Measurement of Exercise Intensity with a Tri-Axial Accelerometer during Military Training

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ABSTRACT

Exercise load and intensity, as reflected in energy expenditure, are determinants of performance. Here, we evaluated a newly developed tri-axial accelerometer for movement registration (Directlife, Philips Research, Eindhoven, The Netherlands) for the assessment of exercise intensity and exercise load at high-intensity field training. Subjects were 16 well-trained men with a mean ($\pm$SD) age of 24 ± 3 y and body fat of 15.8 ± 2.1 %. Physical activity was monitored continuously with accelerometers for a twelve-day interval while total energy expenditure was measured simultaneously with the doubly labelled water technique. Subjects did wear three accelerometers, 3 x 3 x 1 cm and 13 g each, at three different locations, trouser pocket, waist belt and breast pocket. Accelerometer output was stored over one-minute intervals and loaded to a computer at the end of the training interval. Urine samples were collected at baseline, before drinking the doubly labeled water as a last drink of the day, on the subsequent day and at further four-day intervals. Urine samples were analyzed with Isotope Ratio Mass Spectrometry. There was a significant body weight loss of 2.0 ± 1.4 kg ($P < 0.001$) over the twelve-day interval, indicating the intensity of the training. The physical activity level, total energy expenditure as a multiple of predicted basal metabolic rate, was with a mean of 2.5 ± 0.1 around the upper limit for sustainable lifestyles. Variance in activity energy expenditure, calculated as total energy expenditure minus resting expenditure, was explained for 73 % ($P < 0.001$) by body mass. Adding accelerometer output to the model raised the explained variance to 85 % ($P < 0.05$) by including body acceleration measured with the waist- device. In conclusion, after adjusting for differences in body mass, the newly developed tri-axial accelerometer for movement registration explains nearly halve of the variance in exercise intensity and exercise load at high-intensity field training.

Introduction

Optimization of military training to improve performance requires information on exercise intensity and exercise load. Exercise can be defined as body movement, produced by skeletal muscles, resulting in energy expenditure (1). The doubly labeled water method has become the gold standard for the validation of field methods of assessing physical activity and exercise (2). Accelerometers for movement registration are more and more used to objectively assess body movement including frequency, duration and intensity, and can be used at a larger scale than the more expensive doubly labeled water method (3).

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Exercise load and intensity, as reflected in energy expenditure, are determinants of performance. Here, we evaluated a newly developed tri-axial accelerometer for movement registration (Directlife, Philips Research, Eindhoven, The Netherlands) for the assessment of exercise intensity and exercise load at high-intensity field training. Subjects were 16 well-trained men with a mean (±SD) age of 24 ± 3 y and body fat of 15.8 ± 2.1 %. Physical activity was monitored continuously with accelerometers for a twelve-day interval while total energy expenditure was measured simultaneously with the doubly labelled water technique. Subjects did wear three accelerometers, 3 x 3 x 1 cm and 13 g each, at three different locations, trouser pocket, waist belt and breast pocket. Accelerometer output was stored over one-minute intervals and loaded to a computer at the end of the training interval. Urine samples were collected at baseline, before drinking the doubly labeled water as a last drink of the day, on the subsequent day and at further four-day intervals. Urine samples were analyzed with Isotope Ratio Mass Spectrometry. There was a significant body weight loss of 2.0 ± 1.4 kg (P < 0.001) over the twelve-day interval, indicating the intensity of the training. The physical activity level, total energy expenditure as a multiple of predicted basal metabolic rate, was with a mean of 2.5 ± 0.1 around the upper limit for sustainable lifestyles. Variance in activity energy expenditure, calculated as total energy expenditure minus resting expenditure, was explained for 73 % (P < 0.001) by body mass. Adding accelerometer output to the model raised the explained variance to 85 % (P < 0.05) by including body acceleration measured with the waist- device. In conclusion, after adjusting for differences in body mass, the newly developed tri-axial accelerometer for movement registration explains nearly halve of the variance in exercise intensity and exercise load at high-intensity field training.

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About 25 years ago, the doubly labeled water method was introduced for human use (4). The principle of the method is that after a loading dose of water labeled with the stable isotopes of ^{2}H and ^{18}O, ^{2}H is eliminated as water, while ^{18}O is eliminated as both water and carbon dioxide. The difference between the two elimination rates is therefore a measure of carbon dioxide production. The deuterium (^{2}H) equilibrates throughout the body's water pool, and the ^{18}O equilibrates in both the water and the bicarbonate pool. The bicarbonate pool consists largely of dissolved carbon dioxide, which is an end product of metabolism and passes in the blood stream to the lungs for excretion. The rate constants for the disappearance of the two isotopes from the body are measured by mass spectrometric analysis of samples of a body fluid: blood, saliva or urine. The method can be used to measure carbon dioxide production and hence energy production in free-living subjects for periods of some days to several weeks. The optimal observation period is 1-3 biological half-lifes of the isotopes. The biological half-life is a function of the level of the energy expenditure. The minimum observation interval is about 3 days in highly active subjects like cyclists in the 'Tour de France' and Olympic cross-country skiers (5, 6). The maximum interval is about 4 weeks in elderly (sedentary) subjects.

