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Measurement of physical activity and energy expenditure using heart rate, motion sensors and questionnaires

Scott J. Strath
University of Tennessee

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To the Graduate Council:

I am submitting herewith a dissertation written by Scott J. Strath entitled "Measurement of physical activity and energy expenditure using heart rate, motion sensors and questionnaires." I have examined the final electronic copy of this dissertation for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Doctor of Philosophy, with a major in Education.

David R. Bassett, Major Professor

We have read this dissertation and recommend its acceptance:

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 dissertation written by Scott J. Strath entitled "Measurement of Physical Activity and Energy Expenditure Using Heart Rate, Motion Sensors and Questionnaires." I have examined the final copy of this dissertation for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Doctor of Philosophy, with a major in Education.

David R. Bassett, Jr.

David R. Bassett, Major Professor

We have read this dissertation
and recommend its acceptance:

Dixie L Thompson

Edward T. Howley

Eugene C. Fitzhugh

Accepted for the Council:

Interim Vice Provost and
Dean of The Graduate School

MEASUREMENT OF PHYSICAL ACTIVITY AND ENERGY EXPENDITURE USING HEART RATE, MOTION SENSORS AND QUESTIONNAIRES

A Dissertation
Presented for the
Doctor of Philosophy Degree
The University of Tennessee

Scott J. Strath
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ABSTRACT

MEASUREMENT OF PHYSICAL ACTIVITY AND ENERGY EXPENDITURE USING HEART RATE, MOTION SENSORS AND QUESTIONNAIRES

This dissertation was designed to examine new techniques to measure physical activity (PA) and energy expenditure (EE) during lifestyle activities. The specific aims were: 1) to evaluate heart rate (HR), using percent of HR reserve in relation to percent of oxygen uptake reserve, as a method for assessing moderate intensity PA in the field setting; 2) to validate the simultaneous heart rate–motion sensor (HR+M) technique to estimate EE of selected activities; 3) to validate the simultaneous HR+M technique to predict EE over an extended time period; and 4) to use the simultaneous HR+M technique to validate selected PA questionnaires over a 7-day period.

For the first aim, sixty-one males performed physical tasks in both a laboratory and field setting. HR and oxygen uptake (VO_2) were continuously measured during 15-min tasks. HR data was used to predict EE using age-predicted maximum HR and estimated maximal VO_2. The correlation between HR and measured VO_2 was r=0.68. After adjusting for age and fitness level, HR provided an accurate estimate of EE, r=0.87. Using percent HR reserve to estimate percent VO_2 reserve significantly improved the estimation of EE.

In the second aim, 30 participants performed arm and leg work in the laboratory for the purpose of developing individualized HR- VO_2 regression equations. Participants completed 15-min bouts of activity in a field setting, with continuous measurements of HR, motion, and VO_2. Motion sensors were used to discriminate between arm and leg activity, and HR was used to predict EE from the corresponding laboratory regression equation. Simultaneous HR+M technique values were compared to a pedometer, a hip mounted accelerometer, and HR using only the leg regression equation. The simultaneous HR+M technique showed the strongest relationship with VO_2, $r=0.81$, and it accurately estimated the energy cost of activities ($P=0.341$).

For the third aim, the simultaneous HR+M technique, as described above, was validated over a 6 h period of free-living activity. In addition to the simultaneous HR+M technique the FlexHR method was analyzed. The simultaneous HR+M technique showed a stronger relationship with measured min-by-min EE in comparison to the FlexHR method, $r=0.81$ vs. $r=0.63$, respectively. The simultaneous HR+M technique accurately reflected min-by-min EE (SEE=0.55 METs). In addition, this technique accurately determined the amount of time spent in resting/light, moderate, and hard intensity activity.

In the final aim, the simultaneous HR+M technique served as a criterion measure to examine the validity of six PA questionnaires. Subjects wore a HR recording device, and two accelerometers, one placed on the wrist, and the other placed on the leg, for a continuous 7-day period. Questionnaires examined included the Modifiable Activity Questionnaire (MAQ), the Stanford 7-day Physical Activity Recall (PAR), the College Alumnus Questionnaire (CAQ), the Framingham Activity Index (FAI), the Baecke Activity Questionnaire (BAQ), and the Health Insurance Plan of Greater New York (HIP) questionnaire. A significant correlation was observed between the simultaneous HR+M technique and all questionnaires, with the exception of the BAQ. The PAR yielded similar group means, compared to the criterion method, for time spent and EE in moderate and hard intensity activity. In addition, a significant correlation was seen between this questionnaire and criterion measure for both time spent and EE in hard activity ($r = 0.49$, $P<0.05$, respectively). This suggests adequate validity for the PAR to evaluate vigorous PA.

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NOMENCLATURE

$\text{beats}\cdot\text{min}^{-1}$	beats per minute
cm	centimeter
g	gram
h	hour
kg	kilogram
$\text{kg}\cdot\text{m}^{-2}$	kilogram per meter squared
kcal	kilocalorie
$\text{kcal}\cdot\text{min}^{-1}$	kilocalorie per minute
$\text{kcal}\cdot\text{wk}^{-1}$	kilocalorie per week
L	liter
$\text{L}\cdot\text{min}^{-1}$	liter per minute
MET	resting metabolic equivalent
$\text{MET}\cdot\text{min}^{-1}$	resting metabolic equivalent per minute
$\text{MET}\cdot\text{min}\cdot\text{wk}^{-1}$	resting metabolic equivalent per minute per week
min	minute
$\text{min}\cdot\text{wk}^{-1}$	minutes per week
$\text{m}\cdot\text{min}^{-1}$	meters per minute
ml	milliliter
$\text{ml}\cdot\text{min}^{-1}$	milliliter per minute
$\text{ml}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$	milliliter per kilogram body mass per minute
s	second
yr	year

LIST OF ABREVEATIONS

BAQ	Baecke Activity Questionnaire
BMI	body mass index
BF%	body fat percentage
CAQ	College Alumnus Questionnaire
CI	confidence interval
CSA	Computer Science Applications Inc.
EE	energy expenditure
FAI	Framingham Activity Index
HIP	Health Insurance Plan of Greater New York
HR	heart rate
HRR	heart rate reserve
%HRR	percent of heart rate reserve
HR+M	heart rate plus motion sensor
MAQ	Modifiable Activity Questionnaire
PA	physical activity
PAEE	physical activity energy expenditure
SD	standard deviation
VO_2	oxygen uptake
VO_{2max}	maximal oxygen uptake
VO_{2R}	oxygen uptake reserve
$\%VO_{2R}$	percent of oxygen uptake reserve

PART I

INTRODUCTION

Substantial evidence has accumulated over the years to support the link between physical activity and positive health outcomes, as evidenced by the 1996 Surgeon General's Report on *Physical Activity and Health*, (31) as well as by several other public health statements (1, 2). It is now generally accepted that there is an inverse relationship between regular physical activity and health problems such as coronary heart disease (22, 23, 29), hypertension (24, 32), some cancers (6, 13, 14), obesity (4, 7), and type 2 diabetes (17, 18). Physical inactivity is a large public health burden, and its importance is demonstrated by the number of individuals who do not get enough physical activity to obtain positive health benefits. It has been reported that 60% of U.S. adults do not engage in regular leisure-time physical activity, and that about 25% report no physical activity at all in their leisure-time (31). As outlined in the Surgeon General's Report, the greatest impact on public health occurs when the most inactive portion of the population becomes moderately active (31). The recent public health message has seen a paradigm shift away from conventional exercise recommendations to focus on the incorporation of moderate physical activity into one's daily live. The current recommendations set forth by the American College of Sports Medicine (ACSM) and the Centers for Disease Control and Prevention (CDC) suggest that *all American adults accumulate at least 30 minutes of moderate intensity physical activity on most, preferably all, days of the week* (25, 31). This recommendation, which translates to approximately 150 $\text{kcals}\cdot\text{d}^{-1}$, or 1000 $\text{kcals}\cdot\text{wk}^{-1}$, is not replacing conventional exercise suggestions, but is designed as a "*first step*" in getting the inactive population active.

Physical activity is a complex behavior characterized by high levels of inter-individual variation, and is thus difficult to measure. Physical activity is an integral part of everyday life that includes several components such as type, intensity, frequency, duration, and total volume. It is necessary to accurately assess these components of physical activity in order to determine the specific dose-response characteristics between physical activity and selected health outcomes.

The health effects of accumulating physical activity are generally established by assessing physical activity by means of questionnaire. This is because physical activity questionnaires are practical and feasible to administer to large population based samples. However, although physical activity questionnaires are acceptable for recalling structured exercise, significant error may occur due to their inability to accurately recall ubiquitous, light to moderate intensity physical activity (20). Therefore, questionnaires may not truly reflect one's level of physical activity accumulated throughout the day during lifestyle activity (3, 26). To date over 35 different physical activity questionnaires have been developed, which highlights the measurement conundrum investigators are faced with when choosing a questionnaire to use. Furthermore, the accuracy of physical activity questionnaires has not been established to assess the complexity of physical activity under field conditions; this is due to the lack of a suitable criterion measure. In order to more fully understand and better define dose-response characteristics between physical activity and specific health outcomes, the efficacy of physical activity questionnaires needs to be evaluated for measuring different dimensions of activity levels.

There are additional methods of assessing physical activity in addition to the use of questionnaires. The current "gold standard" for measuring total daily energy expenditure is the doubly labeled water technique, which employs the stable isotopes, deuterium and O_2^{18}. There are, however, certain limitations to the use of this method. First due to increasing costs and the need for specialized equipment, its use in large-scale studies is limited. Second, it does not provide information on the "pattern" (i.e. frequency, intensity and duration) of activity (27).

Various types of motion sensors have been developed in an attempt to more objectively and accurately monitor physical activity in the field setting. The electronic pedometer, a low cost device, has been shown to be accurate for measuring walking behavior, expressed either as steps per day, or distance (5). However, these devices have limitations when it comes to measuring lifestyle activities. Only modest relationships were found ($r = .493 - .580$) between the electronic pedometer and indirect calorimetry across selected moderate intensity activities (5). The pedometer cannot distinguish between walking and running, and cannot distinguish whether external work is taking place. Another limitation is that they lack an internal clock, and cannot store data. Thus, the pedometer cannot provide any information on the frequency, intensity or duration of activity.

In addition to pedometers, several types of accelerometers are also commercially available. These devices are able to detect and record the actual magnitude of acceleration and deceleration of motion. The information from these devices can be stored for long periods of time, in some cases up to weeks. Laboratory and field investigations have developed regression equations to predict MET levels and energy expenditure from accelerometer readings; 1 MET is resting metabolic rate, and is taken as being equal to 3.5 $mL \cdot O_2 \cdot kg^{-1} \cdot min^{-1}$. Although laboratory regression equations have shown accelerometers to be fairly accurate for activities such as walking and running (8, 19), regression equations developed in the field and validated against direct measures across a variety of tasks have not shown such favorable results (coefficient values ranging from $r = 0.4 - 0.6$ [5, 10]).

The well-known linear relationship between heart rate and oxygen uptake (from which energy expenditure can be computed) has led investigators to explore the potential for using heart rate to estimate energy expenditure in free-living subjects. It is a method of assessment that is low in cost, non-invasive and can provide information on the pattern of activity. Heart rate monitors have been shown to be valid in relation to electrocardiogram monitoring in both the laboratory and field settings (12, 15, 30). In addition, advancement in microchip technology has resulted in the development of smaller, cheaper monitors capable of continuous recording for several days or even weeks. Most researchers now advocate the use of individualized heart rate-oxygen uptake calibration curves generated in the laboratory, to account for differences in this relationship due to age and levels of cardiorespiratory fitness. A major disadvantage of heart rate monitoring is the variable relationship between heart rate and energy expenditure for low intensity physical activities. Although approaches have been developed to account for this variation, it still remains a limitation. Another significant limitation is that the heart rate-oxygen uptake relationship is also dependent upon factors such as activity mode, emotion, posture, and environmental conditions (11). Therefore, heart rate alone may not be a suitable surrogate for determining energy expenditure.

In an attempt to overcome some of the individual limitations of heart rate monitoring and motion sensors, it was recently proposed that a combination of these monitoring techniques could improve the prediction of energy expenditure (9). Haskell et al. (9) evaluated such an approach, focusing on the use of simultaneous heart rate and motion sensor technology. Their laboratory-based study demonstrated that the accuracy of estimating energy expenditure during a wide range of activities was improved when individualized heart rate-oxygen uptake regressions were used and heart rate and body movement was analyzed simultaneously rather than independently. The authors concluded that individual heart rate-oxygen uptake regressions should be determined first in the laboratory for both arm and leg exercise, thus accounting for variations due to age, cardiorespiratory fitness levels, and activity mode. Then in the field setting, motion sensors could be used to discriminate between arm and leg movement, and heart rate estimates of metabolic energy expenditure refined to discriminate between upper- and lower-body activity. Other laboratory-based investigations have also suggested that the simultaneous heart rate-motion sensor technique is an acceptable method for predicting energy expenditure (16, 21, 28).

Statement of the Problem

The complex nature of physical activity makes it difficult to assess this particular behavior. There is much inter-individual variation in the energy cost of daily activities, especially in relation to age and individual physical activity/physical fitness levels. However, it is necessary to have more accurate measures of physical activity in order to clearly establish the dose-response relationship between physical activity behaviors and specific health outcomes.

Statement of Purpose

The purpose of this dissertation is to examine new techniques to measure dimensions of physical activity and energy expenditure during free-living activities. This dissertation takes a sequential approach. First, Part III evaluates a new method for assessing moderate intensity physical activity in the field setting, based on the use of percent heart rate reserve in relation to percent oxygen uptake reserve. Second, Parts IV and V contain validation studies of the simultaneous use of heart rate and motion sensors to assess the measurement of physical activity and energy expenditure. It was proposed that the simultaneous use of heart rate and motion sensors could eliminate some of the individual limitations associated with these measurement techniques, and serve to improve the prediction of energy expenditure. These studies evaluate this approach in the field setting. Lastly, Part VI uses the newly validated simultaneous heart rate-motion sensor technique to assess the accuracy of selected physical activity questionnaires over a continuous 7-day period of free-living activity.

Significance of these Studies

The simultaneous heart rate-motion sensor technique can accurately evaluate different dimensions of physical activity. Its use may be limited to small physiologic investigations, or to serve as a suitable criterion measure against which other measures can be evaluated.

The establishment of the accuracy of different physical activity questionnaires could enable a more precise measurement of different activity dimensions in large population based investigations. A more accurate estimation of physical activity in free-living population samples could enable a more precise evaluation of the "dose" of physical activity needed to achieve specific health benefits.

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PART II

REVIEW OF LITERATURE

Physical Activity and Positive Health

The importance of physical activity has been known for some time, as far back as 400 B.C. when Hippocrates wrote; *"Eating alone will not keep a man well; he must also take exercise"* (109). Since those early times opinions have varied over how much physical activity is needed to promote health. As advances in technology have now enabled most of modern society to lead an essentially sedentary lifestyle, the consequences of inactivity, and benefits of activity, are becoming increasing apparent. Epidemiological investigations have demonstrated that coronary heart disease mortality decreases in those that are more physically active (1, 17, 72, 75, 93). Furthermore, other studies support the role of physical activity in preventing or managing type 2 diabetes (27, 34, 41, 43, 61, 62), hypertension (38, 49, 76, 84, 115), obesity (16, 23, 30, 67, 95), dislipidemia (28, 29), selected cancers (14, 54), and reducing depression and anxiety (63, 70). After repeated investigations demonstrating the importance of physical activity, many health organizations now acknowledge the causal role of physical activity in positive health (3, 109). Yet even with a plethora of scientific evidence demonstrating the positive association between physical activity and positive health, there still remains a great deal to be learned about the type, intensity, frequency and duration of physical activity needed to bestow specific health outcomes.

Previous exercise recommendations have focused on improving cardiorespiratory fitness by way of advocating physical activity for a sustained 20-60 minute period three times per week at an intensity of 60-90% maximum heart rate (2). Recently there has been a paradigm shift towards a less stringent promotion of an active living recommendation advocating regular moderate intensity physical activity to improve the health of those who are least active (79, 109). The American College of Sports Medicine (ACSM) and the Center for Disease Control and Prevention (CDC) now recommend that *"all Americans accumulate 30 minutes or more of moderate intensity physical activity on most, preferably all, days of the week"* (79). This recommendation was not intended to take the place of the more formal cardiorespiratory fitness recommendations, moreover, it was to promote an active lifestyle to those who are currently inactive. Thus, the recent activity guidelines are designed to promote an active lifestyle through increases in habitual physical activity.

Physical Activity Dimensions

The accurate assessment of physical activity in free-living populations remains a daunting task. Physical activity is a complex behavior that incorporates classifications of type, intensity, frequency, and duration of activity. Within the field of physical activity assessment the terms "physical activity," and "exercise" are often used interchangeably, where in fact they are distinct concepts. For clarity the definitions of Casperson and colleagues will be used (20). "Physical activity" is defined as any bodily movement produced by the contraction of skeletal muscles resulting in caloric expenditure. Physical activity maybe categorized as occupational, sports, household, conditioning, leisure, transportation, or other activities. "Exercise" is a sub-category of physical activity and is any activity that is planned, structured and repetitive having the improvement or maintenance of "physical fitness" as an objective. "Physical fitness" is defined as a multi-dimensional trait including strength, muscular endurance, cardiorespiratory fitness, flexibility, and body composition.

The concept of physical activity can, therefore, have overlapping dimensions. Classifications of physical activity can include type (static, dynamic, upper body, lower body, weight bearing, non-weight bearing), frequency, intensity, and duration. The complex nature of physical activity has led to uncertainty over which dimension is the most important for specific health outcomes. Therefore, it remains necessary to establish the dose-response relationship between varying dimensions of physical activity and specific health outcomes.

The Dose-Response Relationship Between Physical Activity and Health

In the past, physical activity was prescribed with an emphasis on improving physical performance and/or fitness. Physical activity regimes were thus typically evaluated in relation to their ability to increase cardiorespiratory fitness. However, physical activity required to improve cardiorespiratory fitness and performance may not be the same as that required to improve health and prevent disease. To date, the frequency, intensity, duration, and total volume of physical activity required to elicit health outcomes has not been clearly defined. Health benefits might be achieved by frequent bouts of low-intensity activity that is inadequate to promote physical fitness, or they may be a result of the adaptive response of bodily systems to repeated accelerations of energy production during exercise. However, whether it is repeated short-term effects of low intensity activity, chronic training effects, or a combination of these or more dimensions that is the required stimulus for health, still remains uncertain. In order to fully define or measure the dose-response relationship between physical activity and health it is necessary to have accurate methods of assessing all dimensions of physical activity.

Physical Activity Assessment

Habitual physical activity has been assessed in a multitude of ways over recent years with each method capturing various dimensions of the physical activity spectrum. The methods of assessment used include both subjective and objective measures. Subjective measurement tools include physical activity questionnaires/interviews and physical activity diaries, broadly labeled as “recall strategies”. Objective measures of physical activity include the measurement of body motion, and physiological variables such as heart rate, oxygen uptake, and carbon dioxide production. The following review describes the range of methods that are currently available to assess habitual physical activity, including advantages and limitations of each.

Subjective Assessment of Physical Activity

There currently exist in excess of 35 different physical activity questionnaires/interviews used within the field of physical activity assessment. The vast number of these measurement tools in itself represents a quandary to the investigator. The questionnaires differ in the method of administration (telephone, pencil-and-paper, or in-person interview), the time frame over which activity is assessed, and the type of activity that is measured. Some questionnaires ask three to four simple questions, whereas others go into extensive detail covering activities performed during household chores, leisure-time activities and occupational activities. Within the last few years there has been a plethora of information generated about the validity and reliability of selected physical activity questionnaires. It is beyond the scope of this section to describe the whole range of currently available physical activity questionnaires, although these have been reviewed previously (81). However, in the context of this review it is important to discuss the conclusions drawn from investigations utilizing questionnaires and recalled information to assess physical activity levels.

Physical Activity Assessed by Questionnaire

Physical activity questionnaires are extremely effective for recalling structured exercise. Participation in activities such as jogging, swimming, and sports are easily recalled by the individual because they make a purposeful decision to take part in these activities (110). The energy expended during these activities can then be quantified by ascribing a specified metabolic cost to the activity (5). This approach is common to most recall strategies. Even though this approach is common, the essence of focus remains on exercise, and not necessarily on physical activity. Therefore, a major problem with physical activity questionnaires is that they do not capture all of the underlying dimensions of physical activity. For example, energy expended during exercise only represents a portion of the energy expended in physical activity, so questionnaires are unlikely to represent all physical activity performed during the course of a day, week or year. Furthermore, structured exercise is often performed in a vigorous manner, so in this regard physical activity questionnaires may fail to capture ubiquitous light to moderate intensity physical activity (7, 82).

One of the most frequently used physical activity questionnaires is perhaps the *Harvard Alumni Questionnaire*, also referred to as the *College Alumnus Questionnaire*. The original investigation using this questionnaire, carried out by Paffenbarger et al. in 1978, focused on physical activity as an index of heart attack risk in college alumni (75). This investigation, a milestone by any standards, assessed 16,936 male alumni, who were followed from 1962 or 1966 to 1972. During this 6-10 year follow-up, 572 men experienced a first heart attack, 357 nonfatal and 215 fatal. Physical activity was assessed by asking the participants to recall, flights of stairs climbed per day, city blocks walked per day, and sports played. A composite estimate of weekly energy expenditure (kilocalories/week) was then compiled from the gathered information. A physical activity index, <2000 kilocalories·wk^{-1} and >2000 kilocalories·wk^{-1} was developed. This investigation revealed that those alumni expending >2000 kilocalories·wk^{-1} had a 26 percent reduction in heart attack risk in comparison to those expending less than 2000 kilocalories/week.

Although the investigation by Paffenbarger et al. (75) highlighted a positive association between physical activity and health, proposing a recommendation of accumulating >2000 kilocalories·wk^{-1} based on this information warrants a degree of caution. For example, remembering that a large component of the information collected pertained to sports play, does a 2000 kilocalories·wk^{-1} recommendation mainly relate to vigorous activity? In addition, as previously mentioned, vigorous activities are easily recalled, but light-moderate activities such as walking are not so easily recalled. This has been recently shown with a head-to-head comparison between the *Harvard Alumni Questionnaire* and the electronic pedometer (12). Bassett et al. (12) showed that the *Harvard Alumni Questionnaire* underestimates total daily walking distance. So, although physical activity questionnaires are feasible and practical in large-scale studies, they do not fully capture all of the complex dimensions of physical activity. Precision about what physiological exposure is being measured becomes very important when results gathered from physical activity questionnaires are translated into public health recommendations. Although exercise participation may predict health outcome, do we need to recommend vigorous activity, or will light-moderate activity also translate into positive health outcomes? Is expending a total of 2000 kilocalories/week sufficient to promote health, or does this pertain only to energy expended during vigorous activities? This has very important implications to the public, as light activity may also promote health and longevity. Answers to such questions cannot be fully addressed by assessing physical activity by means of questionnaire, simply because the physical activity questionnaire fails to capture all of the dimensions involved.

Validation Studies for Physical Activity Questionnaires/Surveys

Although it is generally accepted that physical activity questionnaires and surveys perform an important function in measuring causal associations between physical activity and health, a factor that warrants discussion is how the validity of these measurement tools are established. A lot rests on the selection of a "gold standard" used to assess the questionnaire/survey. Comparisons between questionnaires/surveys and other subjective instruments will only measure convergent validity, and correlated error is likely to exist (110). There have been numerous studies focusing on the validity of selected physical activity questionnaires incorporating the self-reported physical activity diary, or log, as a criterion measure (4, 22, 83, 86, 105, 114). Williams et al. (114) reported on the convergent validity between the Physical Activity Log, the Stanford 7-day Recall Questionnaire, and the Caltrac accelerometer. Forty-five subjects between the ages of 18 and 52 years took part in this study. All three physical activity measures were obtained over a three-week period. It was reported that the physical activity log, and the Stanford 7-day Recall Questionnaire had high levels of test-retest reliability and a high level of convergent validity for all three weeks of study.

Ainsworth et al. (4) recently reported on the accuracy of a physical activity telephone survey using the physical activity log as a comparison measure. This study assessed the physical activity habits of 38 men (age 47 ± 15 yrs) and 45 women (age 45 ± 16 yrs) for a 21-day period. Each day, participants completed a one-page, 48-item physical activity log. Once a week participants also responded to a telephone survey. Spearman rank-order correlations between the survey items and the physical activity logs were $r = 0.26$-0.54 ($P<0.01$) for moderate and walking activities and $r = 0.09$ ($P>0.05$) for hard/very hard activities. The authors concluded that although these correlations are modest in size, they show that it is possible for a telephone-administered survey to reflect participation in moderate intensity physical activity. Although this study demonstrated that the physical activity log data, and the survey data show similar results, the physical activity log is not a gold standard measure. Therefore, even though this study demonstrated convergent validity, this could simply represent correlated error.

Other physical activity questionnaire validation studies have used either motion sensors (6, 36, 45, 66, 86, 88, 92), variables such as maximal aerobic power or skinfold thickness (6, 45, 86), energy intake (8), or doubly labeled water (36, 82, 97) as gold standard methods. Focusing on the motion sensors versus physical activity questionnaires first, one such study carried out by Miller et al. (66) attempted to compare 5 physical activity questionnaires using the Caltrac accelerometer as the gold standard method. Within this study 33 participants were monitored for seven consecutive days. The Caltrac data were compared with five questionnaires, the Baecke; the Godin and Shephard; the Ross and Jackson; a 3-day record; and a 7-day recall. The foremost conclusion from this investigation was that a strong significant correlation was found between the Caltrac and the 7-day recall questionnaire ($r = 0.79$), and that this represented adequate validity. The inherent limitation of this conclusion is that the Caltrac is not a gold standard measure of physical activity and has considerable limitations as a physical activity measurement device; the Caltrac is reviewed in a later section. Therefore, while the two measures of physical activity were strongly correlated, the Caltrac does not provide quantitatively accurate measurements of physical activity.

One of the most comprehensive attempts at validating physical activity questionnaires was undertaken in the Survey of Activity Fitness and Exercise (SAFE) study (45). In this study 10 physical activity questionnaires were compared with two-day physical activity diaries, collected monthly for 14 months, accelerometry assessment, and other measures, including body fatness, and maximal aerobic power. Although this was a complex study design, the choice of a gold standard method can be scrutinized. Physical activity diaries, or recall information, and accelerometry, discussed in a later section, are not gold standard methods, so again correlated error is likely to occur. Although, physical fitness and body composition might be associated with physical activity, they are not a direct measure of physical activity so cannot be viewed as a gold standard method either. Therefore, this study did not fully assess the ability of the ten physical activity questionnaires selected to quantitate physical activity levels.

Other validation studies of physical activity questionnaires have used energy intake or doubly labeled water as a gold standard method. Albanes et al. (8) examined the validity of eight physical activity questionnaires in relation to energy intake and resting energy expenditure. The questionnaires that they studied where, the Harvard Alumni; the Pennsylvania Alumni; the Five-City Project (7-day recall); the Framingham; the Health Insurance Plan; the Baecke; the Lipid Research Clinics; and the Minnesota Leisure-Time Physical Activity Questionnaire. Twenty-one healthy adult males, 28-55 years old, participated in this study. Under the assumption that if an individual remains weight stable, energy intake is equivalent to energy expenditure, the investigators were able to determine total energy expenditure for this group of participants. Spearman rank-order correlations between the selected physical activity questionnaires/indexes and total energy expenditure ranged from $r = 0.49$ for the Harvard Alumni Questionnaire, to $r = 0.19$ for the Health Insurance Plan Questionnaire. Spearman rank-order correlations between the selected physical activity questionnaires/indexes and activity energy expenditure (total minus resting energy expenditure) ranged from r =0.32 for the Harvard Alumni Questionnaire to r =0.05 for the Health Insurance Plan Questionnaire. The selected physical activity questionnaires demonstrated low to moderate correlations with total energy expenditure and physical activity energy expenditure. Therefore, it was concluded that questionnaires were sufficient to characterize physical activity levels of individuals.

One significant limitation to the method of validation employed by Albanes and colleagues (8) is that the energy intake equivalent to energy expenditure method is only capable of quantifying total energy expenditure. Thus, physical activity energy expenditure can only be estimated by subtracting resting levels and the thermic effect of food. Even so, it only estimates global physical activity energy expenditure (kilocalories/day). It is unable to detect frequency, intensity or duration of physical activity, which are important dimensions to classify in order to fully explore the relationship between physical activity and health. Therefore, this validation study did not assess the validity of physical activity questionnaires for assessing the complete spectrum of physical activity.

In another validation study of physical activity questionnaires, Philippaerts et al. (82) employed doubly labeled water as the criterion measure. The investigators in this study compared the estimated energy expenditure derived from the Baecke Questionnaire, the Five-City Project Questionnaire (7-day recall), and the Tecumseh Community Health Study Questionnaire to that of the doubly labeled water technique.

The study population consisted of 19 males, approximately 40 years of age, from Belgium. Sleeping metabolic rate was determined in a respiration chamber, and average daily metabolic rate was measured over a two-week period using doubly labeled water. Measurement of sleeping metabolic rate permitted the calculation of average level of physical activity (average level of physical activity = average daily metabolic rate minus sleeping metabolic rate). The total activity index from the Baecke Questionnaire was significantly correlated with average level of physical activity determined from the doubly labeled water technique ($r = 0.69$, $P<0.001$) for all participants. The Five-City Project Questionnaire (kilocalories·wk^{-1}) only showed a modest, non-significant correlation ($r = 0.34$) against average level of physical activity for all participants. The Five-City Project Questionnaire (kilocalories·wk^{-1}) was, however, significantly correlated with average daily metabolic rate ($r = 0.61$, $P<0.01$) for all participants. The Tecumseh Community Health Study Questionnaire (kilocalories·wk^{-1}) was significantly correlated with average daily metabolic rate and average level of physical activity determined from the doubly labeled water technique for all participants, $r = 0.63$, $P<0.01$, and $r = 0.64$, $P<0.01$, respectively. This study concluded that valid data could be obtained about physical activity from the Baecke Questionnaire, and the Tecumseh Community Health Study Questionnaire. It is worth noting, however, that the Baecke Questionnaire is an index, and does not quantify energy expenditure.

Although the doubly labeled water technique remains the gold standard for measuring total energy expenditure, one significant limitation, similar to the energy intake method employed by Albanes et al. (8), is that it can only quantify global energy expenditure (kilocalories$\cdot$d^{-1}). In this respect it again can only measure one dimension of physical activity, and is unable to detect frequency, intensity or duration of physical activity. Another limitation to the doubly labeled water technique is that it is extremely expensive, requires specialized equipment, and can only be used for a maximum of 10-20 days; this is discussed in a later section.

The main conclusion drawn from this physical activity assessment section is that strong associations have been demonstrated between physical activity and various disease endpoints. However, physical activity questionnaires are prone to measure exercise rather than all levels of physical activity. Furthermore, the selection of gold standard methods to assess the accuracy of selected questionnaires has not fully examined their true validity for measuring the complete physical activity spectrum. If subjective recall information is going to be used to measure activity levels of population-based samples, additional studies are needed to fully explore the validity of questionnaires/surveys to assess all dimensions of physical activity.

Objective Assessment of Physical Activity

In addition to subjective measurement instruments, such as physical activity questionnaires/surveys, there are a number of objective assessment tools that can be utilized to monitor habitual physical activity.

Doubly Labeled Water

The premise for the doubly labeled water technique is that the oxygen atoms in expired carbon dioxide have isotopically equilibrated with the oxygen atoms in body water. Isotopically labeled oxygen in body water can exit the body as H_2O and as CO_2, whereas isotopically labeled hydrogen in body water can only exit the body as H_2O. Therefore, after a dose of water labeled with hydrogen and $^{18}O_2$ the hydrogen is lost from the body as water, whereas the $^{18}O_2$ is lost from the body as water and carbon dioxide. The difference between the elimination rates is, therefore, proportional to carbon dioxide production, from which energy expenditure can be calculated.

After Lifson et al. (56) suggested that this method of quantifying energy expenditure may be economically feasible in humans, it rapidly became the gold standard for assessing total energy expenditure. Investigations have been conducted to assess the accuracy of the dual isotope technique and the assumptions used in calculating carbon dioxide production by comparing the isotopic turnover information to carbon dioxide production obtained from whole-body calorimetry.

Schoeller and colleagues (89) examined the accuracy of the doubly labeled water method to measure energy expenditure in comparison to whole room calorimetry in nine males. Subjects remained in the room calorimeter for four days. Doubly labeled water overestimated energy expenditure by 4 ± 5%; these differences were not statistically significant.

