasing grade as shown in Figure 8.

Although the FitSense underestimated energy expenditure, it was able to detect the increased energy expenditure requirements that are associated with increases in walking speed (Figure 6). These findings are consistent with other studies using accelerometers (5, 30, 37, 43, 62, 66-68, 71, 98). Although the differences were not statistically different, the FitSense consistently underestimated energy expenditure during treadmill running with increasing speeds (Figure 6). While several studies have tested the accuracy of accelerometers for estimating energy expenditure while running, most of these studies are limited to one running speed (30, 43, 62, 67, 68). Only one other study was found that used an accelerometer to estimate energy expenditure during multiple running speeds. This study found that the Caltrac accelerometer is unable to detect increases in running speed over 8.0 $\text{km} \cdot \text{hr}^{-1}$ (37). The FitSense, however, is able to detect the increased energy expenditure demands that are associated with increases in running speed.

The limitations of the FitSense in estimating energy expenditure could be due to the original method and algorithm used by the FitSense engineers. The method used by the FitSense for estimating energy expenditure is based on the theory that the metabolic cost of locomotion is primarily determined by the cost of supporting total body weight and the rate at which force is generated (42, 53). This theory was developed by testing a number of animals during locomotion while simultaneously measuring oxygen consumption (53, 75). This theory was also tested in a group of men who during treadmill walking and running (42).

The results of this study indicate that the FitSense, which estimates energy expenditure by using the body weight divided by foot contact time formula, underestimates energy expenditure while walking or running. Most of the research on this method has focused on the energy cost of locomotion in a variety of animals. Although, theoretically, the mechanisms used for locomotion are similar in animals and humans, there are fundamental differences between humans and animals during locomotion. In the quadrupeds that Kram and Taylor tested, they reported that the stride length of each animal increased only slightly as speed increased (53). The increase in speed during locomotion at all speeds was due to increasing the frequency in strides rather than increasing the length of strides (53). In humans, increases in speed while running is due mainly to increases in stride length (vs. increases in stride frequency) (40, 118). The one study using this method that focused on humans showed a very strong correlation between actual energy expenditure and estimated energy expenditure (42). However, that study utilized a sensor circuit that was placed in the sole of the shoe and could directly measure the amount of time the foot was in contact with the ground. Although the FitSense cannot directly measure the foot contact time, it is possible to obtain a good estimation of foot contact time based on the acceleration and deceleration information. However, the use of a different method to estimate foot contact time could possibly lead to a larger percentage of error than in the study utilizing a foot pressure sensor.

There appear to be some limitations inherently designed into the FitSense. The results of our study indicated that energy expenditure estimated by the FitSense increases in a linear fashion while walking and running. While the actual energy expenditure increases linearly with running; during walking, the actual energy expenditure vs. speed relationship increases in a curvilinear fashion. Other studies have found similar results for energy expenditure while walking and running (27, 37, 106). In 25% of our subjects, the FitSense appeared to malfunction when the subject was walking at 7.5% grade or higher. The device did not register speed, distance, or energy expenditure for these subjects at higher grades. This appears to be related to the fact that the FitSense is mounted in a horizontal fashion to the shoe. The walking style of these subjects was such that at higher grades, the accelerometer was no longer moving in the horizontal plane and could not detect any movement. This could be a potential problem for a person who plans to use the FitSense while hiking or running on a hilly course.

It is worth noting that the battery life of our device was substantially less than reported by the manufacturer. The manufacturer reports a six-month battery life under "normal use (30 minutes per day)." The battery life of our FitSense averaged about 20 hours of exercise time (vs. ~90 hours reported by the manufacturer). The excessive battery drain problem has been addressed by FitSense engineers and should be corrected in future models.

Future Research

Future studies using FitSense FS-1 Speedometer may include testing of the accuracy of the FitSense for estimating speeds at the higher end of the FitSense's range (reported range of the FitSense is 2.5 – 20.0 $\text{miles}\cdot\text{hr}^{-1}$). Also, studies may focus on the test-retest reliability of the FitSense for estimating distance while walking and running. Other studies may focus on the FitSense's accuracy for estimating distance during longer walking and running tests.

Conclusions

The results of this study indicate that the FitSense is an accurate tool for estimating distance while walking and running. The FitSense is accurate at estimating speed while walking at 3.0 and 4.0 $\text{miles}\cdot\text{hr}^{-1}$ (4.8 and 6.4 $\text{km}\cdot\text{hr}^{-1}$) and while running at 6.0 and 7.0 $\text{miles}\cdot\text{hr}^{-1}$ (9.6 and 11.2 $\text{km}\cdot\text{hr}^{-1}$). However, the FitSense is inaccurate at estimating speed during walking and running 5.0 $\text{miles}\cdot\text{hr}^{-1}$ (8.0 $\text{km}\cdot\text{hr}^{-1}$). The FitSense underestimates energy expenditure while walking or running. Also, the

FitSense is unable to detect increases in energy expenditure due to increasing grade. Based on the results of this study, it is concluded that the FitSense FS-1 Speedometer is an accurate tool for estimating distance and speed during level walking and running.

REFERENCES

1. Ainsworth, B.E., H.J. Montoye, and A.S. Leon. Methods of assessing physical activity during leisure and work. In: *Physical Activity Fitness and Health*, C. Bonchard, R.J. Shepard, and T. Stephens (Eds.). Champaign, IL: Human Kinetics, 1994, pp 146-159.

2. Ballard, J.E., B.C. McKeown, H.M. Graham, and S.A. Zinkgraf. The effect of high level physical activity (8.5 METs or greater) and estrogen replacement therapy upon bone mass in postmenopausal females, aged 50-68 years. *Int. J. Sports Med.* 11(3): 208-214, 1990.

3. Ballor, D.L., L.M. Burke, D.V. Knudson, J.R. Olson, and H.J. Montoye. Comparison of three methods of estimating energy expenditure: Caltrac, heart rate, and video analysis. *Res. Q. Exerc. Sport.* 60(4): 362-368, 1989.

4. Balogun, J.A., N.T. Farina, E. Fay, K. Rossmann, and L. Pozyc. Energy cost determination using a portable accelerometer. *Phys. Ther.* 66(7): 1102-1109, 1986.

5. Balogun, J.A., D.A. Martin, and M.A. Clendenin. Calorimetric validation of the Caltrac accelerometer during level walking. *Phys. Ther.* 69(6): 501-509, 1989.

6. Bassett, D.R., Jr., B.E. Ainsworth, S.R. Leggett, et al. Accuracy of five electronic pedometers for measuring distance walked. *Med. Sci. Sports Exerc.* 28(8): 1071-1077, 1996.

7. Bassett, D.R., Jr. Validity and reliability issues in objective monitoring of physical activity. *Res. Q. Exerc. Sports.* 71(2): 30-36, 2000.

8. Bassett, D.R., Jr., A.L. Cureton, and B.E. Ainsworth. Measurement of daily walking distance-questionnaire versus pedometer. *Med. Sci. Sports Exerc.* 32(5): 1018-1023, 2000.

9. Bassett, D.R., Jr., E.T. Howley, D.L. Thompson, et al. Validity of inspiratory and expiratory methods of measuring gas exchange with a computerized metabolic system. *J. Appl. Physiol.*, (In press).

10. Bassey, E.J., H.M. Dallosso, P.H. Fentem, J.M. Irving, and J.M. Patrick. Validation of a simple mechanical accelerometer (pedometer) for the estimation of walking activity. *Eur. J. Appl. Physiol.* 56(3): 323-330, 1987.

11. Blair, S.N., N.N. Goodyear, L.W. Gibbons, and K.H. Cooper. Physical fitness and incidence of hypertension in healthy normotensive men and women. *JAMA.* 252(4): 487-490, 1984.

12. Bouten, C.V.C., W.P.H.G. Verboeket-Van de Venne, K.R. Westerterp, M. Verduin, and J.D. Janssen. Daily physical activity assessment: comparison between movement registration and doubly labeled water. *J. Appl. Physiol.* 81(2): 1019-1026, 1996.

