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Ambulatory estimates of maximal aerobic power from foot -ground contact times and heart rates in running humans

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Weyand, Peter G., Maureen Kelly, Thomas Blackadar, Jesse C. Darley, Steven R. Oliver, Norbert E. Ohlenbusch, Sam W. Joffe, and Reed 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.—Seeking to develop a simple ambulatory test of maximal aerobic power ($\dot{V}O_{2\,max}$), we hypothesized that the ratio of inverse foot-ground contact time ($1/t_c$) to heart rate (HR) during steady-speed running would accurately predict $\dot{V}O_{2\,max}$. Given the direct relationship between $1/t_c$ and mass-specific O_2 uptake during running, the ratio $1/t_c \cdot$HR should reflect mass-specific O_2 pulse and, in turn, aerobic power. We divided 36 volunteers into matched experimental and validation groups. $\dot{V}O_{2\,max}$ was determined by a treadmill test to volitional fatigue. Ambulatory monitors on the shoe and chest recorded foot-ground contact time (t_c) and steady-state HR, respectively, at a series of submaximal running speeds. In the experimental group, aerobic fitness index ($1/t_c \cdot$HR) was nearly constant across running speed and correlated with $\dot{V}O_{2\,max}$ (r = 0.90). The regression equation derived from data from the experimental group predicted $\dot{V}O_{2\,max}$ from the $1/t_c \cdot$HR values in the validation group within 8.3% and 4.7 ml $O_2 \cdot kg^{-1} \cdot min^{-1}$ (r = 0.84) of measured values. We conclude that simultaneous measurements of foot-ground constant times and heart rates during level running at a freely chosen constant speed can provide accurate estimates of maximal aerobic power.

aerobic fitness index; oxygen pulse; cost coefficient; locomotion; running mechanics

AN INDIVIDUAL'S MAXIMAL RATE of O_2 uptake ($\dot{V}O_{2\,max}$) sets the upper limit for sustained physical activity and is, therefore, the standard measure of aerobic fitness. The extensive laboratory measurements of $\dot{V}O_{2\,max}$ over the last half-century have provided an empirical foundation from which numerous population norms have been developed (2, 25). The wide dissemination of this information has increased public awareness of aerobic fitness and has helped establish the fitness benefits of regular running and walking (5). Despite compelling physiological importance and considerable attention (3, 16, 27, 35), a field method for the assessment of aerobic fitness that can be easily incorporated into daily exercise routines is not available. The development of a simple and reliable means of assessing aerobic fitness during running or walking would provide a valuable public fitness and health tool.

The field tests available to estimate aerobic power outside the laboratory setting cannot be easily incorporated into daily routines. Many measure maximal performance during runs or walks of a specified time or distance (7, 10, 11, 15, 17, 33) and, therefore, require high levels of exertion. These tests provide aerobic power estimates of modest accuracy and can be compromised by insufficient motivation or uneven pacing. The more recently developed 20-m shuttle run test (1, 20, 22, 28, 30, 34) appears to provide more accurate estimates but also requires maximal exertion. Other tests, such as the Åstrand-Ryhming ergometer test and the Harvard bench step test, do not require all-out efforts but are, nonetheless, taxing and require strict adherence to specific protocols (3, 9, 21, 23, 24, 29, 35). Exertion and the requirements for specific procedures that fall outside the realm of normal daily activity limit the practicality of these tests as tools for ongoing personal assessment.

Ambulatory foot-ground contact monitors (12) used simultaneously with conventional heart rate (HR) monitors may allow aerobic power to be assessed from nothing more than several minutes of running at a freely chosen speed. Simply inverting the time of foot-ground contact ($1/t_c$) obtained from the monitors at any running speed provides a close approximation of mass-specific rates of O_2 uptake ($\dot{V}O_2/W_b$, where W_b is body weight) (12, 19). Although the relationship between $1/t_c$ and $\dot{V}O_2/W_b$ varies little with aerobic fitness level, the HR required to support a given $\dot{V}O_2/W_b$ is inversely related to the aerobic power of the individual (32). Regardless of the level of aerobic fitness, HR, $\dot{V}O_2/W_b$, and rates of ground force application increase linearly with running speed. The linear and parallel increases in HR and $1/t_c$ with increases in running speed suggest that the ratio of these two variables may be independent of speed. This outcome would potentially allow

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aerobic fitness to be estimated from the ratio of $1/t_c$ to HR ($1/t_c \cdot$HR) at whatever steady running speed a person chooses.