Clinical laboratory investigations have also examined the accuracy of the doubly labeled water method to energy intake. Schoeller and Santen (90) examined the utility of this method against energy intake over 13 days in four adults. Participants remained housed in a Clinical Research Center for the entire study duration. Meals were prepared for the subjects in the Center's kitchen. Energy expenditure was calculated from energy balance by taking the sum of the dietary intake and the change in body stores. Energy expenditure measured by doubly labeled water overestimated energy intake values by 2 ± 5.6%; this difference was not statistically significant.

Delany and colleages (26) examined the use of doubly labeled water to measure energy expenditure in 16 soldiers in field conditions. This study examined two different levels of energy intake, a 2000 kilocalories$\cdot d^{-1}$ diet versus a non-restricted diet. Body composition was measured by underwater weighing prior and immediately following the study. Measured energy expenditure and doubly labeled water compared well. The doubly labeled water method over-estimated energy expenditure by 5 ± 4.1%. This difference was not significantly different.

From the handful of studies identified it can be seen that the doubly labeled water method of measuring energy expenditure is valid in controlled settings. However, it is important to note there are limitations to this assessment technique. Doubly labeled water requires specialized equipment and is extremely expensive. Another major limitation to using doubly labeled water as an assessment device, is that it is only capable of measuring total energy expenditure over a given period of time, typically 10-20 days. In this sense, this technique is not capable of quantifying the full spectrum of physical activity. Furthermore, there is a worldwide shortage of doubly labeled water, which poses a major limitation also.

Motion Sensors

Pedometers

The pedometer was originally developed hundreds of years ago, and was primarily employed to measure plots of land. However, since about the 1960s researchers have begun to use pedometers to assess physical activity behavior (100). Several kinds of pedometers have been used over the years, ranging from ones worn on the shoe and ankle, to ones worn on the hip. Until recent years only mechanical versions of the pedometer were available. This type of pedometer was plagued with reliability and validity problems, and was generally found to be unacceptable for research use (37, 52, 111). For instance, Kemper and Verschuur (52) examined the validity of two types of mechanical pedometers (German and Russian) in 58 boys aged 12-18 years. Participants walked at 1.2, 2.6, and 3.8 miles per hour, for 5, 4, and 4 minutes respectively. Participants also ran at 3.8, 5.1, 6.4 and 9 miles per hour, for 3, 3, 3, and 2 minutes respectively. The percentage deviation from the actual step rate, measured by hand, for walking was –66.0 ± 35.6% at 1.2 miles per hour, +7.1 ± 33.3% at 2.6 miles per hour, and +6.9 ± 11.4% at 3.8 miles per hour, for the German pedometer. For the Russian pedometer at the same speeds the percentage deviation was -88.8 ± 19.7%, -13.9 ± 33.9%, and +10.2 ± 8.1%. The percentage deviation for running was +5.4 ± 8.7% at 3.8 miles per hour, +3.4 ± 9.8% at 5.1 miles per hour, +0.6 ± 9.5% at 6.4 miles per hour, and +8.6 ± 8.1% at 9 miles per hour, for the German pedometer. For the Russian pedometer at the same running speeds the deviation was +6.8 ± 8.1%, +3.9 ± 6.4%, +3.7 ± 3.4%, and +9.0 ± 8.6%. These results highlighted that these two types of mechanical pedometers greatly under-predicted step rate at slow speeds, and over-predicted step rates at faster walking speeds and running speeds.

A more sophisticated electronic pedometer was later developed. These small, matchbox-size, belt-mounted devices are triggered by vertical movements. A horizontal spring-suspended pendulum arm oscillates with vertical movement of the body, thereby opening and closing an electronic circuit. When this occurs, as with walking, one event or one step is recorded.

The electronic pedometer, a low-cost device, has been shown to be valid and reliable for determining walking behavior, measuring steps per day, and quantifying distance walked (13, 53, 94, 108). One of the most conclusive validation studies to date was carried out in 1996 by Bassett and colleagues (13). This study examined the accuracy and reliability of five electronic pedometers for measuring distance walked. Twenty subjects (18-65 years) walked a 3.03 mile sidewalk course, wearing the same brand of pedometer on each hip. The authors indicated that there were significant differences among pedometers ($P<0.05$) for measuring distance/steps, with the Yamax DW-500 being one of three electronic pedometers to approximate the actual distance accurately. In addition, the Yamax pedometer showed no difference between steps recorded on the right hip in comparison to steps recorded on the left hip, 100.6 and 100.7 percentage of steps recorded, respectively. The effect of different walking speeds was also examined in this study. Participants walked on a motorized treadmill at 2, 2.5, 3, 3.5 and 4 miles per hour. The Yamax electronic pedometer was again significantly more accurate than any of the other models for tracking distance and number of steps taken.

Many pedometers now also have a calorie function, so they are able to identify how many kilocalories are expended during a specific period of time. Eston and colleagues (33) examined the validity of heart rate, pedometry, and accelerometry for predicting the energy cost of children's activities using indirect calorimetry as a criterion measure. Thirty children were studied (mean age 9.2 ± 0.8 yr), from Bangor, Wales. Each child walked (2.5 and 3.8 miles per hour) and ran (5.0 and 6.4 miles per hour) on a treadmill, played hopscotch, and sat and crayoned. Each activity was carried out for 4 minutes at a time. Oxygen uptake values were expressed as a ratio of body mass, raised to the power of 0.75 (scaled oxygen uptake). The relationship between hip pedometer counts for all activities and scaled oxygen uptake was $r = 0.81$, and the standard error of the was estimate $14.6 \text{ ml} \cdot \text{kg}^{-1} \cdot \text{min}^{-1}$. This error represented 25.8 percent error of mean scaled oxygen uptake.

Bassett et al. (11) examined the validity of the pedometer and other motion sensors compared to indirect calorimetry in a field setting in a group of 81 participants (19-74 years). Participants completed 28 selected indoor and outdoor activities for 15 minutes at a time. During each activity indirect calorimetry was measured by a portable metabolic measurement system (Cosmed K4b^2). A modest correlation between the electronic pedometer and indirect calorimetry was established ($r = 0.49$). However, the mean error score between the pedometer and indirect calorimetry (indirect calorimetry minus pedometer) was +1.1 METs, with the 95% confidence interval ranging from ± 3.0 METs. The wide error ranges highlighted in the two aforementioned studies demonstrate that the pedometer in not an accurate measurement device to establish energy expenditure in field conditions during everyday lifestyle activities. Bassett et al. (11) highlighted a number of limitations to the use of the pedometer to predict energy expenditure. Namely, the pedometer fails to account for any upper body activity, and the pedometer cannot detect whether any external work is taking place, such as when carrying or pushing objects. It was noted however, that the pedometer yielded good estimates of energy expenditure during slow and brisk walking. Additional limitations to the use of pedometers is that they lack an internal time clock and cannot store data. Thus, although the newer style electronic pedometer can accurately measure steps per day, distance walked, and even identify accurate estimates for energy expended during walking, it cannot provide any information on the complete spectrum of physical activity, failing to measure frequency, duration or intensity of activity.

Accelerometry

Caltrac

The Caltrac is a single-plane accelerometer that measures the vertical acceleration and deceleration of the body, and is usually clipped to a belt worn on the hip. The movement that is recorded is summed and is then used to estimate energy expenditure. The algorithm that is used to derive estimates of energy expenditure was developed by Montoye and associates (68). The investigators measured a multitude of different activities thought to represent average daily activities. These activities included walking and running at different speeds, knee bends, bench stepping and floor touching.

Numerous investigations have demonstrated that the Caltrac accelerometer overestimates energy expenditure during walking and jogging/running activities (10, 18, 40, 48, 74, 88, 103). Balogun and co-workers validated the Caltrac during level walking in a group of 25 subjects between the ages of 18 to 38 years (10). The subjects walked at four different speeds, 2, 3, 4, and 5 miles per hour, on a motorized treadmill for a period of eight minutes at each speed. During the test oxygen uptake was recorded every 30 seconds, and minutes six-eight were used for analysis. The Caltrac accelerometer output was monitored every two minutes. A strong linear relationship was found between Caltrac accelerometer output and energy expenditure ($r = 0.91$, $p<0.0001$). Paired *t* test results between the accelerometer output and measured energy expenditure revealed that the Caltrac significantly overestimated energy expenditure at the different walking speeds ($p<0.001$). The difference between the Caltrac accelerometer output and the measured energy expenditure ranged from +13.3 to +52.9%.

Pambianco and colleagues (77) focused on the accuracy and validity of the Caltrac accelerometer in ten overweight, >15% above ideal body weight based on the 1983 Metropolitan Life Insurance Tables, and ten normal weight subjects, aged 20-35 years. Each subject walked on a level treadmill for 15 minutes at speeds of 2, 3, and 4 miles per hour. A Caltrac was worn on each hip during the trials. Reliability was assessed by having a sub-sample of six subjects repeat the protocol on three separate occasions over a two-week period. The inter-instrument reliability was high, ranging from $r = 0.87$ to $r = 0.98$ over the three different speeds with a mean absolute percent difference of +10 ± 7 kilocalories. The inter-session reliability was also high with a small mean difference of –3 kilocalories. However, the validity comparisons revealed that the Caltrac significantly overestimated energy expenditure at all speeds, with absolute differences of +13.5 kilocalories at 2 miles per hour, +19 kilocalories at 3 miles per hour, and +25.5 kilocalories at 4 miles per hour. The absolute percent error averaged +23%. Although the Caltrac accelerometer was found to be a reliable predictor of energy expenditure, it was not a quantitatively valid measurement tool.

Haymes and Byrnes (40) examined the accuracy of the Caltrac accelerometer versus indirect calorimetry for both walking and running in twenty subjects. Each subject walked on a level treadmill at speeds of 2, 3, 4, and 5 miles per hour and ran at speeds of 4, 5, 6, 7, and 8 miles per hour. Subjects performed each stage for four minutes, with a ten-minute rest period between the walking and running bouts. The Caltrac accelerometer overestimated the energy cost of brisk walking and slow jogging by approximately +20 to +40%. In addition, this study found that the Caltrac was not able to detect changes in running velocities between speeds of 5 to 8 miles per hour.

An investigation by Bray et al. (18) determined the validity of the Caltrac in estimating energy expenditure in children aged 9-12 years. Seventeen children participated in this study. Energy expenditure predicted from the Caltrac for rest, slow walking, and brisk walking was compared to indirect calorimetry. Two Caltracs were worn, one on each hip. Interinstrument reliability was high during the resting phase, the slow walking phase and the brisk walking phase, r =0.96 (standard error of the estimate .02 kilocalories/min), r =0.93 (standard error of the estimate .12 kilocalories/min), and r =0.96 (standard error of the estimate .16 kilocalories/min), respectively. Correlations between Caltrac estimates of energy expenditure and measured energy expenditure were r =0.53 for rest, r =0.89 for slow walking, and r =0.85 for brisk walking. The Caltrac overestimated energy expenditure at both walking speeds. At the slow walking speed the Caltrac overestimated energy expenditure by 17 ± 9.1% (range, -3 to +30%), and at the brisk speed the Caltrac overestimated energy expenditure by 25 ± 13.3% (range, +5 to +46%). This study highlighted that Caltrac estimates of energy expenditure for children are inaccurate in comparison to indirect calorimetry.

In another study by Bray et al. (19), 24-hour energy expenditure via whole room calorimetry was compared to Caltrac estimates of energy expenditure. Forty girls participated in this study (mean age 13.0 ± 1.8 years). Energy expenditure was estimated by two Caltrac accelerometers, one placed on either hip, for four randomly assigned subjects. Interinstrument reliability was high, mean difference 0.8 ± 0.5%, similar to what other studies have concluded. Although Caltrac estimates of energy expenditure were significantly correlated with total energy expenditure (r =0.80), sedentary energy expenditure (r =0.84), and waking energy expenditure (r =0.85), the Caltrac significantly underestimated energy expenditure in all conditions (range of error –6.8 to –30.4%). One reason for the underestimation may stem from the fact that all subjects were instructed to perform two 20 minute bouts of stationary cycling throughout the day. A Caltrac placed on the hip will be essentially unable to detect the energy expended during stationary cycling, as this represents a majority of leg activity with minimal hip oscillations.

Johnson and colleagues examined the accuracy of the Caltrac accelerometer for estimating energy expenditure in children versus the doubly labeled water technique (48). The sample consisted of 31 children with a mean age of 8.3 ± 2.0 years. Caltrac data were collected for 2 weekdays and one weekend day within a 14-day free-living period.

Activity energy expenditure was established by subtracting resting metabolic rate, measured via indirect calorimetry, from total daily energy expenditure, derived from the doubly labeled water method. The 3-day average mean difference between the criterion method (doubly labeled water) and the Caltrac was –487.4 kilocalories, thus representing a significant overestimation by the Caltrac accelerometer. Perhaps of greater significance, was the fact that the 95% confidence interval ranged from –30.53 to –944.3 kilocalories. In this sample of 31 children the Caltrac accelerometer significantly overestimated measured energy expenditure.

Bassett et al. (11) in their study of accelerometry versus indirect calorimetry in the field, noted that the Caltrac had modest correlations with a criterion measure (portable metabolic measurement system, Cosmed $K4b^2$), $r = 0.58$, but it significantly underestimated energy expenditure by a mean difference of 0.8 METs across 28 different lifestyle physical activities each performed for 15 minutes each.

The literature to date has highlighted that the Caltrac accelerometer, although reliable, significantly overestimates energy expenditure during laboratory investigations, and has been found to both under and overestimate energy expenditure during 24-hour room calorimeter and field investigations. Therefore, it would appear that the Caltrac accelerometer is not an accurate predictor of energy expenditure in either adults or children.

TriTrac

The TriTrac-3RD accelerometer was developed by the same company who manufactured the Caltrac accelerometer. It was hoped that this device would overcome some of the limitations of the Caltrac. The TriTrac combines three independent sensors in orthogonal axes to detect acceleration in three-dimensional space (horizontal, vertical, and lateral). It weighs 170 grams, and is approximately the size of a regular pack of playing cards. The TriTrac provides minute-by-minute data that can be downloaded to a computer. The TriTrac also has the capability to store data for a 14-day period. The TriTrac is capable of measuring both activity energy expenditure, and resting energy expenditure (predicted from gender, age, height and body mass). Thus, the TriTrac can estimate total energy expenditure by summing predicted resting and activity energy expenditure. The TriTrac has the potential to predict the number of minutes spent in different intensity classifications.

There have been a number of studies assessing the reliability and validity of the TriTrac accelerometer to predict energy expenditure in both adults and children (24, 32, 46, 64, 98, 113). Jakicic et al. (46) examined the accuracy of the TriTrac-3RD to estimate energy expenditure in relation to indirect calorimetry in 20 participants (age range 18-35 years). Participants performed five different activities on separate days, each lasting for 20-30 minutes. The activities included: treadmill walking (3 miles per hour at 0% grade, 5.0% grade and 10.0% grade); treadmill running (5 miles per hour at 0% grade and 5.0% grade); cycling (50 revolutions per minute at 1.5kg resistance and 65 revolutions at 1.5kg resistance); stepping (20 cycles per minute up an eight inch step and 30 cycles per minute up an eight inch step); and slideboard (17 cycles per minute and 21 cycles per minute). Each activity was separated into five-minute segments for analysis. Participants wore two TriTrac accelerometers to assess inter-device reliability. There were significant differences between the two devices for all activity segments, highlighting a lack of inter-device reliability. TriTrac accelerometer predicted energy expenditure was significantly correlated with walking (r =0.78 – 0.86), running (r =0.79 – 0.92), stepping (r =0.54 – 0.75), and slideboard (r =0.68 – 0.81). It was not, however, significantly correlated with cycling (r =0.04 – 0.45). Difference scores (TriTrac minus indirect calorimetry) for total energy expenditure (kilocalories) were: –29.8 and –50.0 for unit 1 and unit 2 for walking; +4.8 and +13.8 for unit 1 and unit 2 for running; -51.2 and –44.3 for unit 1 and unit 2 for stepping; -65.9 and –56.4 for unit 1 and unit 2 for slideboard; and –89.1 and –86.5 for unit 1 and unit 2 for cycling. For the activities where predicted energy expenditure significantly correlated with measured energy expenditure, the range of mean error was +2.0% to –44.2%. For cycling, the mean error was –69.1%. Therefore, it would appear that estimates of energy expenditure by the TriTrac-3RD accelerometer are significantly correlated with energy expenditure values measured by indirect calorimetry for selected activities. However, the TriTrac generally underestimates the criterion measure.

Other validation and reliability studies have only examined the TriTrac in relation to subjective criterion measures, such as self-report activity logs or physical activity questionnaires (24, 32, 64, 98), or objective measures known to have potential limitations, such as heart rate monitoring (24, 113), discussed in a latter section. Matthews et al. (64) examined the TriTrac in relation to a 7-day self-report interview and a 3-day physical activity log, in a field trial of 25 participants (mean age 25.5 ± 3.94 years). The TriTrac significantly underestimated daily energy expenditure in comparison to self-report measures, and the physical activity log. The mean difference over 3-days (log) was –362.4 kilocalories·d^{-1}, and over 7-days (interview) was –310.3 kilocalories· d^{-1}. The results of this investigation would suggest that the TriTrac significantly underestimates free-living energy expenditure.

Epstein and coworkers (32) assessed physical activity levels in 59 obese children (mean age 10.5 ± 1.2 years) by both self-report and TriTrac accelerometry. Subjects were studied for two weekdays, after school, and one full weekend day. Self-report was carried out with the assistance of one parent. Although there was a significant correlation between accelerometer and self report ($r = 0.46$), the mean accelerometer values significantly underpredicted mean self-reported activity by 41.2%.

Welk et al. (113) examined the validity of the TriTrac activity monitor for the assessment of physical activity in a field setting within children. Thirty-five children aged 9-11 years participated in this study. All children were monitored over three school days. Children's activity was assessed by a TriTrac accelerometer, a Caltrac accelerometer and by heart rate. Heart rate analysis that controlled for resting heart rate, average activity heart rate, and an individualized heart rate index calculated by dividing mean daily heart rate by resting heart rate, were significantly correlated to one another, ranging from $r = 0.83$ to $r = 0.95$. This demonstrated that these two different ways of analyzing heart rate data yielded similar results. Heart rate data was, however, only moderately correlated with TriTrac accelerometer data, $r = 0.58$, and Caltrac accelerometer data $r = 0.52$. The correlations between the two accelerometers in relation to heart rate were not significantly different to one another. This would suggest that the three dimensional TriTrac did not offer any significant improvement over the single-plane Caltrac. As the two accelerometers are highly correlated to one another, r =0.88, it would appear that they are essentially measuring the same thing. This is of particular interest when one considers that the cost of the Caltrac is approximately $90, whereas the cost of the TriTrac is approximately $500. The major advantage that the TriTrac offers over the Caltrac, is that it is able to store data minute-by-minute and predict the pattern of physical activity.

Although the TriTrac accelerometer has not been as widely studied as the Caltrac accelerometer, the current literature indicates that the TriTrac significantly underestimates energy expenditure in both laboratory and field settings, similar to most of scientific literature on the Caltrac accelerometer. Some fundamental limitations to the current literature involving the TriTrac, is that it has not been validated against a gold standard measure for field-based assessment.

Computer Science Applications, Inc. (CSA)

The CSA is a small lightweight accelerometer that is housed in a durable plastic casing. The device can be easily strapped to a belt, ankle, or wrist. The CSA accelerometer has an internal time clock and is capable of storing data for 22 consecutive days. The data can then be downloaded to an IBM compatible computer. The data can be stored over various time intervals ranging from one second to several minutes. The device monitors activity with a single channel accelerometer that measures and records accelerations ranging in magnitude from 0.05 to 2 G and bandlimited with a frequency response from 0.25 to 2.5 Hz. An analog-to-digital converter quantifies the magnitude of the acceleration, establishing a linear response to accelerations. The features of the CSA make it possible to record information on the pattern of physical activity.

There have been a number of studies focusing on the validity and reliability of the CSA accelerometer in both laboratory and field based research (11, 35, 42, 47, 65, 73, 104, 107). One of the first studies to examine the validity of the CSA was conducted by Melanson and Freedson (65). This study assessed the validity of the CSA (model 5032) accelerometer during level and graded treadmill walking and running in 28 participants. Twenty-one subjects walked at 3 miles per hour, 4 miles per hour, and jogged at 5 miles per hour for eight minutes at a time. At each speed data was collected at 0%, 3% and 6% grades. Energy expenditure established via indirect calorimetry served as the criterion measure. CSA activity counts were significantly correlated to energy expenditure (r =0.89). The CSA data was then used to develop models to estimate energy expenditure (kilocalories per minute) from activity counts. Seven subjects were used in a cross-validation study to determine the accuracy of the prediction model, using CSA counts to estimate energy expenditure, again using indirect calorimetry as the criterion measure. The mean difference between predicted and actual energy expenditure in this group of seven subjects was 0.02 kilocalories per minute. However, the range of error was considerably large, at -2.86 to +3.86 kilocalories·min^{-1}. The CSA accelerometer positioned on the hip was found to be sensitive to changes in velocity, but insensitive to changes in grade.

Trost et al. (107) examined the validity of the CSA accelerometer (model 7164) in children aged 10-14 years. Thirty participants took part in this laboratory based study, which involved having each subject perform three 5-minute treadmill bouts at 3, 4 and 6 miles per hour, respectively. While on the treadmill participants wore a CSA device on the left hip and right hip. Energy expenditure was determined by indirect calorimetry. Mean activity counts were not significantly different between the left and right CSA monitor, with the interclass reliability coefficient for the two CSA devices being 0.87 across all speeds. Activity counts were strongly correlated with energy expenditure, $r = 0.87$. A prediction equation was developed to estimate energy expenditure from CSA counts for 20 participants, and then cross-validated in another 10 participants. Mean energy expenditure predicted for the 10 participants were not significantly different from zero, being 0.01 kilocalories per minute. The correlation between predicted and actual values was $r =0.93$, standard error of the estimate 0.93 kilocalories$\cdot$min^{-1}. This study highlighted that the CSA accelerometer is a valid and reliable measurement tool for quantifying level treadmill walking and running in children.

An additional study by Freedson et al. (35) established the accuracy of the CSA accelerometer (model 7164), and developed count ranges coinciding with MET intensity categories. Fifty participants walked and jogged on a treadmill at 3, 4, and 6 miles per hour. Again indirect calorimetry served as the criterion measure. CSA accelerometer counts and steady-state oxygen consumption were highly correlated with one another ($r =0.88$). Similar to the study by Melanson et al. (65) and Trost et al. (107) a random sample of participants were used to develop a model to predict energy expenditure from

CSA activity counts, in this case 35 participants. The remaining 15 participants performed a cross-validation study to determine the accuracy of the prediction model to determine energy expenditure in relation to indirect calorimetry. No significant differences between actual and predicted energy expenditure were found at any treadmill speed, the differences being -0.19, -0.46, and +0.12 kilocalories per minute for 3, 4, and 6 miles per hour, respectively. Selected cut-points were established coinciding with MET level categories for light ($\leq$ 2.99 METs), moderate (3.0-5.99 METs), hard (6.0-8.99 METs), and very hard activity ($\geq$ 9.0 METs). The authors concluded that these identified cut-points could serve as a method to classify the pattern of physical activity during field monitoring.

Even though the aforementioned studies have shown that the CSA accelerometer is both valid and reliable for level treadmill walking and running, the validity of the CSA device had never been examined in the field setting. In an attempt to further examine the accuracy of the CSA accelerometer, and to assess the relative use of selected cut points, Nichols et al. (73) assessed physical activity with the CSA accelerometer in both the laboratory and field setting. This study tested 60 individuals in the laboratory, and 30 individuals in the field. The laboratory testing involved the subjects walking as 2 and 4 miles per hour, and running at 6 miles per hour at a 0% grade. In addition, the subjects walked at 4 miles per hour at a 5% grade. These velocities were chosen to represent light, moderate, and vigorous intensity activity. The criterion measure for this study was indirect calorimetry. Participants wore one CSA on the left hip, and one CSA on the right hip to assess interinstrument reliability. *T* tests indicated no significant differences in mean counts between devices worn on the left and right hip. Laboratory identified CSA counts were strongly correlated to indirect calorimetry (r =0.88), and were used to develop a regression equation to predict energy expenditure based on activity counts. In addition, CSA cut points were established for light, moderate and vigorous activity. The field tests were performed by 30 different subjects. Each participant was asked to walk lightly, briskly, and jog around a 400-m outdoor track for 5-minutes at a time. Average velocity was determined from minutes 2-4. Estimated counts were obtained by inserting field velocity data into lab-based regression formula, then solving for CSA counts. There was a 15% error between observed and predicted counts for the light intensity, and 31% error for the vigorous intensity. The cut-points for light and vigorous activity performed in the field were higher and lower, respectively, compared to the laboratory cut points. Although the CSA has the potential to determine activity patterns in the field, this study demonstrated that considerable variability could exist when predicting CSA counts in the field from laboratory-generated data.

In 1998 the International Life Style Institute funded a number of studies to assess moderate intensity physical activity within the field setting. The results of these studies added significantly to the literature base on the assessment of physical activity. Two studies in particular, one by Hendleman et al. (42) and one by Swartz et al. (104), developed field regression equations and intensity cut points to predict energy expenditure and time spent in various intensities from CSA accelerometer activity counts. Hendleman et al (42) examined the validity of the CSA to assess moderate intensity physical activity in 25 subjects in a field setting. Activities assessed included; walking at a leisurely, comfortable, moderate, and brisk pace, playing two holes of golf, window-washing, vacuuming, dusting, lawn mowing, and planting shrubs. Energy expenditure during all activities was assessed by the TEEM100 (Aerosport, Inc., Ann Arbor, MI) portable metabolic measurement system. Regression analysis was performed with walking only data, and then with pooled data to develop regression equations predicting metabolic cost from activity counts. These equations were then rearranged to derive count cut-point values coinciding with light (>1 MET to <3.0 METs), moderate (≥3.0 METs to <6.0 METs), and hard activity (≥6.0 METs to <9.0 METs). The CSA cut-points for walking were similar to values previously reported by Freedson et al. (35). The CSA cut-points for the pooled data were 190.7 counts·min^{-1}, 7525.7 counts·min^{-1}, and 14,860.6 counts·min^{-1}, for light, moderate and hard activity, respectively. When CSA regressions for walking data were applied to all activities, the CSA substantially and significantly under-estimated measured energy expenditure by 30.5 to 56.8%. This study demonstrates the limitations of using walking/jogging based CSA regression equations like that of Freedson et al. (35) to estimate the energy expenditure of varied activities.

The study by Swartz et al. (104) not only developed intensity cut points and a regression equation to predict energy expenditure; it also added a wrist CSA site to identify whether this would significantly improve the prediction of energy expenditure (leg counts plus arm counts). Seventy participants took part in this study and completed one to six activities within the categories of yard work, housework, family care, occupation, recreation, and conditioning. Each activity was performed for15 minutes each, with minutes 5 to 15 used to establish mean energy expenditure. Energy expenditure was measured using a portable metabolic measurement system (Cosmed K4b^2). Throughout all activities each participant wore two CSA accelerometers (model 7164), one positioned on the hip, and the other positioned on the wrist of the dominant hand. The Swartz et al. investigation (104), similar to the Hendleman et al. study (42), established cut-points to identify light (<3 METs), moderate (3-6 METs), and hard intensity activity (>6 METs). The CSA cut points for light (>1 MET to <3.0 METs), moderate ($\geq$3.0 METs to <6.0 METs), and hard activity ($\geq$6.0 METs to <9.0 METs) from the Swartz et al. study (104) were 574 counts$\cdot$min^{-1}, 4945 counts$\cdot$min^{-1}, and 9317 counts$\cdot$min^{-1}, respectively. The results of this study demonstrated that the wrist, hip, and combined wrist and hip regression equations accounted for 3.3%, 31.7%, and 34.3% of the variation in energy expenditure, respectively. Even though the addition of the wrist motion sensor significantly improved the relationship between CSA counts and energy expenditure ($P<0.05$), the improvement was small, and was outweighed by the extra cost associated with an additional CSA accelerometer, and time required to analyze the information collected.

Motion sensors can provide an objective measurement of physical activity within the field setting. Motion sensors do, however, have a number of limitations when estimating energy expenditure. Motion sensors cannot identify when individuals are performing any external work, such as walking up a grade, carrying or lifting objects, or ascending stairs. In all these instances the motion sensor will essentially underestimate energy expenditure (11, 42, 104). In addition, estimates of energy expenditure will vary depending on the selection of activities undertaken to establish the regression formulas.

Thus, when using motion sensors to either estimate energy expenditure, or time spent within selected intensity categories, caution should be adhered too as these values may not be accurate.

Heart Rate Monitoring

The use of heart rate as a measure of physical activity is promising since it is a physiological parameter known to have a strong positive association with oxygen consumption. When this relationship is known, exercising heart rates can be used to estimate oxygen uptake, and therefore energy expenditure, during free-living activity. Over the years various techniques have been presented in the literature for using recorded heart rate as a means to estimate energy expenditure. Average pulse rate has been used as a predictor of daily energy expenditure (80), while others have used net heart rate (activity heart rate minus resting heart rate) (9). The most popular approach has been the use of linear predictions, established from heart rate – oxygen uptake calibration curves performed in the laboratory. Initially, the linear predictions were used for all individuals, although, it has now been established that the most accurate predictions are obtained when individual calibrations are used (15, 39, 55, 60). Individual calibrations take into account factors such as gender, age, body weight, and fitness levels. Even though this represents a feasible method to quantify energy expenditure, a concern is that considerable variation in the heart rate – oxygen uptake relationship occurs at the low end of this relationship (112). A multitude of different methods have been used in an attempt to circumvent this difficulty. One procedure that has received considerable attention is the flex heart rate method (FlexHR).

The FlexHR method determines a critical heart rate value in which values below are categorized as resting metabolic rate, and values above are used to estimate oxygen uptake from previously established calibration curves. Typically FlexHR is established as the mean value between the highest HR during rest and the lowest HR during a light exercise session. Spurr at al. (96) examined the FlexHR method to determine energy expenditure in comparison to indirect calorimetry in sixteen men (18-66 years) and 6 women (19-47 years). All subjects were individually calibrated to establish heart rate and oxygen uptake relationships. Values were initially obtained for lying, sitting, standing and then during a graded exercise protocol on a cycle ergometer. Following individual calibration, participants were then required to enter a room calorimeter for a period of 22-hours. During the time in the calorimeter each participant was required to carry out selected tasks ranging from riding a stationary cycle ergometer, to sitting watching television. The room calorimeter measured total energy expenditure, and these values were compared to the minute-by-minute values estimated from heart rate. Individual error predicting from individual calibration curves for total energy expenditure ranged from +20% to –15%.

Cessay et al. (21) also evaluated the FlexHR method to assess total energy expenditure in a group of 20 male and female volunteers. The FlexHR was established, and participants were required to spend 21 continuous hours in a room calorimeter, which included four 30-minute bouts of imposed exercise (cycling, rowing, stepping, jogging).

Recorded heart rate values only exceeded the established FlexHR values for a mean of 98 minutes. The FlexHR method underestimated measured energy expenditure by 1.2 ± 6.2%, range –11.4 to +10.6%. Of particular interest in this study was the fact that out of a continuous 21 hours and four imposed exercise bouts, heart rate only exceeded FlexHR for a mean 98 minutes.

Livingstone and colleagues (58) further validated the FlexHR technique against the simultaneous measurement of free-living energy expenditure using the doubly labeled water method. Fourteen subjects (32 ± 7.1 years) took part in this 15-day study. Individual calibration curves were constructed from cycle ergometer exercise, and FlexHR values were identified. Discrepancies between predicted total energy expenditure from the FlexHR method in comparison to the doubly labeled water method ranged from –22.2% to +52.1%, with two-thirds of the values falling within ± 10%. Similar associated error ranges to the studies reviewed have been noted in additional studies examining the accuracy of this technique to estimate energy expenditure in adults (25, 50, 51, 55, 59, 71, 87, 91).

The FlexHR method has also been examined in children. Livingstone and co-workers assessed the accuracy of the FlexHR method to predict energy expenditure in 36 free-living children, aged 7, 9, 12 and 15 years over 10-15-days, in comparison to the doubly labeled water technique (57). A similar methodology was followed as in the Livingstone study of adults (58). Discrepancies between predicted total energy expenditure from the FlexHR method in comparison to the doubly labeled water method ranged from –16.9% to 18.8%. These differences were more apparent in the 7-9 year old children (-6.1 ± 10.5%) than in the older children (+0.4 ± 7.2%). Additional studies by Treuth et al. (106), Paner-Brick et al. (78), and Emons et al. (31) have found similar associated error ranges for using the FlexHR method to estimate energy expenditure in children.