13. Bray, M.S., J.R. Morrow, Jr., J.M. Pivarnik, and J.T. Bricker. Caltrac validity for estimating caloric expenditure with children. *Ped. Exerc. Sci.* 4: 166-179, 1992.

14. Bray, M.S., W.W. Wong, J.R. Morrow, Jr., N.F. Butte, and J.M. Pivarnik. Caltrac versus calorimeter determination of 24-h energy expenditure in female children and adolescents. *Med. Sci. Sports Exerc.* 26(12): 1524-1530, 1994.

15. Caspersen, C.J., K.E. Powell, and G.M. Christenson. Physical activity, exercise, and physical fitness: definitions and distinctions for health related research. *Public Health Rep.* 100: 126-130, 1985.

16. Ceesay, S.M., A.M. Prentice, K.C. Day, P.R. Murgatroyd, G.R. Goldberg, and W. Scott. The use of heart rate monitoring in the estimation of energy expenditure: a validation study using indirect whole-body calorimetry. *Br. J. Nutr.* 61: 175-186, 1989.

17. Chen, K.Y. and M. Sun. Improving energy expenditure estimation by using a triaxial accelerometer. *J. Appl. Physiol.* 83(6): 2112-2122, 1997.

18. Coleman, K.J., B.E. Saelens, M.D. Wiedrich-Smith, J.D. Finn, and L.H. Epstein. Relationships between Tritrac-R3D vectors, heart rate, and self-report in obese children. *Med. Sci Sports Exerc.* 29(11): 1535-1542, 1997.

19. Coleman, K.L., D.G. Smith, D.A. Boone, A.W. Joseph, and M.A. del Aguila. Step activity monitor: Long-term, continuous recording of ambulatory function. *J. Rehab. Res. Develop.* 36(1): 8-19, 1999.

20. Crespo, C.J., S.J. Keteyian, G.W. Heath, and C.T. Sempos. Leisure-time physical activity among US adults: results from the Third National Health and Nutrition Examination Survey. *Arch. Intern. Med.* 156: 93-98, 1996.

21. Davidson, L., G. McNeill, P. Haggarty, J.S. Smith, and M.F. Franklin. Free-living energy expenditure of adult men assessed by continuous heart-rate monitoring and doubly-labeled water. *Br. J. Nutr.* 78: 695-708, 1997.

22. Dipietro, L. Physical activity, body weight, and adiposity: an epidemiologic perspective. *Exerc. Sport Sci. Rev.* 23: 275-303, 1995.

23. Emons, H.J.G., D.C. Groenenboom, K.R. Westerterp, and W.H.M. Saris. Comparison of heart rate monitoring combined with indirect calorimetry and the doubly labeled water ($^2H_2$ ^{18}O) method for the measurement of energy expenditure in children. *Eur. J. Appl. Physiol.* 65: 99-103, 1992.

24. Epstein, L.H., R.A. Paluch, K.J. Coleman, D. Vito, and K. Anderson. Determinants of physical activity in obese children assessed by accelerometer and self-report. *Med. Sci. Sports Exerc.* 28(9): 1157-1164, 1996.

25. Eston, R.G., A.V. Rowlands, and D.K. Ingledew. Validity of heart rate, pedometry, and accelerometry for predicting the energy cost of children's activities. *J. Appl. Physiol.* 84(1): 362-371, 1998.

26. Fehling, P.C., D.L. Smith, S.E. Warner, and G.P. Dalsky. Comparison of accelerometers with oxygen consumption in older adults during exercise. *Med. Sci. Sports Exerc.* 31(1): 171-175, 1999.

27. Fellingham, G.W., E.S. Roundy, A.G. Fisher, and G.R. Bryce. Caloric cost of walking and running. *Med. Sci. Sports.* 10(2): 132-136, 1978.

28. FitSense. *FitSense FS-1 Speedometer Athlete's Manual.* Wellesley Hills, MA: FitSense, 2000.

29. Freedson, P.S., and S. Evenson. Familial aggregation in physical activity. *Res. Q. Exerc. Sport.* 62(4): 384-389, 1991.

30. Freedson, P.S., E. Melanson, and J. Sirard. Calibration of the Computer Science and Applications, Inc. accelerometer. *Med. Sci. Sports Exerc.* 30(5): 777-781, 1998.

31. Freedson, P.S., and K. Miller. Objective monitoring of physical activity using motion sensors and heart rate. *Res. Q. Exerc. Sports.* 71(2): 21-29, 2000.

32. Gayle, R., H.J. Montoye, and J. Philpot. Accuracy of pedometers for measuring distance walked. *Res. Q.* 48(3): 632-636, 1977.

33. Godsen, R., T. Carroll, and S. Stone. How well does the Polar Vantage XL heart rate monitor estimate actual heart rate? *Med. Sci. Sports Exerc.* Suppl 23(4): 14, 1991.

34. Going, S. Densitometry. In: *Human Body Composition,* A.F. Roche, S.B. Heymsfield, T.G. Lohman, (Eds.). Champaign, IL: Human Kinetics, 1996, pp. 3-23.

35. Groves, D. Beyond the pedometer: new tools for monitoring activity. *Physician Sportsmed.* 16(6): 160-166, 1988.

36. Hatano, Y. Use of the pedometer for promoting daily walking exercise. *Int. Council Health Phys. Educ. Recreat.* 29: 4-8, 1993.

37. Haymes, E.M., and W.C. Byrnes. Walking and running energy expenditure estimated by Caltrac and indirect calorimetry. *Med. Sci. Sports Exerc.* 25(12): 1365-1369, 1993.

38. Helmrich, S.P., D.R. Ragland, R.W. Leung, and R.S. Paffenbarger, Jr. Physical activity and reduced occurrence of non-insulin-dependent diabetes mellitus. *N. Engl. J. Med.* 325(3): 147-152, 1991.

39. Hendelman, D., K. Miller, C. Bagget, E. Debold, and P. Freedson. Validity of accelerometry for the assessment of moderate intensity physical activity in the field. *Med. Sci. Sports Exerc.* 32 Suppl: S442-S449, 2000.

40. Hogberg, P. Length of stride, stride frequency, "flight" period and maximum distance between the feet during running with different speeds. *Arbeitsphysiologie* 14: 431-436, 1952.

41. Hoodless, D.J., K. Stainer, N. Savic, P. Batin, M. Hawkins, and A.J. Cowley. Reduced customary activity in chronic heart failure: assessment with a new shoe-mounted pedometer. *Int. J. Cardiol.* 43(1): 39-42, 1994.

42. Hoyt, R.W., J.J. Knapik, J.F. Lanza, B.H. Jones, and J.S. Staab. Ambulatory foot contact monitor to estimate metabolic cost of human locomotion. *J. Appl. Physiol.* 76(4): 1818-1822, 1994.

43. Jakicic, J.M., C. Winters, K. Lagally, J. Ho, R.J. Robertson, and R.R. Wing. The accuracy of the TriTrac-R3D accelerometer to estimate energy expenditure. *Med. Sci. Sports Exerc.* 31(5): 747-754, 1999.

44. Janz, K.F. Validation of the CSA accelerometer for assessing children's physical activity. *Med. Sci. Sports Exerc.* 26(3): 369-375, 1994.

45. Janz, K.F., J. Witt, and L.T. Mahoney. The stability of children's physical activity as measured by accelerometry and self-report. *Med. Sci. Sports Exerc.* 27(9): 1326-1332, 1995.

46. Johnson, R.K., J. Russ, and M.I. Goran. Physical activity related energy expenditure in children by doubly labeled water as compared with the Caltrac accelerometer. *Int. J. Obes. Relat. Metab. Disord.* 22(11): 1046-1052, 1998.