Here, we hypothesized that the ratio of $1/t_c$ to heart rate would be proportional to the mass-specific energy provided per heartbeat and, therefore, provide an aerobic fitness index (AFI) that could be easily obtained in the field using existing technology. We specifically predicted that the ratio of $1/t_c$ to heart rate during level running would enable us to predict maximal aerobic power to within 10% of measured values.

METHODS

Subjects

Thirty-six subjects (18 men and 18 women) between 18 and 37 yr of age volunteered and provided written informed consent in accordance with the guidelines of Harvard University before participating. All the subjects were healthy and engaged in some form of regular physical activity. The least active subjects performed a minimum of ~20 min of aerobic exercise twice a week. The most active subjects were competitive distance runners who ran for >1 h/day and typically ran at speeds at or above that eliciting $\dot{V}O_{2\,max}$ two to three times per week. Physical characteristics by gender and group appear in Table 1.

Experimental Design

We used a cross-validation approach to test the hypothesis that aerobic power could be predicted to within an average of 10% from the ratio of $1/t_c$ to HR during steady-speed running. We recruited individuals varying from low-average to high levels of aerobic fitness to obtain a range of fitness levels similar to that in the general and military populations that would be potentially served by a new index. After directly measuring the aerobic power of 18 male and 18 female volunteers of various fitness levels, we ranked subjects within each gender on the basis of their maximal aerobic power. Subjects were then paired in a sequential fashion on the basis of these rankings. Within each gender and with respect to aerobic power, this procedure paired the subjects with the first- and second-greatest values, the third- and fourth-greatest values, etc. From each of nine pairs of men and nine pairs of women, one subject was assigned to an experimental group and the other to a validation group in a random fashion.

Once experimental and validation groups were established, a best-fit regression relationship between the ratio of $1/t_c$ to HR during steady-speed submaximal running and $\dot{V}O_{2\,max}$ was formulated for the subjects in the experimental group. Subsequently, predicted $\dot{V}O_{2\,max}$ values for the 18 subjects in the validation group were calculated using their $1/t_c \cdot$HR values. We then compared the predicted and actual $\dot{V}O_{2\,max}$ values for the 18 subjects in the validation group to assess whether the predicted values were within an average of 10% of the measured values as hypothesized.

Table 1. *Physical characteristics by group and gender*

	Age, yr	Mass, kg	Height, cm
Experimental subjects			
Male	27.8 ± 1.7	67.6 ± 3.3	180.1 ± 1.4
Female	25.4 ± 1.9	59.9 ± 1.9	164.1 ± 1.6
Validation subjects			
Male	26.9 ± 1.6	67.2 ± 1.9	179.9 ± 1.8
Female	24.3 ± 1.7	59.4 ± 3.4	163.8 ± 1.7

Values are means ± SE of 9 subjects in each group. Age, mass, or height means did not differ ($P < 0.05$) between experimental and validation subjects of the same gender.

Treadmill Protocol

All subjects underwent a progressive-speed, discontinuous, horizontal treadmill test to volitional fatigue. Each bout of running lasted 5.5 min; rest intervals between bouts lasted 3–5 min. Tests were initiated at 2.4–2.7 m/s, with subsequent speed increments being determined by the level of fitness each subject reported before the test. Speeds were selected conservatively so that a minimum of four speeds would be completed before each subject reached the speed eliciting $\dot{V}O_{2\,max}$. Tests were terminated when the belt speed prevented the subject from completing the full 5.5-min bout while putting forth a maximal effort.

