Simultaneous measurement of heart rate and body motion to quantitate physical activity

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ABSTRACT

HASKELL, W. L., M. C. YEE, A. EVANS, and P. J. IRBY. Simultaneous measurement of heart rate and body motion to quantitate physical activity. *Med. Sci. Sports Exerc.*, Vol. 25, No. 1, pp. 109–115, 1993. None of the various methods used to measure habitual physical activity over days, weeks, or years in the general population have yet proven entirely satisfactory. A major problem is that no "gold standard" exists for the validation of various questionnaires, logs, or diaries that can be used in large sample population studies. Attempts have been made to accurately measure the activity profile by using heart rate or various motion sensors or accelerometers, but each approach has had significant limitations. The availability of new solid state recording techniques and computer-based analytic and display procedures now makes it possible to simultaneously record heart rate and body movement continuously for days and to combine the analysis of these data using customized software. Preliminary evaluation of this concept of simultaneous recording and analysis of heart rate and body motion via movement sensors on an arm and leg were conducted in 19 men. Subjects performed a variety of exercises in the laboratory during which heart rate, leg motion, arm motion, and oxygen uptake were recorded. Various issues regarding the prediction of energy expenditure from heart rate and body movement independently and in combination were evaluated. The results demonstrate that the accuracy of estimating oxygen uptake during a wide range of activities is improved when individualized heart rate—oxygen uptake regressions are used and heart rate and body movement are analyzed simultaneously rather that separately.

EXERCISE, HEART RATE, OXYGEN UPTAKE, ENERGY EXPENDITURE, CALORIC EXPENDITURE

Over the past 40 yr scientific evidence has slowly accumulated supporting the hypothesis that persons who are habitually more physically active or physically fit tend to experience lower mortality rates from chronic degenerative diseases than their less active counterparts (1). However, major gaps exist in these data including the results of randomized clinical trials to demonstrate that an increase in activity causes a reduction in clinical events, definitive information on the specific biologic changes induced by exercise that produce various health benefits, and the specific characteristics of physical activity that are optimal for producing these improvements in health.

One of the difficulties encountered in the attempt to answer many of these important questions is the lack of procedures to obtain accurate and reliable measurements of physical activity on large samples of the general population. Physical activity is a very complex behavior that has a variety of dimensions, most of which are difficult to measure in humans during their time spent at home or on the job. Procedures used to measure physical activity have included various types of self- or interviewer-administered questionnaires or diaries; motion sensors or accelerometers; the measurement of heart rate, pulmonary ventilation, or oxygen uptake; and the determination of carbon dioxide production by the use of doubly labeled isotopes (18). So far, most data relating physical activity status to clinical outcomes in the general population have been obtained using questionnaires or diaries. The other procedures have not proven to be sufficiently accurate or reliable or present major logistical difficulties when used for large samples.

This manuscript describes the conceptual basis and preliminary evaluation of a procedure using the simultaneous recording of heart rate and two motion sensors to provide an accurate profile of physical activity. Since many of the health benefits of exercise appear to be closely related to the exercise-induced increase in energy expenditure and it is the most commonly used parameter for defining both the intensity and amount of activity performed, we have chosen to define physical activity in units of energy expenditure.

BACKGROUND

In the attempt to obtain accurate information on the physical activity status of free-living persons, two of the

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more frequently used procedures have been the continuous monitoring of heart rate (7,17) or use of some type of motion sensor or accelerometer attached to the body (9,12). Both of these procedures have proven useful in helping to describe the activity status of persons assigned to an exercise training program (13) or the amount of activity spent throughout the day (3). However, each procedure has significant limitations in its ability to accurately characterize the intensity, duration, and frequency of a wide range of activities typically performed on the job and during leisure time by many persons.

Heart Rate

Use of heart rate as a measure of physical activity is based primarily on the strong positive association for an individual between the increase in heart rate and the increase in energy expenditure during large muscle dynamic exercise. For example, the within-person correlation between heart rate and oxygen uptake during increasing exercise intensity on a motor driven treadmill or cycle ergometer frequently exceeds 0.95 (2). However, limitations in the use of heart rate include the well-established facts that (a) the slope of the relationship between heart rate and oxygen uptake varies between persons depending on their endurance capacity; (b) the slope of the relationship between heart rate and oxygen uptake within a person is different for exercise using the arms versus the legs and will vary depending on how much of the activity is static or heavy resistance versus dynamic or low resistance (10); and (c) heart rate is influenced by other factors, such as emotional status (anger, fear, anticipation, etc.), body posture, and environmental conditions (temperature, humidity, altitude, etc.). Thus, just recording heart rate throughout the day has not been generally accepted as an accurate method of assessing physical activity as defined by energy expenditure (4).