47. Karvonen, J., J. Chwalbinska-Moneta, and S. Saynajakangas. Comparison of heart rates measured by ECG and microcomputer. *Physician Sportsmed.* 12(6): 65-69, 1984.

48. Katzel, L.I., E.R. Bleecker, E.G. Coleman, E.M. Rogus, J.D. Sorkin, and A.P. Goldberg. Effects of weight loss vs. aerobic exercise training on risk factors for coronary disease in healthy, obese, middle-aged and older men. *JAMA.* 274(24): 1915-1921, 1995.

49. Kemper, H.C.G., and R. Verschuur. Validity and reliability of pedometers in habitual activity research. *Eur. J. Appl. Physiol.* 37(1): 71-82, 1977.

50. Kilanowski, C.K., A.R. Consalvi, and L.H. Epstein. Validation of an Electronic Pedometer for Measurement of Physical Activity in Children. *Ped. Exer. Sci.* 11: 63-68, 1999.

51. Klesges, R.C., L.M. Klesges, A.M. Swenson, and A.M. Pheley. A validation of two motion sensors in the prediction of child and adult physical activity levels. *Am. J. Epidemiol.* 122(3): 400-410, 1985.

52. Kochersberger, G., E. McConnell, M.N. Kuchibhatla, and C. Pieper. The reliability, validity, and stability of a measure of physical activity in the elderly. *Arch. Phys. Med. Rehabil.* 77(8): 793-795, 1996.

53. Kram, R., and C.R. Taylor. Energetics of running: a new perspective. *Nature.* 346: 265-267, 1990.

54. LaPorte, R.E., H.J. Montoye, and C.J. Caspersen. Assessment of physical activity in epidemiologic research: problems and prospects. *Public Health Rep.* 100(2): 131-146, 1985.

55. Léger, L., and M. Thivierge. Heart rate monitors: validity, stability, and functionality. *Physician Sportsmed.* 16(5): 143-151, 1988.

56. Leon, A.S., J. Connett, D.R. Jacobs, Jr., and R. Rauramaa. Leisure-time physical activity levels and risk of coronary heart disease and death. *JAMA.* 258(17): 2388-2395, 1987.

57. Livingstone, M.B.E., A.M. Prentice, W.A. Coward, et al. Simultaneous measurement of free-living energy expenditure by the doubly labeled water method and heart-rate monitoring. *Am. J. Clin. Nutr.* 52: 59-65, 1990.

58. Manson, J.E., E.B. Rimm, M.J. Stampfer, et al. Physical activity and incidence of non-insulin-dependent diabetes mellitus in women. *Lancet.* 338: 774-778, 1991.

59. Matthews, C.E., and P.S. Freedson. Field trial of a three-dimensional activity monitor: comparison with self report. *Med. Sci. Sports Exerc.* 27(7): 1071-1078, 1995.

60. McCrory, M.A., T.D. Gomez, E.M. Bernauer, and P.A. Molé. Evaluation of a new air displacement plethysmograph for measuring human body composition. *Med. Sci. Sports Exerc.* 27(12): 1686-1691, 1995.

61. McMurray, R.G., J.S. Harrell, C.B. Bradley, J.P. Webb, and E.M. Goodman. Comparison of a computerized physical activity recall with a triaxial motion sensor in middle-school youth. *Med. Sci. Sports Exerc.* 30(8): 1238-1245, 1998.

62. Melanson, E.L., Jr. and P.S. Freedson. Validity of the Computer Science and Application, Inc. (CSA) activity monitor. *Med. Sci. Sports Exerc.* 27(6): 934-940, 1995.

63. Miller, D.J., P.S. Freedson, and G.M. Kline. Comparison of activity levels using the Caltrac accelerometer and five questionnaires. *Med. Sci. Sports Exerc.* 26(3): 376-382, 1994.

64. Montoye, H.J., R. Washburn, S. Servais, A. Ertl, J.G. Webster, and F.J. Nagle. Estimation of energy expenditure by a portable accelerometer. *Med. Sci. Sports Exerc.* 15(5): 403-407, 1983.

65. Montoye, H.J., H.C.G. Kemper, W.M. Saris, and R.A. Washburn. *Measuring Physical Activity and Energy Expenditure.* Champaign, IL: Human Kinetics, 1995.

66. Nichols, J.F., P. Patterson, and T. Early. A validation of a physical activity monitor for young and older adults. *Can. J. Sport Sci.* 17(4): 299-303, 1992.

67. Nichols, J.F., C.G. Morgan, J.A. Sarkin, J.F. Sallis, and K.J. Calfas. Validity, reliability, and calibration of the Tritrac accelerometer as a measure of physical activity. *Med. Sci. Sports Exerc.* 31(6): 908-912, 1999.

68. Nichols, J.F., C.G. Morgan, L.E. Chabot, J.F. Sallis, and K.J. Calfas. Assessment of physical activity with the Computer Science and Applications, Inc., accelerometer: laboratory versus field validation. *Res. Q. Exerc. Sport.* 71(1): 36-43, 2000.

69. Paffenbarger, R.S., Jr., A.L. Wing, and R. Robertson. Physical activity as an index of heart attack risk in college alumni. *Am. J. Epidemiol.* 108: 161-165, 1978.

70. Paffenbarger, R.S., Jr., R.T. Hyde, A.L. Wing, and C.H. Steinmetz. A natural history of athleticism and cardiovascular health. *JAMA.* 252(4): 491-495, 1984.

71. Pambianco, G., R.R. Wing, and R. Robertson. Accuracy and reliability of the Caltrac accelerometer for estimating energy expenditure. *Med. Sci. Sports Exerc.* 22(6): 858-862, 1990.

72. Panter-Brick, C., A. Todd, R. Baker, and C. Worthman. Comparative study of flex heart rate in three samples of Nepali boys. *Am. J. Hum. Biol.* 8: 653-660, 1996.

73. Pate, R.R., M. Pratt, S.N. Blair, 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.* 273: 402-407, 1995.

74. Richardson, M.T., A.S. Leon, D.R. Jacobs, Jr., B.E. Ainsworth, and R. Serfass. Ability of the Caltrac accelerometer to assess daily physical activity levels. *J. Cardiopulm. Rehabil.* 15(2): 107-113, 1995.

75. Roberts, T.J., R. Kram, P.G. Weyand, and C.R. Taylor. Energetics of bipedal running : I. metabolic cost of generating force. *J. Exp. Biol.* 201: 2745-2751, 1998.

76. Rowlands, A.V., R.G. Easton, and D.K. Ingledew. Measurement of physical activity in children with particular reference to the use of heart rate and pedometry. *Sports Med.* 24(4): 258-272, 1997.

77. Roza, A.M. and H.M. Shizgal. The Harris Benedict equation reevaluated: resting energy requirements and the body mass cell. *Am. J. Clin. Nutr.* 40: 168-182, 1984.

78. Rutter, S. Comparison of energy expenditure in normal-weight and overweight women using the Caltrac personal activity computer. *Int. J. Eat. Disord.* 15(1): 37-42, 1994.

79. Sallis, J.F., M.J. Buono, J.J. Roby, D. Carlson, and J.A. Nelson. The Caltrac accelerometer as a physical activity monitor for school-age children. *Med. Sci. Sports Exerc.* 22(5): 698-703, 1990.

80. Saris, W.H.M. and R.A. Binkhorst. The use of pedometer and actometer in studying daily physical activity in man. Part I: reliability of pedometer and actometer. *Eur. J. Appl. Physiol.* 37(3): 219-228, 1977.

81. Saris, W.H.M. and R.A. Binkhorst. The use of pedometer and actometer in studying daily physical activity in man. Part II: validity of pedometer and actometer measuring the daily physical activity. *Eur. J. Appl. Physiol.* 37(3): 229-235, 1977.

82. Schoeller, D.A. and E. van Santen. Measurement of energy expenditure in humans by doubly labeled water method. *J. Appl. Physiol.* 53: 955-959, 1982.