Accelerometers are electronic motion sensors that exist of piezo-resistive or piezo-electric sensors. Over the past decades, advances in technology have resulted in the development of small uni- and tri-axial accelerometers for movement registration with a data storage capacity of several days or weeks. Uni-axial accelerometers measure accelerations in one direction, usually mounted in the vertical direction. Tri-axial accelerometers measure accelerations in the anterior-posterior, medio-lateral and vertical direction. For a wide range of different activities, tri-axial accelerometers provide more information and show a better relation with activity energy expenditure than uni-axial (7). About fifteen years ago, a tri-axial accelerometer for movement registration (Tracmor) was developed at our department (8).

Here, a newly developed tri-axial accelerometer for movement registration (Tracmor$_D$; Directlife, Philips Research, Eindhoven, The Netherlands) was evaluated for the assessment of exercise intensity and exercise load at high-intensity field training, with doubly labeled water assessed energy expenditure as a reference. Tracmor$_D$ consists of three separate uni-axial piezo-electric accelerometers, measures 3 x 3 x 1 cm, is waterproof and weighs 13 g with battery included. Battery power and storage capacity allow continuous data acquisition for periods of at least three weeks after which data can be downloaded into a computer.

Methods

Subjects were 16 well-trained men, participating in a two-week high-intensity field-training program in Wales, UK. Physical activity was monitored with Tracmor$_D$ instruments located at three body positions: trouser pocket; waist belt; and breast pocket. Thus, body movement was monitored continuously for twelve subsequent days where instruments were charged before the start and data downloaded into a computer after the observation interval. Simultaneously, total energy expenditure was measured over the twelve-day interval with doubly labeled water. Body composition and changes in body composition were calculated from body weight and total body water as measured at the start and at the end of the observation interval (9).

The training program included non-tactical and tactical off-road marches of varying length, rifle and machine gun training, tactical skills and combat maneuvers and live-fire exercise in a broken ground area. The first part of the twelve-day observation period was dominated by dynamic activities, the second part by stationary activities. Halfway the training program the subjects had one and a halve day off.

Tracmor$_D$ data were analyzed for exercise load and exercise intensity. Total energy expenditure (TEE) was measured with doubly labeled water according to the Maastricht Protocol (9). Briefly, at 10:00 p.m., before the measurements and after collecting a baseline urine sample, the subjects drank a weighed mixture of ^{2}H$_2$O (99.9 atom %) and H$_2$^{18}O (10 atom %) resulting in an initial excess total body water enrichment of 125 ppm for deuterium and 250 ppm for oxygen-18. Total body water was estimated from calculated body composition, based on height, weight, age and gender, with the equation of Deurenberg et

al. (10), assuming a 73% hydration of fat-free mass. Subjects consumed no foods or fluids for 10 hours after dose administration, during the overnight equilibration of the isotopes with the body water. Subsequent urine samples were collected from the second voiding in the morning of day 1, 5, 9, 12 and the evening of day 12. Isotope quantities (deuterium and oxygen-18) in the urine were measured with an isotope ratio mass spectrometer (Optima, VG Isogas, UK), and CO_2 production was calculated from isotope ratios at the baseline, and days 1, 5, 9 and 12, using the equations from Schoeller et al. (11). CO_2 production was converted to daily metabolic rate using an energy equivalent based on the average macronutrient composition of the diet (12). Activity energy expenditure (AEE) was calculated from TEE and basal metabolic rate (BMR) as TEE x 0.9 – BMR, assuming diet-induced thermogenesis of 10% (13). Basal metabolic rate was calculated with a prediction equation based on body composition (14). Additionally, physical activity level (PAL) was calculated by expressing total energy expenditure as a multiple of BMR (PAL = TEE /BMR).

Results

The mean body mass of the subjects was with 24.3 kg/m^2 (Table 1) close to the cut-off point of 25 kg/m^2 for overweight, and the mean body fat content was with 15.9 ± 2.1 % close to the reference value of 15 % for young men. There was no relation between body mass index and body fat content ($P = 0.56$). Three subjects were overweight, body mass index 26.2, 26.7 and 27.2 kg/m^2, while body fat content was 15.2, 19.1 and 15.6 %, respectively, indicating only one of the three overweight subjects was relatively fat.