Motion Sensors

A wide variety of body motion or movement sensors have been used to monitor physical activity, including pedometers that focus on the distance walked (15), motion sensors that count the number of times a limb or the trunk moves (8), and accelerometers that monitor the acceleration of the body during activity (11,16). For such activities as walking or running on the horizontal, the output of these sensors, especially the CALTRAC, correlates quite well with energy expenditure (12,16). Major limitations of these sensors include their inability to accurately identify (a) increases in energy expenditure due to movement up inclines (hills or stairs) or an increase in energy expenditure due to an increase in resistance to movement (increasing the amount of weight lifted or resistance on a cycle ergometer), (b) a single sensor cannot identify movement that involves various parts of the body (a sensor on the leg will not detect movement of the arms), and (c) these sensors do not detect static exercise. Also, currently there is no unit that can be readily used in population-based studies that provides for the continuous recording of data so that a minute-by-minute profile of activity can be obtained. The instruments currently available need to be manually read at selected times or a "total activity" score over the entire period of recording is provided.

Combination of Heart Rate and Body Motion

Conceptually, it appears that by recording simultaneously both heart rate and the motion from sensors on several parts of the body and by calibrating each individual in terms of his/her heart rate and motion sensor output versus oxygen uptake for various types of activity, that it should be possible to obtain an accurate estimate of the profile of energy expenditure due to physical activity performed throughout the day. In this project, we evaluated components of this concept using the Vitalog ambulatory monitor.

The Vitalog Monitor

In the mid 1970s a solid state, multichannel ambulatory monitor was designed at Stanford University for research on sleep disorders (14). This unit was further developed and made available commercially as the Vitalog PMS-8 monitor (Vitalog Corporation, Redwood City, CA). The software was modified so that it could be used to record heart rate and body movement via a single motion sensor on a minute-by-minute basis, which we used to determine the activity status of patients soon after hospitalization for myocardial infarction and adherence to nonsupervised exercise training program recommendations by adults (5,6). For this project the Vitalog was modified to continuously record from two motion sensors as well as heart rate, and the motion sensor was modified to improve both intra- and intersensor reliability.

METHODS

Subjects

Subjects were volunteers who were contacted personally or responded to posters describing the project that were placed in the community. Prior to participation, all subjects signed an informed consent approved by the Stanford University Panel on Human Subjects in Medical Research. The study was conducted in accordance with the policy statements on human research of the American College of Sports Medicine. Each subject first underwent a comprehensive physical examination administered by a nurse practitioner, which included a

12-lead electrocardiogram recorded at rest and during maximal treadmill exercise testing.

After medical screening, 19 clinically healthy males ages 22–64 yr were selected for the study. Ten of the subjects were engaged in endurance training programs at the time of the study. The remaining nine were sedentary, and had not engaged in regular training for at least 6 months. During the study, motion sensor data on two of the subjects were lost due to equipment malfunction. All data for these two subjects, both classified as sedentary, were excluded from the analyses.

Experimental Protocols

Subjects were evaluated while performing the seven exercise conditions listed in Table 1. The activities were chosen to cover a wide range of human experience in physical activity with special emphasis on dynamic leg, arm, and combined arm and leg exercise. Data collected at steady state during each of the evaluations included heart rate (HR), oxygen uptake ($\dot{V}O_2$), and output from motion sensors placed on the wrist and the thigh.

Maximal treadmill exercise test. A maximal treadmill exercise test served as a combined walking and running condition, as both grade and speed were changed during this activity. Workload was increased using a modified Balke-type protocol, which consisted of 3-min stages of progressively increasing speed or grade. The first four stages involved an increase in grade with speed held constant at 3.0 mph, while the last three stages entailed increases in speed every 3 min with grade maintained at 15%. A warm-up session consisting of walking at 0% grade at 2.0 mph preceded the test, so that subjects could become accustomed to the treadmill and to the measurement equipment. Subjects were instructed to walk or run without the aid of the handrail and were exercised to volitional fatigue.