83. Schoeller, D.A. Energy expenditure from doubly labeled water: some fundamental considerations in humans. *Am. J. Clin. Nutr.* 38: 999-1005, 1983.

84. Schoeller, D.A. and P. Webb. Five day comparison of the doubly labeled water method with respiratory gas exchange. *Am. J. Clin. Nutr.* 40: 153-158, 1984.

85. Scholander, P. Analyzer for accurate estimation of respiratory gases in one-half cubic centimeter samples. *J. Biol. Chem.* 167: 235-250, 1947.

86. Schönhofer, B., P. Ardes, M. Geibel, D. Köhler, and P.W. Jones. Evaluation of a movement detector to measure daily activity in patients with chronic lung disease. *Eur. Respir. J.* 10(12): 2814-2819, 1997.

87. Schulz, S., K.R. Westerterp, and K. Brück. Comparison of energy expenditure by the doubly labeled water technique with energy intake, heart rate, and activity recording in man. *Am. J. Clin. Nutr.* 49: 1146-1154, 1989.

88. Seale, J.L., W.V. Rumpler, J.M. Conway, and C.W. Miles. Comparison of doubly labeled water, intake-balance and direct- and indirect-calorimetry methods for measuring energy expenditure in adult men. *Am. J. Clin. Nutr.* 52: 66-71, 1990.

89. Seaward, B.L., R.H. Sleamaker, T. McAuliffe, and J.F. Clapp. The precision and accuracy of a portable heart rate monitor. *Biomed. Instrum. Technol.* 24(1): 37-41, 1990.

90. Sequeira, M.M., M. Rickenbach, V. Wietlisbach, B. Tullen, and Y. Schutz. Physical activity assessment using a pedometer and its comparison with a questionnaire in a large population survey. *Am. J. Epidemiol.* 142(9): 989-999, 1995.

91. Servais, S.B., J.G. Webster, and H.J. Montoye. Estimating human energy expenditure using an accelerometer device. *J. Clin. Eng.* 9: 159-173, 1984.

92. Severson, R.K., A.M.Y. Nomura, J.S. Grove, and G.N. Stemmermann. A prospective analysis of physical activity and cancer. *Am. J. Epidemiol.* 130(3): 522-529, 1989.

93. Shepherd, E.F., E. Toloza, C.D. McClung, and T.P. Schmalzried. Step activity monitor: increased accuracy in quantifying ambulatory activity. *J. Orthop. Res.* 17(5): 703-708, 1999.

94. Sherman, W.M., D.M. Morris, T.E. Kirby, et al. Evaluation of a commercial accelerometer (Tritrac-R3 D) to measure energy expenditure during ambulation. *Int. J. Sports Med.* 19(1): 43-47, 1998.

95. Spurr, G.B., A.M. Prentice, P.R. Murgatroyd, G.R. Goldberg, J.C. Reina, and N.T. Christman. Energy expenditure from minute-by-minute heart-rate recording: comparison with indirect calorimetry. *Am. J. Clin. Nutr.* 48: 552-559, 1988.

96. Starling, R.D., D.E. Matthews, P.A. Ades, and E.T. Poehlman. Assessment of physical activity in older individuals: a doubly labeled water study. *J. Appl. Physiol.* 86(6): 2090-2096, 1999.

97. Steele, B.G., L. Holt, B. Belza, S. Ferris, S. Lakshminaryan, and D.M. Buchner. Quantitating physical activity in COPD using a triaxial accelerometer. *Chest.* 117(5): 1359-1367, 2000.

98. Swan, P.D., W.C. Byrnes, and E.M. Haymes. Energy expenditure estimates of the Caltrac accelerometer for running, race walking, and stepping. *Br. J. Sports Med.* 31(3): 235-239, 1997.

99. Swartz, A.M., S.J. Strath, D.R. Bassett, Jr., W.L. O'Brien, G.A. King, and B.E. Ainsworth. Estimation of energy expenditure using CSA accelerometers at hip and wrist sites. *Med. Sci. Sports Exerc.* 32(9 Suppl.): S450-S456, 2000.

100. Treiber, F.A., L. Musante, S. Hartdagan, H. Davis, M. Levy, and W.B. Strong. Validation of a heart rate monitor with children in laboratory and field settings. *Med. Sci. Sports Exerc.* 21(3): 338-342, 1989.

101. Treuth, M.S., A.L. Adolph, and N.F. Butte. Energy expenditure in children predicted from heart rate and activity calibrated against respiration calorimetry. *Am. J. Physiol.* 275(Endocrinol. Metab. 38): E12-E18, 1998.

102. Trost, S.G., D.S. Ward, S.M. Moorehead, P.D. Watson, W. Riner, and J.R. Burke. Validity of the computer science and applications (CSA) activity monitor in children. *Med. Sci. Science Exerc.* 30(4): 629-633, 1998.

103. Trost, S.G., R.R. Pate, P.S. Freedson, J.F. Sallis, and W.C. Taylor. Using objective physical activity measures with youth: How many days of monitoring are needed? *Med. Sci. Sports Exerc.* 32(2): 426-431, 2000.

104. Tryon, W.W., L.P. Pinto, and D.F. Morrison. Reliability assessment of pedometer activity measurements. *J. Psychopath. Behavioral Assessment.* 13(1): 27-44, 1991.

105. U.S. Department of Health and Human Services. *Physical Activity and Health: A Report of the Surgeon General.* Atlanta, GA: U.S. Dept. of Health and Human Services, Centers for Disease Control and Prevention, National Center for Chronic Disease Prevention and Health Promotion, 1996.

106. Walker, J.L., T.D. Murray, A.S. Jackson, and J.R. Morrow, Jr. The energy cost of horizontal walking and running in adolescents. *Med. Sci. Sports Exerc.* 31(2): 311-322, 1999.

107. Wareham, N.J., and K.L. Rennie. The assessment of physical activity in individuals and populations: Why try to be more precise about how physical activity is assessed? *Int. J. Obes.* 22(Suppl 2): S30-S38, 1998.

108. Washburn, R., M.K. Chin, and H.J. Montoye. Accuracy of pedometer in walking and running. *Res. Q. Exerc. Sport.* 51(4): 695-702, 1980.

109. Washburn, R.A., T.C. Cook, and R.E. LaPorte. The objective assessment of physical activity in an occupationally active group. *J. Sports Med. Phys. Fitness.* 29(3): 279-284, 1989.

110. Weir, J.B.V. New methods for calculating metabolic rate with special reference to protein metabolism. *J. Physiol.* 109: 1-9, 1949.

111. Welk, G.J., and C.B. Corbin. The validity of the Tritrac-R3D activity monitor for the assessment of physical activity in children. *Res. Q. Exerc. Sport.* 66(3): 202-209, 1995.

112. Westerterp, K.R., F. Brouns, W.H.M. Saris, and F. Ten Hoor. Comparison of doubly labeled water with respiratory measurements at low- and high-activity levels. *J. Appl. Physiol.* 65(1): 53-56, 1988.

113. Westerterp, K.R. Physical activity assessment with accelerometers. *Int. J. Obes. Relat. Metab. Disord.* 23(Suppl 3): S45-S49, 1999.

114. Westerterp, K.R. Assessment of physical activity level in relation to obesity: current evidence and research issues. *Med. Sci. Sports Exerc.* 31(11 Suppl.): S522-S525, 1999.

115. Williams, E., R.C. Klesges, C.L. Hanson, and L.H. Eck. A prospective study of the reliability and convergent validity of three physical activity measures in a field research trial. *J. Clin. Epidemiol.* 42(12): 1161-1170, 1989.

116. Williams, P.T. Relationship of distance run per week to coronary heart disease risk factors in 8283 male runners. *Arch. Intern. Med.* 157: 191-198, 1997.

117. Williamson, D.F., J. Madans, R.F. Anda, J.C. Kleinman, H.S. Kahn, and T. Byers. Recreational physical activity and ten-year weight change in a US national cohort. *Int. J. Obes.* 17: 279-286, 1993.

