Accelerometry and heart rate as a measure of physical fitness: proof of concept

Accelerometry and Heart Rate as a Measure of Physical Fitness: Proof of Concept

GUY PLASQUI and KLAAS R. WESTERTERP

Department of Human Biology, Maastricht University, Maastricht, THE NETHERLANDS

ABSTRACT

PLASQUI, G., and K. R. WESTERTERP. Accelerometry and Heart Rate as a Measure of Physical Fitness: Proof of Concept. *Med. Sci. Sports Exerc.*, Vol. 37, No. 5, pp. 872–876, 2005. **Purpose:** This study focused on developing a new method to assess $\dot{V}O_{2max}$ outside laboratory conditions and without the need for maximal exertion. We hypothesized that the combined use of accelerometry and HR monitoring, under daily life conditions, could provide a good estimate of physical fitness. **Methods:** Twenty-six healthy subjects (15 women, 11 men), aged 28 ± 7 yr, performed a maximal incremental test on a bicycle ergometer to determine $\dot{V}O_{2max}$. Body composition was measured with underwater weighing and deuterium dilution using a three-compartment model. A triaxial accelerometer (Tracmor) and an HR monitor were worn for seven consecutive days under free-living conditions. The ratio of HR to activity counts per minute (ACM) was used as a fitness index ($HR \cdot ACM^{-1}$). **Results:** As hypothesized, $HR \cdot ACM^{-1}$ was significantly correlated with $\dot{V}O_{2max}$. Using fat-free mass (FFM) ($P < 0.0001$), age ($P = 0.025$), and $HR \cdot ACM^{-1}$ ($P = 0.021$) as the independent variables, the explained variation in $\dot{V}O_{2max}$ was 76% ($P < 0.0001$, SEE = 363 mL·min^{-1}). In order to generate a prediction formula that is applicable in the field when no data on body composition are available, the same analysis was done with body mass and gender in the model instead of FFM. $HR \cdot ACM^{-1}$ was significantly ($P = 0.023$) correlated with $\dot{V}O_{2max}$. The total explained variation of the model was 71%, with a SEE of 409 mL·min^{-1}, or 13.7% of the average $\dot{V}O_{2max}$. **Conclusion:** After correction for body composition, $\dot{V}O_{2max}$ was significantly related to $HR \cdot ACM^{-1}$. It is, to our knowledge, the first tool that yields a measure of $\dot{V}O_{2max}$ by monitoring people in their daily life activities without the need for a specific protocol or for maximal exertion, and therefore is applicable to a large variety of subjects. **Key Words:** MAXIMAL OXYGEN UPTAKE, PHYSICAL ACTIVITY, TRIAXIAL ACCELEROMETER, BODY COMPOSITION, SUBMAXIMAL EXERTION, DAILY LIFE

Maximal oxygen uptake ($\dot{V}O_{2max}$) indicates the maximal capacity of the cardiovascular system to provide O_2 to muscle cells during sustained exercise, and is the most widely used measure of physical fitness. Although there is a large genetic component, it is mainly determined by a person's activity level, and inversely related to several health outcomes such as cardiovascular disease (2). $\dot{V}O_{2max}$ is usually measured by an incremental test on a motor-driven treadmill or a bicycle ergometer. Because of the need for expensive equipment for the direct measurement of $\dot{V}O_{2max}$, several attempts have been made to estimate $\dot{V}O_{2max}$ outside laboratory settings. Various tests such as the 12-min performance test (3) and the 20-m shuttle run test (10,13) have been proven to correlate well with $\dot{V}O_{2max}$. They require minimal equipment, and can be easily performed with several subjects at the same time, but require high levels of exertion. Other tests are based on submaximal, less exerting exercise protocols, but are still taxing, and demand strict adherence to the protocol (1,4,12). Ideally, an estimate of $\dot{V}O_{2max}$ should be obtained from submaximal, nonexerting activity outside laboratory settings that can be easily incorporated into daily life. Weyand et al. (18) used a combination of foot–ground contact monitoring and HR monitoring during treadmill running to calculate an aerobic fitness index as a measure of $\dot{V}O_{2max}$. The index was independent of treadmill running speed and correlated well with $\dot{V}O_{2max}$. Although the index was not yet tested in the field at volitional running speeds, they correctly stated that it is a potentially powerful tool for the modification of sedentary behavior and the improvement of aerobic fitness and health (18).