Submaximal exercise evaluations. Submaximal activities were performed under two protocols of three activities each, performed on separate days. One protocol consisted of both walking activities and arm cranking (Table 1, nos. 2–4), while the other protocol consisted of stationary cycling, arm and leg exercise using the Air-Dyne ergometer, and bench stepping (Table 1, nos. 5–7). Both submaximal protocols were repeated on subsequent days. Data from repeat visits, after being tested for homogeneity by paired t-test, were pooled and analyzed together.

Each protocol was preceded by a 4-min sitting rest followed by a 4-min standing rest. During exercise, each activity was characterized by 3-min stages of increasing exercise intensity. Different activities during the protocols were separated by 8-min rest periods. If subjects exceeded 90% of their maximal heart rate or $\dot{V}O_{2max}$ during any submaximal protocol, exercise was terminated.

TABLE 1. Exercise testing protocols.

Type of Exercise	Method of Increasing Workload	Increments
1. Walking/running	Vary speed and grade	Maximal treadmill test
2. Walking	Vary speed	2.0, 4.0, 6.0 mph
3. Walking	Vary grade	0.0, 2.5, 7.5, 15.0%
4. Arm cranking	Vary rpm	30, 40, 50 rpm
5. Cycling	Vary resistance	50, 100, 150 W
6. Air-Dyne	Vary rpm	50, 60, 70 rpm
7. Bench step	Vary load carried	0, 2.3, 4.6 Kg

Measurements

Data were collected every 30 s throughout each protocol. Subjects were assumed to reach a physiological steady state during the last minute of each 3-min stage. The mean of the two 30-s values from the last minute of each stage were utilized for analysis. For safety reasons and the accurate recording of heart rate, an ECG was monitored continually during exercise.

Vitalog. The Vitalog recorder is a multichannel solid-state recorder that allows continuous recording of physiological parameters in real time. Heart rate was recorded via a three-lead electrocardiogram using disposable electrodes. The ECG signal was channeled through an analog R-wave to R-wave interval detector, which calculated an average heart rate each 30 s. Body movement was measured by motion sensors composed of a single mercury switch encased in a clear plastic resin (Vitalog Corporation). Switch counts from the motion sensor were stored in a 32-bin memory structure, each bin representing five switch counts. The motion score recorded by the Vitalog was the number of bins necessary to store a given number of switch counts in 30 s.

Two motion sensors were utilized during each exercise evaluation. One was placed on the posterior aspect of the right wrist, over the center line of the wrist and oriented along the long axis of the forearm. The other motion sensor was placed on the lateral aspect of the right thigh, directly on the mid-axillary line, oriented vertically, along the long axis of the femur. Both sensors were held in small nylon pockets. Velcro fasteners were used to affix these pockets to neoprene wraps of the type used for athletic injuries. These wraps fit snugly around the wrist and the thigh, so that the motion sensors experienced little movement extraneous to the movement of the limb.

Electrocardiogram. With the exception of the maximal treadmill exercise test, subjects were prepared with a modified six-electrode system. Limb lead placement was modified for exercise, and leads V2 and V5 were monitored during the evaluation. In the maximal exercise test, a full 10-electrode, 12-lead ECG was monitored. In both cases, a Quinton 3000 recorder and lead system (Quinton Instrument Company, Seattle, WA) were utilized to monitor and record the ECG.

Respiratory gas analysis. All analyses of expired air were performed using a Medical Graphics Model 2001 Metabolic Recorder (Medical Graphics Corporation, Minneapolis, MN). The unit, which continuously measured pulmonary ventilation and the concentrations of expired oxygen and carbon dioxide, was programmed to provide data on ventilation, oxygen uptake, carbon dioxide production and respiratory exchange ratio every 30 s.

Statistical analysis

Univariate regressions were performed between oxygen uptake, leg motion sensor score, arm motion sensor score, and heart rate for each exercise. These analyses were performed for each individual as well as for all individuals grouped together. Multivariate analyses were performed to determine the independent contribution of heart rate, arm motion, and leg motion to the estimation of oxygen uptake for each of the activities separately and for all activities combined. Again, these analyses were perform for each individual alone and for all subjects combined. The level of significance was set at 0.05.