Another way of analyzing heart rate data is to express the percent heart rate reserve to percent of oxygen uptake reserve. The latter term simply expresses the oxygen uptake value as a percent of the difference between resting metabolic rate and maximum oxygen uptake. Other investigators have shown that there is a strong relationship between percent heart rate reserve and percent oxygen uptake reserve (101, 102). A recent study by Strath et al. (99) examined this approach for assessing energy expenditure in the field setting. This study continuously measured heart rate and oxygen uptake during 28 different field tasks, with oxygen uptake being measured by a portable metabolic measurement system (Cosmed K4b^2). Each activity was performed for 15-minutes. Maximum heart rate was estimated by the equation 220-age, and maximal oxygen uptake was predicted by the non-exercise formula of Jackson et al. (44). Over the complete activity range, percent heart rate reserve was linearly related to percent oxygen uptake reserve (r=0.87, SEE 0.76 METs), demonstrating that this method of analyzing heart rate data strongly agrees with measured oxygen uptake in the field. Further work is needed to evaluate this technique as a method for assessing energy expenditure during free-living conditions.

The advantage to heart rate monitoring is that it is a physiological parameter that can assess the full spectrum of physical activity, being able to determine the dimensions of frequency, intensity, duration, and global energy expenditure (kilocalories·d^{-1}). However, heart rate monitoring does have a number of potential limitations. Factors that can affect the heart rate – oxygen uptake relationship include, temperature, emotion, type of contraction, and whether the activity performed is primarily upper-body or lower-body work. However, in light of the advantages to this assessment technique, heart rate monitoring does warrant further exploration as a method to predict individual habitual physical activity patterns.

Simultaneous Heart Rate – Motion Sensor Technique

It has been proposed that the simultaneous use of heart rate and motion sensors may increase the accuracy of predicting energy expenditure and overcome some of the individual limitations of using these devices (39, 60, 69, 85, 106). Haskell et al. (39) evaluated such an approach in a laboratory-based study. Individual calibration curves for heart rate and oxygen uptake were established for nineteen men. Subjects wore two Vitalog single mercury switch motion sensors, one placed on the right wrist, and the other placed on the lateral aspect of the right thigh. Heart rate was recorded via a three-lead electrocardiogram. All information was recorded by the Vitalog recorder. This device is a multichannel recorder that allows continuous recording of physiological parameters. In addition, expired gases were collected during activity via a Medical Graphics metabolic measurement system (Model 2001). Subjects performed various activities, including walking/running, arm cranking, cycling, Air-Dyne, and bench stepping. During this time, heart rate, motion sensor data, and expired gases were collected. This study found that greater accuracy was obtained estimating energy expenditure from heart rate when individual calibration curves were used, rather than pooling the data to construct a group calibration curve. Heart rate alone appeared to be a good predictor of energy expenditure with the average R^2 being 0.94. Multiple regression analyses were performed to predict oxygen uptake from heart rate, leg motion, and arm motion during all activities. The mean R^2 was 0.89, with the mean standard error of the estimate being 2.3 $ml \cdot kg^{-1} \cdot min^{-1}$. Heart rate was the most important predictor for all activities. However, for certain activities the addition of the motion sensor data increased the R^2 above what was obtained for heart rate alone. This occurred for the Air-Dyne ergometer when arm motion data was added to heart rate it increased the R^2 from 0.69 to 0.82. The authors of this study concluded by stating that heart rate – oxygen uptake relationships should be developed in the laboratory for both arm and leg exercise. Then in the field setting, arm and leg motion sensors could establish whether primarily arm activity, primarily leg activity, or a combination of the two was taking place. Energy expenditure could then be estimated from the corresponding heart rate – oxygen uptake regression equation.

Other investigators have also examined the simultaneous use of heart rate and motion sensors. Luke et al. (60) examined the simultaneous monitoring of heart rate and motion to assess energy expenditure in ten subjects simulating different activities of daily living. This study concentrated on the benefit of adding motion sensors to heart rate to improve the prediction of energy expenditure primarily during low to moderate intensity activities, such as vacuuming, grocery shopping, loading and unloading a grocery cart, and walking with intermittent stair climbing. Motion was recorded by the Ambulatory

Monitoring System 1000. This device was worn at waist level with the mercury switch of the motion sensor positioned at the top of the left calf. The mercury switch was held in place by a velcro strap. Heart rate was recorded by an electrocardiograph telemetry unit. Motion sensor data alone was a moderate predictor of energy expenditure, mean $R^2 = 0.53$. Heart rate alone was a good predictor of energy expenditure, mean $R^2 = 0.81$. The addition of motion sensor data to heart rate data to improve the prediction of energy expenditure resulted in a small, but not significant, improvement for the group as a whole, with an increase in R^2 from 0.81 to 0.86.

Moon and Butte also examined the potential for combining heart rate and motion sensor data to predict energy expenditure. In this study twenty male and female adults (19-40 yrs) were studied for a five-day period. Day one and day five were spent in a room calorimeter. Days two-four consisted of free-living activity. The authors developed thirteen linear and non-linear functions of heart rate alone, and heart rate combined with physical activity as models to predict energy expenditure. Day one in the room calorimeter was used to conduct individualized heart rate-oxygen uptake calibration curves. This consisted of a variety of sedentary, light, moderate and heavy activities. During this time heart rate was measured by telemetry, and motion was measured by the Mini-mitter activity recorder which was taped to the thigh of the dominant leg. Days two through four were free-living days, with heart rate and motion monitored continuously during all waking hours. Heart rate during the free-living activity was monitored by a Polar heart rate watch (Vantage XL), and motion was again monitored by the Mini-mitter. Day five was spent back in the room calorimeter. The most accurate predictor of energy expenditure was from using the activity monitor to separate periods of time into active and inactive periods. Two heart rate regressions were developed in the room calorimeter, one for active periods and one for inactive periods. The motion sensor was used to determine whether the individual was active or inactive. Heart rate was then used to predict energy expenditure from the corresponding room calorimeter-developed regression equation. In this group of adults, the heart rate in combination with the motion sensor determining periods of physical activity and physical inactivity produced the smallest measurement errors of –3.3 ± 3.5% (range –10.1 to + 4.6%).

Recently, Rennie and colleagues (85) evaluated a combined heart rate and movement sensor. This new device is worn around the chest and monitors and records both heart rate and body motion. In this study eight subjects underwent individual heart rate – oxygen uptake calibration. Subjects were then required to spend a day in a room calorimeter while heart rate, body motion, and oxygen uptake were continuously measured. The estimation of energy expenditure from the combined heart rate – movement sensor was compared to the estimation of energy expenditure from the FlexHR method.

The movement sensor was used to determine periods of activity and inactivity. If the activity counts were greater than 40 counts$\cdot$min^{-1}, then the subject was assessed as being active. If the activity counts were less than 40 counts$\cdot$min^{-1}, then the individual was assessed as being inactive, and was assumed to be at resting metabolic rate. This was done to screen out elevations in heart rate due to emotional stimuli or ambient temperature. The mean error (±1 SD) associated with predicting kilojoules from the combined heart rate – movement sensor was 0.0 ± 12.5%, in comparison to the FlexHR method that had a mean percentage error of 16.5 ± 30.2%. In this validation study the combined heart rate – movement sensor predicted energy expenditure with a smaller margin of error than the FlexHR method.

It would appear from the handful of laboratory studies carried out examining the simultaneous heart rate – motion sensor technique, that as a measurement device these two methods used in unison rather than individually, can improve the prediction of energy expenditure.

Summary

In reviewing the literature on assessment strategies to estimate free-living physical activity, there is a definite need for improved techniques, especially during field and free-living conditions. In addition, much of the literature to date has failed to accurately measure the full spectrum of physical activity. Physical activity questionnaires, although easily administered to large studies, often fail to account for ubiquitous low-moderate activities, which may make-up the majority of an individual's activity accumulated throughout the day. Additional assessment approaches for measuring field based activity, such as doubly labeled water and energy intake, are only capable of measuring global energy expenditure, while others, such as motion sensors, are able to measure more dimensions but have a degree of error associated with them as to render the results questionable.

The need for accurate assessment techniques to predict all dimensions of physical activity is amplified by recent health promotion strategies calling for "*all Americans to accumulate 30 minutes or more of moderate intensity activity on most, preferably all, days of the week" (79).* In conjunction with population-based studies it is important to ascertain baseline patterns of physical activity on which well-versed recommendations can be made. At present we lack an accurate procedure to establish all dimensions of physical activity behavior within free-living conditions. Therefore, the purpose of this collection of studies was to examine new techniques of measuring habitual physical activity.

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PART III

EVALUATION OF HEART RATE AS A METHOD FOR ASSESSING MODERATE INTENSITY PHYSICAL ACTIVITY

Abstract

STRATH, S. J., A. M. SWARTZ, D. R. BASSETT, W. L. O'BRIEN, G. A. KING, and B. E. AINSWORTH. Evaluation of heart rate as a method for assessing moderate intensity physical activity. *Med. Sci. Sports Exerc.*, Vol. 32, No. 9, Suppl., pp. S465-S470, 2000. To further develop our understanding of the relationship between habitual physical activity and health, research studies require a method of assessment which is objective, accurate and non-invasive. Heart rate (HR) monitoring represents a promising tool for measurement since it is a physiological parameter that correlates well with energy expenditure (EE). However, one of the limitations of HR monitoring is that fitness level and age can affect the HR- VO_2relationship. ***Purpose:*** The primary purpose of this study was to examine the relationship between HR (beats·min^{-1}) and VO_2 (ml·$kg^{-1}min^{-1}$) during field and laboratory based moderate intensity activities. In addition, we examined the validity of estimating EE from HR after adjusting for age and fitness. This was done by expressing the data as a percent of heart rate reserve (%HRR) and percent of VO_2reserve (%VO_{2R}). ***Methods:*** Sixty-one adults (18-74 yrs) performed physical tasks in both a laboratory and field setting. HR and VO_2 were measured continuously during the 15 minute tasks. Mean values over minutes 5-15 were used to perform linear regression analysis on HR versus VO_2. HR data were then used to predict EE (METs), using age-predicted HR_{max} and estimated VO_{2max}. ***Results:*** The correlation between HR and VO_2 was $r = 0.68$, with HR accounting for 47% of the variability in VO_2. After adjusting for age and fitness level, HR was an accurate predictor of EE ($r = 0.87$, SEE =0.76 METs). ***Conclusion:*** This method of analyzing HR data, following age and fitness adjustment, could allow researchers to more accurately quantify physical activity in free-living individuals. **Key Words:** KARVONEN FORMULA, ENERGY EXPENDITURE, OXYGEN UPTAKE, EXERCISE.

Introduction

Over the last four decades there has been substantial evidence to support the importance of habitual physical activity (PA) in maintaining good health and avoiding chronic disease (17). To further develop our understanding of the association between habitual PA and health, and to define an optimal quantity of PA needed to produce improvements in health, accurate methods of PA assessment are needed. At present researchers encounter difficulties in measuring habitual PA levels non-invasively and accurately (10, 16). To further explore the relationship between PA and health, a method that would address these issues is required.

Heart rate (HR) has been commonly employed as an objective method of assessing PA (6, 20, 23, 26). The use of HR as a measure of PA is promising since it is a physiological parameter known to have a strong positive association with energy expenditure (EE) during large muscle dynamic exercise (7). HR has been shown to be valid compared with ECG monitoring in both the laboratory (12, 14, 23) and field settings (23). Reproducibility within subjects has also been shown to be quite high (25). HR recording is a method which is relatively low cost, non-invasive, and able to give information on the pattern of physical activity. In addition, technological advancements now enable HR recorders to store information over a period of days or weeks, thus providing data on various components of PA, including frequency, intensity and duration.

Various techniques have been presented in the literature for using HR data as an estimate of EE. Average pulse rate has been used as a predictor of daily EE (7, 18). A second method uses net HR (activity HR – resting HR), which has been shown to be a simple and relatively accurate method for assessing EE in the field (26). A third approach was single and multiple individual HR- VO_2calibration curves performed in the laboratory which offers the most accurate way to predict EE (1, 3, 15, 18). This approach accounts for differences in VO_{2max} and HR $_{max}$ that exist between individuals. However, the latter technique cannot be employed in large-scale epidemiological studies due to limitations in both time and expense.

The primary purpose of this study was to examine the relationship between HR and VO_2 during field and laboratory based moderate intensity activities. However, factors such as the individual's age and fitness level can affect the HR- VO_2 relationship. Thus, a secondary purpose was to examine the validity of using HR data to predict EE, after adjustment for age and fitness. This was accomplished by expressing the data as a percent of heart rate reserve (%HRR) and percent of VO_2 reserve (%VO_{2R}). The latter variables, %HRR and % VO_{2R}, have been shown to be tightly coupled and numerically similar over the entire range of exercise intensities (21, 22). This method allowed us to predict EE in METs (1 MET = average rate of EE at rest, or 3.5 $ml \cdot kg^{-1} min^{-1}$), based on the activity HR and well-established physiological relationships.

Methods

Eighty-one participants (19-74 years) volunteered to take part in this study. Twenty participants were excluded due to HR data not being collected. Therefore, 61 people (14% African American, 3% Asian, 1% Hispanic and 82% Caucasian), including 31 males (age 41 ± 13 yrs, BMI 26.2 ± 5.7 $kg \cdot m^2$, mean ± SD) and 30 females (age 40 ± 12 yrs, BMI 27.1 ± 6.2 $kg \cdot m^2$, mean ± SD), were included in this study. All participants were recruited from within the university and surrounding community through public postings and word of mouth. Each participant read and signed an informed consent approved by the University of Tennessee Institutional Review Board. Along with the informed consent, the participants completed a physical activity readiness questionnaire (PAR-Q).

Before testing, each subject's height and weight (one layer of clothes, no shoes) were measured via a stadiometer and a standard physician's scale respectively. Body density and percentage of body fat were estimated from skinfolds using the three site equations of Pollock, Schmidt and Jackson (chest, abdomen and thigh for men, tricep, suprailiac and thigh for women) by means of Lange Calipers (Cambridge, MD) (19).

Procedures

Each participant performed from one to seven of the following activities:

Activities performed at the participants' homes and at local golf and tennis clubs

Inside. Vacuuming, sweeping and mopping, laundry, ironing, washing dishes, cooking, light cleaning, and grocery shopping with a cart, feeding and grooming animals, and caring for small children.

Outside. Mowing the lawn (manual and power mowers), raking, trimming, and gardening, playing with children in the yard, and playing with animals in the yard, doubles tennis, golf-carrying clubs, golf-pulling clubs, and softball.

Activities performed in the University of Tennessee's Applied Physiology Laboratory and surrounding grounds

Inside. Walking at 67 $m \cdot min^{-1}$ while carrying items of 6.8 kg, walking at 93.8 $m \cdot min^{-1}$ while carrying items of 6.8 kg, loading and unloading boxes of 6.8 kg; stretching, and light calisthenics.

Outside. Slow walk (average 78 $m \cdot min^{-1}$) and fast walk (average 100 $m \cdot min^{-1}$) performed on an outdoor track.

Activities were performed for 15 minutes at the participants' own self selected pace. Before each activity, and between activities, the participant was asked to sit quietly for five minutes.

Indirect Calorimetry

Each participant wore the Cosmed K4b^2 (Cosmed S.r.I, Rome, Italy), a portable indirect calorimetry system, while performing every activity and throughout the rest periods. The Cosmed K4b^2 unit was mounted on the participant via a chest harness. A flexible facemask (Hans-Rudolph, Kansas City, MO), with disposable gel seal, covered the participant's mouth and nose and was attached to a flowmeter. The facemask and adjoining flowmeter were secured to the participant via a headstrap. The flowmeter is a bi-directional digital turbine and uses an opto-electric reader. The Cosmed K4b^2 oxygen analyzer and the carbon dioxide analyzer were calibrated immediately prior to each test session according to manufacturer's guidelines. After the calibration process was completed, subject characteristics (age, gender, height and weight) were entered into the Cosmed K4b^2.

Heart Rate Monitoring

The Cosmed K4b^2 also recorded HR throughout each activity, via a Polar HR transmitter (Polar Electro, Tampere, Finland). As previously cited, the use of HR recording has been shown to be valid in both laboratory (12, 14, 23) and field settings (23). The Cosmed K4b^2 uses a Polar HR "detection board" (PCBA receiver 380193) to receive HR data from the Polar HR transmitter. This is the same technology as that found in Polar heart watches, which have previously been shown to be valid (13). We decided to further assess its accuracy in a validation study among a subgroup of eight volunteers from this study. In this validation study, HR was measured during the final minute of successive 3-min stages, which included seated rest on a Monarch 818E cycle ergometer, and pedaling at power outputs of 50, 100, 150 and 200 W. The correlation between HR, from the Cosmed K4b^2 and an ECG tracing (Burdick EK10, Milton WI), using the number of complete cardiac cycles in a 60s interval (Lead II), was r = 1.00, SEE (standard error of the estimate) = 0.65 beats·min^{-1}.

Nonexercise $VO_{2\,max}$ and HR_{max} Prediction

A non-exercise prediction equation estimate of VO_{2max}, and age-predicted HR_{max} were employed. VO_{2max} was predicted for each participant using the equation of Jackson et al. (9) which incorporated physical activity level, age in years, percent body fat, and gender. Physical activity status was evaluated using a 0-7 scale which was developed by NASA's Johnson Space Center and used by Jackson et al. (9, 21). Body density, and subsequently percent body fat, was estimated from skinfold measures as described previously. The Jackson et al. (9) equation follows:

VO_{2max} (ml·kg·$^{-1}$min^{-1}) = 50.513 + 1.589 (PA[0-7]) – 0.289(yrs) – 0.552(%fat) + 5.863(F=0, M=1).

%VO_{2R} was then calculated using predicted VO_{2max}, and the measured resting and activity VO_2 values. The use of %$VO_{2R}$was employed rather than %VO_{2max} as it has recently been shown to more accurately reflect %HRR (21, 22).

Calculations

The oxygen uptake and HR data from the Cosmed K4b^2 were stored in memory and directly downloaded to a Windows-based laptop PC after the test was completed. EE in METs was computed from the participants' activity HR (Figure 1). Recorded HR values were transformed into %HRR values by utilizing the formula;

$$\%HRR = [(\text{activity HR} - \text{resting HR}) / (\text{est. HR}_{max} - \text{resting HR})] * 100\%$$

where HR_{max} was assumed to equal 220 minus age (yrs) (11). Taking into consideration that %HRR is approximately equal to the $\%VO_{2R}$, as shown by Swain et al. (21, 22), the relative intensity of the exercise bout was determined. $\%VO_{2R}$ for each activity was transformed to an absolute oxygen consumption (VO_2 $ml \cdot kg^{-1} min^{-1}$) using the formula;

$$\% VO_{2R} = [(\text{activity } VO_2 - \text{resting } VO_2) / (\text{est. } VO_{2max} - \text{resting } VO_2)] * 100\%$$

where VO_{2max} was obtained from the non-exercise prediction equation of Jackson et al. (9). VO_2 ($ml \cdot kg^{-1} min^{-1}$) was converted to METs by dividing by 3.5.

Statistical Analysis

Minute-by-minute values were obtained for HR and VO_2. For each subject the mean HR ($beats \cdot min^{-1}$) and mean VO_2 ($ml \cdot kg^{-1} min^{-1}$) were computed from minutes 5-15 for each activity. Statistical analyses were performed within SPSS 9.0 for Windows (Chicago, IL). The mean values for the subjects were then pooled and a linear regression analysis was performed to demonstrate the relationship between EE and HR. In addition,

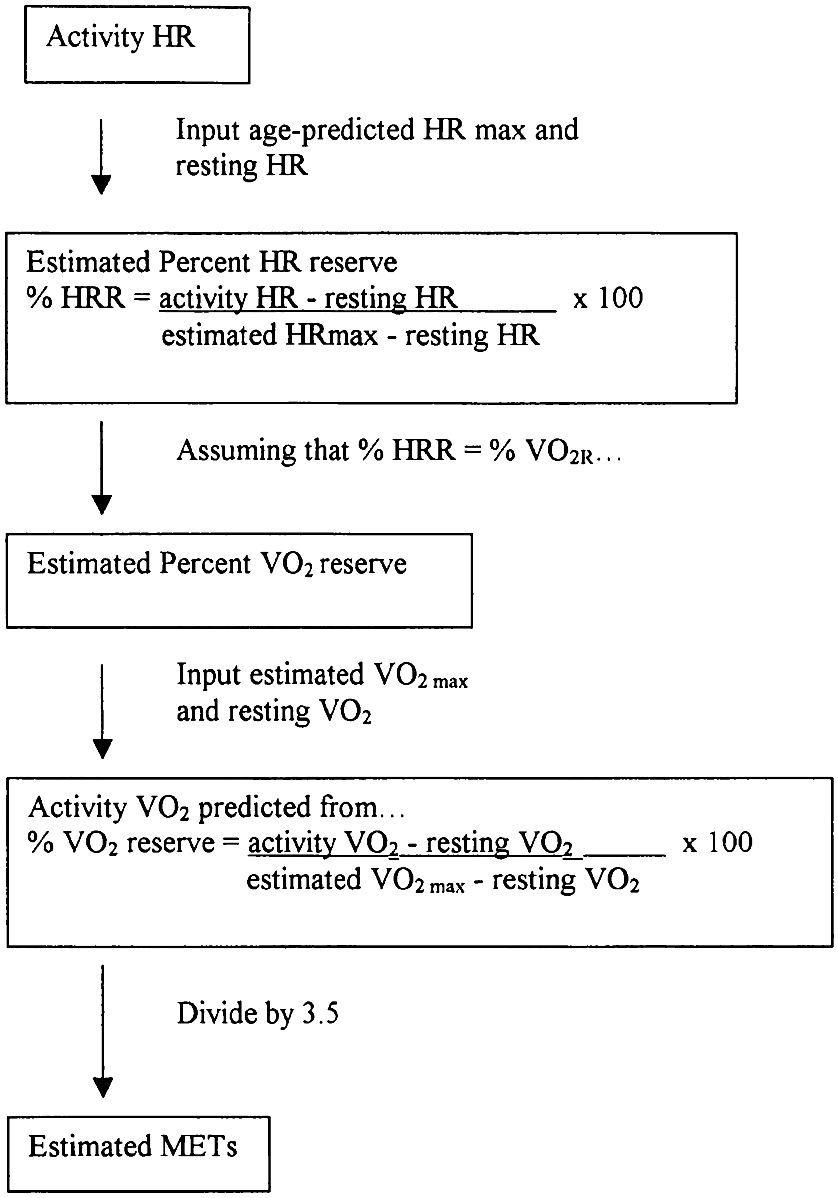

Figure 1 – Flow diagram demonstrating the use of activity HR to calculate EE (METs) via age-predicted %HRR and estimated %VO_{2R}.

correlational analysis was used to determine the validity of estimating EE from activity HR following adjustment for individual age and fitness level. A Bland-Altman plot was constructed to show the relationship of the error score (measured EE – estimated EE) across a wide range of exercise intensities.

Results

The ability of HR to track VO_2 during activity is shown in the minute-by-minute graph of HR (beats·min^{-1}) and VO_2 (ml·kg·$^{-1}$min^{-1}) for an activity period that included: lawn mowing (manual push mower), trimming (electric), and gardening (pulling weeds, planting flowers) (Figure 2).

Figure 3 shows the relationship between HR (beats·min^{-1}) and oxygen uptake (ml·kg·$^{-1}$min^{-1}) with a correlation of r =0 .68. Heart rate accounted for 47% of the variability in oxygen uptake, SEE = 18.23 ml·kg·$^{-1}$min^{-1}.

Figure 4 shows the relationship between measured EE and estimated EE (using HR data and adjusting for age and fitness) with a correlation of r =0 .87. Estimated EE accounted for 78% of the variability in measured EE, SEE = 0.76 METs.

Figure 5 highlights the relationship of the error score (measured EE – estimated EE) across a wide range of exercise intensities, mean error = 0.04 METs, 95% confidence interval (CI) = (-1.48, 1.56) METs.

Figure 2. Minute-by-minute tracking of VO_2 (ml·kg·$^{-1}$min^{-1}) and HR (beats·min^{-1}) for the activities of lawn mowing (manual push mower), trimming (electric), and gardening (pulling weeds, planting flowers).

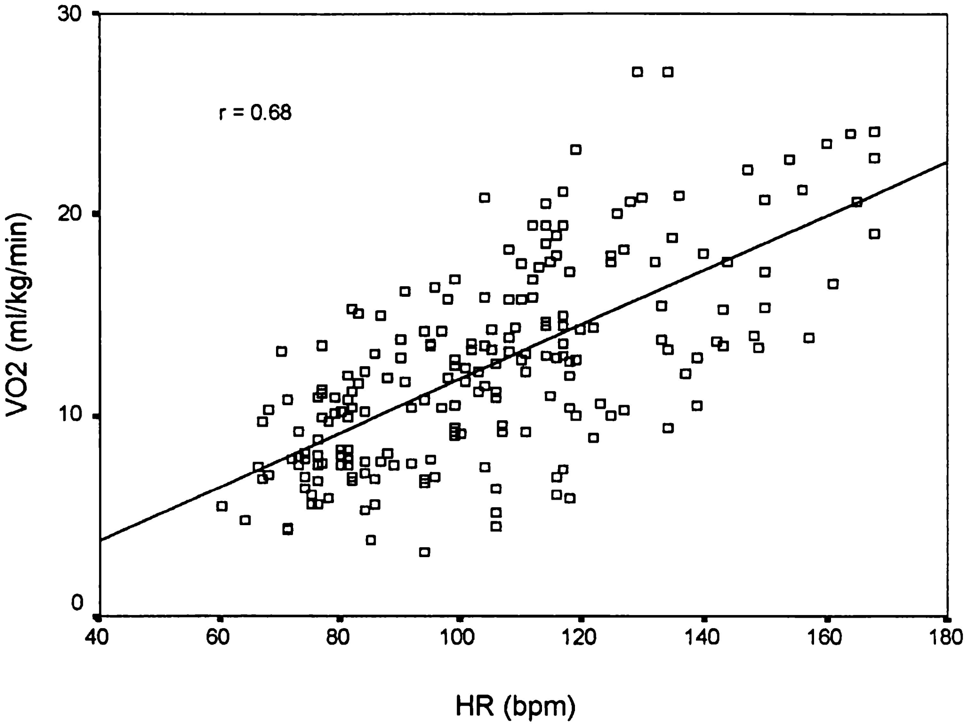

Figure 3. Relationship between HR (beats·min^{-1}) and VO$_2$ (ml·kg·$^{-1}$min^{-1})

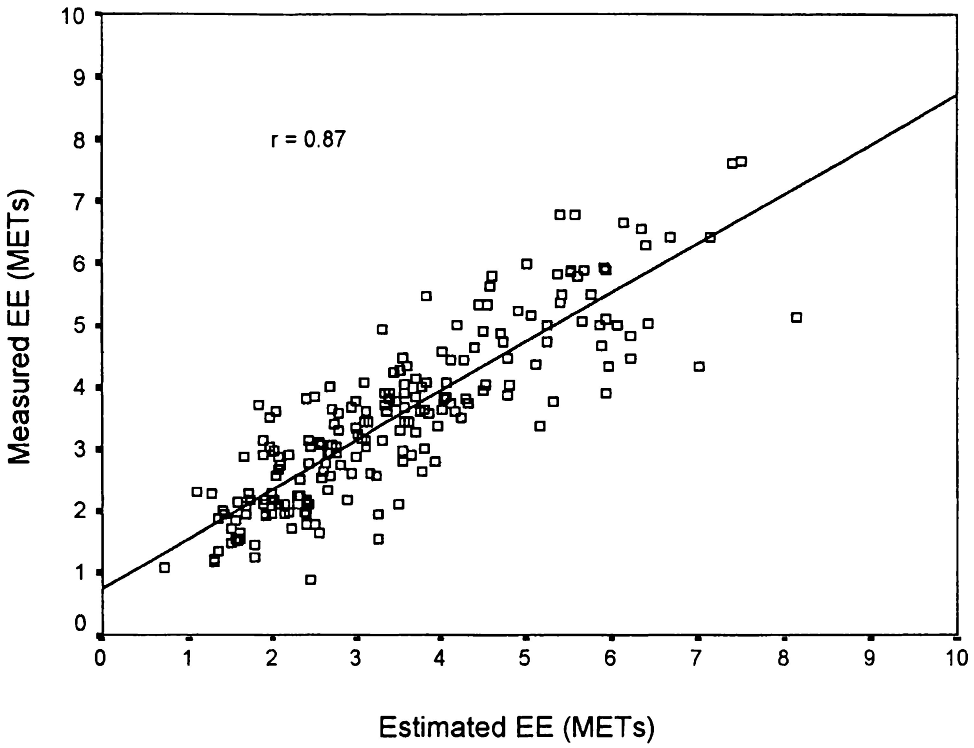

Figure 4. Relationship between measured METs and estimated METs.

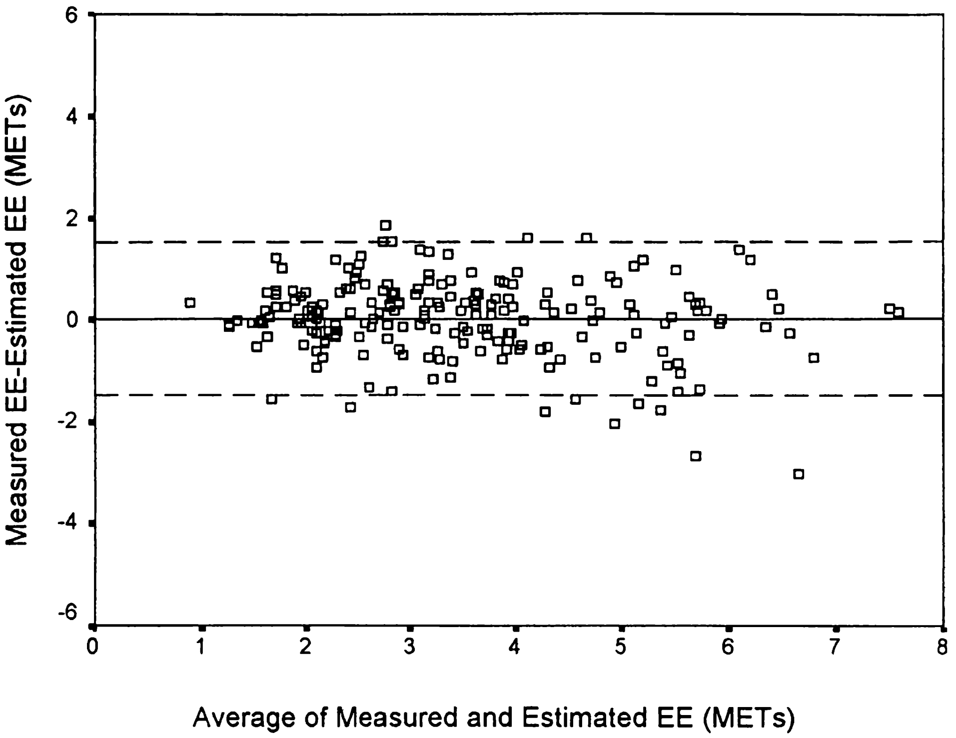

Figure 5. Bland-Altman plot showing the relationship of the error score (measured EE – estimated EE) across a wide range of exercise intensities.

Discussion

This study found that HR (beats·min^{-1}) is moderately correlated to VO_2 (ml·kg·$^{-1}$min^{-1}) during field and laboratory activities ($r = 0.68$). Rodahl et al. (20) looked at the relationship between simultaneously recorded HR and VO_2 in Nordic ocean fishermen. Oxygen uptake was measured by the Douglas bag method during specific activities. The measured VO_2 values were compared with predicted VO_2 values estimated from the HR- VO_2 relationship determined in the laboratory. The results showed that the predicted VO_2 values deviated from the measured values by no more than ± 15 percent (20).

Individual variation in gender, age, and training status have been shown to affect the HR- VO_2 relationship (5). It has long been known that trained persons have a lower HR at a given VO_2 (4). Thus, if one correlates HR versus VO_2 the correlation can be low because it does not take into account that a more highly fit individual has a lower HR at any given VO_2. This factor causes difficulty for the estimation of EE from raw HR.

The relationship between markers of relative intensity (%HRR and %VO_{2R}) is much tighter than the relationship between HR and VO_2 (21, 22). Therefore, we applied the well-established equations for age-predicted HR_{max} (11) and non-exercise estimates of VO_{2max} (9) to allow the relative intensity of the activity to be expressed. A limitation of the present study was that we did not directly measure maximal exercise values. However, this might be impractical and/or unfeasible in larger studies, particularly those studies where elderly participants are involved. Despite this limitation our findings were in agreement with those of Swain et al. (21, 22) who demonstrated a strong numerically similar relationship between %HRR and %VO_{2R} in the laboratory. Had we actually measured HR_{max} and VO_{2max}, it would have most likely improved the estimate of EE.