118. Zarrugh, V.M., S.L. Werner, and M.A. Kamin. Basic kinematics of walking: step length and step frequency: a review. *J. Sports Med. Phys. Fitness.* 34(2): 109-134, 1974.

APPENDICES

Appendix A

Health History Questionnaire

Subject Number: __________ **Test Date:** __________

HEALTH HISTORY QUESTIONNAIRE

NAME: ______________________________ AGE: _______ DATE OF BIRTH: ______________
First M.I. Last

ADDRESS: ____
Street City State Zip

TELEPHONE (home): ________________________

OCCUPATION: ____________________________

Person to contact in case of an emergency: __________________________ Phone # __________________

(relationship) ______________________

PLEASE CHECK YES or NO

PAST HISTORY
Have you ever had?

	YES	NO
1. High blood pressure...	☐	☐
2. Any heart trouble...	☐	☐
3. Disease of the arteries...	☐	☐
4. Heart murmur...	☐	☐
5. Irregular heart beat...	☐	☐
6. Seizures...	☐	☐

List any other conditions that have limited your ability to be physically active. ____________________________

____

____

____

PRESENT SYMPTOMS
Any of the following?

	YES	NO
1. Chest pain...	☐	☐
2. Shortness of breath...	☐	☐
3. Weakness in arm...	☐	☐
4. Feeling faint/dizzy...	☐	☐
5. Heart palpitations...	☐	☐
6. Blurred vision...	☐	☐
7. Severe headache...	☐	☐

Other illness that may affect your participation...____________________

____

____

____

Are you taking any prescription or over-the counter medications? Yes ___ No ___

Name of medication	Reason for Taking	For How Long?

ACTIVITY LEVEL EVALUATION

What is your occupational activity level? Sedentary _____ Light _____ Moderate _____ Heavy ____

Do you currently engage in vigorous physical activity on a regular basis? Yes ____ No ____

If so, what type? ____________________________________ How many days per week? _____________

How much time per day? (check one) < 15 min ____ 15-30 min ____ 30-45 min ____ > 60 min ____

How long have you been vigorously active? (check one) < 1 mo __ 1-6 mos. __ 6-12 mos. __> 12 mos. __

Do you ever have an uncomfortable shortness of breath during exercise? Yes ____ No ____

Do you ever have chest discomfort during exercise? Yes __ No __ If so does it go away with rest? ___

FOR EXERCISE TESTING STAFF USE:

SJS 4/00

Appendix B

Informed Consent Form

(Part I)

INFORMED CONSENT FORM

TITLE: Accuracy of the FitSense FS-1 Speedometer during a Field Test

Investigators: Scott A. Conger, B.A.
David R. Bassett, Jr., Ph.D.

Address:
Exercise Science and Sport Management
HPER Building
University of Tennessee
1914 Andy Holt Ave., Knoxville, TN 37996-2700

Phone: (865) 974-5091

PURPOSE

You are invited to participate in a research study. The purpose of this study is to determine the accuracy of the FitSense FS-1 Speedometer. This device consists of a foot pod that attaches to the top of the shoe on the shoelaces, a heart rate band that is worn around the chest, and a wristwatch. The FitSense will be tested for its accuracy in measuring distance traveled, speed, and calories burned during walking and jogging exercise bouts.

PROCEDURES

You will be asked to come to the Applied Physiology Laboratory in the Health, Physical Education & Recreation (HPER) building on one occasion. Prior to beginning testing, you will be asked to fill out a health history questionnaire and a researcher will measure your height and weight. The field test will consist of four 1-mile tests (two walking, two jogging) on the University of Tennessee athletic track at self-selected speeds. Between each 1-mile test, you will be given a 5-minute rest period. For this test, you will wear the FS-1 speedometer. You will be free to stop the test for any reason. The time commitment for the test will be approximately one hour.

BENEFITS OF PARTICIPATION

From the information that we generate, we will be able to give you information on how many calories you burn while walking and jogging.

RISKS OF PARTICIPATION

The potential risks that may occur with participating in this study include those associated with exercise. These include: leg discomfort, muscle/joint soreness, dizziness, headache, and, in rare instances, heart attack (4 $\leq$ in 10,000). In addition, the Applied Physiology Laboratory has a planned response to any emergency procedure, and all testing personnel are CPR certified.

CONFIDENTIALITY

The information gathered by the investigators in this study will be confidential and will be kept in a locked file cabinet in the possession of the investigators. Only those individuals directly involved with this study will have access to these records. The information will eventually be used in a research report, but no reference of any kind will be made which could link you as a participant to the study.

CONTACT INFORMATION

If you have questions or concerns at any time during the course of the testing procedures or after completion of the testing procedures, you may contact Dr. David Bassett at (865) 974-8766. If you have questions concerning your rights as a participant, contact the Compliance Section of the Office of Research at (865) 974-3466.

PARTICIPATION

You are free to make a decision to participate in this study, and if you should choose to participate, you may withdraw from the study at any time without penalty. If you withdraw from the study, your data will be given to you or destroyed.

AUTHORIZATION

By signing this informed consent form, I am indicating that I have read and understood this document and have received a copy of it for my personal records. I have been given the opportunity to ask questions on any matters that I am not clear on. By signing this form I indicate that I agree to serve as a participant in this research study.

____
Participant's name

________________________________ ______________
Participant's signature Date

________________________________ ______________
Investigator's signature Date

Appendix C

Informed Consent Form

(Parts I-III)

INFORMED CONSENT FORM

TITLE: Accuracy of the FitSense FS-1 Speedometer

Investigators: Scott A. Conger, B.A.
David R. Bassett, Jr., Ph.D.

Address:
Exercise Science and Sport Management
HPER Building
University of Tennessee
1914 Andy Holt Ave., Knoxville, TN 37996-2700

Phone: (865) 974-5091

PURPOSE

You are invited to participate in a research study. The purpose of this study is to determine the accuracy of the FitSense FS-1 Speedometer. This device consists of a foot pod that attaches to the top of the shoe on the shoelaces, a heart rate band that is worn around the chest, and a wristwatch. The FitSense will be tested for its accuracy in measuring distance traveled, speed, and calories burned during walking and jogging exercise bouts.

PROCEDURES

You will be asked to come to the Applied Physiology Laboratory in the Health, Physical Education & Recreation (HPER) building on four separate occasions. On the first day, your level of physical fitness will be determined during a maximal treadmill test. You will also be asked to fill out a health history questionnaire and a researcher will measure your height, weight, and body fat percentage. Your body fat percentage will be measured using the Bod Pod. The Bod Pod estimates body fat by measuring body weight and size. You will sit in a sealed chamber for approximately three minutes. You will be able to breathe normally and see your surroundings during this time. For this procedure you will wear a lycra swimsuit. The remaining days will consist of three submaximal exercise tests: two laboratory tests and a field test. Each day, you will complete one of the three tests. The laboratory tests will consist of two treadmill tests at different walking and jogging speeds and grades. While exercising, you will breathe through a mouthpiece and wear a nose clip. The mouthpiece allows the researchers to collect the expired air. From this air, we will determine how many calories you burn during exercise. You will also be wearing the FS-1 speedometer, which will measure speed, distance, and estimate caloric (energy) expenditure. The device will also allow the researchers to monitor your heart rate during testing. The field test will consist of walking and jogging on the University of Tennessee athletic track at self-selected speeds. For this test, you will wear the FS-1 speedometer. You will be free to stop any test for any reason. The time commitment for the tests will be approximately one hour per test, for a total of four hours over the course of four separate days.

BENEFITS OF PARTICIPATION

From the information that we generate, we will be able to tell you your fitness level, body fat percentage, and how many calories you burn while walking and jogging at various speeds.