The lower HR observed in trained subjects is a consequence of an increased stroke volume, resulting from an increase in left ventricular size, myocardial contractility, and end-diastolic volume, along with a decreased sensitivity to catecholamines (6). Many of the field tests used to estimate $\dot{V}O_{2max}$ are based on the inverse relationship between $\dot{V}O_{2max}$ and HR at a given exercise intensity. That is, if one can measure the exercise intensity in the field and the corresponding HR, then $\dot{V}O_{2max}$ can be predicted. Accelerometers can provide accurate information about intensity, frequency, and duration of a variety of activities in daily life. They have been widely used as a measure of physical activity and activity patterns, and have proven to correlate well with energy expenditure during standard exercise protocols (11) and in daily life (5,16). We hypothesized that the combined use of accelerometry and HR monitoring could

Address for correspondence: Guy Plasqui, Department of Human Biology, Maastricht University, PO Box 616, 6200 MD Maastricht, The Netherlands; E-mail: G.Plasqui@HB.Unimaas.NL.

Submitted for publication June 2004.
Accepted for publication January 2005.

0195-9131/05/3705-0872
MEDICINE & SCIENCE IN SPORTS & EXERCISE®

DOI: 10.1249/01.MSS.0000161805.61893.C0

provide an accurate measure of $\dot{V}O_{2max}$ in daily living conditions, without the use of standardized protocols. Subjects with a high level of physical fitness should be able to generate higher activity counts (activity counts per minute (ACM)) at a lower HR than their "unfit" counterparts. More specifically, the aim was to use the ratio $HR \cdot ACM^{-1}$ as a new fitness index, and to investigate its potential as a predictor of $\dot{V}O_{2max}$.

SUBJECTS AND METHODS

Subjects. The subjects were 26 healthy volunteers (15 females and 11 males) between the ages of 18 and 50. Detailed information about the objective and the protocol of the study was provided. Written informed consent was obtained, and the study was approved by the ethics committee of Maastricht University. Subjects were selected to have a wide range in physical activity levels and physical fitness. A portion of the subjects were recruited from a local fitness center ($N = 12$), where they were either a new member ($N = 4$), already an active member for several months ($N = 5$), or an instructor ($N = 3$). The remaining subjects were recruited at the university. One subject was excluded from all analyses due to missing data of the HR monitor. The subject's characteristics ($N = 25$) are described in Table 1.

Body composition. Anthropometric measurements were taken in the morning before the consumption of any foods or drinks. Body mass (BM) was measured on an electronic scale (Mettler Toledo ID1 Plus, Germany) to the nearest 0.01 kg. Height was measured to the nearest 0.1 cm (SECA Mod. 220, Germany). Body volume was measured with underwater weighing. Residual lung volume was simultaneously measured using the helium dilution technique. Total body water (TBW) was measured with deuterium dilution according to the Maastricht protocol (17). Body composition was calculated from body density and TBW using Siri's (14) three-compartment model. $\dot{V}O_{2max}$ was corrected for body composition by using $\dot{V}O_{2max} \cdot kg^{-1}$ FFM.

Maximal aerobic power. $\dot{V}O_{2max}$ was determined during an incremental test on a cycle ergometer according to the protocol of Kuipers et al. (8). After a 5-min warm-up at 100 W for men and 75 W for women, workload was increased with 50 W every 2.5 min. When the HR reached 35 bpm below the age-predicted maximal HR (220 bpm − age) or the respiratory quotient exceeded 1, workload was increased by 25 W every 2.5 min until exhaustion. Subjects were equipped with a mouthpiece and nose clip, and expired air was continuously analyzed for O_2 consumption and CO_2 production (Oxycon-β, Bunnik, The Netherlands).