RESULTS

All of the subjects completed the testing without any medical complications. Selected characteristics of the subjects are listed in Table 2. Maximal oxygen uptake was highly variable among subjects, ranging from 29 to 73 $ml \cdot kg^{-1} \cdot min^{-1}$ with a mean of 49.6. Most of the subjects were relatively lean with a mean BMI of 23.7 $kg \cdot m^{-2}$. Results are presented that address selected issues regarding the combined use of heart rate and motion sensors to estimate energy expenditure during various physical activities. The heart rate, oxygen uptake, and motion sensor responses to all of the activities listed in Table 1 are presented in Table 3.

Accuracy of Estimating Energy Expenditure from Heart Rate: The Value of Establishing an Individual Regression

The relationship between heart rate and oxygen uptake ($ml \cdot kg^{-1} \cdot min^{-1}$) recorded during maximal treadmill exercise and during submaximal exercise on the treadmill and cycle ergometer was evaluated. Regression analyses were performed for each subject separately and for all the data for all subjects pooled together. The values for the pooled data were obtained by combining the raw data for all subjects together and performing a single regression analysis. The average R^2 when regressions were calculated for each subject separately is 0.94 compared with the single R^2 calculated for the pooled data of 0.81 ($P < 0.01$). The difference between the magnitude of these R^2s and the standard errors of estimate is a measure of the added accuracy achieved for predicting energy expenditure from heart rate during dynamic exercise using primarily large muscles when regressions are developed for each individual instead of pooling data and using an average for the entire group or some estimate for the population. Thus, increased accuracy for estimating energy expenditure from heart rate during these types of activities can be achieved by "calibrating" each person by establishing in the laboratory or clinic their heart rate-oxygen uptake relationship (slope and intercept).

TABLE 2. Characteristics of subjects.

	Mean	SD	Range
Age (yr)	36.2	13.5	22–64
Height (cm)	174	7.1	155–183
Weight (kg)	71.7	8.7	60–93
Body mass index ($kg \cdot m^{-2}$)	23.6	1.9	20.4–27.7
$\dot{V}O_{2max}$ ($ml \cdot kg^{-1} \cdot min^{-1}$)	49.6	10.7	29–73

TABLE 3. Heart rate, oxygen uptake, and motion sensor responses to all activities performed in the laboratory by all subjects.

	N	Mean	SD	Range
Heart rate ($beats \cdot min^{-1}$)	785	111	24.4	62–194
Oxygen uptake ($ml \cdot kg^{-1} \cdot min^{-1}$)	803	20.8	9.4	4.0–67.0
Leg motion (counts)	687	4.0	4.8	0–22
Arm motion (counts)	783	3.1	3.8	0–21

Variations in the Heart Rate—Energy Expenditure Relationship for Different Types of Exercise

Presented in Figure 1 are data using the relationships between heart rate and oxygen uptake during exercise on the treadmill, arm cranking, and on the Air-Dyne ergometer. The treadmill represents dynamic exercise performed mainly with the legs, arm cranking represents mainly dynamic arm exercise, and the Air-Dyne represents combined dynamic arm and leg exercise. Data from the regression analysis performed for each subject for each type of exercise were combined to obtain representative values for that exercise. While the

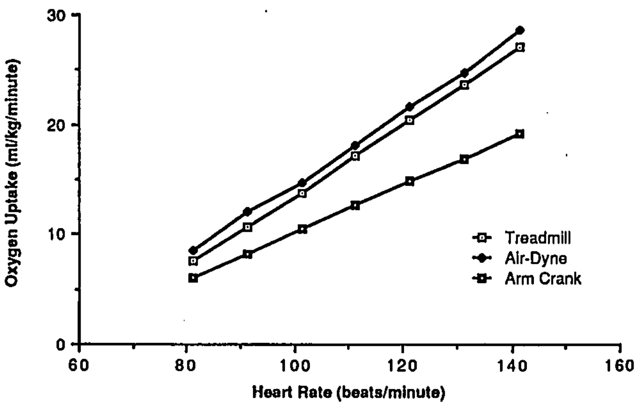

Figure 1—The relationship of heart rate to oxygen uptake during treadmill walking, arm and leg exercise using an Air-Dyne ergometer, and arm cranking.

slopes are similar for data from exercise on the treadmill and Air-Dyne, the slope is significantly different for arm cranking, with less of an increase in oxygen uptake for a given increase in heart rate. These data demonstrate the potential for increasing the accuracy for estimating energy expenditure from heart rate by having separate regression lines for dynamic arm and dynamic leg exercise. Also, they indicate that the same regression line can be used for dynamic leg exercise or when dynamic arm is added to dynamic leg exercise.