An important advantage of using HR over motion sensors is that HR monitoring provides an index of both the relative (%VO_{2R}), as well as the absolute intensity (METs) of the physical activity performed. The importance of relative intensity can be seen when classifying different individuals on the basis of exercise intensity. The recommendation of the Centers for Disease Control and Prevention and the American College of Sports Medicine states that *every U.S. adult should accumulate 30 minutes or more of moderate intensity physical activity on most, preferably all, days of the week* (17). Moderate intensity refers to an intensity level of 3-6 METs. However, the use of absolute cut points, such as 3 and 6 METs holds limited validity when considering populations of different ages and different fitness levels. Six METs could be perceived as "light" for a young athlete, but "hard" for an 80-yr old person. Figure 4 highlights this fact. The activities undertaken in this study were thought to represent moderate intensity physical activity, however, there were a number of older subjects who were above this level of intensity and approached 80-100% of their estimated %HRR and % VO_{2R}.

To account for this problem, the Surgeon General's report on *Physical Activity and Health* suggests the use of age-adjusted absolute MET cut-points (24). However, an alternative approach suggested in the report is the use of five relative intensity categories- very light (<25% HRR), light (25-44% HRR), moderate (45-59% HRR), hard (60-84% HRR) and very hard (≥85% HRR). In fact, it may be preferable to limit the number of categories to lower the possibility of misclassification, and use relative intensity cut points of less than 30% HRR (light), 30 to 60% HRR (moderate) and greater than 60% HRR (hard).

Figure 2 shows the time course of changes in VO_2 and HR for the activities of mowing, trimming and gardening. From this figure it can be seen that HR takes 2-3 minutes to increase to a level representative of the activity being performed, as does VO_2, the gold standard for EE measurement. Likewise at the termination of activity both HR and VO_2 take a few minutes to decrease to resting levels. This is different from the instantaneous response known to occur with motion sensors. With regards to motion sensors, other papers in this series have reported on their accuracy in estimating EE (2, 8, 27). Such studies have found lower correlation coefficients ($r = 0.4 - 0.6$) between EE and accelerometers during "lifestyle activities", than the one shown in this paper between EE and the HR method ($r = 0.87$). In addition, the variation of error involved in the HR method is less than those seen with motion sensors during "lifestyle activities" (2). The 95% CI of the error score was (–1.48, 1.56) METs, as compared to those seen with motion sensors, ranging from approximately (–2.3, 2.3) to (–2.7, 3.8) METs (2). It is important to note that there are still limitations in using HR to estimate the quantity and quality of PA and EE. These include the effects of ambient temperature, emotional state, hydration status, type of contraction and size of muscle mass involvement (4, 7, 14, 20, 24).

In conclusion, from the data collected in this study HR was shown to be a moderate physiological indicator of VO_2, and thus EE, during a wide range of "lifestyle activities". After adjusting for age and fitness level HR was a strong predictor of EE (r = 0.87, SEE = 0.76 METs). This finding could have great practical significance in large-scale studies. Therefore, HR monitoring warrants further exploration, either individually or in conjunction with other quantitative assessment methods, as a tool for the measurement of habitual PA in free-living individuals.

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PART IV

SIMULTANEOUS HEART RATE-MOTION SENSOR TECHNIQUE TO ESTIMATE ENERGY EXPENDITURE

Abstract

STRATH S. J., D. R. BASSETT, Jr., A. M. SWARTZ, and D. L. THOMPSON. Simultaneous heart rate-motion sensor technique to estimate energy expenditure. Med. Sci. Sports Exerc. In Press. Heart rate (HR) and motion sensors represent promising tools for physical activity (PA) assessment, as each provides an estimate of energy expenditure (EE). Although each has inherent limitations, the simultaneous use of HR and motion sensors may increase the accuracy of EE estimates. ***Purpose:*** The primary purpose of this study was to establish the accuracy of predicting EE from the simultaneous HR-motion sensor technique. In addition, the accuracy of EE estimated by the simultaneous HR-motion sensor technique was compared to that of HR and motion sensors used independently. ***Methods:*** Thirty participants (16 males: 33.1 yrs ± 12.2, BMI 26.1 $kg{\cdot}m^{-2}$ ± 0.7; and 14 females: 31.9 yrs ± 13.1, BMI 27.2 $kg{\cdot}m^{-2}$ ± 1.1 (mean ± SD)) performed arm and leg work in the laboratory for the purpose of developing individualized HR- VO_2 regression equations. Participants then performed physical tasks in a field setting for 15-min each. CSA accelerometers placed on the arm and leg were used to discriminate between upper- and lower-body movement, and HR was then used to predict EE (METs) from the corresponding arm or leg laboratory regression equation. A hip mounted CSA and Yamax pedometer were also used to predict EE. Predicted values (METs) were then compared to measured values (METs), obtained via a portable metabolic measurement system (Cosmed $K4b^2$). ***Results:*** The Yamax pedometer and the CSA accelerometer on the hip significantly underestimated the energy cost of selected physical activities, whereas HR alone significantly overestimated the energy cost of selected physical activities. The simultaneous HR-motion sensor technique showed the strongest relationship with VO_2 ($R^2 = 0.81$) and did not significantly over- or under-predict the energy cost ($P=0.341$). ***Conclusion:*** The simultaneous HR-motion sensor technique is an accurate predictor of EE during selected lifestyle activities, and allows researchers to more accurately quantify free-living PA. **Key Words:** PHYSICAL ACTIVITY, OXYGEN UPTAKE, EXERCISE, PEDOMETER, ACCELEROMETER.

Introduction

Numerous epidemiological studies have reported inverse relationships between physical activity (PA), assessed by questionnaire, and selected disease outcomes such as coronary artery disease, hypertension, diabetes mellitus and some cancers (8, 12, 16, 20-23). Although PA questionnaires are acceptable for recalling structured exercise, significant error may occur due to inaccuracy in recall of ubiquitous, light or moderate intensity PA (18). Consequently, questionnaires may not truly reflect one's level of PA accumulated throughout the day during lifestyle activities (2, 24). Therefore, more accurate and reliable methods for estimating PA in free-living individuals are required to generate greater clarity of the role of PA as a factor relating to human health.

The potential for using heart rate (HR) and motion sensors to assess PA and daily energy expenditure (EE) have been discussed elsewhere (3, 5, 9, 14, 18). Although each method can provide an estimate of EE, there are inherent limitations to their individual use. Heart rate is a physiological variable that closely reflects changes in PA intensity, however, it is influenced by factors such as activity mode, emotion, posture, environmental conditions and fitness level (10). Electronic motion sensors, typically placed on the hip, are growing in popularity, but are unable to detect arm movements, or the external work done in lifting or pushing objects, which may represent a considerable component of lifestyle activity (3). It has been proposed that the simultaneous use of HR and motion sensors may increase the accuracy of EE prediction and overcome some of their individual limitations (7, 15, 19, 25). Haskell et al. (7) proposed that individual calibration curves between HR and oxygen uptake (VO_2) first be established in the laboratory for both arm and leg exercise. Then in the field setting, motion sensors could discriminate between arm and leg movement, and HR could be used to predict the VO_2 from the corresponding regression equation. With the development of valid portable metabolic measurement systems (17) this important question can be fully explored within a field setting.

Therefore, the primary purpose of this study was to test the accuracy of predicting EE from the simultaneous HR-motion sensor technique over a wide range of lifestyle activities. A secondary purpose was to compare EE obtained by this technique with EE estimated from HR and motion sensors independently.

Methods

Thirty participants, 16 male and 14 female, were recruited from the Knoxville, Tennessee area to take part in this study. Individuals were recruited from within the University and surrounding community through public announcements and word of mouth. In an effort to obtain results generalizable to the U.S. population, participants within an age range of 18-60 yrs, including ethnic minorities, were included for participation (80% Caucasion, 17% African American, 3% Hispanic). Each participant read and signed an informed consent form approved by the University of Tennessee Institutional Review Board prior to participation. A health history questionnaire was also completed by all participants to screen for any contraindications to exercise.

Prior to testing, participants had their weight measured using a calibrated physician's scale (Health-O-Meter, Bridgeview, IL), and their height measured using a stadiometer (Seca Corp., Columbia, MD). The physical characteristics of the participants are listed in Table 1.

Experimental Protocols

Submaximal Treadmill Test

Participants walked on a treadmill (Quinton Instrument Co., Q65, Bothell, WA) using a modified Balke-type protocol, consisting of continuous 3-min stages. Initial speed was 2.5 mph, and was increased to 3.5 mph, after which speed remained constant while grade was increased 2% each stage. The test was terminated once the subject reached 80-85% of their age-predicted maximal HR.

Submaximal Arm Ergometer Test

Participants performed successive 3-min stages on a Monark arm ergometer (Monark 881E, Varberg, Sweden). The initial cadence was set at 50 rpm, and initial resistance at 0 kp. Thereafter, cadence remained constant and resistance increased

Table 1. Descriptive characteristics of the study participants (mean ± SD).

	Men (n=16)	Women (n=14)	All (n=30)
Age (yr)	33.1 ± 12.2	31.9 ± 13.1	32.5 ± 12.7
Height (cm)	176.3 ± 8.4	163.5 ± 14.2	170.0 ± 11.3
Weight (kg)	79.6 ± 9.1	60.7 ± 6.4	70.2 ± 7.8
BMI ($kg{\cdot}m^{-2}$)	26.1 ± 0.7	27.2 ± 1.1	26.7 ± 0.9

0.25 kp every stage. The test was terminated once the participant reached 80-85% of their age-predicted maximal HR, or they requested to stop. Five participants (4 female and 1 male) requested to stop at, 69, 71, 72, 76, and 77% of their age-predicted maximal HR, respectively.

Lifestyle Activity

Activities were chosen to represent a wide range of experiences, employing primarily arm, primarily leg, or combined arm and leg motion. HR, VO_2 and motion sensor data were collected continuously throughout each activity. Participants performed each activity for 15-min. Eleven participants performed the housework activities (6 male, 5 female), 9 performed the yard work activities (5 male, 4 female), and 10 performed the conditioning activities (5 male, 5 female). The specific activities are listed below:

1. Housework: Vacuuming, scrubbing floors, ironing, washing windows, washing dishes, and light cleaning.
2. Yard work: Power mowing, raking, trimming, and general gardening.
3. Conditioning: Slow walking, brisk walking, walking with intermittent stair climbing, and dumbbell exercises.

Portable Metabolic Measurement System

The Cosmed K4b^2 (Cosmed, S.r.l., Rome, Italy) is a portable indirect calorimeter that continuously measures expired gases. It has been shown to be a valid instrument for the measurement of VO_2, and hence EE. McLaughlin et al. (17) showed that the VO_2

values measured by the Cosmed $K4b^2$ were within 0.096 $L \cdot min^{-1}$ of Douglas bag values during a continuous incremental cycle ergometer protocol, consisting of seated rest, and five-minute stages at 50, 100, 150, 200, and 250 watts. This portable unit was calibrated in accordance with manufacturer's instructions and was used throughout all testing protocols and activities to derive measurements of VO_2.

Heart Rate

The Polar Vantage XL (Polar Electro, Kempele, Finland) was used to assess HR throughout all testing protocols and activities. This HR watch has been shown to be valid in both laboratory and field settings relative to electrocardiograph measurements of HR (11, 13, 26).

Motion Sensors

The Computer Science Applications (CSA) Inc. model 7164 (Shalimar, Florida) accelerometers were used to monitor motion during the lifestyle activities. Three CSA motion sensors were utilized. One was placed on the dominant wrist oriented along the axis of the forearm. Velcro fasteners were used to attach the CSA monitor to the wrist. A second CSA monitor was placed on the hip in accordance with manufacturer's instructions. The hip CSA was placed in a nylon pouch (manufacturer supplied) and affixed to the hip via a belt. The third CSA accelerometer was placed on the lateral aspect of the right thigh, on the mid-axillary line, orientated vertically along the femur. An elastic bandage was used to hold the CSA monitor in place on the thigh. In addition to the CSA accelerometers, an electronic pedometer (Yamax SW-701, Tokyo, Japan) was affixed in accordance to manufacturer's instructions to the hip via a belt.

Data Collection

Heart rate, VO_2, and motion sensor data were recorded every min throughout submaximal exercise and lifestyle activity protocols. Participants performed each lifestyle activity for 15-min. Each activity was preceded with 5 min of sitting rest. The data recorded between min 5-15 of each lifestyle activity were averaged to obtain mean HR, VO_2 and CSA values. Absolute VO_2 data ($ml \cdot min^{-1}$) were converted to relative VO_2 ($ml \cdot kg \cdot^{-1} min^{-1}$), and these values were then divided by 3.5 to convert them into METs (resting metabolic equivalents).

The CSA measures activity with a single channel accelerometer that records accelerations ranging in magnitude from 0.05 to 2 G. The device is programmed to detect a frequency response from 0.25 to 2.5 Hz, so as to discard movements due to vibration. An analog to digital converter quantifies the magnitude of the acceleration, establishing a linear response to accelerations. These values are then integrated over a user-specified time interval (epoch). Sixty-second epochs were specified. The three CSA accelerometers were synchronized to the same external time-piece to ensure that data from the Cosmed $K4b^2$, data from the accelerometers, data from the pedometer, and HR data were collected simultaneously. All CSA data was downloaded following each test and imported into a digital file. Average $counts \cdot min^{-1}$ were calculated from min

5-15. Average values from the CSA placed on the hip were used to determine estimates of gross EE (METs) using the regression equation of Freedson et al. (6)

The Yamax pedometer provided estimates of EE in kilocalories. The participant's body weight was entered and an assumed stride length (2.5 ft [76 cm]) was input into the pedometer. The Yamax was reset to zero immediately prior to each activity, and after 15 min of data collection the cumulative value was recorded. The cumulative EE value for the 15 min activity was divided by 15 to obtain a mean EE value in $\text{kcal}\cdot\text{min}^{-1}$. Kilocalorie values were transformed into METs using standard constants ($1 \text{ L } O_2 = 4.8$ kcals, $1 \text{ MET} = 3.5 \text{ ml}\cdot\text{kg}^{-1}\text{min}^{-1}$). Yamax values were assumed to represent net EE and were converted to gross EE. To account for the added weight of the Cosmed $K4b^2$ unit and motion sensors worn by the individual, one kilogram was added to the measured body weight in all calculations.

Statistical Analysis

For each activity performed by a participant, an error score was computed by subtracting the estimate (HR, belt-mounted motion sensors worn on the hip, simultaneous HR-motion sensor technique) from the criterion (Cosmed $K4b^2$). The mean error scores for each of the techniques were compared using a repeated measures analysis of variance using SPSS for Windows Version 10.0.0 (SPSS Inc., Chicago). Post-hoc testing was performed with Bonferroni adjustment to locate significant differences.

Error scores were graphically illustrated via Bland-Altman plots (4). In addition, linear regression analysis was performed for all measures of EE, to depict the strength of the relationship between these variables. The overall significance level was set at alpha = 0.05.

Results

Table 2 shows the mean (± SD) values for METs determined from the Cosmed K4b^2 for each activity. The mean MET range for all 14 activities were 2.1 METs to 6.1 METs, thus incorporating light, moderate and some hard intensity activities. The mean MET values for all activities are also shown for the Yamax, CSA, HR, and the simultaneous HR-motion sensor technique. The mean range for percent of age-predicted maximal heart rate indicated that the participants were working between 15.7 and 52.4 percent of their relative capacity. The MET values from the updated Compendium of Physical Activities (1) are given for comparison purposes. All mean measured values were found to be in close agreement with those listed in the Compendium, falling within ± 1 SD. The individual HR- VO_2 data collected during both submaximal exercise protocols was used to develop individualized regression equations. The treadmill component represented leg exercise, whereas the arm ergometer component represented arm exercise. Data from the individualized regression analysis for each activity were combined to show the different relationship between HR and VO_2 for arm and leg exercise (Figure 1). We chose not to examine combined arm-and-leg activity as this has been shown to closely reflect the legs-only condition (7).

Table 2. Measured and predicted energy expenditure requirements (METs), percent of age-predicted maximal heart rate, and Compendium values for selected activities.

	Measured METs	Yamax METs	CSA METs	HR METs	Sim HR-M METs	%HRmax[a]	Comp.[b] METs
Vacuuming	3.9	1.4	2.3	4.1	3.7	30.9	3.5
	(0.6)	(0.3)	(0.4)	(0.8)	(0.8)	(8.2)	
Cleaning	3.0	1.4	2.2	2.9	2.9	21.6	3.0
	(0.8)	(0.3)	(0.5)	(0.6)	(0.7)	(6.3)	
Scrubbing Floors	3.3	1.1	2.3	4.0	3.2	25.3	3.8
	(0.5)	(0.1)	(0.3)	(0.8)	(0.8)	(7.3)	
Washing Dishes	2.1	1.1	1.6	2.6	2.0	18.3	2.3
	(0.5)	(0.1)	(0.2)	(0.7)	(0.5)	(8.4)	
Window Washing	3.0	1.3	1.7	3.3	3.0	28.5	3.0
	(0.6)	(0.4)	(0.2)	(0.5)	(0.6)	(6.1)	
Ironing	2.1	1.1	1.5	2.5	1.9	15.7	2.3
	(0.4)	(0.1)	(0.1)	(0.6)	(0.7)	(8.0)	
Slow walk	3.2	4.1	3.0	3.3	3.3	35.6	3.0
	(0.6)	(1.3)	(1.0)	(0.9)	(0.9)	(5.6)	
Brisk walk	5.0	7.1	5.2	5.1	5.1	46.3	5.0
	(1.1)	(1.6)	(0.9)	(1.2)	(1.2)	(11.5)	
Weight Circuit	2.8	1.1	1.5	5.8	3.1	44.2	3.0
	(0.8)	(0.2)	(0.1)	(0.5)	(0.6)	(7.3)	
Stair Climbing	6.1	6.4	4.4	6.4	6.4	47.6	N/A
	(1.5)	(1.2)	(0.9)	(1.3)	(1.3)	(13.7)	
Power Mowing	5.6	3.0	4.2	6.3	6.3	52.4	5.5
	(0.7)	(0.7)	(1.0)	(0.9)	(0.9)	(12.0)	
Gardening	3.6	1.7	2.4	3.6	3.6	27.4	4.0
	(1.1)	(0.4)	(0.6)	(1.0)	(1.0)	(12.4)	
Manual Trimming	4.2	1.4	1.9	5.2	4.0	46.4	4.5
	(0.6)	(0.2)	(0.5)	(1.0)	(0.8)	(13.5)	
Raking	3.9	1.5	2.0	4.6	4.0	45.3	4.3
	(0.8)	(0.3)	(0.4)	(1.2)	(1.2)	(16.4)	

[a] Percent of age-predicted maximal heart rate

[b] Compendium MET values and corresponding activity codes taken from Ainsworth et al. (1)

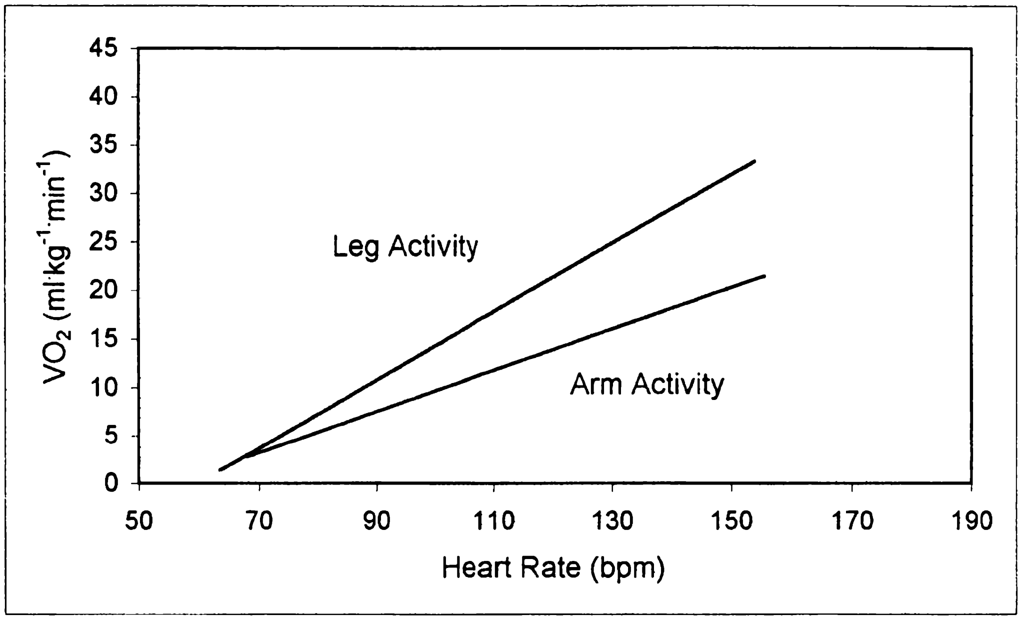

Figure 1. The relationship between heart rate and measured oxygen uptake during treadmill walking and arm ergometer exercise.

Yamax SW-701 Electronic Pedometer

The relationship between predicted METs from the electronic pedometer and measured METs from the Cosmed K4b^2 was R^2=0.36 for all participants (Table 3). The shared variance for men was R^2=0.29, and for women was R^2=0.41 (data not shown). The Yamax pedometer significantly under-estimated the measured EE by an average of 1.2 METs, or 59.2%, as shown in Figure 2 ($P<0.001$). The extent of the under-estimation was similar for men and women, +1.2 METs, and +1.2 METs, respectively (data not shown).

CSA Hip Mounted Accelerometer

The strength of the relationship between MET values predicted from the CSA accelerometer on the hip (using the regression equation of Freedson et al. [6]) and measured METs from the Cosmed K4b^2 was R^2=0.54 for all participants (Table 3). The shared variance for men was R^2=0.45, and for women was R^2=0.69 (data not shown). The CSA significantly under-estimated the measured MET values by an average of 1.1 METs, or 29.5%, as shown in Figure 3 ($P<0.001$). The extent of the under-estimation was similar for men and women, 1.0 METs (27.6%), and 1.2 METs (31.4%), respectively (data not shown).

Table 3. Shared variance (R^2) values between various methods of obtaining METs during physical activities in field settings.

	Cosmed	**CSA**	**Yamax**	**HR**	**Sim. HR-Motion**
Cosmed	1.000				
CSA	0.536**	1.000			
Yamax	0.360**	0.669**	1.000		
HR	0.667**	0.349**	0.227**	1.000	
Sim. HR-Motion	0.810**	0.536**	0.353**	0.869**	1.000

** Significant at the 0.01 level.

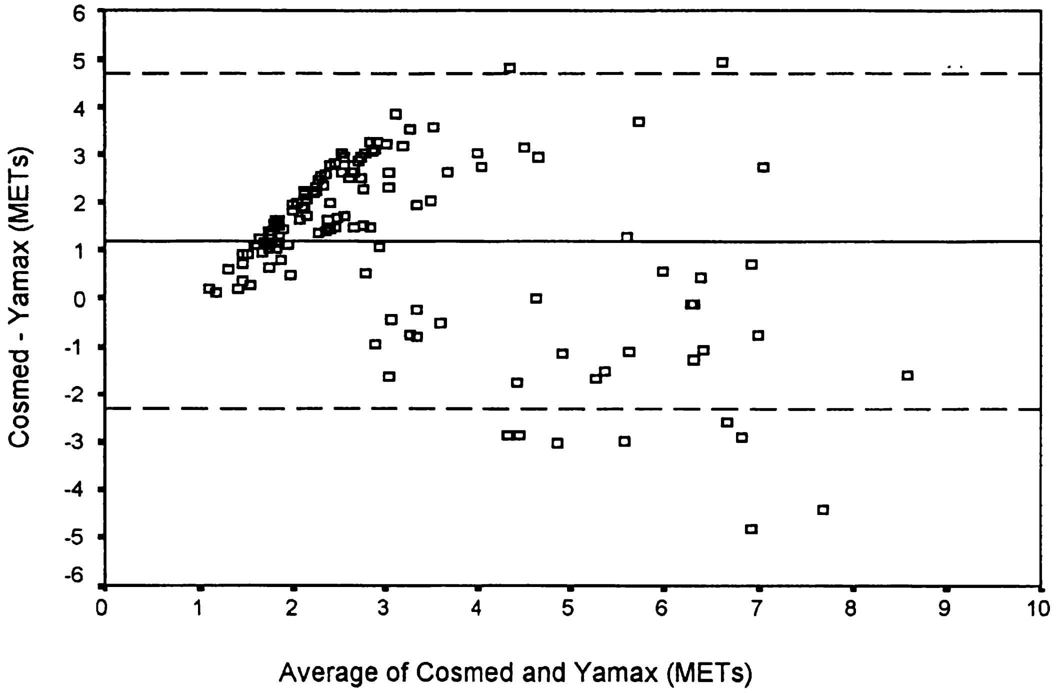

Figure 2. Bland-Altman plots depicting error scores for energy expenditure (criterion minus estimate) for the Yamax pedometer in METs. The solid line represents the mean, and the dashed lines represent the 95% confidence interval.

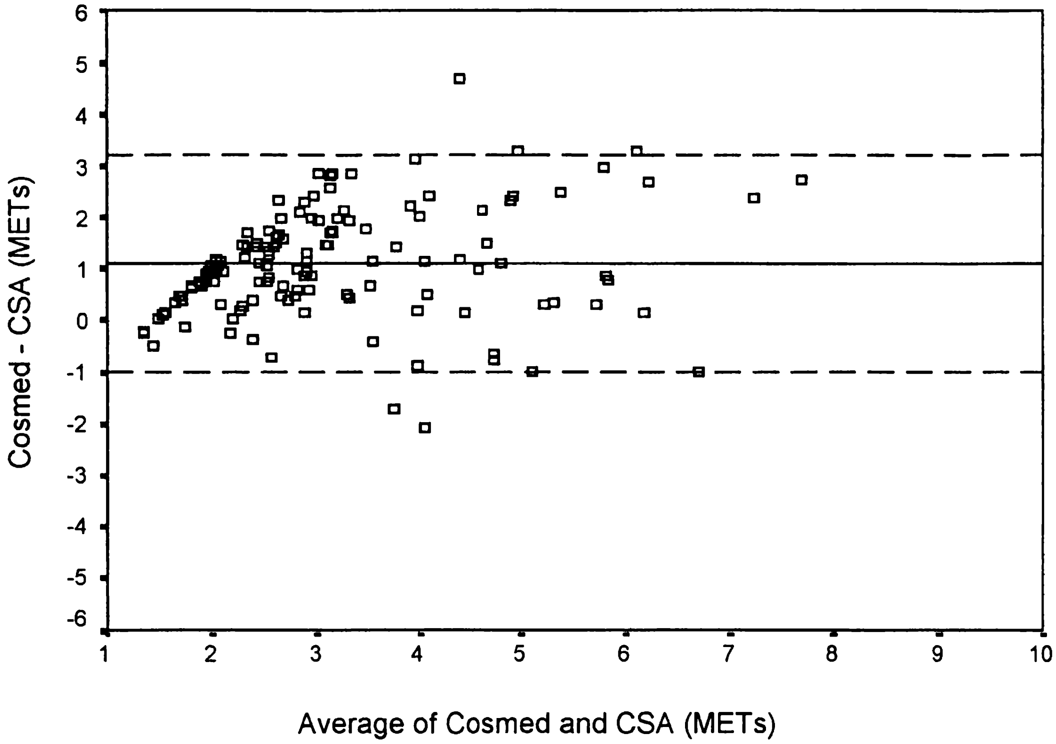

Figure 3. Bland-Altman plots depicting error scores for energy expenditure (criterion minus estimate) for the CSA hip accelerometer in METs. The solid line represents the mean, and the dashed lines represent the 95% confidence interval.

Heart Rate

Predicted METs were obtained using the individual HR- VO_2 relationship obtained during the treadmill test. The strength of the relationship between the HR method and measured METs from the Cosmed $K4b^2$ was $R^2=0.67$ for all participants (Table 3). The shared variance for men was $R^2=0.53$, and for women was $R^2=0.77$ (data not shown). The HR method significantly over-estimated the measured EE by an average of 0.4 METs, or 11.1%, as shown in Figure 4 ($P<0.001$). The extent of the over-estimation was similar for men and women, 0.3 METs (9.6%), and 0.5 METs (11.1%), respectively (data not shown).

Simultaneous Heart Rate-Motion Sensor Technique

The motion sensors were used to determine whether predominately arm or leg exercise was taking place by using a ratio between the arm and leg CSA counts. A ratio of greater than or equal to 25 was used to reflect arm work, while a ratio of less than 25 represented leg work. For example, when the arm CSA recorded 4500 counts and the leg CSA recorded 165 counts, the ratio between arm and leg motion was 27.3. Thus, the ratio was greater than 25 illustrating that predominately arm exercise was taking place, therefore we used the arm regression equation to predict METs for that particular activity. If the ratio was less than 25, we predicted METs from the leg regression equation. The strength of the relationship between predicted MET values from the simultaneous HR-motion sensor technique and measured MET values from the Cosmed $K4b^2$ was $R^2=0.81$ for all participants (Table 3). The shared variance for men was $R^2=0.71$, and for

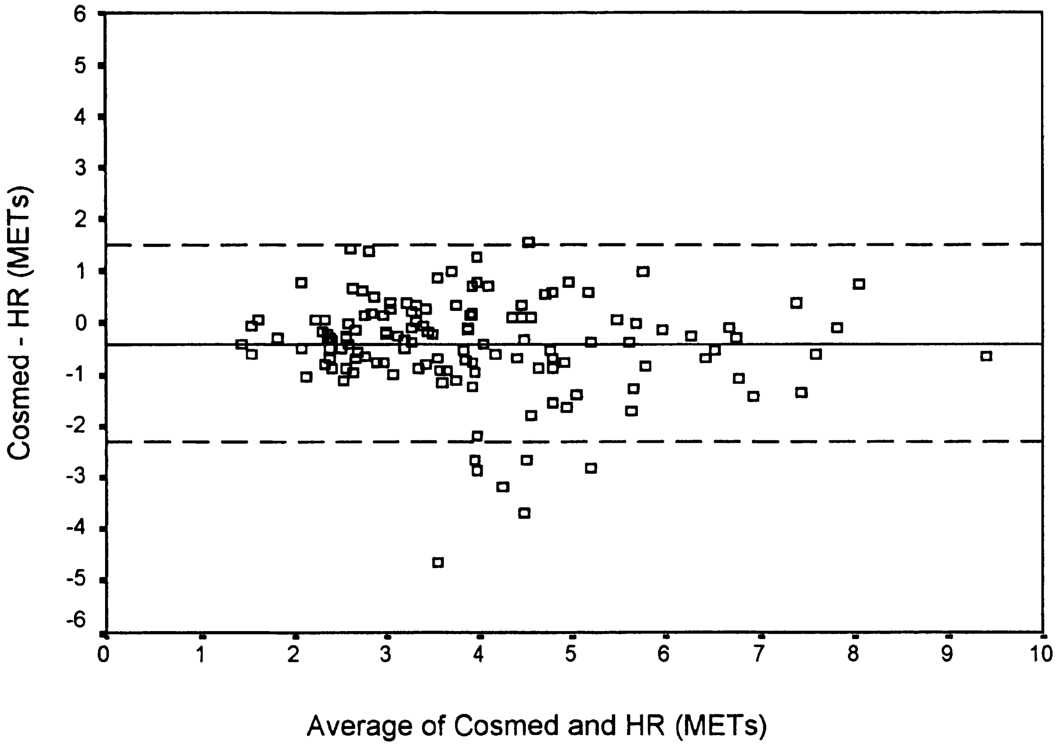

Figure 4. Bland-Altman plots depicting error scores for energy expenditure (criterion minus estimate) for HR in METs. The solid line represents the mean, and the dashed lines represent the 95% confidence interval.

women was R^2=0.89, (data not shown). The simultaneous HR-motion sensor technique showed a significantly higher relationship with VO_2 for all participants than HR alone (P<0.001), the hip-mounted CSA (P<0.001), and the Yamax pedometer (P<0.001). The simultaneous HR-motion sensor method did not significantly over- or under-predict measured EE (-0.1 METs, Figure 5 [P=0.341]). This relationship was similar for both men and women, -0.1 METs, and -0.1 METs, respectively (data not shown).