Accelerometry. The triaxial accelerometer for movement registration (Tracmor; Philips Research, Eindhoven, The Netherlands) is an improved version of the earlier validated Tracmor (5). The Tracmor contains three uniaxial piezoelectric accelerometers, measures 7.2 × 2.6 × 0.7 cm, and weighs 22 g (battery included). It is attached to the lower back by means of an elastic belt, measuring accelerations in the anteroposterior, mediolateral, and longitudinal axes of the trunk. Subjects were instructed to wear the Tracmor for seven consecutive days, during waking hours, except during water activities. The Tracmor was designed to enable data storage for at least 3 wk and for optimal wearing comfort in order not to interfere with daily activities. The Tracmor output is defined as ACM, and is the sum of all absolute values in three axes.

HR monitoring. HR was continuously registered for seven consecutive days using a Polar (S610i) HR monitor (Polar Electro Oy, Kempele, Finland). Subjects were instructed on how to use the transmitter belt and the wristwatch, and were asked to wear the monitor at the same time as the accelerometer (i.e., waking hours except during water activities). The HR monitor was programmed to store the heartbeat every minute, allowing synchronization in time with the accelerometer. After 7 d, the data were downloaded to computer files.

Calculations. The accelerometer and HR monitor were synchronized in time, and stored minute averages for HR and activity counts. The data for all 7 d were combined as one data set. When the HR monitor generated inaccurate data (due to bad contact of the transmitter belt with the skin or telemetric interference from other electric devices), the corresponding accelerometer value was also removed. For each subject, one average value (over the entire 7-d registration) was calculated for both ACM and HR (bpm). The ratio of $HR \cdot ACM^{-1}$ was then used as our fitness index.

Statistics. Differences between men and women for all variables were tested with Student's *t*-test for unpaired samples. Multiple regression analysis was used to generate prediction formulas for $\dot{V}O_{2max}$. All analyses were done with SPSS 10.0 for Macintosh (SPSS Inc., Chicago, IL). The statistical significance level was set at $P < 0.05$.

RESULTS

Results from metabolic testing for $\dot{V}O_{2max}$, $\dot{V}O_{2max}$ corrected for BM and FFM, and the weekly averages for the fitness index $HR \cdot ACM^{-1}$ are presented in Table 2. As could be expected, there was a significant gender difference for $\dot{V}O_{2max}$, except after correction for FFM. There was no gender difference for the fitness index $HR \cdot ACM^{-1}$.

Based on the results in Table 2, men and women were combined in the regression analysis. When FFM was used as an independent variable, no correction for gender was needed. When BM was used as an independent variable, gender was also included to correct for the difference in body composition. Since $\dot{V}O_{2max}$ was inversely related with age, age was always included in the model.

After correction of $\dot{V}O_{2max}$ for FFM and age, $HR \cdot ACM^{-1}$ was negatively related with $\dot{V}O_{2max}$ ($P = 0.02$), resulting in a total explained variation of 76% ($P < 0.0001$). Regression coefficients with SE, significance levels, and correlations are presented in Table 3. The SEE of the model was 363 $mL \cdot min^{-1}$, or 12.2% of the average $\dot{V}O_{2max}$.

TABLE 1. Subjects' characteristics.

	Men	Women
No.	10	15
Age (yr)	28 ± 7 (19–42)	28 ± 7 (22–46)
Body mass (kg)	73.6 ± 16.6 (51.4–106.0)	64.7 ± 7.8 (52.1–78.1)
BMI (kg·m^{-2})	23.2 ± 3.9 (16.2–30.4)	23.0 ± 2.9 (19–27.9)
%FM	17.3 ± 5.6 (9.3–24.9)	27.7 ± 7.4 (14.9–37.1)*

Values are mean ± SD (range).
BMI, body mass index; FM, fat mass.
* Significantly different between men and women, $P < 0.001$.

TABLE 2. Fitness parameters by gender ($\dot{V}O_{2max}$) as determined by the incremental cycle ergometer test.

	Men	Women
$\dot{V}O_{2max}$ (mL·min^{-1})	3556 ± 657	2587 ± 388**
$\dot{V}O_{2max}$·BM^{-1} (mL·kg^{-1}·min^{-1})	49.56 ± 10.18	40.68 ± 8.42*
$\dot{V}O_{2max}$·FFM^{-1} (mL·kg^{-1}·min^{-1})	59.72 ± 9.88	55.88 ± 7.19
HR·ACM^{-1} (beats per AC)	0.17 ± 0.06	0.20 ± 0.04

Values are mean ± SD.
BM, body mass; FFM, fat-free mass; ACM, activity counts per minute; AC, activity counts.
Significant gender difference: * $P < 0.05$ and ** $P < 0.001$.