Ability of Motion Sensor to Detect Significant Body Movement

Presented in Figure 2A are data (mean ± SD) from motion sensors on the leg and the arm while subjects are at rest and then while walking at 2, 4, and 6 mph on the treadmill. These data demonstrate the ability of a low-cost motion sensor to detect when subjects are at rest and when they are moving slowly. We did not collect data at 1 mph. Thus, it is possible to use this type of motion sensor to determine when a person is performing dynamic exercise using large muscles and in a combined heart rate-motion sensor system to determine when to consider an increase in heart rate due to an increase in exercise and not due to some nonexercise stimulus.

Inability of the Motion Sensor to Detect Increasing Intensity of Some Types of Exercise

Presented in Figure 3 are leg and arm motion sensor data collected during walking on the treadmill while varying just gradient (stages I–IV) and then while varying just the speed (stage V–VII). These data show, as one would expect, that while the motion sensor quite accurately tracks the change in speed, it does not respond in any quantitative way to changes in slope. This response is a major limitation in using just a motion sensor or accelerometer for trying to estimate energy expenditure during daily activity if a significant amount of the activity includes climbing stairs or hills or any type of activity where the intensity changes in response to resistance rather than an increase in speed or frequency of movement.

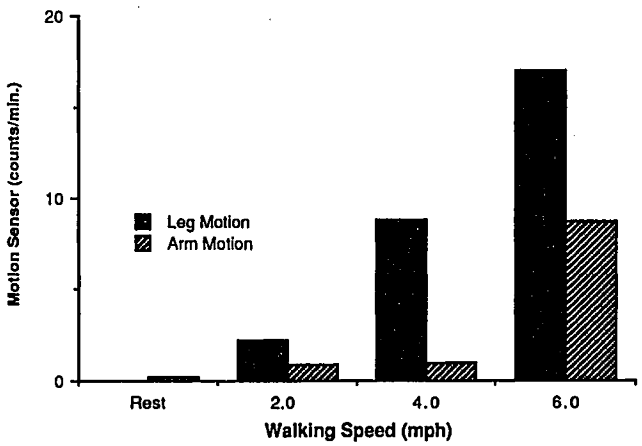

Figure 2—The response of motion sensors on the arm (wrist) and leg (thigh) during rest and walking on the treadmill at increasing speeds.

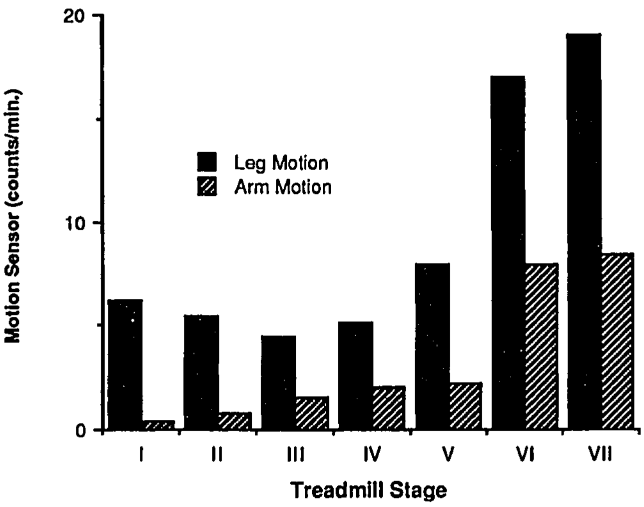

Figure 3—The response of motion sensors on the arm and leg during treadmill walking at increasing grades (stages I–IV) and at increasing speed (stages V–VII).