Measurements

Rates of oxygen uptake ($\dot{V}O_2$, ml·kg^{-1}·min^{-1}). Steady-state $\dot{V}O_2$ values (ml·kg^{-1}·min^{-1}) were determined in accordance with Consolazio et al. (6) using a Douglas bag method. Each subject wore nose clips and headgear equipped with a mouthpiece and one-way valve. One side of the valve was open to room air; the other directed gas via corrugated tubing into one of two valved latex balloons arranged in series on a rack next to the treadmill. Air was collected during the last 2 min of each 5.5-min exercise bout to ensure steady-state $\dot{V}O_2$. A 400-ml aliquot of the expired air in each bag was then analyzed for O_2 (model SA 3, Ametek, Pittsburgh, PA) and CO_2 (model CD-3A, Ametek) fractions after calibration of the analyzer with a gas of known concentrations. Gas volumes were determined by pushing the collected gas through a Parkinson-Cowan dry gas meter with simultaneous temperature reading. $\dot{V}O_2$ values (STPD) were determined from O_2 and CO_2 fractions and the expired volumes.

Maximal aerobic power (ml O_2·kg^{-1}·min^{-1}). $\dot{V}O_{2\,max}$ (ml·kg^{-1}·min^{-1}) was the highest single-minute $\dot{V}O_2$ measured during the progressive, discontinuous treadmill test with an accompanying criterion of a minimum respiratory exchange ratio of 1.10.

Foot-ground contact times (s). In this study, a patented foot pod device (model 6122340, FitSense Technology, Wellesley, MA), in which the authors affiliated with FitSense hold a proprietary interest, was used to measure t_c (s). The plastic pods contained accelerometers (0–10 g; model ADXL-210, Analog Devices, Norwood, MA), radio transmitters, and microprocessors (Fig. 1) that analyzed the vertical waveforms generated during the stride to identify periods of foot-ground contact to within ±2 ms. The pods were mounted on the top of each subject's shoe and secured with the shoe's laces before the start of the treadmill test. For each step, t_c values were telemetered to a receiver mounted on the railing of the treadmill. Accelerometric t_c values at each speed were averaged from ≥20 consecutive steps of the same foot at some point later than 30 s in the bout. Foot pod t_c values were identified by the microprocessor from the time elapsing between foot-down and foot-up for each step. The identification of the time of foot strike and toe off from the waveform output of the accelerometer is depicted for a representative trace in Fig. 2.

Because the method for obtaining ambulatory t_c values used here differed from that used in previous work (12, 13), we validated the ambulatory t_c values measured by our accelerometers against those measured simultaneously from