Discussion

One of the findings of this study was that the Yamax pedometer and the CSA accelerometer placed on the hip underestimated the energy cost of selected physical activities by slightly more than 1 MET (see figures 2, 3). Motion sensors used independently have a number of limitations. For instance, motion sensors worn on the hip are unable to differentiate between walking on the flat versus up or down hill or stairs, and also fail to account for upper-body activity. These limitations greatly affect the ability of motion sensors to accurately predict EE. The underestimation noted in this study for predicting EE from hip worn motion sensors is consistent with previous research examining the accuracy of estimating EE using these devices (3, 9). Results from this study also indicate that the HR method resulted in a small, but significant overestimation (0.4 METs [see figure 4]). This is due to a different relationship between HR and VO_2 when a significant amount of upper-body work is taking place. More specifically, HR will be higher for any given VO_2 during arm activity in comparison to leg activity, or combined arm-and-leg activity. This is primarily due to the

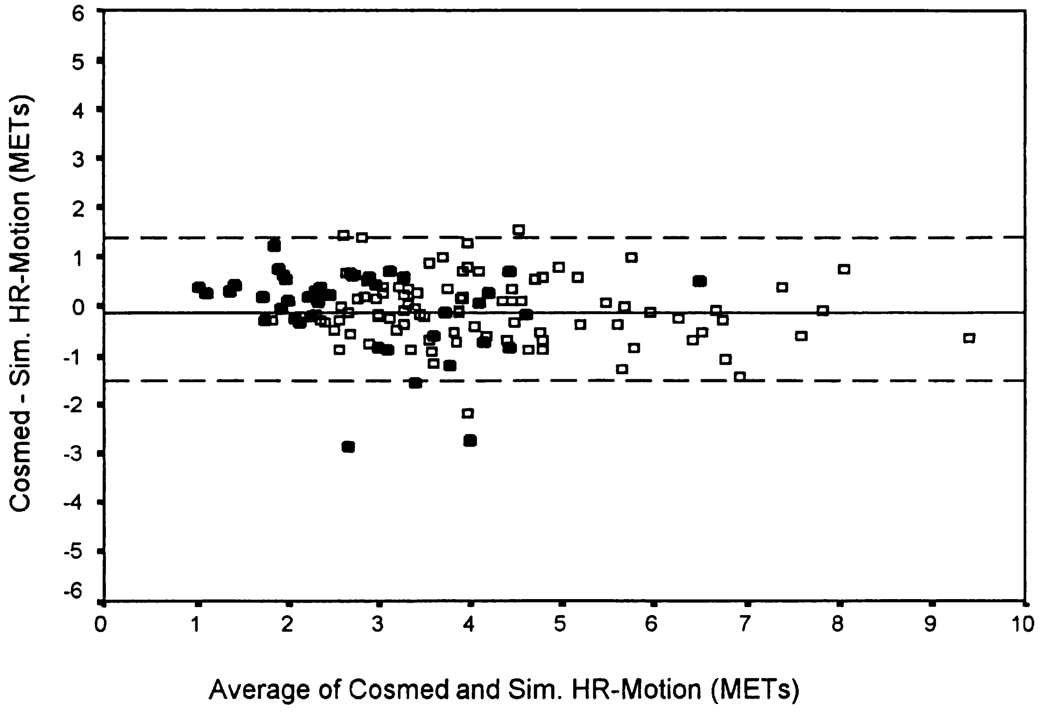

Figure 5. Bland-Altman plots depicting error scores for energy expenditure (criterion minus estimate) for the simultaneous heart rate-motion sensor technique, in METs. Closed data points in (•) indicate MET values predicted from individualized arm regression equations. Open data points (o) indicate MET values predicted from individualized leg regression equations. The solid line represents the mean, and the dashed lines represent the 95% confidence interval.

smaller amount of muscle mass involved with arm only activity. The difference in the relationship between HR and VO_2 for arm and leg activity is shown in Figure 1. Although Figure 1 highlights the different relationship between arm and leg work using group regression data, individualized data were used for predicting EE. Using a group regression equation for arm and leg activity would have introduced greater error, as other investigators have shown (7, 15). Individualized HR- VO_2 regression equations provide greater accuracy as they account for individual levels of fitness.

New information from this study indicates that the simultaneous use of HR and motion sensors provides a more accurate prediction of EE in the field setting compared to the use of HR or motion sensors independently. Arm and leg activity monitoring can, therefore, be used to refine HR estimates of metabolic EE during lifestyle activities, by differentiating between upper- and lower-body work. This differentiation allows the investigator to predict EE based on an individualized arm or leg HR- VO_2 regression equation. The results from this study show that the simultaneous HR-motion sensor technique neither under or over-predicted measured VO_2 values. The range of error (95% CI) for the simultaneous HR-motion sensor technique was within ± 1.5 METs. These results were a significant improvement over using either assessment tool independently. Although not tested in this study, another advantage of the simultaneous technique is that the motion sensors can differentiate between an increase in HR caused by PA and that caused by other influences such as emotion. A limitation to the present study was that it was only carried out over selected activities for a relatively short period of time. Additional validation studies are needed to determine whether this dual technology can accurately estimate EE over an extended period of time, and across a broader range of activities.

In summary, our results found that the simultaneous HR-motion sensor technique was an accurate predictor of EE during selected field-based activities of varying intensities. In light of these results, this technique warrants further exploration as a tool for assessing habitual PA in free-living individuals.

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PART V

VALIDITY OF THE SIMULTANEOUS HEART RATE-MOTION SENSOR TECHNIQUE FOR MEASURING ENERGY EXPENDITURE

Abstract

STRATH S. J., D. R. BASSETT Jr., A. M. SWARTZ and D. L. THOMPSON. Validity of the Simultaneous Heart Rate-Motion Sensor Technique for Measuring Energy Expenditure. To better define the dose-response relationship between physical activity (PA) and health, it is necessary to accurately quantify physical activity energy expenditure (PAEE). ***Purpose:*** The purpose of this study was to determine the validity of the simultaneous heart rate-motion sensor (HR+M) technique for estimating energy expenditure (EE) by comparing it to indirect calorimetry. In addition, we examined the validity of the flex heart rate (FlexHR) method to estimate EE. ***Methods:*** Ten participants (4 males: age 26.7 yrs ± 1.5, and 6 females: age 26.5 yrs ± 3.3) performed arm and leg work in the laboratory for the purpose of developing individualized HR-oxygen uptake (VO_2) regression equations. Participants completed physical tasks in a field setting while HR, VO_2, and motion sensor data were collected on a near continuous basis for 6 h. Accelerometers, one on the arm and one on the leg, were used to discriminate between upper- and lower-body movement. HR was used to predict EE (METs) from the corresponding laboratory regression equation. Predicted values (METs) were compared to measured values (METs) obtained via a portable metabolic measurement system. ***Results:*** The simultaneous HR+M technique showed a significantly stronger relationship with VO_2 (R^2=0.81, SEE=0.55 METs) in comparison to the FlexHR method (R^2=0.63, SEE=0.76 METs), ($P<0.001$). The FlexHR method significantly over-estimated measured min-by-min EE ($P<0.001$), whereas the simultaneous HR+M technique did not. The simultaneous HR+M technique accurately reflected time spent in resting/light, moderate, and hard activity, whereas the FlexHR method under-predicted time spent in resting/light activity (P=0.02), and over-predicted time spent in moderate activity (P=0.02). The simultaneous HR+M technique also accurately estimated total 6 h EE. ***Conclusion:*** The simultaneous HR+M technique is an accurate predictor of EE during free-living activity, and provides a valid measure of the time spent in various intensity categories. **Key Words:** PHYSICAL ACTIVITY, OXYGEN UPTAKE, ACCELEROMETER, VALIDITY.

Introduction

Evidence has accumulated over the years supporting the role of physical activity (PA) in preventing or managing certain chronic diseases (5, 8, 14, 16-18, 20, 21). Based on this research many health organizations conclude that there is a causal association between PA and positive health (1, 2, 4, 24). Even with a plethora of scientific evidence supporting the association between PA and health, there still remains a great deal to be learned about the type, intensity, frequency, and duration of PA needed to elicit specific health benefits and prevent certain diseases.

To better define the dose-response relationship between PA and health, it is necessary to accurately quantify physical activity energy expenditure (PAEE). Haskell et al. (7) proposed that the simultaneous use of heart rate (HR) and motion sensors may increase the accuracy of energy expenditure (EE) prediction. They suggested that individual calibration curves between HR and oxygen uptake (VO_2) first be established in the laboratory for both arm and leg exercise. Then in the field setting, motion sensors could discriminate between arm and leg movement, and HR could be used to predict the VO_2 from the corresponding regression equation. Recently our laboratory demonstrated that this technique can more accurately quantify EE than either motion sensors or HR used individually during selected 15-min lifestyle tasks (22).

In 1996, the U.S. Surgeon General's Report recommended the accumulation of 30 min or more of moderate intensity PA on most, if not all, days of the week (24). This emphasized the need for a method of PA assessment to accurately detect time spent in different intensity categories. Thus, the purpose of this study was to test the validity of the simultaneous HR+M technique over 6 h of near-continuous measurement. A secondary purpose was to examine the validity of the flex heart rate (FlexHR) method.

Methods

Ten participants (4 men and 6 women) were recruited from the Knoxville, Tennessee area to take part in this study. Four subjects were graduate students, 3 undergraduate students, and the remaining 3 had white-collar clerical occupations. Participants with clerical occupations were monitored on work days, whereas the students were monitored on either work days or non-work days (see table 1). Each participant read and signed an informed consent form approved by the Institutional Review Board prior to participation. A health history questionnaire was also completed by all participants to screen for any contraindications to exercise.

Table 1. Descriptive characteristics of the study participants (mean ± SD).

Subject	Gender	Age (yrs)	Height (meters)	Weight (kg)	BMI ($kg \cdot m^{-2}$)	Day of observation
1	F	27	1.67	62.1	22.3	M
2	M	28	1.80	77.0	23.8	Sa
3	M	25	1.88	75.2	21.3	F
4	F	22	1.57	91.0	36.9	R
5	F	25	1.63	59.1	22.2	F
6	M	29	1.80	72.4	22.3	T
7	F	31	1.71	57.3	19.6	W
8	F	28	1.57	71.8	29.1	Su
9	M	20	1.92	88.6	24.0	R
10	F	23	1.65	62.1	22.8	W
Mean		25.8	1.70	71.7	24.4	
SD		3.4	0.1	11.8	5.0	

Prior to testing, participants had their body mass measured to the nearest 0.1 kg using a calibrated physician's scale (Health-O-Meter, Bridgeview, IL), and their height measured to the nearest 0.1 cm using a stadiometer (Seca Corp., Columbia, MD). Descriptive characteristics of the participants are listed in Table 1.

Procedures

Participants were asked to come to the Applied Physiology Laboratory having abstained from exercise for at least 12 h and in a post-prandial state for at least 2 h. After completing the health history questionnaire and informed consent anthropometric measurements were made. Afterwards each person was fitted with a Polar heart rate watch (Polar NV, Polar Oy Finland), a transmitter band placed around the chest, and a portable metabolic measurement system (Cosmed $K4b^2$, Cosmed, S.r.l., Italy [see equipment section]). Participants were then instructed to remain supine for a 10-min period. They then sat upright for 5 min, and stood for an additional 5 min. Following these rest periods each participant completed a submaximal leg, followed by a submaximal arm ergometer test (see protocol section). Between each submaximal test they remained in the supine position for 30-45 min. This rest period was included to establish resting physiological levels before the second test began, until HR and VO_2were within 5% of initial rest values. Heart rate and VO_2 were continuously measured throughout all rest and exercise periods.

Following the completion of both submaximal tests, individualized arm and leg regression equations for HR and VO_2 were developed for each participant. Data from the individualized regression analysis for each activity were combined to show the different relationship between HR and VO_2 for arm and leg exercise (Figure 1). Participants did not perform combined arm-and-leg activity as this has been shown to closely reflect the legs-only condition (7). Figure 1 demonstrates the different relationship between arm and leg work using group regression data, although individualized regressions were used for predicting EE. This was done to provide greater accuracy, as other investigators have shown that utilizing group regression equations introduces greater error than when using individualized regression equations (7, 13).

Experimental Protocols

Submaximal Treadmill Test

Participants walked on a treadmill (Quinton Instrument Co., Q65, Bothell, WA) following an incremental protocol, consisting of continuous 3-min stages. Initial speed was 2.5 mph, and was increased to 3.5 mph, after which speed remained constant while grade was increased 2% each stage. The test was terminated once the participant reached 80-85% of his/her age-predicted maximal HR. During this time HR was measured using a Polar Heart Rate Vantage NV watch and transmitter, and VO_2 was measured using the Cosmed $K4b^2$ (see equipment section).

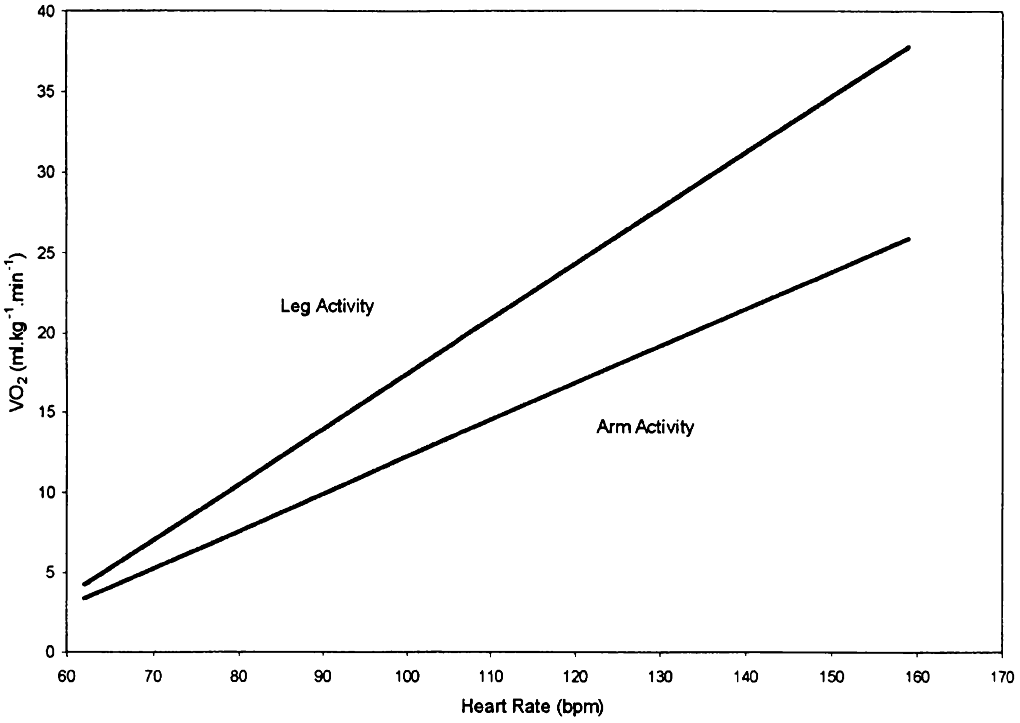

Figure 1. The relationship between heart rate and measured oxygen uptake during treadmill walking and arm ergometer exercise.

Submaximal Arm Ergometer Test

Participants performed successive 3-min stages on a Monark arm ergometer (Monark 881E, Varberg, Sweden). The initial cadence was set at 50 rpm, and initial resistance at 0 kp. Thereafter, cadence remained constant and resistance increased by 0.25 kp for each stage. The test was terminated once the participant reached 80-85% of their age-predicted maximal HR. Heart rate and VO_2 were again measured by a Polar Heart Rate Vantage NV watch and transmitter, and Cosmed $K4b^2$, respectively.

Free-Living Activity

Within a week of completing all laboratory tests participants were monitored during their normal daily routine. This activity took place outside of the laboratory, either at the participant's place of work or at their home. Min-by-min HR, VO_2, and motion sensor data were collected on a near- continuous basis for a 6 h period. After every 2 h period of activity the battery pack was changed on the Cosmed $K4b^2$ unit, and the data were downloaded. Therefore, participants were given on average a 10 min break at each 2 h interval. During the free-living activity period the investigator was on-site, but not communicating or directly supervising the participants. During this time participants engaged in a variety of activities including, but not limited to; television viewing, general office work, reading, resistance training, walking, jogging, cooking, light cleaning, vacuuming, washing dishes, grocery shopping, and yard work.

Equipment

Portable Metabolic Measurement System

The Cosmed K4b^2 (Cosmed, S.r.l., Rome, Italy) was used as the criterion measure for EE during laboratory and field testing. This portable indirect calorimetry unit continuously measures breath-by-breath expired gases. The Cosmed K4b^2 oxygen analyzer and carbon dioxide analyzer were calibrated immediately prior to each testing session in accordance with manufacturer's guidelines. At 2 h intervals during the free-living activity period the battery pack was changed on the Cosmed K4b^2 unit, and the calibration process was repeated (a 10 min process). Data from the portable Cosmed K4b^2 were stored in memory and downloaded to a laptop computer after each test was completed. Breath-by-breath data were averaged over one minute periods to derive VO_2 values. The validity of the Cosmed K4b^2 has previously been demonstrated in our laboratory. McLaughlin et al. (15) showed that the mean VO_2 values measured by the Cosmed were within 0.096 $L \cdot min^{-1}$ of Douglas Bag values during an incremental cycle ergometer protocol, consisting of seated rest, and five min stages at 50, 100, 150, 200, and 250 watts.

Heart Rate

The Polar Vantage NV watch is capable of storing 134 h of HR information in one min epochs. This watch was used for both laboratory and field testing, and was set to record in 60-s intervals. The Polar transmitter belt was attached to an elastic strap and placed around the chest. The transmitter belt's electrodes were dampened with water in accordance with manufacturer's instructions to aid in conductance. Heart rate information was downloaded via an interface and imported into a digital file following each test. Polar HR technology has been shown to be valid in both laboratory and field settings compared to electrocardiograph measurements of HR (10, 11, 23).

Motion Sensors

The Computer Science Applications (CSA) Inc. model 7164 (Shalimar, Florida) accelerometer was used to monitor motion during free-living activity. This device is a lightweight (42g), small (5.08 X 4.06 X 1.52 cm), lithium battery-powered accelerometer designed to measure and record acceleration and deceleration between magnitudes of 0.05 and 2 G. It is also programmed to detect movements within a frequency range of 0.25 to 2.5 Hz. This characteristic reduces artifact due to vibration. Acceleration and deceleration is measured in a single vertical plane over a user-specified time interval (epoch). Both CSA monitors were initialized 60 min before each participant began the free-living activity, and were programmed to record data in 60-s epochs. Min-by-min data from the Cosmed K4b^2, CSA accelerometers, and the Polar HR watch were all synchronized to the same external stop-watch to ensure that all information were collected simultaneously. The CSA data were downloaded following each test and imported into a digital file.

One CSA device was placed on the posterior aspect of the dominant hand, over the center-line of the wrist. A velcro strap was used to attach the CSA monitor to the wrist. A second CSA accelerometer was placed on the mid-axillary line of the dominant thigh, orientated vertically along the femur. An elastic bandage was used to hold the CSA monitor in place on the thigh. Calibration of the CSA accelerometers took place at the beginning and end of the study. The two CSA accelerometers were found to produce a response that met manufacturer's standards (within ± 5% of a reference value). The accelerometers were labeled "wrist" and "leg" so that the same device was consistently used for each body location throughout the study.

Simultaneous Heart Rate – Motion Sensor Technique

The CSA motion sensors were used to determine whether the activity performed was primarily upper- or lower-body activity. In addition, the motion sensors were used to screen out elevations in HR due to emotion or temperature. We examined thresholds of 100, 200, 300, 400, 500, and 1000 relative to periods of activity and inactivity. During free-living activities a CSA value of 0-499 counts·min^{-1} coincided with measured EE values of 1 MET 96% of the time. A CSA value of greater than 500 counts·min^{-1} coincided with measured EE values of greater than 1 MET 82% of the time. Therefore, a CSA threshold of 500 counts·min^{-1} reflected a demarcation between rest and light activity. For example, if both the leg and arm CSA counts were less than 500, we considered the individual to be at resting metabolic rate (1 MET). If the leg counts·min^{-1} were 450 and the arm counts·min^{-1} were 1000, we used measured HR to predict EE from the corresponding arm regression equation, and vice versa. If both arm and leg counts·min^{-1} were above the 500 threshold then we used a ratio technique between arm and leg counts·min^{-1} to determine whether EE should be predicted from either the arm or leg HR- VO_2 regression equation. We recently demonstrated that a ratio of greater than 25 between arm and leg activity accurately reflected measured EE when using the simultaneous HR+M technique (22). Therefore, a ratio of greater than 25 between arm and leg counts·min^{-1} was considered to represent predominantly arm activity. It has been shown that the HR- VO_2 relationship for leg activity closely represents combined arm-and-leg activity (7). Therefore, if the arm-to-leg counts·min^{-1} ratio was less than 25, and both values were greater than 500, we predicted METs from the corresponding leg regression equation.

Flex Heart Rate

The FlexHR was established similar to the technique of Livingstone et al. (12). Prior to the participants completing the submaximal treadmill test, they were required to lay supine, sit and stand for 10, 5, and 5 min, respectively. During this time HR and VO_2 were measured continuously using the Polar Vantage NV HR watch, and the Cosmed K4b^2. For each individual the FlexHR point was determined by taking the average of the highest HR during rest and the lowest HR during incremental exercise during the submaximal treadmill test. The FlexHR ranged from 83-101 beats·min^{-1} for our subject sample. During the 6 h of near-continuous activity if HR was below an individual's FlexHR point, EE was assumed to be 1 MET. For HR values above individual FlexHR points, EE was predicted from individualized HR- VO_2 leg regression lines.

Data Collection

During the free-living activity period some HR values were lost due to an insufficient contact between the chest strap and the participant, or interference with the telemetry signal. For this reason we had 329 ± 21 minutes of HR data per participant to predict min-by-min EE. No missing data occurred for VO_2or the motion sensors during the free-living activity period. Absolute VO_2 data ($ml \cdot min^{-1}$) were converted to relative VO_2 ($ml \cdot kg^{\cdot -1} min^{-1}$), and these values were then divided by 3.5 to convert them into METs (resting metabolic equivalents).

Min-by-min data from the Cosmed $K4b^2$ and Polar HR watch were analyzed to compute the average min spent in resting/light (<3 METs), moderate (3-6 METs), and hard (>6 METs) activity, for the 6 h period.

Statistical Analysis

For each min an error score was computed by subtracting the estimate for EE (simultaneous HR+M technique or FlexHR method) from the criterion (Cosmed $K4b^2$) for all participants. Mean error scores were computed for time spent in resting/light, moderate, and hard activity. Values were compared with a repeated measures analysis of variance using SPSS for Windows Version 10.0.7 (SPSS Inc., Chicago). Post-hoc testing was performed with Bonferroni adjustment to locate significant differences.

Error scores were graphically illustrated via Bland-Altman plots (6) for min-by-min data. The shared variance was computed for both min-by-min predicted values of EE, and for time spent in resting/light, moderate, and hard activity, in comparison to the

Cosmed to depict the strength of the relationship between these variables. The overall significance level was set at alpha = 0.05.

Results

The ability of the simultaneous HR+M technique to predict measured EE for a 6 h period is demonstrated for two participants in Figure 2. These participants were chosen as representative examples of individuals with relatively high periods of activity for the 6 h period (figure 2a), and relatively low levels of activity for the 6 h period (figure 2b). From this figure it can be seen that the simultaneous HR+M technique is a valid method of closely tracking changes in PAEE in a field setting.

Simultaneous Heart Rate-Motion Sensor Technique

Min-by-Min Analysis

The shared variance between predicted METs from the simultaneous HR+M technique and the Cosmed was R^2=0.81 (SEE=0.55 METs). The mean error for min-by-min analysis was 0.0 METs, with the 95% confidence interval (CI) ranging from +1.3 to -1.3 METs. Post-hoc testing revealed the mean error score for the simultaneous HR+M technique was not significantly different from zero (P=0.916), illustrating that this technique neither over- nor under-predicted measured EE. This relationship was similar for both men and women (data not shown). Figure 3 depicts a graphical relationship of the min-by-min error scores.

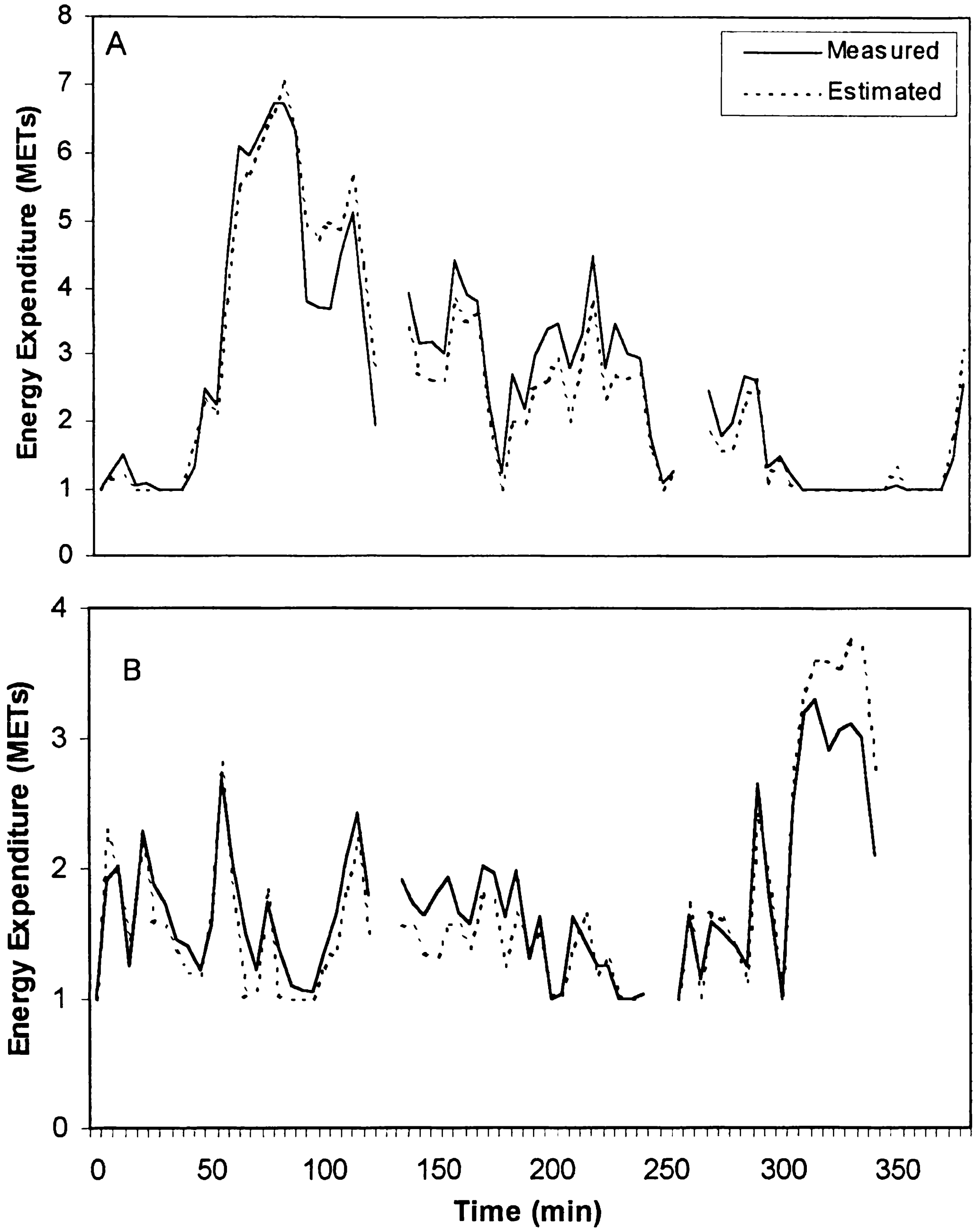

Figure 2. Measured (Cosmed K4b^2) versus estimated (simultaneous HR+M technique) energy expenditure for 6 h of free-living activity for two participants: (A) representative sample of different PA intensities; (B) representative sample of lower intensity activity. Breaks in monitoring represents the time the Cosmed K4b^2 was calibrated. Values represent 5-min averages.

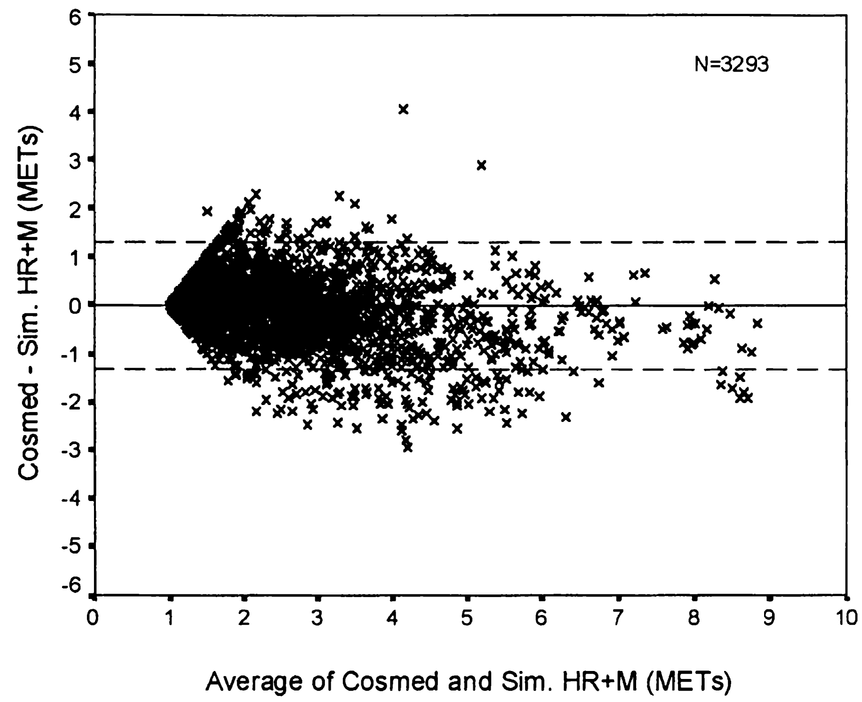

Figure 3. Bland-Altman plots depicting error scores for min-by-min energy expenditure (criterion minus estimate) for the simultaneous HR+M technique. The solid line represents the mean error, and the dashed lines represent the 95% confidence interval

Total Energy Expenditure

We summed 6 h min-by-min MET values to derive an estimate of total EE. Total EE values predicted by the simultaneous HR+M technique (748 ± 178 MET·min^{-1}) were not significantly different to measured values obtained by the Cosmed K4b^2 (749 ± 138 MET·min^{-1}).

Time Spent in Different Intensities of Physical Activity

The mean error scores revealed that the simultaneous HR+M technique accurately predicted time spent in resting/light, moderate and hard activity ($P=0.09$, $P=0.13$, and $P=0.11$, respectively) (Table 2). Figure 4 shows the mean values for time spent in resting/light, moderate, and hard activity.

Flex Heart Rate

Min-by-Min Analysis

The shared variance between predicted METs using FlexHR and Cosmed measured METs were $R^2=0.63$ (SEE=0.76 METs). The mean error for min-by-min EE was -0.4 METs, with the 95% CI ranging from +1.6 to −2.4 METs. Post-hoc testing revealed that the FlexHR method significantly over-estimated measured min-by-min EE ($P<0.0001$). This relationship was similar across genders (data not shown). Figure 5 depicts a graphical relationship of the min-by-min error scores.

Table 2. Mean error scores (criterion minus device) for time spent in resting/light (<3 METs), moderate (3-6 METs), and hard activity ($\geq$6 METs) (n=10).

	Mean Error Scores	
	Cosmed K4b^2 minus Sim. HR+M	**Cosmed K4b^2 minus FlexHR**
Min of Resting/Light Activity	+12 ± 19	+45 ± 51*
Min of Moderate Activity	-9 ± 16	-38 ± 43*
Min of Hard/ Activity	-3 ± 5	-6 ± 9

* Mean error score is significantly different from zero at the 0.05 level.