Table 1: Characteristics of 16 men participating in the study

	Mean ± SD	range
Age (y)	24 ± 3	19 - 29
Body weight (kg)	83.9 ± 9.6	72.4 - 107.6
Body mass index (kg/m^2)	24.3 ± 1.6	21.4 – 27.2
Body fat (%)	15.9 ± 2.1	12.0 - 20.1
Total energy expenditure (MJ/d)	20.9 ± 2.2	17.9 - 26.1
Activity energy expenditure (MJ/d)	10.5 ± 1.3	8.5 – 12.9
Physical activity level*	2.5 ± 0.1	2.3 - 2.8

*Total energy expenditure as a multiple of basal metabolic rate

Total energy expenditure was high as reflected in the mean PAL value of 2.5 ± 0.1. Subjects lost 2.0 ± 1.4 kg body weight over the twelve-day observation interval ($P < 0.001$). The change in body weight was mainly due to a loss of body fat of 1.1 ± 1.6 kg ($P = 0.01$). The change in fat free mass of -0.9 ± 1.8 kg was just not significant ($P = 0.07$).

Overall variance in exercise load between subjects, as reflected in activity energy expenditure, was mainly explained by differences in body weight and exercise intensity. (Table 2). Subjects with a larger weight need more energy to perform weight-bearing activities. The next variable was exercise intensity as measured at the waist, explaining 12 % of the total variance in activity energy expenditure. The output from the Tracmor$_D$ in the breast- and trouser pocket did not significantly contribute to the explanation of variance in activity energy expenditure. Thus body acceleration measured at the waist explained nearly halve of the remaining variance in activity energy expenditure after body weight.

Table 2: Explained variance and regression coefficients (ß) of activity energy expenditure on body weight and accelerometer output as measured at the waist (Tracmor$_{D,waist}$)

	Explained variance (%)	ß
Body weight	73	0.096***
Tracmor$_{D,waist}$ after body weight	12	1.467*
Body weight and Tracmor$_{D,waist}$	85	-

P <0.05; *** P < 0.001

Over the separate three 4-day intervals of the 12-day observation interval, training in the first 4 days was dominated by dynamic activities, the second 4-day interval included the end of the dynamic interval, the free 1.5-day interval and the start of the final interval dominated by stationary activities. The change from dynamic to stationary activities was clearly reflected in the decrease of AEE from 11.7±1.2 MJ/d to 10.5±1.8 MJ/d (P <0.01) to 8.9 MJ/d (P <0.01) over the subsequent intervals, respectively. Over the first interval, body weight and activity intensity significantly contributed to explained variation in AEE ($R^2 = 0.36$, P <0.05), over the last interval the significantly explaining variable was activity time ($R^2 = 0.62$, P < 0.001).

Discussion

The mean PAL of 2.5 ± 0.1 reflects subjects performed at the upper limit of daily energy turnover. The main determinants of the exercise load were body weight, including standard load carriage, and body acceleration during the first interval with mainly dynamic exercises and activity time during the last interval with mainly stationary exercises.

The observed weight loss of 2.0 ± 0.1 kg over 12 days or 1.2 ± 0.1 kg/wk is similar to the weight loss of 0.4 to 2.3 kg/wk as observed in five studies on soldiers during field training, together including 66 subjects with a mean PAL of 2.4 ± 0.5 (15). High levels of exercise reduce appetite. To maintain energy balance at high intensity endurance activities might require the consumption of energy-rich drinks, a practice common in endurance sports (16).

The main determinant of exercise load is the weight to be displaced, especially during dynamic exercises like walking. The value of the regression coefficient of 0.096 is close to what is expected from a recent study using a tri-axial accelerometer to estimate AEE during activities including walking (17). The best-fit equation was a model where AEE was corrected for the square root of body weight. In the current study, body weight of the subjects ranged from 72 to 108 kg, resulting in a coefficient of 0.117 to 0.096 without load carriage and 0.095 to 0.082 with carriage of 40 kg, respectively.

Not surprisingly, activity intensity significantly explained a large part of the remaining variation in exercise load after inclusion of body weight, in the first part of the training period with mainly dynamic exercises. In the last part of the training period, dominated by stationary exercises, body weight was not a significant explanatory factor for inter-individual variation in AEE. Then, most of the variation in AEE was explained by activity time as read from the accelerometer.

The accelerometer location at the waist was superior to trouser pocket and breast pocket for estimating inter-individual variation in AEE. Theoretically, the waist location is closest to the center of gravity of the body. Additionally, the trunk is the largest part of the body mass to move during dynamic activities and thus trunk movements should have the largest impact on AEE. Indeed, many studies using accelerometers for the prediction of AEE located the accelerometer similarly (18-22).

An important weakness of the current study is the similarity of the subjects and the exercise protocol. All subjects were men in a narrow age range, 19-29 y, and similar physical fitness. They all participated

simultaneously in the same training program as reflected in the narrow PAL range of 2.3 to 2.8. Thus, it is surprising the newly developed tri-axial accelerometer for movement registration explained nearly halve of the variance in exercise intensity and exercise load at high-intensity field training.

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