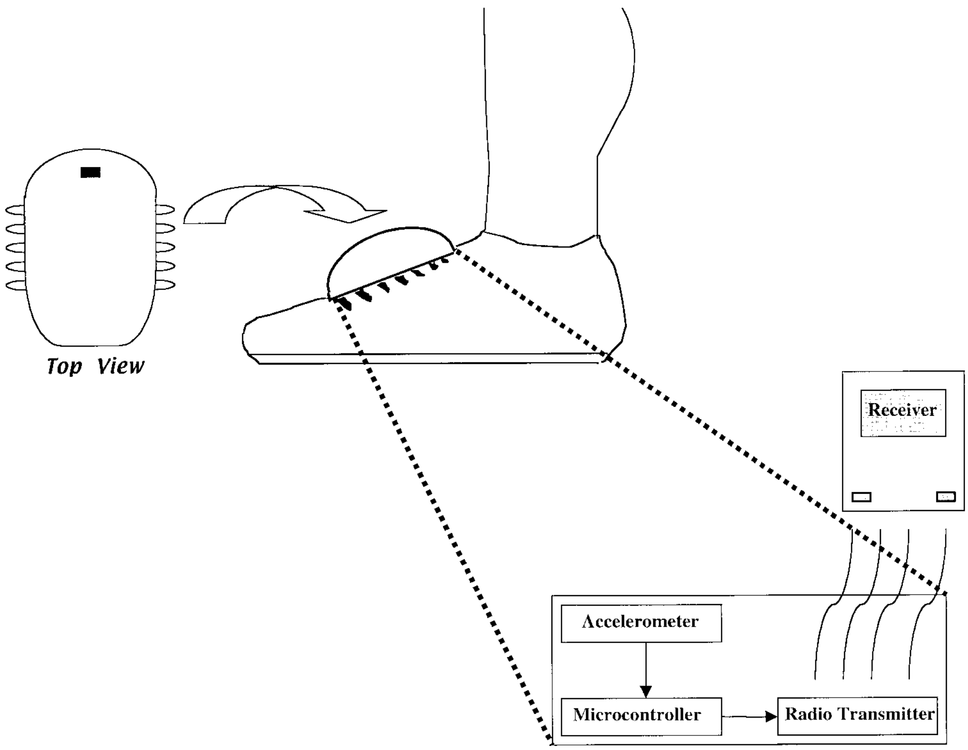

Fig. 1. Diagram of the foot-ground contact monitor and components. The foot pod, mounted on the shoe of the runner, contains an accelerometer and a microcontroller, which uses an algorithm to convert the waveform produced by the accelerometer to a foot-ground contact time (±2 ms). Contact times for each step are then transmitted via radio waves to the receiver for display.

a force plate mounted into the bed of the treadmill (18). Force plate signals were augmented by an amplifier (model 2110, Vishay Instruments, Raleigh, NC) and recorded and analyzed by a Macintosh computer running LabView (version 4.0) custom software. Force plate t_c values were defined as the time during each stance phase when the force exerted on the plate exceeded 0 N. Average values were determined from duplicate 10-s intervals beyond 30 s in each bout.

Heart rates (beats/min). HR (beats/min) was measured using HR monitors (Polar Electrode Oy, Kempele, Finland), which telemetered a running 5-s average from a bipolar electrode unit fastened to the subject's chest to a wristwatch display mounted on the treadmill rail. Values were recorded at 3.75, 4.75, and 5.25 min of each bout and averaged to obtain a final value for each speed. The highest value recorded was considered the subject's maximum HR.

Aerobic fitness index (1/beat). A single average value for $1/t_c \cdot$HR was determined for each subject at each speed using the accelerometric t_c and the average of the three HR values recorded during each bout.

Statistical Analyses

Means for age, mass, height, $\dot{V}O_{2\,max}$, maximal HR, and the aerobic fitness index for the experimental and validation groups were compared using the Student's t-test for paired samples ($P < 0.05$). The aerobic fitness index with respect to speed was tested for slopes significantly different from zero

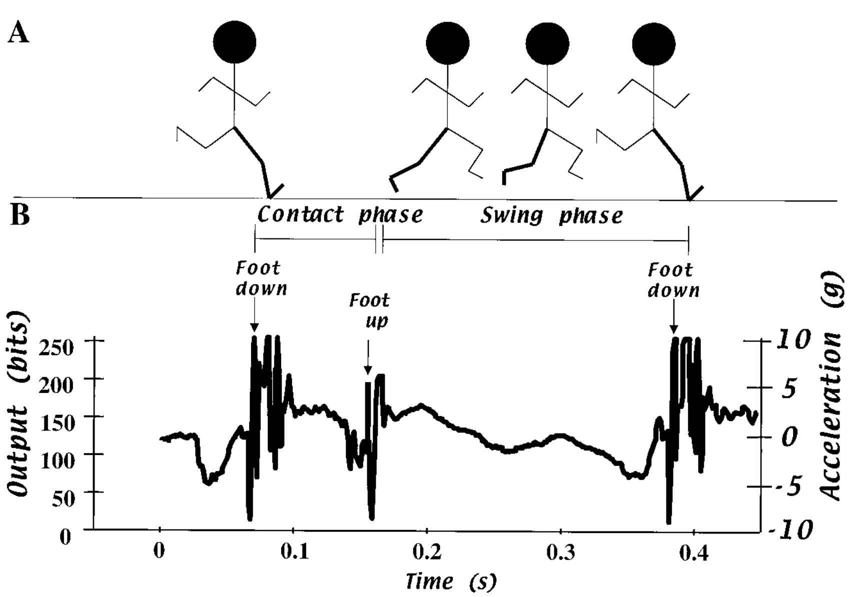

Fig. 2. Foot-ground contact and swing periods of a representative running stride (A) and simultaneous waveform output from the accelerometer (B).

using simple linear regression ($P < 0.05$). Linear least-squares regression lines were formed to assess the relationship between $\dot{V}O_{2\,max}$ and the AFI for the experimental group and between actual and predicted aerobic power for the validation group. Values are means ± SE.