To generate a prediction formula that is applicable in the field when no data on body composition are available, the same analysis was done with BM and gender in the model instead of FFM. HR·ACM^{-1} was significantly ($P = 0.02$) correlated with $\dot{V}O_{2max}$. The total explained variation of the model was 71% with a SEE of 409 mL·min^{-1}, or 13.7%. Regression coefficients with SE, significance levels, and correlations are presented in Table 4. When the same model was used with body mass index (BMI) instead of BM as an independent variable, BMI just failed to reach significance ($P = 0.06$), and did not improve the model (R = 0.81).

DISCUSSION

This study aimed to predict $\dot{V}O_{2max}$ with a new fitness index, based on the relationship between HR and activity counts. As we hypothesized, our fitness index HR·ACM^{-1} was significantly related to $\dot{V}O_{2max}$ corrected for differences in body composition and age.

It is clear that a substantial part of the variation in the prediction of $\dot{V}O_{2max}$ was explained by our measure of FFM. Because measuring FFM with a three-compartment model is at least as expensive and labor intensive as measuring $\dot{V}O_{2max}$ in the laboratory, it would not be fair to claim to have found a field test for the measurement of $\dot{V}O_{2max}$ using FFM in the model. For the discussion, we therefore focus on the second model using BM and gender instead of FFM in the regression equation.

Although physical fitness is a complex term that cannot be captured in one definition, $\dot{V}O_{2max}$ is the most widely used measure of cardiorespiratory fitness, and has been shown to be strongly related to several health outcomes (19). Even though direct measurement of $\dot{V}O_{2max}$ in a laboratory setting using a graded exercise test is the most accurate assessment, these tests are limited by the need for expensive equipment and trained technicians, the low number of subjects that can be measured simultaneously, and the maximal exertion required. Many attempts have been made to develop a field test for the measurement of $\dot{V}O_{2max}$, resulting in good to very good prediction equations (3,10). Léger and Lambert (10) reported a correlation of 0.84 (SEE = 11.4% of the average $\dot{V}O_{2max}$) between $\dot{V}O_{2max}$ and maximal speed achieved in the 20-m shuttle run. These results are comparable with those of the present study, which showed a correlation of 0.84 with a SEE of 13.7%. These tests, although providing good estimates of $\dot{V}O_{2max}$, are limited by the maximal exertion needed. The use of submaximal exercise tests to estimate $\dot{V}O_{2max}$ is generally based on the inverse relationship between HR at a given exercise intensity and $\dot{V}O_{2max}$ (1,12). Kline et al. (7) developed a fitness measure based on a 1-mile track walk, explaining 86% of the variation in $\dot{V}O_{2max}$ (R = 0.93, SEE = 12.4% of the mean $\dot{V}O_{2max}$).

Various tests should be evaluated not only for their accuracy and validity but also for their applicability in a varied study population, costs, and ease and convenience of the protocol. It is obvious that protocols requiring maximal exertion as well as submaximal running protocols are too strenuous or even unsafe for individuals with low functional capacities. Weyand et al. (18) developed a fitness index that predicted $\dot{V}O_{2max}$ independent of running speed. However, the lowest speed tested was 2.4 m·s^{-1}, which may already be difficult for some subjects, for example, the obese, which is a study population of great interest regarding physical activity and fitness. Furthermore, tests were performed with a controlled treadmill protocol and not in the field.

We aimed to develop a fitness index to estimate $\dot{V}O_{2max}$ that does not require adherence to a strict protocol, is applicable to a wide variety of subjects, and can be used in

TABLE 3. Multiple regression analysis with $\dot{V}O_{2max}$ as the dependent variable and FFM, age, and HR·ACM^{-1} as the independent variables.