RISKS OF PARTICIPATION

The potential risks that may occur with participating in this study include those associated with exercise. These include: leg discomfort, muscle/joint soreness, dizziness, headache, and, in rare instances, heart attack ($4 \leq$ in 10,000). In addition, the Applied Physiology Laboratory has a planned response to any emergency procedure, and all testing personnel are CPR certified.

CONFIDENTIALITY

The information gathered by the investigators in this study will be confidential and will be kept in a locked file cabinet in the possession of the investigators. Only those individuals directly involved with this study will have access to these records. The information will eventually be used in a research report, but no reference of any kind will be made which could link you as a participant to the study.

CONTACT INFORMATION

If you have questions or concerns at any time during the course of the testing procedures or after completion of the testing procedures, you may contact Dr. David Bassett at (865) 974-8766. If you have questions concerning your rights as a participant, contact the Compliance Section of the Office of Research at (865) 974-3466.

PARTICIPATION

You are free to make a decision to participate in this study, and if you should choose to participate, you may withdraw from the study at any time without penalty. If you withdraw from the study, your data will be given to you or destroyed.

AUTHORIZATION

By signing this informed consent form, I am indicating that I have read and understood this document and have received a copy of it for my personal records. I have been given the opportunity to ask questions on any matters that I am not clear on. By signing this form I indicate that I agree to serve as a participant in this research study.

____
Participant's name

____________________________ ____________
Participant's signature Date

____________________________ ____________
Investigator's signature Date

Appendix D

$\dot{V}O_{2max}$ Data

APPENDIX D

$\dot{V}O_{2max}$ DATA

Subject	$\dot{V}O_{2max}$ ($ml \cdot kg^{-1} \cdot min^{-1}$)	Post-test Lactate ($mmol \cdot L^{-1}$)	Max Heart Rate ($beats \cdot min^{-1}$)	RER	RPE
1	50.7	10.2	184	1.08	19
2	58.1	9.9	182	1.08	20
3	57.4	8.9	196	1.02	20
4	57.8	-	182	1.14	20
5	46.6	10.9	196	1.13	19
6	47.7	8.1	187	1.03	19
7	57.5	8.4	191	1.12	17
8	48.3	15.4	200	1.21	20
9	53.3	9.0	199	1.10	19
10	57.0	9.9	204	1.08	20
11	62.9	9.3	189	1.05	19
12	58.9	8.7	167	1.11	20

Appendix E

Calibration Values

APPENDIX E-1

CALIBRATION VALUES (CalVals) PART I

Subject	CalVal (Walking)	Walking Time (sec.)	Walking Speed (miles $\cdot$ hr^{-1})	CalVal (Running)	Running Time (sec.)	Running Speed (miles $\cdot$ hr^{-1})
1	139	187.08	4.81	79	119.85	7.51
2	84	216.84	4.15	111	102.28	8.80
3	57	245.47	3.67	41	111.99	8.04
4	62	208.52	4.32	69	92.59	9.72
5	173	172.33	5.22	49	122.53	7.35
6	112	195.79	4.60	91	109.42	8.23
7	57	218.92	4.11	74	77.74	11.58
8	63	239.33	3.76	44	121.40	7.41
9	109	212.31	4.24	79	113.10	7.96
10	88	214.69	4.19	96	132.09	6.81
11	115	188.51	4.77	76	91.33	9.85
12	102	231.39	3.89	99	121.09	7.43
13	66	232.86	3.86	56	119.82	7.51
14	140	208.71	4.31	126	121.22	7.42
15	80	207.01	4.35	59	86.92	10.35
16	74	227.18	3.96	79	65.34	13.77
17	98	224.69	4.01	91	133.78	6.73
18	74	246.34	3.65	49	106.43	8.46
19	145	225.84	3.99	109	141.13	6.38
20	76	284.79	3.16	71	81.25	11.08
21	77	230.91	3.90	84	106.77	8.43
22	87	239.2	3.76	84	124.44	7.23
23	80	250.75	3.59	81	119.04	7.56
24	82	239.63	3.76	56	108.37	8.30

APPENDIX E-2

CALIBRATION VALUES (CalVals) PARTS I, II, III

Subject	Test	Method	CalVal (Walking)	Walking Time (sec.)	CalVal (Running)	Running Time (sec.)
1	1	1	104	41.00	84	31.63
1	2	1	105	42.39	79	36.46
1	3	2	139	187.08	79	119.85
2	1	1	84	44.49	81	30.45
2	2	1	90	46.20	69	31.43
2	3	2	84	216.84	111	102.28
3	1	1	59	49.44	44	44.35
3	2	1	59	50.37	41	35.02
3	3	2	57	245.47	41	111.99
4	1	1	59	57.16	81	32.08
4	2	1	54	51.33	74	32.90
4	3	2	62	208.52	69	92.59
5	1	1	102	42.09	51	32.52
5	2	1	100	41.19	51	32.03
5	3	2	173	172.33	49	122.53
6	1	1	94	43.75	126	33.54
6	2	1	93	46.76	116	30.76
6	3	2	112	195.79	91	109.42
7	1	1	70	44.99	64	32.19
7	2	1	64	45.19	111	34.69
7	3	2	57	218.92	74	77.74
8	1	1	66	45.10	56	33.48
8	2	1	61	49.90	49	35.72
8	3	2	63	239.33	44	121.40
9	1	1	104	42.96	84	30.03
9	2	1	103	45.95	86	28.26
9	3	2	109	212.31	79	113.10
10	1	1	84	43.27	96	29.66
10	2	1	90	45.35	104	32.37
10	3	2	88	214.69	96	132.09
11	1	1	104	44.86	79	29.61
11	2	1	111	41.27	89	31.49
11	3	2	115	188.51	76	91.33

Subject	**Test**	**Method**	**CalVal (Walking)**	**Walking Time (sec.)**	**CalVal (Running)**	**Running Time (sec.)**
12	1	1	94	44.82	106	34.61
12	2	1	89	42.82	111	30.95
12	3	2	102	231.39	99	121.09

Test: 1 – Treadmill Speed
2 – Treadmill Grade
3 – Track Distance

Method: 1 – Treadmill Calibration
2 – Track Calibration

Appendix F

Distance Data

APPENDIX F-1

DISTANCE MEANS (WALK)

Subject	Actual Distance	Distance Walk 1	Distance Walk 2	Average Distance (Walk)	Speed Walk 1	Speed Walk 2	Average Speed (Walk)
1	1600	1947.21	1995.49	**1971.35**	5.02	5.15	**5.09**
2	1600	1609.27	1577.08	**1593.17**	4.46	4.47	**4.47**
3	1600	1544.89	1528.80	**1536.85**	3.75	3.70	**3.72**
4	1600	1673.64	1689.73	**1681.68**	4.50	4.58	**4.54**
5	1600	1625.36	1625.36	**1625.36**	5.17	5.13	**5.15**
6	1600	1593.17	1560.99	**1577.08**	4.70	4.73	**4.72**
7	1600	1593.17	1577.08	**1585.13**	4.13	4.10	**4.11**
8	1600	1528.80	1303.51	**1416.15**	3.73	3.63	**3.68**
9	1600	1577.08	1560.99	**1569.03**	4.26	4.15	**4.21**
10	1600	1560.99	1577.08	**1569.03**	4.19	4.24	**4.22**
11	1600	1593.17	1593.17	**1593.17**	4.83	4.77	**4.80**
12	1600	1560.99	1544.89	**1552.94**	4.04	3.94	**3.99**
13	1600	1528.80	1577.08	**1552.94**	3.95	3.80	**3.88**
14	1600	1496.62	1496.62	**1496.62**	4.28	4.18	**4.23**
15	1600	1593.17	1609.27	**1601.22**	4.43	4.44	**4.43**
16	1600	1528.80	1544.89	**1536.85**	3.79	3.68	**3.73**
17	1600	1577.08	1560.99	**1569.03**	3.96	3.89	**3.92**
18	1600	1544.89	1512.71	**1528.80**	4.17	4.10	**4.13**
19	1600	1609.27	1593.17	**1601.22**	4.16	4.19	**4.18**
20	1600	1544.89	1609.27	**1577.08**	4.26	4.52	**4.39**
21	1600	1432.25	1480.52	**1456.39**	3.90	3.91	**3.91**
22	1600	1577.08	1560.99	**1569.03**	3.96	3.90	**3.93**
23	1600	1512.71	1512.71	**1512.71**	3.40	3.46	**3.43**
24	1600	1528.80	1512.71	**1520.76**	3.66	3.49	**3.58**