RESULTS

Force Plate vs. Accelerometric Foot-ground Contact Times

The t_c values identified by the accelerometers were highly correlated with those measured using the treadmill-mounted force plate (Fig. 3). On average, accelerometric t_c values were 14.6 ± 0.5% longer than those measured from the force plate. Longer contact times from the accelerometer resulted primarily from the interval during the latter portion of the contact period when no force is exerted on the plate but the foot has not yet been accelerated off the running surface to begin the swing phase. The ratio of accelerometric to force plate t_c values increased slightly with running speed. From the slowest to the fastest speed administered to each subject, the average increase in this ratio was +5.9%. These increases tended to be greater in the subjects tested over a greater range of speeds.

Inverse Foot-ground Contact Times vs. Mass-specific Rates of Oxygen Uptake

In the 36 subjects tested, $1/t_c$ accounted for an average of 98.5% of the within-subject variance measured in $\dot{V}O_2/W_b$ as a function of running speed in the 36 subjects tested. The slope and intercept representing the average for all subjects appears in Fig. 4, as do the regression relationships for three individual subjects:

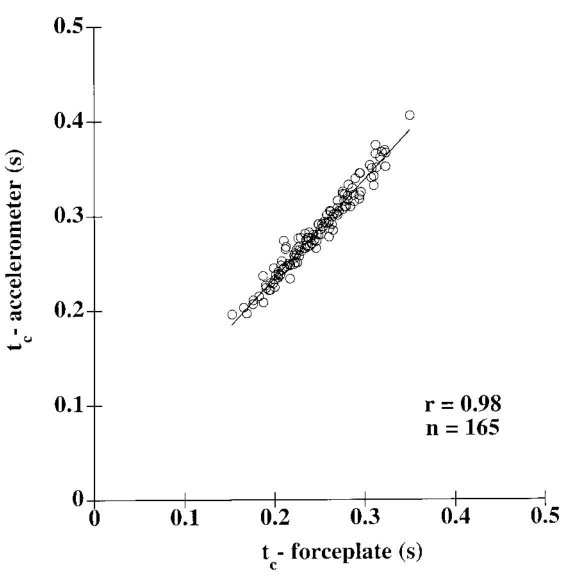

Fig. 3. Accelerometer vs. treadmill-mounted force plate contact times (t_c). Accelerometric t_c values were slightly longer than the periods of vertical force applied to the treadmill (t_c pod = 0.0275 + 1.036·t_c force plate) because of the interval during the latter portion of the contact period when force is not exerted on the plate, but the foot has not yet been accelerated off the running surface to begin the swing phase of the stride.

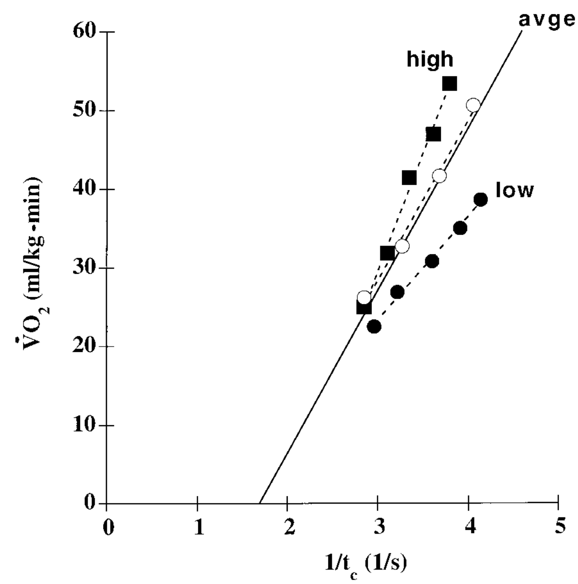

Fig. 4. Mass-specific rates of O_2 uptake ($\dot{V}O_2$) increased linearly with inverse t_c ($1/t_c$). Solid line, best-fit line for all 36 subjects; dashed lines, best-fit lines for 3 individual subjects.