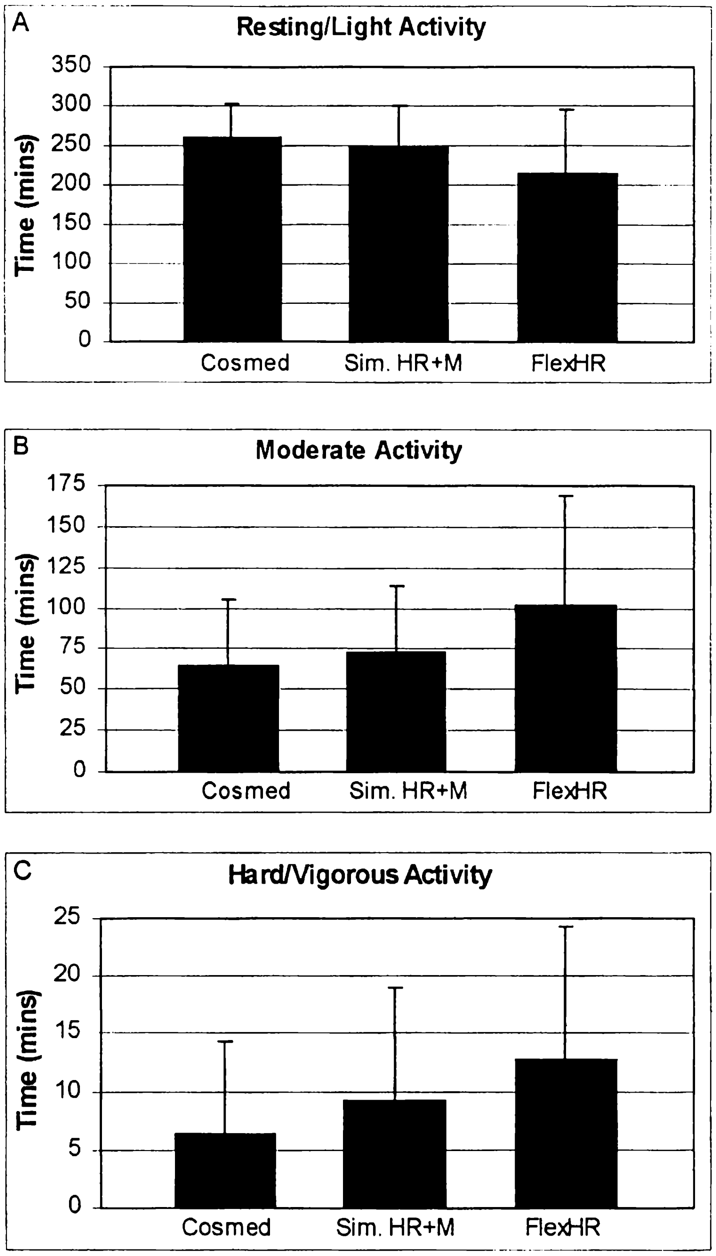

Figure 4. Mean values for (A) time spent in resting/light activity (<3 METs), (B) time spent in moderate activity (3-6 METs), (C) time spent in hard activity ($\geq$6 METs). *Bars* represent mean values ± 1 standard deviation at each activity level.

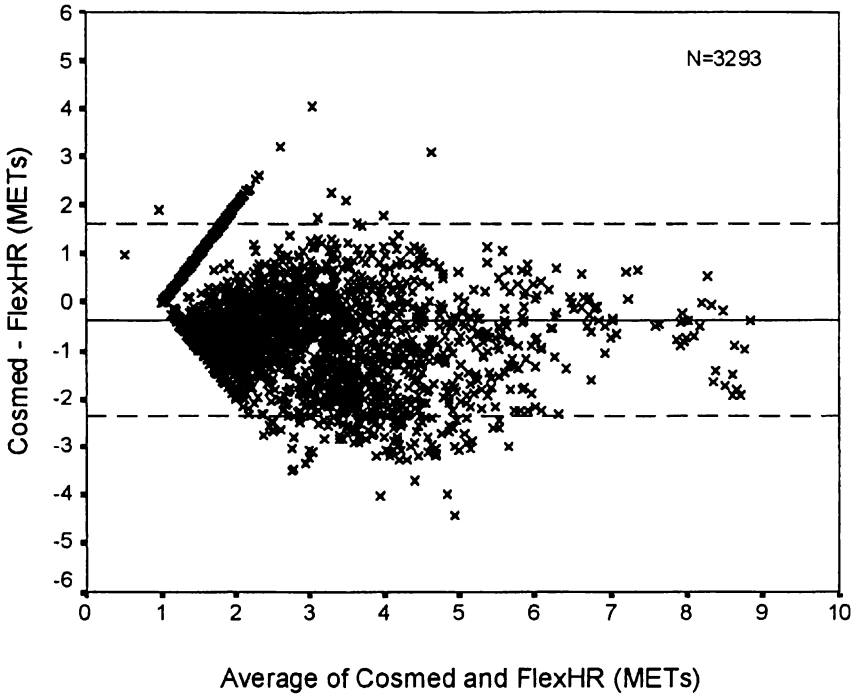

Figure 5. Bland-Altman plots depicting error scores for min-by-min energy expenditure (criterion minus estimate) for the FlexHR method. The solid line represents the mean error, and the dashed lines represent the 95% confidence interval.

Total Energy Expenditure

The 6 h total EE values predicted from the FlexHR method were significantly different from measured values by the Cosmed K4b^2 (871 ± 274 MET·min^{-1} vs. 749 ± 138 MET·min^{-1}, respectively).

Time Spent in Different Intensities of Physical Activity

The FlexHR method under-estimated time spent in resting/light activity by 45 ± 51 min (P=0.02), and over-estimated time spent in moderate activity by 38 ± 43 min (P=0.02). The FlexHR method marginally over-estimated time spent in hard activity by 6 ± 9 min (P=0.06) (Table 2). Overall mean values are presented in Figure 4.

Discussion

In this study we compared estimates of free-living daily activity using the simultaneous HR+M technique and the FlexHR method to indirect calorimetry for a near-continuous 6 h period. Results from this study found that the FlexHR method resulted in a small, but significant over-estimation ($P<0.001$) of min-by-min EE. Although the FlexHR method attempts to screen out elevations in HR due to non-related activity by establishing a critical threshold, it is unable to account for the different relationship that exists between HR and VO_2 for arm and leg activity, as shown in figure 1. During the present study participants performed an average of 56 min of arm activity, comprising 14% of the total. Since HR is higher for any given VO_2 during arm activity compared to leg activity, this may have accounted for the FlexHR method over-estimating the measured min-by-min EE. This significant overestimation was also apparent for total 6 h EE.

We previously demonstrated during 15-min bouts of selected lifestyle activities, that using arm and leg HR- VO_2 regression equations significantly improves the prediction of EE over a single leg regression equation (22). We demonstrated that HR predictions of EE using a single leg regression equation over-estimated measured EE by 11%. We also illustrated in our previous study that the simultaneous HR+M technique was considerably more accurate in estimating EE than a motion sensor place on the hip. CSA accelerometer and Yamax pedometer predictions of EE under-estimated measured EE by 30-59%, this is in agreement with other studies examining the utility of predicting EE using hip mounted motion sensors (3, 9). The reason for this underestimation is that hip-mounted motion sensors fail to account for any external work taking place, such as carrying or pushing objects, or ascending stairs.

The major finding of the present study was that arm and leg monitoring can be used to refine HR estimates of EE during free-living activity, by discriminating between upper and lower body activity, as suggested by Haskell et al. (7). The 95% CI for the simultaneous HR+M technique for min-by-min EE in this study was ± 1.3 METs. The level of agreement between measured EE and the simultaneous HR+M technique (R^2=0.81, SEE 0.55 METs), is similar to the laboratory values reported by Haskell et al. (7) using this same technique (R^2=0.89, SEE 0.66 METs),.

The U.S. Surgeon General's Report and other public health organizations emphasize the importance of accumulating 30 min or more of moderate intensity activity on most, if not all, days of the week (19, 24). In order to establish the number of min individuals spend in different PA intensity categories, one needs an accurate technique to assess time spent in intensity classifications. This was the reason we chose to express the data on a min-by-min scale rather than simply averaging the information. The simultaneous HR+M technique was found to be a valid method of assessing time spent in different PA intensity categories. In contrast, the FlexHR method was found to significantly under-estimate time spent in resting/light activity, and significantly over-estimate time spent in moderate activity (Table 2). A visual representation of the mean values for time spent in resting/light, moderate, and hard activity can be seen in Figure 4. This figure shows that EE values predicted from the simultaneous HR+M technique have a closer relationship with indirect calorimetry, in comparison to the FlexHR method. Therefore, the simultaneous HR+M technique was able to predict PA intensity patterns with a greater degree of accuracy than the FlexHR method. Furthermore, the simultaneous HR+M technique showed a greater level of agreement than the FlexHR method for the amount of time spent in all activity categories, in comparison with indirect calorimetry (Table 3).

This study has strengths that contribute to the understanding of measuring PAEE using the simultaneous HR+M technique. The simultaneous HR+M technique was compared to the FlexHR method over a near-continuous time period by analyzing min-by-min data in relation to a criterion method for assessing free-living activity. To our knowledge, this is the first study to attempt this type of analysis. As nearly as possible participants performed their normal daily routines. A limitation of the present study is

Table 3. Shared variance values (R^2) between the Cosmed K4b^2, simultaneous HR+M technique, and FlexHR method for time spent in resting/light (<3 METs), moderate (3-6 METs), and hard activity (≥6 METs) (n=10).

	Prediction Methods vs. Cosmed K4b^2	
	Sim. HR+M	**FlexHR**
Min. of Resting/Light Activity	0.89*	0.69*
Min. of Moderate Activity	0.87*	0.63*
Min. of Hard Activity	0.79*	0.36

* Significant at the 0.01 level.

that the Cosmed K4b^2 is somewhat intrusive; but none-the-less it provides a "gold standard" against which other methods can be compared. An additional limitation to this study was that all free-living activities undertaken were not recorded in terms of type and mode. The use of a PA log may have enhanced the utility of the simultaneous HR+M technique by allowing different types of activity under free-living conditions to be described and evaluated.

In summary, our results showed that the simultaneous HR+M technique is a valid measurement tool for assessing the amount of time spent in resting/light, moderate, and hard activity. Analysis showed that this technique can accurately predict min-by-min EE, and that it was accurate for assessing total EE over a 6 h period. This finding has important implications for the study of PA assessment. The simultaneous HR+M technique allows researchers to more accurately quantify PA intensity with a higher degree of accuracy than currently available assessment measures during free-living activity.

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Finland. The use of trade names and commercial sources in this document is for the purposes of identification only, and does not imply endorsement.

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PART VI

VALIDITY OF SIX PHYSICAL ACTIVITY QUESTIONNAIRES USING THE SIMULTANEOUS HEART RATE-MOTION SENSOR TECHNIQUE

Abstract

Validity of Six Physical Activity Questionnaires using the Simultaneous Heart Rate-Motion Sensor Technique. Although a number of studies have documented the validity of physical activity (PA) questionnaires, few have used a criterion standard capable of accurately quantifying energy expenditure (EE) in terms of intensity, and time spent in different intensity classifications. This study examined the validity of PA questionnaires frequently administered in population-based studies using a group of 25 males and females with varying activity levels. ***Methods:*** Subjects completed arm and leg work in the laboratory for the purpose of developing individualized HR-VO_2 regression equations. Subjects wore a heart rate (HR) recording device, and two CSA accelerometers, one placed on the dominant wrist and the other placed on the leg, during all waking hours for a continuous 7-day period. The CSA accelerometers were used to discriminate between upper- and lower-body activity and HR was used to predict min-by-min EE from the corresponding laboratory regression equations. The simultaneous heart rate-motion sensor (HR+M) technique was compared with six questionnaires, including the Modifiable (MAQ), the Stanford 7-day Physical Activity Recall (PAR), the College Alumnus (for time spent only [CAQ]), the Framingham (FAI), the Baecke (BAQ), and the Health Insurance Plan (HIP). ***Results:*** For total EE a significant Spearman rank order correlation coefficient was observed between the simultaneous HR+M technique and all studied questionnaires, with the exception of the BAQ (r values ranging from 0.38 to 0.59). Upon breaking down EE into subcategories of resting/light, moderate and hard intensity, the PAR and the MAQ accurately quantified group mean moderate and hard intensity EE. For the analyses of time spent in different intensity categories, the PAR accurately predicted mean time spent in moderate and hard activity, whereas the CAQ over-estimated these variables. ***Conclusion:*** These data indicate that all of the questionnaires were able to discriminate between low-active and high-active individuals. The PAR yielded similar group means, compared to the criterion method, for time spent and EE in moderate and hard intensity activity. In addition, a significant correlation was seen between the questionnaire and criterion measure for both time spent and EE in hard activity ($r = 0.49$, $P<0.05$, respectively). This suggests adequate validity for the PAR to evaluate vigorous PA. ***Key Words:*** ENERGY EXPENDITURE, ACCURACY, PHYSICAL ACTIVITY.

Introduction

Physical activity (PA) has been identified as a behavior that is linked to positive health outcomes, including reduced risks for coronary heart disease, hypertension, type 2 diabetes, some cancers, and overall mortality (2, 6, 10, 11, 13-16, 23). Despite the importance of PA in maintaining overall health, national surveillance studies have documented that approximately one in four U.S. adults lead a sedentary lifestyle, with no leisure time PA. A further one-third of adults are insufficiently active to achieve health benefits (23).

In 1996, the Surgeon General's Report recommended that all individuals accumulate 30 min or more of moderate intensity PA on most, preferably all, days of the week (23). Consequently, there has been a heightened interest in studying the association between PA and health in order to assess how many individuals are currently meeting national PA targets. Physical activity questionnaires are typically used to assess PA in large population-based studies due to practicality and applicability (24). However, the ability to relate PA data collected by questionnaire to health outcomes depends on the accuracy of the data measurement. Therefore, there is a need to evaluate PA questionnaires for their efficacy in measuring different dimensions of PA.

Recently, our laboratory has demonstrated that the simultaneous heart rate-motion sensor (HR+M) technique is accurate for quantifying certain aspects of PA. This assessment tool was shown to accurately quantify energy expenditure (EE) over 15-min bouts during fourteen different lifestyle tasks, with most of the average values being within ± 0.3 METs of criterion numbers obtained by indirect calorimetry (20). In a subsequent field study, this technique was also shown to accurately quantify min-by-min EE, total EE, and time spent in varying activity intensities over a near-continuous 6 h period in comparison with indirect calorimetry (21).

The validity of some commonly-used PA questionnaires against an assessment tool capable of accurately quantifying intensity subcategories of EE and time spent in different activity classifications has not been previously reported. The purpose of this study was to examine the validity of six PA questionnaires against the simultaneous HR+M technique in 25 men and women with varying PA levels.

Materials and Methods

Twenty-five participants (12 men and 13 women) were recruited from the Knoxville, Tennessee area to take part in this study. Each participant read and signed an informed consent form approved by the University of Tennessee Institutional Review Board prior to participation. A health history questionnaire was also completed by all participants to screen for any contraindications to exercise. Prior to testing, participants underwent measurements of body composition (whole body plethysomography, Bod Pod body composition measurement system, Life Measurement Instruments, Concord, CA), weight, using a calibrated physician scale (Health-O-Meter, Bridgeview, IL), and height, using a stadiometer (Seca Corp., Columbia, MD).

Laboratory Testing

Study participants performed a submaximal treadmill test and a submaximal arm ergometer test, in a post-prandial state, to establish individualized arm and leg HR-VO_2 regression equations. Tests were counterbalanced and separated by a 30-40 min supine rest period.

Submaximal Treadmill Test

Participants walked on a treadmill (Quinton Instrument Co., Q65, Bothell, WA) following an incremental protocol, consisting of continuous 3 min stages. Initial speed was 67 $m \cdot min^{-1}$, and was increased to 94 $m \cdot min^{-1}$, after which speed remained constant while grade was increased 2% each stage. The test was terminated once the subject reached 80-85% of age-predicted maximal HR. During this time HR and VO_2 were measured continuously. Heart rate was measured by a Polar Vantage HR watch (Polar NV, Polar Oy Finland). This watch is capable of storing 134 h of HR information in 60-s epochs. The Polar transmitter belt was attached to an elastic strap and placed around the chest. This Polar device was used to derive measurements of HR during both laboratory and field-testing. All HR data were immediately downloaded following a test via an interface and imported into a digital file.

The TrueMax 2400 computerized metabolic measurement system (ParvoMedics, Salt Lake City, UT) was used to measure oxygen uptake during submaximal exercise protocols. The validity of the TrueMax 2400 system has previously been demonstrated in our laboratory. Bassett et al. (5) showed that mean VO_2 values measured by the TrueMax were within 18 $ml \cdot min^{-1}$ of Douglas bag values during an incremental cycle ergometer protocol, ranging from seated rest to 250 watts. Min-by-min gas exchange data were imported into a Windows-based program for latter analysis.

Submaximal Arm Ergometer Test

Participants performed successive 3 min stages on a Monark arm ergometer (Monark 881E, Varberg, Sweden). The initial cadence was set at 50 rpm, and initial resistance at 0 kp. Thereafter, cadence remained constant and resistance increased by 0.25 kp for each stage. The test was terminated once the participant reached 80-85% of age-predicted maximal HR. Heart rate and VO_2 were again measured continuously.

7-Day Field Test

After preliminary testing was completed participants were shown how to wear two motion sensors, one placed on the wrist and one placed on the thigh. Participants were also shown how to operate the Polar HR watch. All participants began wearing the HR and motion sensor devices the following morning for a continuous 7-day period. The 7 days of monitoring were started on random days of the week. Upon completion of the 7 day monitoring phase participants visited the Applied Physiology Laboratory, returned the monitoring equipment, and completed six different PA questionnaires in randomized order.

During the 7-day field test the HR data being transmitted between the chest strap and the watch-receiver was sometimes subject to interference. This is typically caused by interference from certain types of electronic equipment that are close by, such as hairdryers or select radios. Such interference is typically manifest as a HR greater than 220 beats·min^{-1}. In addition, occasionally a loose contact between the individual and the chest strap results in readings of 0 beats·min^{-1}. Some participants also had readings of 0 beats·min^{-1} when traveling in an automobile. Aberrant readings were replaced by the average of the previous and subsequent value, however, if more than five aberrant readings occurred in succession, the data were not used in the analysis.

The Computer Science Applications (CSA) Inc. model 7164 (Shalimar, Florida) accelerometer was used to monitor motion during the 7 days of free-living activity. The CSA monitors were initialized the day before the 7-day monitoring began, and were programmed to record data in 60-s epochs. The CSA data were downloaded following the 7-day period and imported into a digital file. Calibration of the CSA accelerometers took place at the beginning and end of the study. One CSA device was placed on the posterior aspect of the dominant hand, over the center-line of the wrist. A velcro strap was used to attach the CSA monitor to the wrist. Another CSA accelerometer was placed on the mid-axillary line of the dominant thigh, orientated vertically along the femur. An elastic bandage was used to hold the CSA monitor in place on the thigh.

Estimation of Energy Expenditure During Free-Living

Heart rate and arm and leg motion were recorded during all waking hours of free-living activity. All devices were removed during bathing and swimming. Data from the HR and motion sensors were analyzed to derive min-by-min measures of EE using the simultaneous HR+M technique. This technique utilizes CSA motion sensors placed on the arm and leg to determine whether the activities performed were primarily upper- or lower-body activities. A CSA threshold of 500 counts$\cdot$min^{-1} was used to distinguish between activity and inactivity. Once above this threshold, a ratio of 25:1 between arm and leg counts$\cdot$min^{-1} was used to distinguish between arm or leg activity. Min-by-min EE was predicted from HR values using either the arm or leg HR- VO_2 laboratory generated regression equations. A more thorough description of this procedure is provided elsewhere (20, 21).

Questionnaires

Six PA questionnaires that have previously been used to derive estimates of activity in population-based studies were used. The original design of these questionnaires, and elements of analysis have been described previously (17). Two of the six activity questionnaires comprised a 7-day recall: the College Alumnus Questionnaire (CAQ) (14), and the Stanford 7-day Physical Activity Recall Questionnaire (PAR) (18). Other questionnaires asked about "usual" activity: the Modifiable Activity Questionnaire (MAQ) (9), the Framingham Activity Index (FAI) (8), the Baecke Activity Questionnaire (BAQ) (4), and the Health Insurance Plan of Greater New York Questionnaires (HIP) (19). To allow for a direct comparison between these questionnaires and 7 days of objective monitoring, the questionnaires were modified to refer to activity in the past week only.

The PA questionnaires were originally designed to be either self-administered (CAQ, MAQ, BAQ, HIP), or used in interview format (PAR, FAI). In the present study, all questionnaires were administered in their original format. Two questionnaires (PAR, MAQ) were used to estimate EE (MET·min·wk^{-1}). The other questionnaires yielded numerical indices of activity (FAI, BAQ, HIP). In addition, the PAR and the CAQ were used to derive estimates for time spent in resting/light, moderate, and hard intensity activity over the 7-day period.

The questionnaires that derived quantitative EE values in MET·min·wk^{-1} gave representative examples of moderate and vigorous activities. For example, golf and walking at your usual pace were considered to be moderate activities, while running and singles tennis were considered to be vigorous activities. The PAR used ascribed MET values of 1.5, 4, 6, and 10 METs to calculate light, moderate, hard and very hard activity, respectively. The MAQ used corresponding MET values obtained from the Compendium of Physical Activities (1) to estimate the metabolic cost of each activity listed on the questionnaire. As such, EE values recorded were in absolute terms, which enabled a direct comparison with the simultaneous HR+M technique, which served as the criterion.

Computation of Energy Expenditure and Time Spent in Various Activity Intensities

Min-by-min EE values over the 7 days of activity monitoring were used to derive the individual pattern of EE. In this study, two measures of the pattern of EE are reported. The first measure is the total amount of energy expended in light, moderate and hard intensity activities. These values were recorded in $\text{MET}\cdot\text{min}\cdot\text{wk}^{-1}$ to express energy cost independent of body weight (one $\text{MET}\cdot\text{min}\cdot\text{wk}^{-1}$ is the equivalent to one $\text{kcal}\cdot\text{wk}^{-1}$ for a 60kg person). The second measure is the proportion of time spent in light, moderate and hard intensity activities; these values were expressed as $\text{min}\cdot\text{wk}^{-1}$. All values were reported as means and standard deviations.

Statistical Analysis

A one-way repeated measures analysis of variance was used to determine differences between weekly EE classifications (resting/light, moderate, and hard) for the simultaneous HR+M technique, the PAR, and the MAQ. The hard and very hard intensity categories on the PAR were combined into one classification of hard activity. The MAQ was analyzed including walking as a moderate activity as recommended by Kriska et al. (9).

To examine the accuracy of the PAR and the CAQ for estimating time spent in resting/light, moderate, and hard activities, one-way repeated measures analysis of variance tests were used. To further examine the association between the variables identified, Pearson product moment correlation coefficients were run between resting/light, moderate, and hard EE, and time spent in light, moderate and hard activities between the questionnaires identified and the simultaneous HR+M technique.

Spearman rank order correlation coefficients were generated for all six questionnaires in comparison to the simultaneous HR+M technique. In an attempt to evaluate the ability of the activity questionnaires to further differentiate between high and low activity, participants were grouped into either a "high active" or "low active" group on the basis of their median simultaneous HR+M readings for total activity. Participants were then also classified into either high or low active groups using the median scores from each activity questionnaire. Percent agreement between the simultaneous HR+M technique and the activity questionnaires were then calculated using chi-square. Cohen's Kappa was used to evaluate percent agreement between the different measures. A Kappa value of greater than 0.75 represented excellent agreement, 0.4-0.75 fairly good agreement, and less than 0.4 poor agreement. All analyses were performed using SPSS version 10.0.7 (Chicago, IL) with the alpha set at 0.05.

Results

Participant demographic, physiological, and PA characteristics are listed in Table 1. Maximal oxygen uptake (VO_{2max}) was estimated from the linear VO_2 leg regression at maximal HR (220-age) and is expressed in Table 1 per unit body weight. On average, after removing all aberrant HR values, men and women had 14:00 ± 0:59 h, and 13:31 ± 0:40 h of data for analysis, respectively. A total of 22 ± 7 min were not used in data analyses.

Correlation of Physical Activity with Activity Questionnaires

Spearman rank order correlation coefficients between total weekly activity from the simultaneous HR+M technique and activity questionnaires are found in Table 2. The relationship between the simultaneous HR+M technique and the activity questionnaires were significant, with the exception of the BAQ. Significant correlations between several of the questionnaires were also observed.

High and Low Activity Agreement

After dividing the subjects into two groups (above and below the median score), the percent agreement was significant ($P<0.01$) for the MAQ (76%; $\chi 2 = 6.7$, $K = 0.52$), and the BAQ ($P<0.05$; 72%, $\chi 2 = 4.9$, $K = 0.44$) in comparison with the simultaneous HR+M technique. The PAR demonstrated marginal agreement with the simultaneous HR+M technique ($P=0.07$; 68%, $\chi 2 = 3.2$, $K = 0.36$). The percent agreement, chi-square values, and Cohen's kappa for all activity questionnaires are presented in Table 3.

Table 1. Participant demographic and physiological characteristics (mean ± SD).

Variable	**Men (n=12)**	**Women (n=13)**	**All (n=25)**
Age (yr)	30.6 ± 9.9	29.5 ± 11.4	30 ± 10.5
Height (cm)	1.83 ± 0.1	1.63 ± 0.1	1.73 ± 0.1
Mass (kg)	79.9 ± 11.3	65.4 ± 12.1	72.4 ± 11.7
BMI ($kg \cdot m^{-2}$)	23.8 ± 3.2	24.7 ± 5.2	24.3 ± 4.3
% Body Fat	16.1 ± 6.9	29.5 ± 9.3	22.5 ± 10.5
Estimated VO_{2max} ($ml \cdot kg^{-1} \cdot min^{-1}$)	46.4 ± 9.2	39.8 ± 6.5	43 ± 8.4

Table 2. Spearman rank order correlation coefficients between total weekly energy expenditure (MET·min·wk^{-1}) from the simultaneous HR+M technique and each activity questionnaires (n=25).

	Sim. HR+M	MAQ	PAR	FAI	BAQ	HIP
Sim. HR+M[a]	1.00					
MAQ[b]	0.59**	1.00				
PAR[c]	0.53**	0.55**	1.00			
FAI[d]	0.54**	0.46*	0.59**	1.00		
BAQ[e]	0.38	0.59**	0.28	0.49*	1.00	
HIP[f]	0.50*	0.67**	0.47*	0.63**	0.80**	1.000

*Correlation is significant at the .05 level

**Correlation is significant at the .01 level

[a] Simultaneous heart rate – motion sensor technique

[b] Modifiable Activity Questionnaire

[c] Stanford 7-day Physical Activity Recall Questionnaire

[d] Framingham Activity Index

[e] Baecke Activity Questionnaire

[f] Health Insurance Plan of Greater New York

Table 3. Classification of participants into either high active or low active groups: percent agreement, chi-square, and Cohen's kappa values for the simultaneous HR+M technique versus all questionnaires (MET·min·wk^{-1}) (n=25).

Questionnaire	% Agreement	Chi-square	K
MAQ[a]	76	6.7**	0.52
PAR[b]	68	3.2	0.36
FAI[c]	64	2.0	0.28
BAQ[d]	72	4.9*	0.44
HIP[e]	64	2.0	0.28

*Significant at the .05 level

**Significant at the .01 level

[a] Modifiable Activity Questionnaire

[b] Stanford 7-day Physical Activity Recall Questionnaire

[c] Framingham Activity Index

[d] Baecke Activity Questionnaire

[e] Health Insurance Plan of Greater New York

Energy Expenditure at Various Intensities

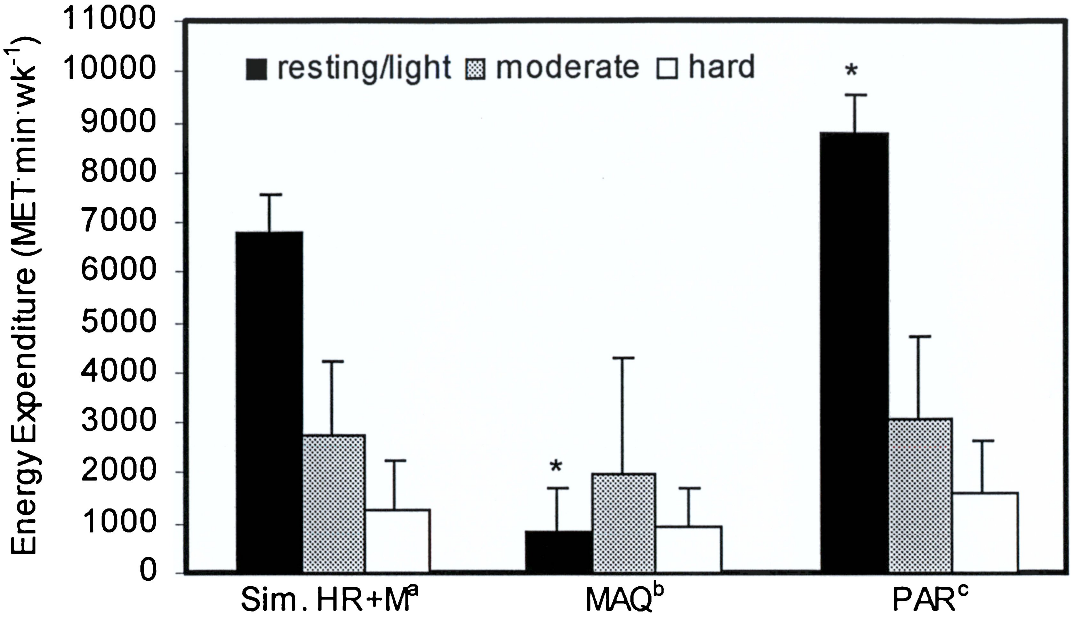
For resting/light intensity EE the MAQ and PAR gave mean values 88% below and 27% above that measured by the simultaneous HR+M technique, respectively (Figure 1). Questionnaire estimates for moderate and hard intensity EE did not differ from measured values (Figure 1). There were no differences across gender comparisons for resting/light, moderate or hard intensity EE (data not shown). Table 4 presents correlation coefficients for resting/light, moderate and hard intensity EE estimated from the MAQ and PAR compared with the simultaneous HR+M technique. The PAR showed a significant association with the simultaneous HR+M technique for hard intensity activity.

Time Spent at Various Intensities

Figure 2 illustrates that the PAR accurately estimated time spent in moderate and hard intensity activity. The CAQ over-estimated time spent in moderate and hard intensity activity. Table 5 shows correlation coefficients for weekly time spent in resting/light, moderate and hard activity estimated from the CAQ and the PAR compared with the simultaneous HR+M technique. The only significant correlation was for time spent in hard activity estimated from the PAR.

Discussion

In 1996, the Surgeon General's Report summarized what was currently known about the relationship between PA and health, drawing mostly upon epidemiological



* Significantly different from the Simultaneous Heart Rate-Motion Sensor Technique at the .0001 level

[a] Simultaneous Heart Rate-Motion Sensor Technique

[b] Modifiable Activity Questionnaire

[c] Stanford 7-day Physical Activity Recall Questionnaire

Figure 1. Resting/light, moderate and hard energy expenditure values. Values recorded in MET·min·wk^{-1} (mean ± SD) (n=25).

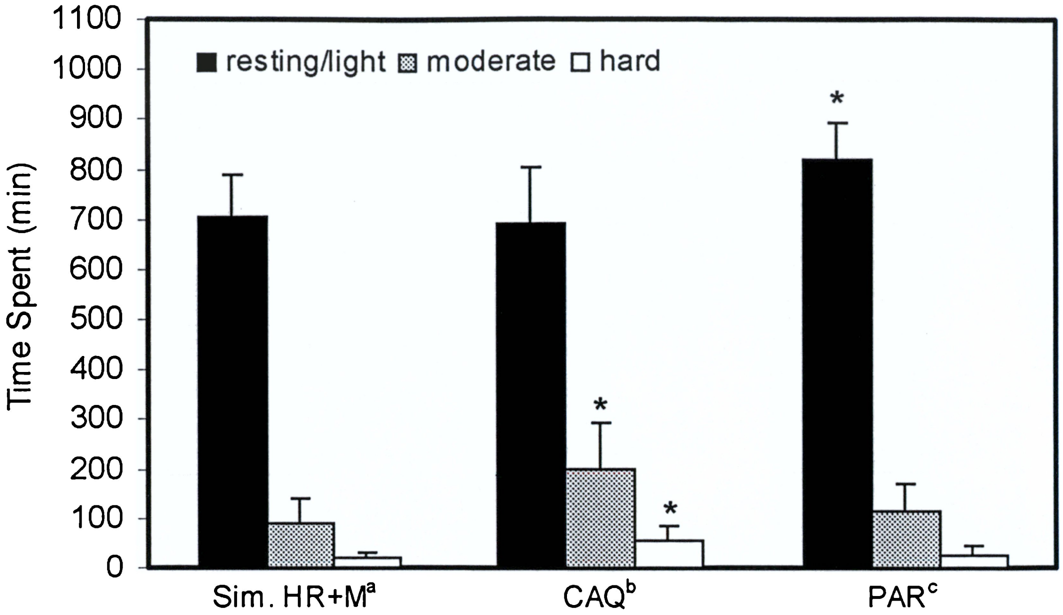
Table 4. Pearson product moment correlation coefficients between energy expended (MET·min·wk^{-1}) in resting/light, moderate, and hard intensity activities from the simultaneous HR+M technique and selected activity questionnaires (n=25).

	Simultaneous HR+M Technique
MAQ[a]	
Resting/light Intensity Activity	-0.05
Moderate Intensity Activity	0.36
Hard Intensity Activity	0.30
PAR[b]	
Resting/light Intensity Activity	-0.05
Moderate Intensity Activity	0.26
Hard Intensity Activity	0.49*

*Correlation is significant at the .05 level

[a] Modifiable Activity Questionnaire

[b] Stanford 7-day Physical Activity Recall Questionnaire



* Significantly different from the Simultaneous Heart Rate-Motion Sensor Technique at the .0001 level

[a] Simultaneous Heart Rate-Motion Sensor Technique

[b] College Alumnus Questionnaire

[c] Stanford 7-day Physical Activity Recall Questionnaire

Figure 2. Time spent in resting/light, moderate and hard intensity activity (mean ± SD) (n=25).