Speed: miles · hr^{-1} Distance: meters

APPENDIX F-2

DISTANCE MEANS (RUN)

Subject	Actual Distance	Distance Run 1	Distance Run 2	Average Distance (Run)	Speed Run 1	Speed Run 2	Average Speed (Run)
1	1600	1577.08	1560.99	**1569.03**	6.99	7.02	**7.01**
2	1600	1480.52	1271.32	**1375.92**	9.55	9.95	**9.75**
3	1600	1593.17	1609.27	**1601.22**	8.25	8.30	**8.27**
4	1600	1577.08	1560.99	**1569.03**	9.21	9.39	**9.30**
5	1600	1528.80	1512.71	**1520.76**	6.63	6.80	**6.71**
6	1600	1673.64	1689.73	**1681.68**	7.31	6.82	**7.07**
7	1600	1464.43	1255.23	**1359.83**	10.26	9.91	**10.08**
8	1600	1577.08	1609.27	**1593.17**	7.36	7.38	**7.37**
9	1600	1560.99	1512.71	**1536.85**	7.66	8.31	**7.98**
10	1600	1625.36	1593.17	**1609.27**	6.97	7.12	**7.05**
11	1600	1544.89	1560.99	**1552.94**	9.75	9.33	**9.54**
12	1600	1593.17	1544.89	**1569.03**	7.23	7.41	**7.32**
13	1600	1577.08	1544.89	**1560.99**	8.07	8.41	**8.24**
14	1600	1448.34	1464.43	**1456.39**	7.01	7.06	**7.03**
15	1600	1560.99	1544.89	**1552.94**	9.75	9.73	**9.74**
16	1600	1448.34	1383.97	**1416.15**	11.14	10.99	**11.07**
17	1600	1577.08	1528.80	**1552.94**	6.32	6.38	**6.35**
18	1600	1770.19	1786.28	**1778.24**	8.80	8.93	**8.87**
19	1600	1528.80	1528.80	**1528.80**	6.74	6.82	**6.78**
20	1600	1673.64	1609.27	**1641.45**	10.04	10.54	**10.29**
21	1600	1303.51	1239.13	**1271.32**	8.03	8.11	**8.07**
22	1600	1544.89	1560.99	**1552.94**	7.25	7.30	**7.28**
23	1600	1577.08	1577.08	**1577.08**	7.27	7.43	**7.35**
24	1600	1609.27	1609.27	**1609.27**	7.64	8.09	**7.87**

Speed: miles · hr^{-1} Distance: meters

APPENDIX F-3

DISTANCE DIFFERENCES

Subject	Actual Distance	Distance Difference Walk 1	Distance Difference Walk 2	Average Difference Walk	Distance Difference Run 1	Distance Difference Run 2	Average Difference Run
1	1600	-347.21	-395.49	**-371.35**	22.92	39.01	**30.97**
2	1600	-9.27	22.92	**6.83**	119.48	328.68	**224.08**
3	1600	55.11	71.20	**63.15**	6.83	-9.27	**-1.22**
4	1600	-73.64	-89.73	**-81.68**	22.92	39.01	**30.97**
5	1600	-25.36	-25.36	**-25.36**	71.20	87.29	**79.24**
6	1600	6.83	39.01	**22.92**	-73.64	-89.73	**-81.68**
7	1600	6.83	22.92	**14.87**	135.57	344.77	**240.17**
8	1600	71.20	296.49	**183.85**	22.92	-9.27	**6.83**
9	1600	22.92	39.01	**30.97**	39.01	87.29	**63.15**
10	1600	39.01	22.92	**30.97**	-25.36	6.83	**-9.27**
11	1600	6.83	6.83	**6.83**	55.11	39.01	**47.06**
12	1600	39.01	55.11	**47.06**	6.83	55.11	**30.97**
13	1600	71.20	22.92	**47.06**	22.92	55.11	**39.01**
14	1600	103.38	103.38	**103.38**	151.66	135.57	**143.61**
15	1600	6.83	-9.27	**-1.22**	39.01	55.11	**47.06**
16	1600	71.20	55.11	**63.15**	151.66	216.03	**183.85**
17	1600	22.92	39.01	**30.97**	22.92	71.20	**47.06**
18	1600	55.11	87.29	**71.20**	-170.19	-186.28	**-178.24**
19	1600	-9.27	6.83	**-1.22**	71.20	71.20	**71.20**
20	1600	55.11	-9.27	**22.92**	-73.64	-9.27	**-41.45**
21	1600	167.75	119.48	**143.61**	296.49	360.87	**328.68**
22	1600	22.92	39.01	**30.97**	55.11	39.01	**47.06**
23	1600	87.29	87.29	**87.29**	22.92	22.92	**22.92**
24	1600	71.20	87.29	**79.24**	-9.27	-9.27	**-9.27**

Distance: meters
Difference = measured distance-estimated distance

Appendix G

Speed Data

APPENDIX G-1

SPEED MEANS

Walking: Stages 1-3; Running: Stages 4-6 ($\text{miles} \cdot \text{hr}^{-1}$)

Subject	Stage	Measured	Estimated	Subject	Stage	Measured	Estimated
1	1	3.06	3.08	7	1	3.09	3.20
1	2	4.02	4.20	7	2	4.02	4.14
1	3	5.05	6.80	7	3	5.04	7.76
1	4	5.05	4.68	7	4	5.06	5.48
1	5	6.15	6.12	7	5	6.13	6.60
1	6	7.10	6.88	7	6	7.14	7.18
2	1	3.05	3.04	8	1	3.07	3.30
2	2	4.04	4.00	8	2	4.04	3.94
2	3	5.06	5.96	8	3	5.06	5.20
2	4	5.05	5.00	8	4	5.08	5.28
2	5	6.12	6.22	8	5	6.11	6.26
2	6	7.03	8.74	8	6	7.13	6.86
3	1	3.08	3.20	9	1	2.97	2.96
3	2	4.03	4.04	9	2	4.03	4.14
3	3	5.04	5.42	9	3	5.05	6.54
3	4	5.06	8.52	9	4	5.06	4.92
3	5	6.15	6.14	9	5	6.15	5.86
3	6	7.12	7.10	9	6	7.09	6.66
4	1	3.01	3.98	10	1	3.08	3.16
4	2	4.01	4.12	10	2	4.02	4.04
4	3	5.06	6.12	10	3	5.05	6.34
4	4	5.05	4.78	10	4	5.07	7.50
4	5	6.08	6.08	10	5	6.15	6.16
4	6	7.09	7.06	10	6	7.06	6.92
5	1	2.98	2.98	11	1	3.06	3.10
5	2	4.05	4.16	11	2	4.04	3.80
5	3	5.05	7.00	11	3	5.03	6.44
5	4	5.05	5.50	11	4	5.05	5.08
5	5	6.14	6.28	11	5	6.18	6.22
5	6	7.10	6.84	11	6	7.14	6.98
6	1	2.97	2.92	12	1	2.96	3.04
6	2	4.04	3.94	12	2	4.05	4.26
6	3	5.08	5.78	12	3	5.07	6.66
6	4	5.09	5.14	12	4	5.08	5.16
6	5	6.20	5.84	12	5	6.17	6.22
6	6	7.11	6.66	12	6	7.12	6.88