one extremely low, one average, and one extremely high, with respect to $\dot{V}O_2$ at a given $1/t_c$ during running. Although $1/t_c$ values accounted for virtually all the variance in $\dot{V}O_2$ across speed for individual subjects, there was appreciable between-subject variation, as illustrated by the different values for the three individual subjects in Fig. 4. Consequently, the proportion of variance in $\dot{V}O_2/W_b$ accounted for by $1/t_c$ among the entire group of 36 was considerably less than that accounted for across speed in individual subjects (61 vs. 98%).

Aerobic Fitness Index

HR and $1/t_c$ increased linearly with increases in running speed for all 36 subjects. These relationships are illustrated in Fig. 5 for two subjects: one with high aerobic power and another with lesser aerobic power. The linear and parallel increases in HR and $1/t_c$ resulted in values of $1/t_c$·HR (i.e., our proposed aerobic fitness index) that were independent of running speed. The slope of the relationship between running speed and $1/t_c$·HR was not different from zero ($P < 0.05$) in 31 of the 36 subjects tested; the average percent change from the slowest to the highest speed completed was +5.8%.

Mean values for the aerobic fitness index were 17.9 and 20.0% greater for men than for women in the experimental and validation groups, respectively, but were not different between experimental and validation groups for either gender (Table 2).

Maximal Aerobic Power

$\dot{V}O_{2\,max}$ (Table 2) did not differ between the experimental and validation groups, with similar ranges of 37.4–72.6 and 40.8–74.8 ml·kg^{-1}·min^{-1}, respectively. Mean values for aerobic power were 24.5 and 29.1%

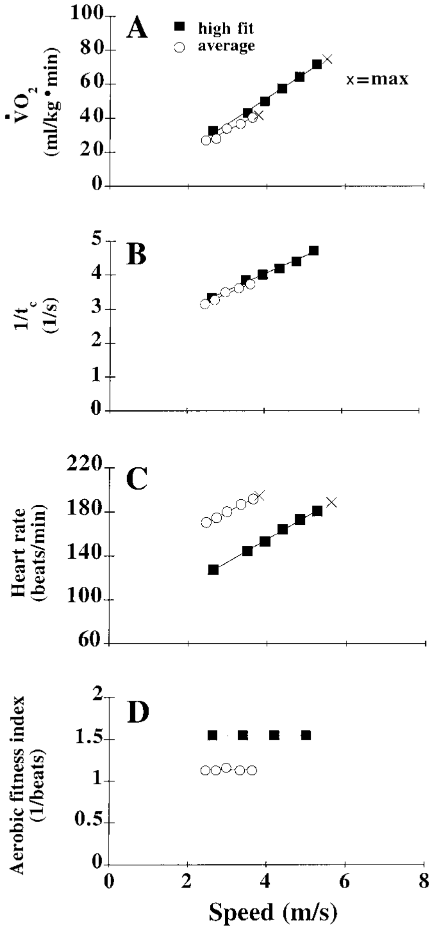

Fig. 5. Mass-specific $\dot{V}O_2$ (*A*), $1/t_c$ (*B*), and heart rate (HR; *C*) increased linearly with speed during level running for highly fit and average subjects. Thus the ratio of $1/t_c$ to HR ($1/t_c \cdot$HR; *D*) did not change with speed and had a greater value in more-fit than in less-fit subjects. This aerobic fitness index, here presented as inverse heartbeats (1/beats), is proportional to the mass-specific energy provided per heartbeat with the assumption of a fixed relationship between $1/t_c$ and mass-specific metabolic rates.

lower, and maximum HR values were 11 and 5 beats/min greater for women than for men in the experimental and validation groups, respectively. Mean respiratory exchange ratios at $\dot{V}O_{2\,max}$ were 1.15 and 1.16 for the experimental and validation groups, respectively.