				Correlations (R)		
$\dot{V}O_{2max}$	Coefficients	SE	P	Zero order[a]	Partial[b]	Part[c]
Constant	1834	532	0.002			
FFM (kg)	50.61	7.49	<0.0001	0.76	0.83	0.72
Age (yr)	−27.16	11.29	0.025	−0.18	−0.47	−0.26
HR·ACM^{-1} (beats per AC)	−3844	1545	0.021	−0.49	−0.48	−0.27
Model		SEE				
		363	<0.0001		0.87	

FFM, fat-free mass; ACM, activity counts per minute; AC, activity counts.
[a] The zero-order correlation is the simple (Pearson) correlation between the dependent and the independent variables.
[b] The partial correlation is the correlation between the dependent variable and an independent variable when the linear effects of the other independent variables in the model have been removed from both.
[c] The part (semipartial) correlation is the correlation between the dependent variable and an independent variable when the linear effects of the other independent variables in the model have been removed from the independent variable only.

TABLE 4. Multiple regression analysis with $\dot{V}O_{2max}$ as the dependent variable and age, gender, BM, and HR·ACM^{-1} as the independent variables.

$\dot{V}O_{2max}$	Coefficients	SE	*P*	Correlations (R)		
				Zero order[a]	Partial[b]	Part[c]
Constant	2714	541	<0.0001			
Age (yr)	−31.48	14.06	0.037	−0.18	−0.45	−0.27
Gender	592	194	0.006	0.70	0.56	0.37
BM (kg)	25.46	8.28	0.006	0.44	0.57	0.37
HR·ACM^{-1} (beats per AC)	−4401	1789	0.023	−0.49	−0.48	−0.30
Model		SEE				
		409	<0.0001		0.84	

BM, body mass; ACM, activity counts per minute; AC, activity counts.
[a] The zero-order correlation is the simple (Pearson) correlation between the dependent and the independent variables.
[b] The partial correlation is the correlation between the dependent variable and an independent variable when the linear effects of the other independent variables in the model have been removed from both.
[c] The part (semipartial) correlation is the correlation between the dependent variable and an independent variable when the linear effects of the other independent variables in the model have been removed from the independent variable only.

daily life. Accelerometers have been proven to correlate well with activity-related energy expenditure during standard running tests as well as in daily life (5,11,15,16). They provide information about the amount, frequency, and intensity of activity performed. The total amount of physical activity performed is best reflected by the sum of all counts or counts per day, whereas counts per minute, the output variable used in this study, is more a reflection of exercise intensity, and thus represents a measure of the mechanical work rate performed. By combining activity counts with a measure of HR, the physiological basis of our fitness index is comparable to that of many other submaximal tests based on the inverse relationship between physical fitness and HR at a given exercise intensity.

Daily life consists of a huge variety of different activities all resulting in different accelerometer output and HR readings. Both methods have their shortcomings with regard to the measurement of different activities. Accelerometers, for example, do not measure static activities, such as carrying loads. HR is influenced by factors besides activity including emotions and environmental temperature. Despite these shortcomings, our data demonstrate that "fitter" subjects generate higher activity counts at a lower HR than less fit individuals. The long observation period (1 wk) that we used allows for an enormous variety in activity intensities and therefore a large range in Tracmor output and HR.

This fitness measure is useful for both research purposes and public use. Motivating people to engage in sufficient physical activity is a major problem. Because goal setting and self-monitoring are commonly used tools to modify behavior (9), an instrument that provides feedback on a subject's personal physical fitness might be very useful to stimulate people to engage in physical activity.

A shortcoming of this study is that the number of subjects was too small to divide the subjects into an experimental and a cross-validation group. Our further research will aim at testing the prediction formula in a different group as well as testing our fitness index for the ability to detect changes in fitness over time. Furthermore, validity in other study populations, such as the obese and elderly, should be addressed. However, to our knowledge it is the first tool that yields a measure of $\dot{V}O_{2max}$ by monitoring people in their daily life activities without the need for a specific protocol or for maximal exertion, and therefore applicable to a large variety of subjects. We conclude that this fitness index is a promising tool for the measurement of $\dot{V}O_{2max}$, both for research purposes and to improve public health by stimulating people to engage in physical activity.