APPENDIX G-2

SPEED DIFFERENCES

Walking: Stages 1-3; Running: Stages 4-6 $(\text{miles} \cdot \text{hr}^{-1})$

Subject	Stage 1	Stage 2	Stage 3	Stage 4	Stage 5	Stage 6
1	-0.02	-0.18	-1.75	0.37	0.03	0.22
2	0.01	0.04	-0.90	0.05	-0.10	-1.71
3	-0.12	-0.01	-0.38	-3.46	0.01	0.02
4	-0.97	-0.11	-1.06	0.27	0.00	0.03
5	0.00	-0.11	-1.95	-0.45	-0.14	0.26
6	0.05	0.10	-0.70	-0.05	0.36	0.45
7	-0.11	-0.12	-2.72	-0.42	-0.47	-0.04
8	-0.23	0.10	-0.14	-0.20	-0.15	0.27
9	0.01	-0.11	-1.49	0.14	0.29	0.43
10	-0.08	-0.02	-1.29	-2.43	-0.01	0.14
11	-0.04	0.24	-1.41	-0.03	-0.04	0.16
12	-0.08	-0.21	-1.59	-0.08	-0.05	0.24

Difference = measured speed-estimated speed

Appendix H

Energy Expenditure Data

APPENDIX H-1

ENERGY EXPENDITURE MEANS

Walking: Stages 1-3; Running: Stages 4-6; Level Grade (kcals·min^{-1})

Subject	Stage	Measured	Estimated
1	1	3.0	2.0
1	2	4.1	3.0
1	3	7.6	4.5
1	4	7.6	5.0
1	5	9.2	7.5
1	6	11.2	8.5
2	1	2.9	3.5
2	2	4.6	4.5
2	3	9.0	5.5
2	4	8.3	8.5
2	5	10.0	11.5
2	6	11.5	15.0
3	1	3.9	2.5
3	2	6.4	5.0
3	3	12.5	4.5
3	4	11.2	5.5
3	5	13.0	7.5
3	6	15.3	9.5
4	1	3.7	0.5
4	2	5.8	3.5
4	3	9.7	5.0
4	4	9.7	8.5
4	5	11.4	11.0
4	6	13.2	13.0
5	1	2.6	2.0
5	2	4.2	3.0
5	3	8.0	4.0
5	4	7.8	4.0
5	5	9.4	5.5
5	6	11.1	6.0
6	1	3.1	2.0
6	2	5.0	2.5
6	3	8.7	4.0
6	4	8.9	7.5
6	5	10.1	9.0
6	6	11.6	10.0
7	1	3.4	3.5
7	2	4.8	4.0
7	3	8.3	6.5
7	4	9.1	9.0
7	5	10.9	11.5
7	6	12.7	12.5
8	1	3.8	3.5
8	2	6.0	4.5
8	3	11.2	5.5
8	4	11.8	9.5
8	5	13.6	11.5
8	6	16.6	13.0
9	1	2.6	2.0
9	2	4.0	3.0
9	3	7.4	4.5
9	4	7.0	5.5
9	5	8.3	7.0
9	6	9.7	8.5
10	1	3.1	3.0
10	2	4.8	3.5
10	3	11.4	5.0
10	4	8.3	11.5
10	5	9.6	11.0
10	6	11.5	12.0
11	1	3.0	3.0
11	2	4.4	3.5
11	3	7.8	5.0
11	4	8.3	7.0
11	5	9.9	9.0
11	6	11.7	10.0
12	1	2.6	2.0
12	2	4.3	2.5
12	3	9.5	3.5
12	4	7.9	6.0
12	5	9.0	7.5
12	6	10.5	8.5

APPENDIX H-2

ENERGY EXPENDITURE (MEASURED AND ESTIMATED)

Walking – Increasing Grade (kcals·min^{-1})

Subject	Stage	Measured	Estimated
1	1	2.9	2.0
1	2	3.6	2.0
1	3	4.7	2.0
1	4	5.4	2.0
1	5	6.5	2.5
2	1	3.0	3.5
2	2	3.9	3.0
2	3	5.2	3.0
2	4	6.3	3.0
2	5	7.7	3.5
3	1	4.2	2.5
3	2	5.0	2.5
3	3	6.1	2.5
3	4	7.1	2.5
3	5	8.6	2.5
4	1	4.0	2.0
4	2	4.9	2.5
4	3	6.1	2.0
4	4	7.2	0.0
4	5	8.6	0.0
5	1	2.6	1.5
5	2	3.4	2.0
5	3	4.5	2.0
5	4	5.5	2.0
5	5	6.6	2.0
6	1	3.0	2.0
6	2	3.7	2.0
6	3	4.5	2.0
6	4	5.8	0.0
6	5	7.1	0.0
7	1	3.4	3.0
7	2	4.2	3.0
7	3	5.2	3.0
7	4	6.4	3.0
7	5	7.7	3.5
8	1	4.0	3.0
8	2	4.8	3.5
8	3	6.2	3.5
8	4	7.4	3.5
8	5	9.2	1.5
9	1	2.6	2.5
9	2	3.1	2.0
9	3	4.1	2.0
9	4	5.2	2.0
9	5	6.2	2.0
10	1	2.8	2.5
10	2	3.8	2.5
10	3	4.4	2.5
10	4	5.8	3.0
10	5	6.6	2.5
11	1	3.0	2.5
11	2	3.6	2.5
11	3	4.5	2.5
11	4	5.8	2.5
11	5	6.8	2.5
12	1	2.8	1.5
12	2	3.5	1.5
12	3	4.2	1.5
12	4	5.2	1.5
12	5	6.2	1.5

APPENDIX H-3

ENERGY EXPENDITURE DIFFERENCES

Walking: Stages 1-3; Running: Stages 4-6; Level Grade (kcals·min^{-1})

Subject	Stage 1	Stage 2	Stage 3	Stage 4	Stage 5	Stage 6
1	1.02	1.07	3.12	2.62	1.72	2.72
2	-0.62	0.13	3.48	-0.22	-1.52	-3.52
3	1.38	1.43	8.03	5.68	5.53	5.83
4	3.19	2.29	4.69	1.19	0.44	0.24
5	0.64	1.19	3.99	3.84	3.94	5.14
6	1.09	2.49	4.74	1.44	1.09	1.64
7	-0.13	0.82	1.82	0.07	-0.58	0.17
8	0.33	1.53	5.73	2.33	2.13	3.63
9	0.65	1.00	2.90	1.50	1.30	1.25
10	0.15	1.30	6.40	-3.20	-1.35	-0.45
11	0.00	0.90	2.80	1.30	0.95	1.75
12	0.62	1.82	6.02	1.87	1.52	2.02

Difference = measured kcals-estimated kcals

Walking – Increasing Grade (kcals·min^{-1})

Subject	Stage 1	Stage 2	Stage 3	Stage 4	Stage 5
1	0.92	1.62	2.72	3.42	3.97
2	-0.52	0.88	2.23	3.33	4.18
3	1.68	2.48	3.58	4.63	6.08
4	2.04	2.44	4.09	7.19	8.64
5	1.14	1.44	2.54	3.54	4.64
6	1.04	1.69	2.54	5.84	7.14
7	0.42	1.17	2.22	3.37	4.17
8	0.98	1.33	2.68	3.93	7.68
9	0.10	1.15	2.10	3.20	4.20
10	0.30	1.30	1.95	2.80	4.15
11	0.50	1.15	2.05	3.30	4.35
12	1.32	1.97	2.72	3.67	4.67

Difference = measured kcals-estimated kcals

VITA

Scott A. Conger was born in Lansing, Michigan on August 1, 1975. He was raised in Little Rock, Arkansas where he graduated from Joe T. Robinson High School in May 1993. His college career began at the University of Arkansas, Fayetteville in August 1993. After transferring to the University of Arkansas at Little Rock, he received a Bachelor of Arts degree in Psychology in May 1998. In August 1999, his academic focus shifted from psychology to exercise science at the University of Tennessee, Knoxville. In May 2001, he received his Master of Science degree in Human Performance and Sports Studies.