Aerobic Fitness Index as a Predictor of $\dot{V}O_{2\,max}$

Among the 18 subjects in the experimental group, mean values for the aerobic fitness index accounted for 82% of the variance in $\dot{V}O_{2\,max}$ (Fig. 6). When average values for the aerobic fitness index measured for the 18 subjects in the validation group were calculated using the regression equation formulated on the experimental group, the predicted values for $\dot{V}O_{2\,max}$ were within an average of 8.3% (4.7 ± 0.8 $ml \cdot kg^{-1} \cdot min^{-1}$, range 0.2–11.6 $ml \cdot kg^{-1} \cdot min^{-1}$) of the actual values. Predicted values accounted for 70% of the variance in measured values (Fig. 7). Predicting aerobic power from the aerobic fitness index values at all speeds, rather than a single average value, had almost no effect on the accuracy of the predictions. In the latter case, the proportion of variance in $\dot{V}O_{2\,max}$ accounted for was 74.2 and 66.5% for the experimental and validation group subjects, respectively. Finally, predicting $\dot{V}O_{2\,max}$ from an aerobic fitness index determined using force plate, rather than accelerometric, t_c values had virtually no effect on the accuracy of the predictions provided (r^2 difference < 0.02).

To evaluate for the possible influence of gender on the relationship between our AFI and $\dot{V}O_{2\,max}$, regression equations were formulated for the 18 male and 18 female subjects separately. The resulting best-fit regression relationships ($\dot{V}O_{2\,max}$ = 11.1 + 34.4·AFI and 10.3 + 30.9·AFI for men and women, respectively) indicated that, in the range of gender overlap for aerobic power (47.5 to 63.7 $ml \cdot kg^{-1} \cdot min^{-1}$) for any given value of the AFI, $\dot{V}O_{2\,max}$ was 9.8% greater in male than in female subjects. When the AFI and gender were used to predict aerobic power using multiple regression, the proportion of variance accounted for

Table 2. *Physiological means by group and gender*

	$\dot{V}O_{2max}$, $ml \cdot kg^{-1} \cdot min^{-1}$	AFI, 1/beats	Maximum HR, beats/min
Experimental subjects			
Male	61.1 ± 3.0*	1.43 ± 0.05*	185 ± 3.0*
Female	48.2 ± 2.7	1.23 ± 0.07	197 ± 2.7
Validation subjects			
Male	61.7 ± 3.0*	1.44 ± 0.06*	190 ± 2.7*
Female	47.8 ± 2.1	1.20 ± 0.07	195 ± 2.5

Values are means ± SE of 9 subjects in each group. $\dot{V}O_{2max}$, maximal aerobic power; AFI, aerobic fitness index; HR, heart rate. $\dot{V}O_{2max}$ and AFI means did not differ ($P < 0.05$) between experimental and validation subjects of the same gender; while maximum HR values were significantly lower for male, but not female, subjects of the experimental vs. the validation group. Multiplying AFI values by 0.18 ml O_2/kg provides approximate mass-specific O_2 pulses. *Significantly different from female ($P < 0.05$).

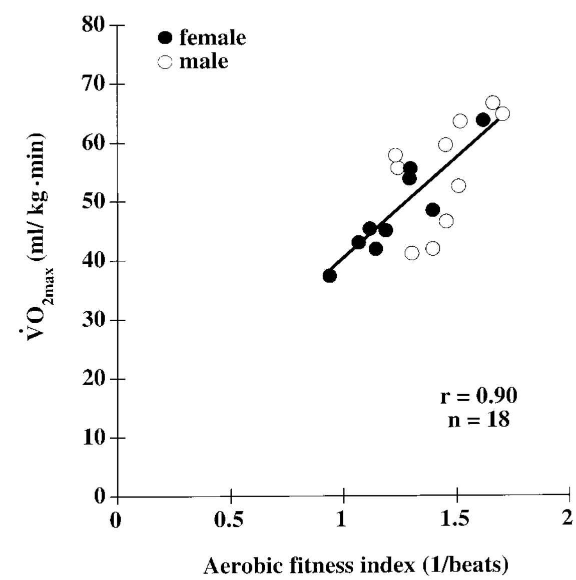

Fig. 6. Relationship between the aerobic fitness index and maximal aerobic power ($\dot{V}O_{2max}$) among experimental group subjects ($\dot{V}O_{2max}$ = −5.075 + 44.9·aerobic fitness index).