Estimation of Exercise Expenditure from Combining Heart Rate and Motion Sensor Data Using Multiple Regression Analysis

Multiple regression analyses were performed to predict oxygen uptake from heart rate, leg motion, and arm motion during all of the activities listed in Table 1. These analyses were run for each subject separately and then the mean for all subjects was calculated for R^2 and the standard error of the estimate. There were 15 subjects that had technically acceptable data for all activities. The R^2 for predicting the oxygen uptake during all of the activities ranged from 0.86 to 0.93 among the subjects, with a mean of 0.89. The mean standard error of estimate was 2.3 ml · kg^{-1} · min^{-1}, with a range of 1.36 to 3.16 ml · kg^{-1} · min^{-1}. In 12 of the 15 subjects the addition of leg motion data (N = 8), arm motion data (N = 3), or combined leg plus arm data (N = 1) significantly contributed to the prediction. Heart rate was the most significant predictor for all subjects.

When the data points for all activities for all subjects were combined in a single regression analysis, the R^2 decreased to 0.73 and the standard error of the estimate increased to 5.2 ml · kg^{-1} · min^{-1}. For certain activities the addition of data from the motion sensor substantially increased the R^2 over what was obtained for heart rate alone. For example, when arm motion sensor data were added to heart rate for the prediction of oxygen uptake when riding the Air-Dyne ergometer, the R^2 was increased from 0.69 to 0.82

DISCUSSION

Much of the data collected during this research is highly consistent with previously published data on the relationship between heart rate and oxygen uptake (3), the influence of the size of the muscle mass on the relationship of heart rate to oxygen uptake (11), and the failure of motion sensors to accurately estimate energy expenditure when exercise intensity is increased using resistance rather than rate of movement (12). New information includes the demonstration that a combination of heart rate and body motion data collected simultaneously is a better predictor of oxygen uptake during a variety of physical activities than heart rate alone. Also, two motion sensors, one on the arm and one on the leg, are likely to increase the accuracy of the prediction if a significant amount of arm only exercise is performed. It appears that the heart rate versus oxygen uptake relationship is similar for dynamic leg exercise and combined dynamic leg and arm exercise.

The use of a multiple regression approach to predicting oxygen uptake from heart rate and one or two motion sensors on the body appears to be quite accurate even when a relatively wide range of activities are involved (individual R^2 of 0.89 and standard error of estimate of 2.3 $ml \cdot kg^{-1} \cdot min^{-1}$). However, there may be a much more efficient way to analyze these types of data. Given appropriate software, it should be possible to use the motion sensor data to determine when meaningful physical activity is being performed, and then to use the heart rate-oxygen uptake relationship to accurately estimate the rate of oxygen uptake during the identified periods of activity.

The steps to be taken and the contribution they make to improved accuracy in the estimation of energy expenditure during physical activity of free-living persons using the continuous monitoring of heart rate and motion sensors are as follows.

Use an ambulatory monitoring system that enables the recording and storage of data from an accurate sensor of heart rate (bipolar ECG electrodes with R-wave detector) and one motion sensor on a leg and one on an arm that accurately and reliably detect each major movement of the limb. Data should be stored in intervals of not longer than 1 min and provide continuous recording for up to 72 h. The capability should exist to electronically transfer data rapidly and accurately to a computer for storage and analysis.

Develop a heart rate versus oxygen uptake regression for dynamic arm and dynamic leg exercise by submaximal testing with simultaneous measurement of heart rate and oxygen uptake. This procedure eliminates the variance in the estimate due to (a) interindividual differences in the slope of the heart rate versus oxygen uptake regression and (b) provides a specific estimate for the two forms of activity that contribute most to the energy expenditure due to exercise. The regression for dynamic leg exercise would be used for dynamic exercise that involves both legs and arms as well as just leg exercise. Pure static or very heavy resistance exercise does not contribute much to energy expenditure for most people.

Using the motion sensor data, determine when the person was active and establish if the activity was primarily leg exercise, primarily arm exercise, or a combination of the two. Once these exercise periods have been established, determine the exercise intensity (energy expenditure) using the heart rate/oxygen uptake regressions. This procedure excludes the inclusion of increased energy expenditure estimated from an elevation in heart rate due to nonexercise reasons and provides a more accurate estimate of energy expenditure than obtained from the use of only a regression determined only for leg exercise.

Develop a profile of energy expenditure on a minute-by-minute basis throughout the day and summarize the data in terms of duration spent at various intensities, frequency of bouts at various intensities, and overall energy expenditure.

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