Table 5. Pearson product moment correlation coefficients between time spent in resting/light, moderate, and hard intensity activities from the simultaneous HR+M technique and selected activity questionnaires (min·d^{-1}) (n=25).

	Simultaneous HR+M Technique
CAQ[a]	
Resting/light Intensity Activity	0.16
Moderate Intensity Activity	0.39
Hard Intensity Activity	0.28
PAR[b]	
Resting/light Intensity Activity	0.26
Moderate Intensity Activity	0.23
Hard Intensity Activity	0.49*

*Correlation is significant at the .05 level

[a] College Alumnus Questionnaire

[b] Stanford 7-day Physical Activity Recall Questionnaire

studies. New PA guidelines were established highlighting the importance of accumulating at least 30 min of moderate or vigorous PA, on most, preferably all, days of the week (22). This translates to approximately 150 $kcals \cdot d^{-1}$ or 1000 $kcals \cdot wk^{-1}$. The health effects of accumulating regular PA are generally established by assessing PA by means of questionnaire. This is often the measurement tool of choice in large-scale population based studies for reasons of practicality and feasibility (23). However, the ability to relate the quantity and intensity of PA to health depends on accurate, precise, and reproducible measures. If these questionnaires do not provide accurate quantitative information about EE or time spent at various intensities, then PA recommendations based on them could be erroneous.

In this study, the accuracy of six selected PA questionnaires were examined in a sample of 25 males and females with varying activity levels. We observed that total activity EE values, as estimated by the questionnaires, were positively correlated with the simultaneous HR+M technique (r values ranging from 0.38 to 0.66). These values are comparable with other values reported using Caltrac accelerometer scores, energy intake, and subjective methods as criterion standards (2, 6, 8, 11, 17, 21). These findings show that paper-and-pencil activity questionnaires were able to discriminate between less-active and more-active individuals. Interquestionnaire correlation coefficients were generally high, suggesting that these instruments are providing similar information about certain aspects of PA. This is also seen when examining the percent agreement between high- and low-active groups based on their median score.

The MAQ and PAR by design enabled an examination of their ability to predict activity intensity classifications in $\mathrm{MET \cdot min \cdot wk^{-1}}$ in comparison with the simultaneous HR+M technique. The large underestimation reported for resting/light intensity EE by the MAQ reflects the fact that this questionnaire includes only light occupational activity and not light activity performed in the course of leisure time activities or household chores. Overall we found that both questionnaires were able to produce similar estimates of group mean moderate and hard intensity EE. Correlational analyses for the different activity intensities only revealed a significant correlation for hard intensity activity between the simultaneous HR+M technique and the PAR. The finding that hard activity generally showed a strong association with the simultaneous HR+M technique for group mean EE and correlational analysis confirms suggestions that questionnaires are effective for recalling vigorous, structured exercise (23).

Of additional interest, we sought to evaluate the ability of the questionnaires to predict time spent in different intensity classifications. The questionnaires that permitted this evaluation were the CAQ and the PAR. The results demonstrate that in comparison to the criterion measure for group mean values, the CAQ overestimated time spent in both moderate and hard intensity activities by 106 and 36 min respectively, whereas the PAR produced similar estimates of time spent in both moderate and hard intensity activities. For time spent in hard activity a significant correlation was only found between the PAR and the criterion measure. This result coincides with that for EE classifications described above. Furthermore, the criterion measure used in this study revealed that our sample population spent an average of 90 ± 49 min in moderate intensity activity. This mean value is considerably higher than that which is currently recommended (30 min of moderate intensity activity, on most, preferably all days of the week). This suggests that the national activity recommendations are set too low.

One approach used to predict time spent or energy expended in resting/light activity is to subtract time spent in moderate activity, hard activity, and sleep from a 24 h period. For the simultaneous HR+M technique we chose to include only the values recorded throughout the day to establish activity levels. As such, a limitation to this study is that the total number of $\text{min}\cdot\text{d}^{-1}$ for the simultaneous HR+M technique was less than the self-reported minutes for non-sleep on the PAR, 825 ± 48 vs. 944 ± 50 $\text{min}\cdot\text{d}^{-1}$, respectively. The majority of this difference would appear to be made up within the resting/light category, so it does not directly bias the results for moderate or hard intensity activity. An additional limitation to this study is that it was carried out over a 7-day period, which may not be representative of "usual" activity.

This study has strengths in that it allowed for an evaluation of PA questionnaires against a criterion able to evaluate different dimensions of PA. In order to evaluate the conclusions drawn from questionnaire data, their ability to assess different dimensions of activity is of paramount importance. The key finding from this study is that the PAR was strongly correlated with, and had modest percent agreement with total PA in comparison with the simultaneous HR+M technique. The PAR also demonstrated similar group estimates for EE and time spent in moderate intensity activity, and similar group and individual estimates for EE and time spent in hard intensity activity over a continuous 7-day period in comparison with the criterion measure. This finding has considerable significance for researchers evaluating information collected from the PAR, and those attempting to measure levels of PA and estimate compliance with national activity recommendations.

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APPENDICES

APPENDIX A

PART III

Informed Consent Form

INFORMED CONSENT FORM

Title: Energy cost and measurement of moderate intensity physical activity in field settings

Investigators: David R. Bassett, Jr.
Edward T. Howley

Address:
Exercise Science Unit
College of Education
University of Tennessee, Knoxville
1914 Andy Holt Av., Knoxville TN 37996

Phone: (865) 974-8766

You are invited to take part in a research study, the purpose of which is to determine the calorie cost of moderate intensity activities and determine the accuracy of small devices worn on the belt for measuring how many Calories you burn.

You will perform selected physical activities for 15-min segments. During this activity you will wear a portable oxygen analyzer (strapped to your chest) to measure oxygen uptake (VO_2). This will involve breathing into a face mask while your exhaled air is analyzed for oxygen and carbon dioxide content. In addition, you will wear several small devices attached to your belt or waist-band to measure the duration and intensity of movement. You will rest for 5 minutes before and after each activity as a control period.

The selected physical activities are those that are circled:
Yard work: Mowing the lawn (manual & power mowers), raking, trimming, raking, trimming, and general gardening.
Occupation: Walking at 2.0-3.0 mph and carrying items of 10-20 lbs.; load/unload boxes of 10-20 lbs each.
Housework: Vacuuming, sweeping and mopping, laundry, ironing, washing dishes, cooking, light cleaning (kitchen, dusting, watering plants), grocery shopping with a cart.
Family Care: Feeding and grooming animals, caring for small children (bathing, walking and carrying), playing with children and animals in the yard.
Conditioning: Situps, pushups, stretching.
Recreation: Doubles tennis, walking on a golf course carrying club and pulling clubs, softball, walking at 2.0-4.0 mph.

Your total time involvement for the study will be less than 2.5 hours.

Risks and Benefits: There are very few risks associated with submaximal exercise. the risks include abnormal blood pressure responses and heart rhythm disturbances. The benefits to participation include knowledge of your physical activity level and exposure to a device that may provide accurate information about Calorie expenditure.

Confidentiality: All information pertaining to your participation in this study will be kept confidential. The only persons who will have access to your exercise results will be the main researchers, Dr. David Bassett and Dr. Ed Howley, and the students directly involved in data collection. The information obtained from these tests will be treated as privileged, and as such it will not be released to any other person, other than the involved researchers, without your consent. This information will be used in research reports or presentations, but your name and any other potentially identifying marks will not be disclosed.

Participation in this research study is entirely voluntary, and you are free to decide whether or not you want to take part, and you are also free to withdraw from this study at any time without any form of penalty.

Please ask questions that you may have concerning any aspect of this study which you are unclear about, before you sign this form. If you think of any questions at a latter time, please feel free to call the investigators noted on the front of this consent form.

AUTHORIZATION:

I, ____________________, have read the above and decided to participate in the research project described above. My signature also indicates that I have received a copy of this consent form.

____________________________________ ________________

Participant's signature Date

I hereby certify that I have given the above individual an explanation of the contemplated study and its risks and potential complications

____________________________________ ________________

Investigator's signature Date

APPENDIX A1

PART III, IV, V, VI

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: ____________________________

SOCIAL SECURITY NUMBER (for payment purposes only): ____________________________

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. Lung disease................	[ ]	[ ]
5. Asthma......................	[ ]	[ ]
6. Diabetes.....................	[ ]	[ ]
7. Heart murmur............	[ ]	[ ]
8. Irregular heart beat.........	[ ]	[ ]
9. Arthritis.....................	[ ]	[ ]
10. Seizures.....................	[ ]	[ ]

_________________________________.

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?

Do you currently smoke? Yes ____ No ____ If so, what? Cigarettes ____ Cigars ____ Pipe ____

How much per day: < .5 pack ____ 0.5 to 1 pack ____ 1.5 to 2 packs ____ > 2 packs ____

Have you ever quit smoking? Yes ___No ___When? ___How many years and how much did you smoke?

___

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? ____

Do you engage in any recreational or leisure-time physical activities on a regular basis?

Yes ____ No ____ If so, what activities? ____

On average: How often? _________ times/week; For how long? __________ time/session

---

FOR EXERCISE TESTING STAFF USE:

____

____

____

____

APPENDIX A2

PART III

Raw Data

Table 1. Activity heart rate and activity oxygen uptake for household activities compared with predicted oxygen uptake reserve values established from the 1:1 relationship with heart rate reserve.

		House Activities								
Subject #	Activity ID	Act HR[a] (bpm)	RHR[b] (bpm)	HRR[c] (bpm)	VO2 (ml/min)	Rest VO2 (ml/min)	Predicted VO2 max (ml/kg/min)	Predicted VO2 max (ml/min)	VO2R[d] %	HRR %
House 02	Vacuuming	80	60	15	787	273	51.17	3940	14	15
House 03	Vacuuming	87	63	20	1148	271	48.25	3684	26	20
House 04	Vacuuming	122	82	37	817	202	37.88	2152	32	37
House 05	Vacuuming	77	61	14	1032	271	37.92	2895	29	14
House 06	Vacuuming	84	72	14	565	196	30.11	1656	25	14
House 07	Vacuuming	114	77	37	923	223	29.64	1859	43	37
House 08	Vacuuming	88	60	25	664	198	32.40	1804	29	25
House 09	Vacuuming	117	80	42	904	221	29.51	1837	42	42
House 02	Sweep/Mop[e]	78	60	13	750	273	51.17	3940	13	13
House 03	Sweep/Mop	86	63	19	1000	271	48.25	3684	21	19
House 04	Sweep/Mop	150	82	62	877	202	37.88	2152	35	62
House 05	Sweep/Mop	81	61	18	919	271	37.92	2895	25	18
House 06	Sweep/Mop	82	72	12	572	196	30.11	1656	26	12
House 07	Sweep/Mop	106	77	29	703	223	29.64	1859	29	29
House 08	Sweep/Mop	90	60	26	719	198	32.40	1804	32	26
House 09	Sweep/Mop	111	80	35	761	221	29.51	1837	33	35
House 12	Sweep/Mop	94	60	32	857	439	16.16	2013	27	32
House 02	Laundry	73	60	10	611	273	51.17	3940	9	10
House 03	Laundry	77	63	11	851	271	48.25	3684	17	11
House 05	Laundry	73	61	11	703	271	37.92	2895	16	11
House 06	Laundry	80	72	10	445	196	30.11	1656	17	10
House 07	Laundry	99	77	22	593	223	29.64	1859	23	22
House 08	Laundry	74	60	12	456	198	32.40	1804	16	12
House 09	Laundry	99	80	22	565	221	29.51	1837	21	22
House 12	Laundry	75	60	14	750	439	16.16	2013	20	14
House 02	Lgt Cleaning[f]	74	60	10	601	273	51.17	3940	9	10
House 03	Lgt Cleaning	76	63	11	678	271	48.25	3684	12	11
House 04	Lgt Cleaning	106	82	22	619	202	37.88	2152	21	22
House 05	Lgt Cleaning	79	61	16	831	271	37.92	2895	21	16
House 06	Lgt Cleaning	82	72	12	618	196	30.11	1656	29	12
House 07	Lgt Cleaning	100	77	23	576	223	29.64	1859	22	23
House 09	Lgt Cleaning	117	80	42	847	221	29.51	1837	39	42
House 12	Lgt Cleaning	87	60	25	966	439	16.16	2013	33	25
House 02	Ironing	74	60	10	489	273	51.17	3940	6	10
House 03	Ironing	77	63	11	757	271	48.25	3684	14	11
House 05	Ironing	76	61	14	574	271	37.92	2895	12	14
House 06	Ironing	76	72	5	372	196	30.11	1656	12	5
House 07	Ironing	96	77	19	434	223	29.64	1859	13	19
House 08	Ironing	80	60	18	420	198	32.40	1804	14	18
House 12	Ironing	78	60	17	731	439	16.16	2013	19	17

[a] Activity heart rate

[b] Resting heart rate

[c] Heart rate reserve

[d] Oxygen uptake (VO_2) reserve

[e] Sweeping and mopping

[f] Light cleaning

Table 2. Activity heart rate and activity oxygen uptake for house and family activities compared with predicted oxygen uptake reserve values established from the 1:1 relationship with heart rate reserve.

					House Family Activities					
Subject #	Activity ID	Act HR[a] (bpm)	RHR[b] (bpm)	HRR[c] (bpm)	VO2 (ml/min)	Rest VO2 (ml/min)	Predicted VO2 max (ml/kg/min)	Predicted VO2 max (ml/min)	VO2R[d] %	HRR %
HFam1	Wash Dishes[e]	76	60	12	488	217	43.54	2656	11	12
HFam2	Wash Dishes	81	58	17	577	272	56.63	4349	7	17
HFam3	Wash Dishes	89	80	8	392	186	41.94	2181	10	8
HFam4	Wash Dishes	71	64	7	318	258	19.17	1393	5	7
HFam5	Wash Dishes	86	60	19	580	299	44.96	3790	8	19
HFam10	Wash Dishes	82	64	20	445	233	20.21	1328	19	20
HFam12	Wash Dishes	116	88	26	646	375	19.97	2116	16	26
HFam1	Caring/Child[f]	72	60	9	476	217	43.54	2656	11	9
HFam3	Caring/Child	84	80	4	374	186	41.94	2181	9	4
HFam4	Caring/Child	71	64	7	311	258	19.17	1393	5	7
HFam5	Caring/Child	86	60	19	468	299	44.96	3790	5	19
HFam6	Caring/Child	68	56	10	528	266	47.82	3587	8	10
HFam10	Caring/Child	76	64	13	366	233	20.21	1328	12	13
HFam12	Caring/Child	106	88	17	475	375	19.97	2116	6	17
HFam1	Grocery Shop[g]	73	60	10	461	217	43.54	2656	10	10
HFam3	Grocery Shop	81	80	1	433	186	41.94	2181	12	1
HFam4	Grocery Shop	79	64	15	739	258	19.17	1393	42	15
HFam6	Grocery Shop	68	56	10	778	266	47.82	3587	15	10
HFam10	Grocery Shop	82	64	20	458	233	20.21	1328	21	20
Groc11	Grocery Shop	60	54	4	424	277	51.17	3991	4	4
HFam12	Grocery Shop	106	88	17	547	375	19.97	2116	10	17
HFam1	Feed/Groom[h]	70	60	7	813	219	43.54	2686	24	7
HFam2	Feed/Groom	77	58	14	867	272	56.63	4349	15	14
HFam3	Feed/Groom	103	80	21	586	186	41.94	2181	20	21
HFam4	Feed/Groom	74	64	10	505	258	19.17	1393	22	10
HFam5	Feed/Groom	64	60	3	401	299	44.96	3790	3	3
HFam6	Feed/Groom	67	56	9	733	266	47.82	3587	14	9
HFam19	Feed/Groom	75	64	12	366	233	20.21	1328	12	12
Pet11	Feed/Groom	94	87	7	392	211	31.22	1851	11	7
Pet12	Feed/Groom	94	80	14	274	310	39.38	3445	0	14
HFam1	Play w/childl	80	60	15	513	219	43.54	2686	12	15
HFam2	Play w/child	67	58	7	530	272	56.63	4349	6	7
HFam3	Play w/child	104	80	22	704	186	41.94	2181	26	22
Hfam4	Play w/child	77	64	13	557	258	19.17	1393	26	13
Hfam5	Play w/child	71	60	8	914	299	44.96	3790	18	8
Hfam6	Play w/child	82	56	21	1150	266	47.82	3587	27	21
Hfam6	Play w/child	84	74	9	344	233	22.82	1495	9	9
HFam10	Play w/child	84	64	22	512	233	20.21	1328	25	22
Pet11	Play w/child	99	87	13	742	211	31.22	1851	32	13
Pet12	Play w/child	94	80	14	943	310	39.38	3445	20	14

[a] Activity heart rate
[b] Resting heart rate
[c] Heart rate reserve
[d] Oxygen uptake (VO_2) reserve
[e] Washing dishes
[f] Caring for a small child
[g] Grocery shopping
[h] Feeding and grooming a small animal
[I] Playing with a small child

Table 3. Activity heart rate and activity oxygen uptake for conditioning activities compared with predicted oxygen uptake reserve values established from the 1:1 relationship with heart rate reserve.

Conditioning Activities										
Subject #	Activity ID	Act HR[a] (bpm)	RHR[b] (bpm)	HRR[c] (bpm)	VO2 (ml/min)	Rest VO2 (ml/min)	Predicted VO2 max (ml/kg/min)	Predicted VO2 max (ml/min)	VO2R[d] %	HRR %
Con2	Slow Walk[e]	81	65	14	796.4	261	48.22	3544	16	14
Con4	Slow Walk	81	64	13	569.4	259	53.31	3892	9	13
Con5	Slow Walk	66	56	8	549	263	47.82	3539	9	8
Con6	Slow Walk	139	98	41	875.4	242	30.76	2092	34	41
Con7	Slow Walk	83	61	23	1151.1	270	42.16	3208	30	23
Con11	Slow Walk	97	84	16	1137	283	40.91	3264	29	16
Con12	Slow Walk	115	74	46	1281	412	15.64	1823	62	46
Con2	Fast Walk[f]	99	65	30	1233.2	261	48.22	3544	30	30
Con4	Fast Walk	98	64	27	1154.6	259	53.31	3892	25	27
Con6	Fast Walk	161	98	64	1128.4	242	30.76	2092	48	64
Con7	Fast Walk	104	61	45	1586.3	270	42.16	3208	45	45
Con11	Fast Walk	114	84	37	1481	283	40.91	3264	40	37
Con12	Fast Walk	119	74	50	1500	412	15.64	1823	77	50
Con2	Stretch[g]	92	75	14	664.7	225	45.68	2896	16	14
Con6	Stretch	118	98	20	397.9	242	30.76	2092	8	20
Con7	Stretch	76	61	16	829.7	270	42.16	3208	19	16
Con11	Stretch	99	84	19	737	283	40.91	3264	15	19
Con12	Stretch	104	74	33	871	412	15.64	1823	33	33
Con2	Calisthenics[h]	101	75	21	745	225	45.68	2896	19	21
Con6	Calisthenics	134	98	36	638.9	242	30.76	2092	21	36
Con7	Calisthenics	84	61	24	929.1	270	42.16	3208	22	24
Con11	Calisthenics	108	84	30	1058	283	40.91	3264	26	30
Con12	Calisthenics	118	74	49	1213	412	15.64	1823	57	49

[a] Activity heart rate
[b] Resting heart rate
[c] Heart rate reserve
[d] Oxygen uptake (VO$_2$) reserve
[e] Slow walking on an outside 400m track
[f] Fast walking on an outside 400m track
[g] Stretching
[h] Light calisthenics

Table 4. Activity heart rate and activity oxygen uptake for occupational activities compared with predicted oxygen uptake reserve values established from the 1:1 relationship with heart rate reserve.

		Occupation Activities								
Subject #	Activity ID	Act HR[a] (bpm)	RHR[b] (bpm)	HRR[c] (bpm)	VO2 (ml/min)	Rest VO2 (ml/min)	Predicted VO2 max (ml/kg/min)	Predicted VO2 max (ml/min)	VO2R[d] %	HRR %
Occ1	Walking[e]	98	66	24	940	279	47.37	3723	19	24
Occ2	Walking	91	60	23	781	236	31.14	2068	30	23
Occ3	Walking	117	79	36	986	269	22.48	1706	50	36
Occ8	Walking	133	88	56	1481	338	29.35	2808	46	56
Occ10	Walking	103	69	28	811	237	30.38	2023	32	28
Occ1	Walk/Carry[f]	112	66	34	1317	279	47.37	3723	30	34
Occ2	Walk/Carry	115	60	41	1177	236	31.14	2068	51	41
Occ5	Walk/Carry	154	82	73	1521	237	33.54	2241	64	73
Occ6	Walk/Carry	165	79	82	1572	269	22.48	1706	91	82
Occ8	Walk/Carry	147	88	74	2127	338	29.35	2808	72	74
Occ9	Walk/Carry	136	78	62	1176	200	29.38	1645	68	62
Occ10	Walk/Carry	126	69	48	1335	237	30.38	2023	61	48
Occ11	Load/Unload[g]	102	66	27	1044	279	47.37	3723	22	27
Occ2	Load/Unload	104	60	33	1058	236	31.14	2068	45	33
Occ5	Load/Unload	140	82	59	1210	237	33.54	2241	49	59
Occ6	Load/Unload	148	79	66	1062	269	22.48	1706	55	66
Occ8	Load/Unload	144	90	69	1695	338	29.35	2808	55	69
Occ9	Load/Unload	114	78	39	727	200	29.38	1645	36	39
Occ10	Load/Unload	114	69	38	967	237	30.38	2023	41	38

[a] Activity heart rate
[b] Resting heart rate
[c] Heart rate reserve
[d] Oxygen uptake (VO_2) reserve
[e] Walking on a treadmill 3mph
[f] Walking on a treadmill 3mph carrying 10-20lb loads
[g] Loading and unloading 10-20lb boxes

Table 5. Activity heart rate and activity oxygen uptake for leisure activities compared with predicted oxygen uptake reserve values established from the 1:1 relationship with heart rate reserve.

						Leisure Activities				
Subject #	Activity ID	Act HR[a] (bpm)	RHR[b] (bpm)	HRR[c] (bpm)	VO2 (ml/min)	Rest VO2 (ml/min)	Predicted VO2 max (ml/kg/min)	Predicted VO2 max (ml/min)	VO2R[d] %	HRR %
Golf 1	Golf Pull[e]	90	66	18	928	238	51.33	3439	22	18
Golf 2	Golf Pull	110	78	43	1041	211	22.60	1340	74	43
Golf 5	Golf Pull	113	85	28	1341.4	274	48.25	3729	31	28
Golf 7	Golf Pull	116	60	41	1135	224	43.54	2743	36	41
Golf 8	Golf Pull	108	72	30	914	207	42.96	2492	31	30
Golf 9	Golf Pull	108	77	29	858.5	219	35.39	2180	33	29
Golf 10	Golf Pull	142	94	56	1177.8	305	27.49	2364	42	56
Golf 11	Golf Pull	133	108	22	1131.5	290	40.91	3346	28	22
Golf 12	Golf Pull	123	89	37	1007	335	30.62	2903	26	37
Golf 1	Golf Carry[f]	94	66	21	951	238	51.33	3439	22	21
Golf 2	Golf Carry	128	78	68	1223	211	22.60	1340	90	68
Golf 5	Golf Carry	110	85	25	1218	274	48.25	3729	27	25
Golf 7	Golf Carry	116	81	31	1194.5	224	43.54	2743	39	31
Golf 8	Golf Carry	102	72	25	790	207	42.96	2492	26	25
Golf 9	Golf Carry	110	77	31	788.6	219	35.39	2180	29	31
Golf 10	Golf Carry	149	94	64	1150.9	305	27.49	2364	41	64
Golf 11	Golf Carry	143	108	31	1101.5	290	40.91	3346	27	31
Golf 12	Golf Carry	118	89	31	1207	335	30.62	2903	34	31
Softball 1	Softball[g]	127	60	49	1003	196	55.58	3057	28	49
Softball 4	Softball	91	64	21	1183	259	53.31	3892	25	21
Softball 6	Softball	104	78	28	645	200	29.38	1645	31	28
Softball 7	Softball	125	60	48	1131	224	43.54	2743	36	48
Softball 9	Softball	117	105	20	854	412	15.64	1823	31	20
Softball 10	Softball	143	90	68	1470	340	29.35	2817	46	68
Softball 11	Softball	83	56	22	894	272	47.82	3668	18	22
Softball 12	Softball	127	96	39	653	225	27.97	1768	28	39
Tennis 2	Tennis[h]	117	74	55	1361	249	21.84	1529	87	55
Tennis 3	Tennis	117	68	52	1126	190	37.44	1992	52	52
Tennis 5	Tennis	95	71	32	966	253	37.28	2662	30	32
Tennis 7	Tennis	112	60	39	1269	284	51.17	4093	26	39
Tennis 10	Tennis	116	87	27	813	224	43.54	2743	23	27
Tennis 11	Tennis	96	65	27	1206	261	48.22	3544	29	27

[a] Activity heart rate
[b] Resting heart rate
[c] Heart rate reserve
[d] Oxygen uptake (VO_2) reserve
[e] Playing golf pulling clubs
[f] Playing golf carrying clubs
[g] Simulated softball practice
[h] Doubles tennis

Table 6. Activity heart rate and activity oxygen uptake for yard work activities compared with predicted oxygen uptake reserve values established from the 1:1 relationship with heart rate reserve.

		Yard Work Activities								
Subject #	Activity ID	Act HR[a] (bpm)	RHR[b] (bpm)	HRR[c] (bpm)	VO2 (ml/min)	Rest VO2 (ml/min)	Predicted VO2 max (ml/kg/min)	Predicted VO2 max (ml/min)	VO2R[d] %	HRR %
Yard 02	Push Mow[e]	114	63	39	1545	266	45.46	3409	41	39
Yard 03	Push Mow	160	84	69	1715	258	29.89	2174	76	69
Yard 04	Push Mow	164	74	83	1748	258	22.24	1618	110	83
Yard 05	Push Mow	125	77	50	1588	317	33.54	3003	47	50
Yard 06	Push Mow	129	73	67	1955	256	37.69	2715	69	67
Yard 08	Push Mow	135	79	61	1266	238	24.36	1633	74	61
Yard 10	Push Mow	109	60	45	1154	284	19.95	1601	66	45
Yard 11	Push Mow	134	76	62	1762	466	14.85	1961	87	62
Yard 02	Power Mow[f]	112	63	37	1460	266	45.46	3409	38	37
Yard 03	Power Mow	168	84	76	1660	258	29.89	2174	73	76
Yard 04	Power Mow	168	74	87	1754	258	22.24	1618	110	87
Yard 05	Power Mow	130	77	55	1866	317	33.54	3003	58	55
Yard 06	Power Mow	119	73	55	1677	256	37.69	2715	58	55
Yard 08	Power Mow	150	79	77	1393	238	24.36	1633	83	77
Yard 10	Power Mow	117	60	53	1203	284	19.95	1601	70	53
Yard 11	Power Mow	137	76	65	1598	466	14.85	1961	76	65
Yard 02	Raking[g]	108	63	34	1374	266	45.46	3409	35	34
Yard 03	Raking	157	84	66	1011	258	29.89	2174	39	66
Yard 04	Raking	156	74	76	1545	258	22.24	1618	95	76
Yard 05	Raking	132	77	57	1580	317	33.54	3003	47	57
Yard 06	Raking	118	73	54	1235	256	37.69	2715	40	54
Yard 09	Raking	134	70	54	1901	249	45.67	3207	56	54
Yard 10	Raking	95	60	32	1091	284	19.95	1601	61	32
Yard 11	Raking	107	76	33	1254	466	14.85	1961	53	33
Yard 03	Trimming[h]	99	84	14	765	258	29.89	2174	26	14
Yard 05	Trimming	105	77	29	1196	317	33.54	3003	33	29
Yard 06	Trimming	101	73	34	895	256	37.69	2715	26	34
Yard 08	Trimming	119	79	43	670	238	24.36	1633	31	43
Yard 11	Trimming	122	76	49	1182	466	14.85	1961	48	49
Yard 02	Gardening[I]	81	63	14	743	266	45.46	3409	15	14
Yard 03	Gardening	88	84	4	591	258	29.89	2174	17	4
Yard 04	Gardening	150	74	70	1252	258	22.24	1618	73	70
Yard 05	Gardening	120	77	45	1283	317	33.54	3003	36	45
Yard 06	Gardening	114	73	49	1405	256	37.69	2715	47	49
Yard 08	Gardening	125	79	50	670	238	24.36	1633	31	50
Yard 11	Gardening	116	76	43	919	466	14.85	1961	30	43

[a] Activity heart rate

[b] Resting heart rate

[c] Heart rate reserve

[d] Oxygen uptake (VO_2) reserve

[e] Mowing the lawn using a push mower

[f] Mowing the lawn using a power mower

[g] Raking leaves

[h] Trimming hedges using an manual trimmer

[I] General gardening (planting shrubs, weeding)

APPENDIX B

PART IV

Informed Consent Form

INFORMED CONSENT FORM

TITLE OF THE STUDY: Simultaneous Heart Rate – Motion Sensor Technique to Estimate Energy Expenditure

Investigators: Scott J. Strath
David R. Bassett, Jr.

Address:
Exercise Science and Sport Management
College of Education
University of Tennessee, Knoxville
1914 Andy Holt Ave. Knoxville, TN 37996

Phone: (865) 974-1271

PURPOSE

You are invited to take part in a research study, the purpose of which is to study the use of both heart rate and motion sensors to measure how many Calories you burn during certain activities.

PROCEDURES

You will be required to come to the Applied Physiology Laboratory in the Health, Physical Education & Recreation (HPER) Building on the University of Tennessee campus on two different occasions. The sessions will last approximately 2-3 hours each day. On the first day you will be asked to fill out a medical history questionnaire, and will undergo testing procedures to measure blood pressure, height, weight and body fat percentage. On the second day you will undergo two separate exercise tests, one for arm exercise only and one for leg exercise only.

Survey Information

You will fill out surveys which ask questions about your medical history, your family's medical history and your current activity patterns. This information is confidential. The surveys you complete will be assigned a number so that your name cannot be associated with any information given. Only the researchers will have access to the number codes.

Body Composition

We will measure your height and weight. We will also measure your body fat percentage. This will be done by using skinfold calipers that measure the thickness of your skin.

Blood Pressure

We will place a cuff around your upper right arm. This cuff will be inflated with air, and then slowly let down again. By listening to the sound of the pulse in your arm we are able to determine your blood pressure reading.

Arm Only Exercise Test

You will sit on an Air-Dyne, and will be required to push each arm alternately forward. This will start out easy, and will slowly get harder and harder. During this time you will be wearing a heart rate monitor, which is a thin strap that goes around the chest. You will also be wearing a portable oxygen analyzer. A mask will be placed over your nose and mouth to capture all of the air that you breathe out. You will be able to breathe normal room air throughout. The test will stop when you reach 85% of your age predicted maximal heart rate (220-age), or you request to stop.

Leg Only Exercise Test

This will be performed on a treadmill. You will begin by walking slowly on a flat level. The speed will slowly increase until you reach a brisk walk, after which the slope will begin to increase. During this time you will be wearing a heart rate monitor, which is a thin strap that goes around the chest. You will also be wearing a portable oxygen analyzer. A mask will be placed over your nose and mouth to capture all of the air that you breathe out. You will be able to breathe normal room air throughout. The test will stop when you reach 85% of your age predicted maximal heart rate (220-age), or you request to stop.

Home Testing

For this I will come to your home. I will ask you to perform a variety of tasks. Either:

Yard work: Power mowing, raking leaves, trimming, and gardening.
House work: Vacuuming, light cleaning, ironing, and sweeping and mopping.
OR
Conditioning: Slow walk, fast walk, stretching, and stair climbing interspersed with walking.

The conditioning component will take place on the UTK campus outdoor all-weather track. During these activities you will again be asked to wear a heart rate monitor and the portable oxygen analyzer. In addition you will be asked to wear several small motion sensors attached to you waist, leg and wrist. These motion sensors are small matchbox size devices that record vertical movement. Each activity will last for 15 minutes, with a 5-10 minute rest before you begin the next activity.

BENEFITS OF PARTICIPATION

From the information that we generate we will be able to tell you your body fat percentage, your blood pressure, and how many calories you burn during selected activities. You will also be paid $40.00 for participating in this study.