REFERENCES

1. Astrand, P. O., and I. Ryhming. A nomogram for calculation of aerobic capacity (physical fitness) from pulse rate during submaximal work. *J. Appl. Physiol.* 7:218–221, 1954.
2. Blair, S. N., Y. Cheng, and J. S. Holder. Is physical activity or physical fitness more important in defining health benefits? *Med. Sci. Sports Exerc.* 33:S379–399; discussion S419–320, 2001.
3. Cooper, K. H. A means of assessing maximal oxygen intake. Correlation between field and treadmill testing. *JAMA.* 203:201–204, 1968.
4. George, J. D., P. R. Vehrs, P. E. Allsen, G. W. Fellingham, and A. G. Fisher. $\dot{V}O_{2max}$ estimation from a submaximal 1-mile track jog for fit college-age individuals. *Med. Sci. Sports Exerc.* 25: 401–406, 1993.
5. Goris, A. H., E. P. Meijer, A. Kester, and K. R. Westerterp. Use of a triaxial accelerometer to validate reported food intakes. *Am. J. Clin. Nutr.* 73:549–553, 2001.
6. Jones, A. M., and H. Carter. The effect of endurance training on parameters of aerobic fitness. *Sports Med.* 29:373–386, 2000.
7. Kline, G. M., J. P. Porcari, R. Hintermeister, P. S. Freedson, A. Ward, R. F. McCarron, J. Ross, and J. M. Rippe. Estimation of $\dot{V}O_{2max}$ from a one-mile track walk, gender, age, and body weight. *Med. Sci. Sports Exerc.* 19:253–259, 1987.
8. Kuipers, H., F. T. Verstappen, H. A. Keizer, P. Geurten, and G. van Kranenburg. Variability of aerobic performance in the laboratory and its physiologic correlates. *Int. J. Sports Med.* 6:197–201, 1985.
9. Leermakers, E. A., A. L. Dunn, and S. N. Blair. Exercise management of obesity. *Med. Clin. North Am.* 84:419–440, 2000.
10. Leger, L. A., and J. Lambert. A maximal multistage 20-m shuttle run test to predict $\dot{V}O_{2max}$. *Eur. J. Appl Physiol. Occup Physiol.* 49:1–12, 1982.

11. LEVINE, J. A., P. A. BAUKOL, and K. R. WESTERTERP. Validation of the Tracmor triaxial accelerometer system for walking. *Med. Sci. Sports Exerc.* 33:1593–1597, 2001.
12. MARGARIA, R., P. AGHEMO, and E. ROVELLI. Indirect determination of maximal O2 consumption in man. *J. Appl Physiol.* 20:1070–1073, 1965.
13. PALICZKA, V. J., A. K. NICHOLS, and C. A. BOREHAM. A multistage shuttle run as a predictor of running performance and maximal oxygen uptake in adults. *Br J. Sports Med.* 21:163–165, 1987.
14. SIRI, W. E. *Body Composition from Fluid Spaces and Density: Analysis of Methods*. Washington, DC: National Academy of Sciences, National Research Council, 1961, pp. 223–224.
15. WESTERTERP, K. R. Physical activity assessment with accelerometers. *Int. J. Obes.* 23:S45–S49, 1999.
16. WESTERTERP, K. R., and C. V. C. BOUTEN. Physical activity assessment: comparison between movement registration and doubly labeled water method. *Z. Ernahrungswiss.* 36:263–267, 1997.
17. WESTERTERP, K. R. L. WOUTERS, and W. D. v. MARKEN-LICHTENBELT. The Maastricht protocol for the measurement of body composition and energy expenditure with labeled water. *Obes. Res.* 3:49–57, 1995.
18. WEYAND, P. G., M. KELLY, T. BLACKADAR, J. C. DARLEY, S. R. OLIVER, N. E. OHLENBUSCH, S. W. JOFFE, and R. W. HOYT. Ambulatory estimates of maximal aerobic power from foot-ground contact times and heart rates in running humans. *J. Appl Physiol.* 91:451–458, 2001.
19. WILLIAMS, P. T. Physical fitness and activity as separate heart disease risk factors: a meta-analysis. *Med. Sci. Sports Exerc.* 33:754–761, 2001.