RISKS OF PARTICIPATION

The potential risks that may occur with participating in the proposed research include those associated with exercise testing. These include: leg discomfort, muscle/joint soreness, dizziness, headache, and in rare instances heart attack (1 in 10,000). A strict screening process will help eliminate any of these potential risks. In addition the Applied Physiology Laboratory has a planned response to any emergency procedure, and all testing personnel are CPR certified. There are no known physical risks to any of the home testing.

RIGHT TO ASK QUESTIONS AND/OR WITHDRAW FROM THIS STUDY

If you have any questions or concerns at any time during the course of the testing procedures or after completion of the procedures you can contact either Dr. Bassett or myself at (865) 974-1271. As a volunteer in this study you have the right to withdraw at any time.

CONFIDENTIALITY

Only Dr. Bassett, myself and you will have access to any of the information collected during this research project. All information collected will be kept in a locked file cabinet in the office of Scott Strath. The final results of this research will be published, but your name will not be associated with any of the material published.

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.

Participants signature ____________ Date ____________

Investigators signature ____________ Date ____________

APPENDIX B1

PART IV

Raw Data

Table 1. Comparison of energy expenditure values (METs) measured by indirect calorimetry (Cosmed) in comparison to the CSA accelerometer, Yamax pedometer, HR leg (Leg Reg) and HR arm (Arm Reg) regression equations, and the simultaneous heart rate-motion sensor technique for select housework activities.

Housework Activities							
ID	Activity	Cosmed	CSA	Yamax	Leg Reg	Arm Reg	Sim. HR+M
1	Vacuuming	4.4	1.8	0.3	4.3	3.0	4.3
2	Vacuuming	4.0	2.3	0.0	3.8	2.8	3.8
3	Vacuuming	4.0	2.0	0.5	3.1	2.3	3.1
4	Vacuuming	3.8	2.4	0.2	3.9	3.3	3.9
5	Vacuuming	3.4	2.4	0.4	3.4	2.5	3.4
6	Vacuuming	3.3	1.8	0.1	3.5	2.4	3.5
7	Vacuuming	3.6	3.0	1.1	4.1	2.8	4.1
8	Vacuuming	2.9	2.1	0.6	2.3	1.2	2.3
9	Vacuuming	4.4	2.6	0.3	3.6	2.3	3.6
10	Vacuuming	3.9	2.0	0.3	3.6	2.4	3.6
11	Vacuuming	5.0	3.0	0.5	5.4	3.4	5.4
1	Light Cleaning	3.0	1.6	0.6	2.9	2.3	2.9
2	Light Cleaning	3.8	2.4	0.3	3.9	2.9	3.9
3	Light Cleaning	2.6	1.6	0.2	2.6	2.2	2.6
4	Light Cleaning	2.9	2.1	0.2	3.1	2.2	3.1
5	Light Cleaning	2.2	1.6	0.5	2.7	1.9	2.7
6	Light Cleaning	3.0	2.8	0.0	3.4	2.4	3.4
7	Light Cleaning	2.0	2.3	0.4	2.7	1.9	1.9
8	Light Cleaning	1.7	1.8	0.4	2.0	1.0	2.0
9	Light Cleaning	3.5	3.1	1.0	2.1	1.4	2.1
10	Light Cleaning	3.4	2.5	0.9	3.1	2.1	3.1
11	Light Cleaning	4.3	2.3	0.2	3.6	2.2	3.6
1	Scrubbing floor	3.6	2.3	0.0	4.3	3.0	3.0
2	Scrubbing floor	3.9	3.2	0.0	4.2	3.1	4.2
3	Scrubbing floor	4.0	2.3	0.1	3.8	2.7	3.8
4	Scrubbing floor	3.5	2.3	0.0	4.2	3.3	4.2
5	Scrubbing floor	3.0	1.9	0.2	3.3	2.4	2.4
6	Scrubbing floor	2.6	2.2	0.0	2.7	1.9	2.7
7	Scrubbing floor	3.0	2.3	0.3	3.2	2.2	3.2
8	Scrubbing floor	2.4	2.2	0.2	2.3	1.2	2.3
9	Scrubbing floor	3.3	2.3	0.1	1.9	1.3	1.9
10	Scrubbing floor	3.5	1.9	0.1	3.1	2.1	3.1
11	Scrubbing floor	4.0	2.3	0.3	3.8	2.3	3.8
1	Washing Dishes	2.4	1.5	0.0	2.7	2.2	2.2
2	Washing Dishes	2.5	1.5	0.1	3.1	2.1	2.1
3	Washing Dishes	2.1	1.5	0.0	2.6	2.3	2.3
4	Washing Dishes	2.0	1.5	0.0	2.8	2.3	2.3
5	Washing Dishes	1.9	1.5	0.0	3.1	2.2	2.2
6	Washing Dishes	1.9	1.5	0.0	2.7	1.9	1.9
7	Washing Dishes	1.5	1.5	0.3	1.6	1.2	1.2
8	Washing Dishes	1.2	1.4	0.1	1.6	0.8	0.8
9	Washing Dishes	2.3	1.5	0.0	2.2	1.5	1.5
10	Washing Dishes	2.2	2.2	0.1	2.5	1.7	1.7
11	Washing Dishes	3.0	1.5	0.0	3.8	2.3	2.3
1	Washing Windows	3.2	1.8	0.0	3.9	3.3	3.9
2	Washing Windows	3.4	1.7	0.1	3.6	2.6	3.6
3	Washing Windows	4.2	1.8	0.3	3.2	2.2	3.2
5	Washing Windows	2.5	1.5	0.4	3.2	2.3	3.2
6	Washing Windows	2.6	1.5	0.1	3.3	2.3	2.3
7	Washing Windows	2.3	1.6	0.3	3.0	2.1	2.1
8	Washing Windows	2.3	1.9	0.1	2.6	1.3	2.6
9	Washing Windows	3.2	1.8	0.0	2.8	1.9	2.8
10	Washing Windows	3.2	1.9	0.1	2.9	1.9	2.9
11	Washing Windows	3.5	1.8	1.4	4.4	2.7	2.7
1	Ironing	2.4	1.5	0.1	2.8	2.3	2.3
2	Ironing	2.4	1.6	0.3	3.0	2.0	3.0
3	Ironing	2.1	1.5	0.2	3.0	2.0	3.0
4	Ironing	2.2	1.5	0.1	3.1	2.3	2.3
5	Ironing	1.8	1.5	0.1	2.3	1.6	1.6
6	Ironing	1.6	1.5	0.0	2.6	1.9	1.9
7	Ironing	1.6	1.5	0.3	1.6	1.2	1.2
8	Ironing	1.2	1.5	0.1	1.8	0.9	0.9
9	Ironing	2.5	1.5	0.2	1.7	1.2	1.2
10	Ironing	2.2	1.5	0.2	2.4	1.6	1.6
11	Ironing	2.5	1.5	0.0	3.6	2.2	2.2

Table 2. Comparison of energy expenditure values (METs) measured by indirect calorimetry (Cosmed) in comparison to the CSA accelerometer, Yamax pedometer, HR leg (Leg Reg) and HR arm (Arm Reg) regression equations, and the simultaneous heart rate-motion sensor technique for select conditioning activities.

		Conditioning Activities					
ID	**Activity**	**Cosmed**	**CSA**	**Yamax**	**Leg Reg**	**Arm Reg**	**Sim. HR+M**
12	Slow Walk	3.6	4.4	4.3	3.3	2.7	3.3
13	Slow Walk	4.3	5.1	4.5	5.2	4.0	5.2
14	Slow Walk	4.1	3.9	6.1	4.7	3.5	4.7
15	Slow Walk	2.9	2.5	2.7	2.7	1.3	2.7
16	Slow Walk	3.0	2.5	1.5	2.4	1.9	2.4
17	Slow Walk	2.2	2.6	2.9	2.4	1.1	2.4
18	Slow Walk	2.9	2.4	2.6	3.8	1.7	3.8
19	Slow Walk	2.4	2.1	2.3	2.7	1.9	2.7
20	Slow Walk	3.3	2.4	2.8	3.3	2.3	3.3
21	Slow Walk	3.2	2.6	2.5	3.3	2.7	3.3
22	Slow Walk	2.8	2.1	2.3	2.7	2.3	2.7
12	Brisk Walk	4.6	5.6	5.1	4.5	3.8	4.5
13	Brisk Walk	6.2	7.2	5.3	7.6	6.0	7.6
14	Brisk Walk	5.4	5.1	6.9	6.2	4.6	6.2
15	Brisk Walk	5.5	5.1	8.9	4.9	3.0	4.9
16	Brisk Walk	6.2	6.1	4.0	5.2	3.9	5.2
17	Brisk Walk	3.0	5.1	4.9	4.2	2.6	4.2
18	Brisk Walk	4.4	5.0	5.1	5.1	2.9	5.1
19	Brisk Walk	3.4	3.7	5.4	3.3	2.3	3.3
20	Brisk Walk	5.4	4.3	7.3	4.6	3.7	4.6
21	Brisk Walk	5.9	5.6	6.0	6.0	5.1	6.0
22	Brisk Walk	4.5	4.4	8.3	4.4	3.5	4.4
15	Weight Circuit	2.5	1.4	0.0	5.4	3.4	3.4
16	Weight Circuit	3.2	1.5	0.0	5.8	4.4	4.4
17	Weight Circuit	1.2	1.7	0.0	5.9	4.1	4.1
18	Weight Circuit	2.7	1.5	0.0	5.8	3.5	3.5
19	Weight Circuit	3.6	1.7	0.1	5.4	3.8	3.8
20	Weight Circuit	3.8	1.5	0.0	6.6	4.5	4.5
21	Weight Circuit	2.6	1.4	0.0	6.3	5.4	5.4
22	Weight Circuit	2.6	1.5	0.0	5.3	4.1	4.1
12	Walking/Stairs	4.6	3.5	3.6	4.3	3.6	4.3
13	Walking/Stairs	6.2	5.4	5.4	7.3	5.8	7.3
14	Walking/Stairs	7.3	4.3	5.6	7.9	5.8	7.9
15	Walking/Stairs	5.7	3.5	5.9	5.7	3.6	5.7
16	Walking/Stairs	8.4	6.0	4.7	7.7	5.7	7.7
17	Walking/Stairs	2.9	4.6	4.7	5.1	3.4	5.1
18	Walking/Stairs	6.3	5.4	4.7	6.8	4.4	6.8
19	Walking/Stairs	5.1	4.1	5.2	4.5	3.1	4.5
20	Walking/Stairs	6.6	3.3	6.4	6.7	4.6	6.7
21	Walking/Stairs	6.6	4.1	5.2	6.9	5.9	6.9
22	Walking/Stairs	7.8	4.5	8.4	7.9	6.0	7.9

Table 3. Comparison of energy expenditure values (METs) measured by indirect calorimetry (Cosmed) in comparison to the CSA accelerometer, Yamax pedometer, HR leg (Leg Reg) and HR arm (Arm Reg) regression equations, and the simultaneous heart rate-motion sensor technique for select yardwork activities.

Yardwork Activities							
ID	Activity	Cosmed	CSA	Yamax	Leg Reg	Arm Reg	Sim. HR+M
23	Power Mowing	6.1	3.7	2.2	6.4	5.2	6.4
24	Power Mowing	9.1	6.3	3.1	9.7	7.2	9.7
25	Power Mowing	5.0	3.8	1.4	4.4	2.8	4.4
28	Power Mowing	4.3	3.8	1.4	4.6	4.0	4.6
29	Power Mowing	5.4	3.9	1.7	5.8	5.1	5.8
30	Power Mowing	6.1	3.7	1.9	6.8	4.7	6.8
23	Gardening	2.9	1.7	0.1	3.1	2.5	3.1
24	Gardening	4.2	2.2	0.9	5.1	3.1	5.1
25	Gardening	3.4	1.8	0.7	3.0	1.9	3.0
26	Gardening	5.3	2.9	0.7	3.7	2.2	3.7
27	Gardening	4.5	3.1	1.5	5.0	3.0	5.0
28	Gardening	3.1	1.7	0.6	2.6	1.9	2.6
29	Gardening	2.2	2.9	0.7	2.5	1.8	2.5
30	Gardening	3.1	2.5	0.7	4.0	2.9	4.0
23	Electric Trimming	3.9	1.8	0.6	4.5	3.6	4.5
24	Electric Trimming	6.7	2.0	0.9	8.1	6.2	6.2
25	Electric Trimming	3.2	1.7	0.5	4.1	2.6	2.6
26	Electric Trimming	4.4	1.6	0.2	3.7	2.2	3.7
27	Electric Trimming	4.8	1.9	0.6	6.5	4.1	4.1
28	Electric Trimming	4.5	1.7	0.3	5.3	4.7	4.7
29	Electric Trimming	4.0	1.7	0.2	5.6	4.8	4.8
30	Electric Trimming	4.1	3.0	0.3	5.8	4.1	4.1
23	Raking leaves	5.5	2.4	1.5	5.4	4.4	5.4
24	Raking leaves	7.6	4.9	2.9	7.2	5.7	7.2
25	Raking leaves	3.2	1.7	0.7	4.3	2.7	2.7
26	Raking leaves	4.6	1.7	0.4	3.3	1.9	3.3
27	Raking leaves	5.0	2.8	0.2	6.3	3.9	6.3
28	Raking leaves	3.3	1.9	0.6	4.5	3.9	3.9
29	Raking leaves	3.1	2.0	0.2	3.4	2.8	3.4
30	Raking leaves	4.3	2.2	0.7	5.8	4.1	4.1

APPENDIX C

PART V

Informed Consent Form

INFORMED CONSENT FORM

TITLE OF THE STUDY: Simultaneous Heart Rate – Motion Sensor Technique to Estimate Energy Expenditure

Investigators: Scott J. Strath
David R. Bassett, Jr.
Address:
Exercise Science and Sport Management
College of Education
University of Tennessee, Knoxville
1914 Andy Holt Ave. Knoxville, TN 37996
Phone: (865) 974-1271

PURPOSE

You are invited to take part in a research study, the purpose of which is to study the use of both heart rate and motion sensors to measure how many Calories you burn during certain activities.

PROCEDURES

You will be required to come to the Applied Physiology Laboratory in the Health, Physical Education & Recreation (HPER) Building on the University of Tennessee campus. The session will last approximately 2 hours. You will be asked to fill out a medical history questionnaire, and will undergo testing procedures to measure blood pressure, height, weight and body fat percentage. You will also undergo two separate exercise tests, one for arm exercise only and one for leg exercise only. Then on a separate day you will be required to participate in a "usual day" testing phase lasting approximately 6-7 hours. This is to represent physical activity within a typical day, and is to be carried out on either a weekday, or a weekend day at your place of employment or at home.

Survey Information

You will fill out surveys which ask questions about your medical history, your family's medical history and your current activity patterns. This information is confidential. The surveys you complete will be assigned a number so that your name cannot be associated with any information given. Only the researchers will have access to the number codes.

Body Composition

We will measure your height and weight. We will also measure your body fat percentage. This will be done by using skinfold calipers that measure the thickness of your skin.

Blood Pressure

We will place a cuff around your upper right arm. This cuff will be inflated with air, and then slowly let down again. By listening to the sound of the pulse in your arm we are able to determine your blood pressure reading.

Arm Only Exercise Test

You will sit on an Air-Dyne, and will be required to push each arm alternately forward. This will start out easy, and will slowly get harder and harder. During this time you will be wearing a heart rate monitor, which is a thin strap that goes around the chest. You will also be wearing a portable oxygen analyzer. A mask will be placed over your nose and mouth to capture all of the air that you breathe out. You will be able to breathe normal room air throughout. The test will stop when you reach 85% of your age predicted maximal heart rate (220-age), or you request to stop.

Leg Only Exercise Test

This will be performed on a treadmill. You will begin by walking slowly on a flat level. The speed will slowly increase until you reach a brisk walk, after which the slope will begin to increase. During this time you will be wearing a heart rate monitor, which is a thin strap that goes around the chest. You will also be wearing a portable oxygen analyzer. A mask will be placed over your nose and mouth to capture all of the air that you breathe out. You will be able to breathe normal room air throughout. The test will stop when you reach 85% of your age predicted maximal heart rate (220-age), or you request to stop.

Usual Day Activity

For this segment I will come to your home/place of employment. I will ask you to conduct yyour usual daily activities but while wearing the heart rate monitor, and the portable oxygen analyzer. In addition, you will be asked to wear several small motion sensors attached to your waist, leg and wrist. These motion sensors are small matchbox size devices that record vertical movement. This activity period will last for a total of 6-7 hours. Hopefully this will be conducted in 3 two-hour bouts. At the end of each two-hour bout I will allow you to take a break for refreshments or anything else you may need. However, you may stop at any time during the two-hour bout if you need/request to do so.

BENEFITS OF PARTICIPATION

From the information that we generate we will be able to tell you your body fat percentage, your blood pressure, and how many calories you burn during selected activities. You will also be paid $40.00 for participating in this study.

RISKS OF PARTICIPATION

The potential risks that may occur with participating in the proposed research include those associated with exercise testing. These include: leg discomfort, muscle/joint soreness, dizziness, headache, and in rare instances heart attack (1 in 10,000). A strict screening process will help eliminate any of these potential risks. In addition the Applied Physiology Laboratory has a planned response to any emergency procedure, and all testing personnel are CPR certified. There are no known physical risks to any of the home testing.

RIGHT TO ASK QUESTIONS AND/OR WITHDRAW FROM THIS STUDY

If you have any questions or concerns at any time during the course of the testing procedures or after completion of the procedures you can contact either Dr. Bassett or myself at (865) 974-1271. As a volunteer in this study you have the right to withdraw at any time.

CONFIDENTIALITY

Only Dr. Bassett, myself and you will have access to any of the information collected during this research project. All information collected will be kept in a locked file cabinet in the office of Scott Strath. The final results of this research will be published, but your name will not be associated with any of the material published.

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.

Participants signature ____________________ Date ____________

Investigators signature ____________________ Date ____________

APPENDIX C1

PART V

Raw Data

Table 1. Total energy expenditure (MET·min^{-1}) for the Criterion (Cosmed K4b^2), simultaneous heart rate-motion sensor (HR+M) technique, and the Flex heart rate method (FlexHR) for six hours of near-continuous activity.

	TOTAL MET·min^{-1}		
Subject	**Cosmed**	**Sim. HR+M**	**FlexHR**
1	692	498	556
2	613	605	575
3	772	827	965
4	559	549	698
5	931	1082	1500
6	941	902	955
7	900	868	967
8	612	659	690
9	743	744	938
10	725	748	871
MEAN	**749**	**748**	**871**
SD	**138**	**178**	**274**

Table 2. Time spent data (minutes) for the Criterion (Cosmed K4b^2), simultaneous heart rate-motion sensor (HR+M) technique, and the Flex heart rate method (FlexHR) for six hours of near-continuous activity.

	Cosmed			Sim. HR+M			HRFlex		
Subject	**Light**	**Moderate**	**Hard**	**Light**	**Moderate**	**Hard**	**Light**	**Moderate**	**Hard**
1	298	33	0	308	22	1	290	39	2
2	219	26	10	191	52	12	175	67	13
3	246	93	3	233	100	9	203	120	19
4	301	20	0	274	47	0	261	60	0
5	209	111	4	165	141	18	31	262	31
6	228	109	22	246	95	18	235	106	18
7	242	118	0	246	113	1	213	146	1
8	346	14	0	337	23	0	331	29	0
9	276	74	6	259	91	6	230	111	15
10	223	44	18	214	43	28	174	83	28
Mean	**259**	**64**	**6**	**247**	**73**	**9**	**214**	**102**	**13**
SD	**45**	**41**	**8**	**51**	**41**	**10**	**81**	**67**	**12**

APPENDIX D

PART VI

Informed Consent Form

INFORMED CONSENT FORM

TITLE OF THE STUDY: Validation of Six Physical Activity Questionnaires
Using the Simultaneous Heart Rate – Motion Sensor Technique

Investigators: Scott J. Strath
David R. Bassett, Jr.
Address:
Exercise Science and Sport Management,
University of Tennessee, Knoxville
1914 Andy Holt Ave. Knoxville, TN 37996-2700
Phone: (865) 974-5091

PURPOSE

You are invited to take part in a research study, the purpose of which is to establish the accuracy of selected physical activity questionnaires for measuring how many Calories you burn during a week-long period.

PROCEDURES

You will be asked to come to the Applied Physiology Laboratory in the Health, Physical Education & Recreation (HPER) Building on the University of Tennessee campus on two different occasions. The sessions will last approximately 2-3 hours each. On the first day you will be asked to fill out a medical history questionnaire, and will undergo testing procedures to measure blood pressure, height, weight and body fat percentage. You will also undergo two separate exercise tests, one for arm exercise and one for leg exercise. You will then be asked to wear a heart rate watch and transmission belt, and three small motion sensors for a continuous 7-day period. At the end of this period you will be asked to come back into the Laboratory, return the heart rate watch, transmission belt, and motion sensors. At this time you will also be asked to fill out 6 different physical activity questionnaires.

VISIT ONE

Survey Information

You will fill out surveys that ask questions about your medical history and your current activity patterns. This information is confidential. The surveys you complete will be assigned a number so that your name cannot be associated with any information given. Only the researchers will have access to the number codes.

Body Composition

We will measure your height and weight. We will also measure your body fat percentage. This will be done by using whole body plethysmography (Bod Pod® body composition assessment system). We will also take measurements of your hips and waist, height, and weight.

Blood Pressure

We will place a cuff around your upper right arm. This cuff will be inflated with air, and then slowly let down again. By listening to the sound of the pulse in your arm we are able to determine your blood pressure reading.

Arm Exercise Test

This will take place on an arm ergometer. This machine is like a stationary cycle for the arms. You will sit on a chair, and will be required to push each arm alternately forward, in a pedaling type motion. This will start out at a light effort, and will slowly get harder and harder. During this time you will be wearing a heart rate monitor, which is a thin strap that goes around the chest. You will also have a mouth-piece in your mouth, and nose clips on your nose. This is to measure all expired gases, and prevent nasal breathing. You will be able to breathe normal room air throughout. The test will stop when you reach 85% of your age predicted maximal heart rate (220-age), or you request to stop.

Leg Exercise Test

This will be performed on a treadmill. You will begin by walking slowly on a treadmill without an incline. The speed will slowly increase until you reach a brisk walk, after which the incline will begin to increase, so that you are walking uphill. During this time you will be wearing a heart rate monitor, which is a thin strap that goes around the chest. You will also have a mouth-piece in your mouth, and nose clips on your nose. This is to measure all expired gases, and prevent nasal breathing. You will be able to breathe normal room air throughout. The test will stop when you reach 85% of your age predicted maximal heart rate (220-age), or you request to stop.

VISIT TWO

Physical Activity Surveys

You will be asked to complete 6 different physical activity questionnaires. The questionnaires will ask you about different activities that did in the previous week.

BENEFITS OF PARTICIPATION

From the information that we generate we will be able to tell you your body fat percentage, your blood pressure, and how many calories you burn during a week. You will also be paid $50.00 for participating in this study.

RISKS OF PARTICIPATION

The potential risks that may occur with participating in the proposed research include those associated with exercise testing. These include: leg discomfort, muscle/joint soreness, dizziness, headache, and in rare instances heart attack (≤4 in 10,000). A strict screening process will help eliminate any of these potential risks. In addition the Applied Physiology Laboratory has a planned response to any emergency procedure, and all testing personnel are CPR certified.

RIGHT TO ASK QUESTIONS AND/OR WITHDRAW FROM THIS STUDY

If you have any questions or concerns at any time during the course of the testing procedures or after completion of the procedures you can contact either Dr. Bassett at (865) 974-8766, or Scott Strath at (865) 974-5091. As a volunteer in this study you have the right to withdraw at any time.

CONFIDENTIALITY

Only Dr. Bassett, Scott Strath and you will have access to any of the information collected during this research project. All information collected will be kept in a locked file cabinet in the office of Scott Strath. The final results of this research will be published, but your name will not be associated with any of the material published.

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.

______________________________ ________________

Participants Signature Date

______________________________ ________________

Investigator's Signature Date

APPENDIX D1

PART VI

Raw Data

Table 1. Total energy expenditure in MET·min^{-1} for the Simultaneous HR+M Technique (HRMET), the Modifiable Activity Questionnaire with walking (MQMETa) and without walking (MQMETb), and the Stanford 7-Day Physical Activity Recall Questionnaire (PAR). Total activity values for the Framingham Activity Index (FAI), the Baecke Activity Questionnaire (BAQ) and the Health Insurance Plan of Greater New York Questionnaire (HIP) are reported in indices.

ID	Gender	HRMET	MQMETa	MQMETb	PAR	FAI	BAQ	HIP
1	1	11617	3833	3474	13125	37.8	6.5	16
2	2	11127	1722	1008	12660	40.1	8.51	21
3	1	7334	720	720	10613	35.7	6.5	10
4	1	16010	5798	5134	14325	36.3	5.76	14
5	1	9874	2177	1920	12630	33.5	5.9	13
6	2	14181	3252	2790	15758	37.2	7.75	19
7	2	9105	2925	2655	13935	36.4	7.5	17
8	1	10807	3432	3198	12863	35.2	8.5	15
9	2	9595	6435	6075	16148	41.9	10.9	21
10	2	9186	3530	3380	13433	36.8	7.25	16
11	1	12197	4685	4155	15113	36	7.25	19
12	1	9671	2807	2530	12468	34.3	6.88	18
13	1	14366	6485	5872	15060	35.2	9.33	20
14	2	8726	2892	690	12698	28.9	7	12
15	1	8439	2808	2370	12038	30.1	6.75	12
16	2	8737	4360	4285	11655	31.1	8.11	20
17	1	11064	4235	3038	13058	34.5	7.5	16
18	2	9879	3255	3090	14093	33.6	6.75	7
19	1	12278	3664	3345	12300	36.5	8.38	17
20	2	7915	2550	2250	11550	30.6	6.25	13
21	1	9684	1006	931	11438	30.4	7	9
22	1	6320	351	120	9248	29.2	4.5	5
23	2	15170	5320	5320	12683	36.3	7.5	18
24	2	11424	5070	4830	12458	32.8	7.91	19
25	2	14107	12113	11240	13770	45.8	9.63	22

Table 2. Energy expenditure values for the Simultaneous HR+M Technique (HRM), the Modifiable Activity Questionnaire with walking (MAQa), and without walking (MAQb), and the Stanford 7-Day Physical Activity Recall Questionnaire (PAR) for light (Lgt), moderate (Mod), and hard (Hrd) activity.

ID	Gender	HRMLgt	HRMMod	HRMHrd	MAQModa	MAQHrda	MAQModb	MAQHrdb	PARLgt	PARMod	PARHrd
1	1	6936	3099	1582	848	1005	489	1005	7245	7200	1680
2	2	6272	3795	1060	1032	240	318	240	9630	1920	1110
3	1	5050	1482	802	0	720	0	720	8573	1140	900
4	1	7731	6341	1938	304	964	0	964	8505	4020	1800
5	1	7295	1080	1499	587	960	330	960	8550	2520	1560
6	2	6581	4578	3022	1452	1080	990	1080	8078	5700	1980
7	2	6531	1189	1385	765	1080	495	1080	8415	4080	1440
8	1	5406	4341	1058	1704	1008	1470	1008	8123	3180	1560
9	2	5761	1607	2227	2475	3600	2115	3600	8708	2340	5100
10	2	6617	2195	374	380	0	230	0	8573	4140	720
11	1	7914	3576	707	529	1755	0	1755	8843	3240	3030
12	1	8286	1322	63	1047	1410	670	1410	9338	3600	1530
13	1	7313	4260	2794	1100	1620	488	1620	7560	5520	1980
14	2	7378	1349	0	2542	0	240	0	7808	4560	330
15	1	6979	992	467	648	240	210	240	8528	2520	990
16	2	6794	1743	200	75	1810	0	1810	8415	1560	1680
17	1	6309	3128	1627	1535	0	338	0	8258	2100	2700
18	2	6994	1752	1133	615	1200	450	1200	7853	4740	1500
19	1	6538	2785	2955	1869	1120	1550	1120	8460	2280	1560
20	2	5868	1622	425	300	0	0	0	10170	1200	180
21	1	7099	1971	613	75	796	0	796	10058	1140	240
22	1	5649	650	20	231	120	0	120	7808	900	540
23	2	6934	5205	3031	870	160	840	160	9563	1620	1500
24	2	6664	3833	927	1950	780	1710	780	9518	1620	1260
25	2	8066	3857	2184	1313	1200	440	1200	7830	3360	2580

Table 3. Time spent in light (Lgt), moderate (Mod), and hard (Hrd) intensity activities in minutes for an average weekday for the Simultaneous HR+M Technique (HRM), the College Alumnus Questionnaire (CAQ), and the Stanford 7-day Physical Activity Recall Questionnaire (PAR).

ID	Gender	HRMLgt	HRMMod	HRMHrd	CAQLgt	CAQMod	CAQHrd	PARLgt	PARMod	PARHrd
1	1	662	125	26	750	180	30	639	315	30
2	2	713	137	22	840	120	60	917	84	24
3	1	543	54	16	810	60	90	774	36	18
4	1	634	265	44	840	120	60	784	159	42
5	1	811	46	29	810	20	60	819	96	30
6	2	598	185	68	720	180	120	717	249	48
7	2	759	53	12	660	270	60	825	138	9
8	1	593	188	20	600	240	90	795	129	24
9	2	624	66	34	660	180	60	855	69	90
10	2	760	77	7	600	300	120	795	174	15
11	1	799	156	21	540	300	120	819	132	51
12	1	790	59	2	780	120	60	894	108	48
13	1	699	147	62	750	180	90	744	156	42
14	2	857	59	0	900	60	0	795	111	6
15	1	791	42	12	570	240	90	783	87	30
16	2	768	49	0	900	45	35	819	57	6
17	1	559	108	37	600	180	60	831	24	45
18	2	694	84	27	720	240	0	768	156	30
19	1	670	104	67	780	120	0	873	39	15
20	2	677	70	11	690	180	0	930	39	3
21	1	818	83	14	780	180	60	936	48	6
22	1	671	24	1	780	60	0	747	27	0
23	2	628	188	81	690	300	120	975	45	18
24	2	717	98	19	660	240	120	927	24	42
25	2	780	147	34	780	240	60	750	120	66

Table 4. Time spent in light (Lgt), moderate (Mod), and hard (Hrd) intensity activities in minutes for an average weekend day for the Simultaneous HR+M Technique (HRM), the College Alumnus Questionnaire (CAQ), and the Stanford 7-day Physical Activity Recall Questionnaire (PAR).

ID	Gender	HRMLgt	HRMMod	HRMHrd	CAQLgt	CAQMod	CAQHrd	PARLgt	PARMod	PARHrd
1	1	764	82	26	630	300	30	818	113	30
2	2	655	115	17	720	180	60	893	45	23
3	1	549	60	2	960	0	0	923	53	0
4	1	773	132	5	720	240	60	885	105	0
5	1	821	28	9	780	20	20	825	53	6
6	2	802	90	3	600	300	60	900	90	0
7	2	733	18	45	540	360	60	743	165	53
8	1	572	61	16	300	300	60	705	90	15
9	2	719	35	29	720	120	60	780	105	105
10	2	673	82	9	660	300	60	855	98	23
11	1	763	43	1	660	300	60	900	75	45
12	1	856	27	0	720	180	120	885	180	0
13	1	671	163	4	420	420	0	675	285	0
14	2	658	93	0	540	360	0	615	293	8
15	1	725	19	1	360	450	60	885	98	8
16	2	570	100	15	840	20	60	758	53	75
17	1	462	141	24	420	360	60	675	203	23
18	2	865	23	1	840	0	0	803	218	0
19	1	605	91	29	660	180	120	645	188	68
20	2	805	27	1	660	120	0	1065	53	8
21	1	705	43	8	600	180	120	1013	23	0
22	1	622	26	0	720	120	0	735	45	30
23	2	692	164	7	690	360	60	750	90	60
24	2	772	221	17	580	260	40	855	150	0
25	2	835	24	21	840	30	30	750	120	30

VITA

Scott James Strath was born in Elgin, Scotland on March 30, 1973. He attended schools in the public system of Leicestershire, England. He completed his O-Levels in June 1989. He then went on to complete Advanced-Levels in Geography, Economics, and British and American Politics, completing his studies in June 1991. In August of 1992, he entered Sheffield Hallam University, Sheffield, England. He completed a Bachelors of Education in Physical Education, with a teaching certification in grades K7-12. Following graduation from Sheffield Hallam University in June 1996 he moved to the United States of America to pursue a Master's of Science Degree in Adult Fitness and Cardiac Rehabilitation at Ball State University, Indiana. He graduated from Ball State University in May 1998. In August 1998 he attended the University of Tennessee at Knoxville to pursue a Doctorate of Education in Exercise Science – Exercise Physiology. The doctoral degree was received August 2001. He has accepted a position as a post-doctoral fellow in the College of Medicine at the University of Kentucky Medical Center.