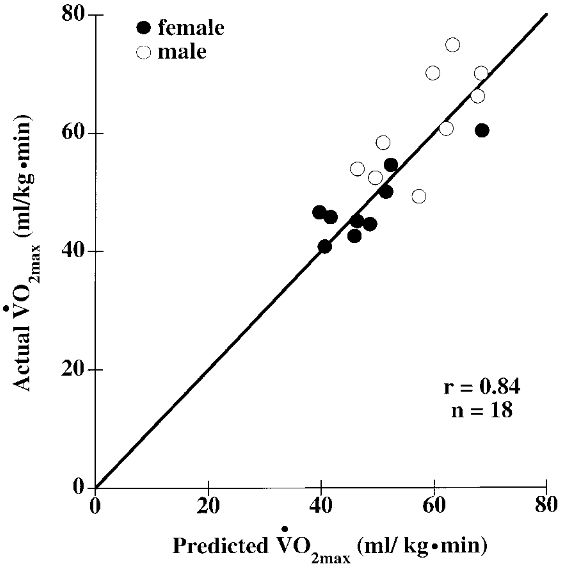

Fig. 7. Measured $\dot{V}O_{2max}$ values for subjects in the validation group vs. values predicted from the equation derived from subjects in the experimental group.

increased from 74.0 to 79.8% ($\dot{V}O_{2\,max}$ = 19.4 + 32.45·AFI − 5.5·gender, where a value of 1 was assigned to males and 2 to females, P = 0.02).

DISCUSSION

As anticipated, we succeeded in predicting $\dot{V}O_{2\,max}$ from $1/t_c$·HR during running to within 10% of actual values. The values for $\dot{V}O_{2\,max}$ predicted from our aerobic fitness index matched the values measured in the 18 validation group subjects to within an average of 8.3%. Of equal importance to the accuracy of these estimates is the ease with which they can be attained. The virtual independence of the aerobic fitness index from running speed allows estimates to be acquired from only a few minutes of running at whatever constant speed a person chooses. This new technique offers the public a practical means of assessing aerobic fitness during day-to-day living.

Physiological Basis of $1/t_c$·HR as an Index of Aerobic Fitness

Our strategy for establishing an ambulatory index of aerobic fitness combines a novel approach with one that is nearly a half-century old (3). The earliest field tests of $\dot{V}O_{2\,max}$ and many in use today are based on the inverse relationship between $\dot{V}O_{2\,max}$ and HR at some known sustainable mechanical work rate. These tests provide reasonable estimates of $\dot{V}O_{2\,max}$ as long as physical activity incurring a known $\dot{V}O_2$, and therefore cardiovascular demand, can be implemented in the testing. In practice, this can be achieved by having subjects perform mechanical work at prescribed rates, either against the pedals of a cycle ergometer or against gravity during bench stepping. Here, in the interest of developing an ambulatory assessment tool, we combined the old idea of using steady-state HRs with a promising approach to estimating $\dot{V}O_2/W_b$ during locomotion (12, 13, 19).

The immediate impetus for our attempt to develop an ambulatory index was provided by the close relationship between $1/t_c$ and the mass-specific metabolic rates of runners originally reported by Kram and Taylor (19). These authors presented this relationship as follows: $\dot{E}_{metab}/W_b = C \cdot 1/t_c$, where C represents the amount of energy expended per unit of force applied to the ground to support the body's weight. Although Kram and Taylor reported that the value of C was nearly invariant among different species of quadrupedal runners over a 10-fold range of running speeds, we did not know a priori how much C might vary among different human runners. A similarly invariant relationship among human runners would have enabled us to express the fitness index as the amount of O_2 provided per heartbeat or as a mass-specific O_2 pulse. However, appreciable variability in C among different runners and across running speeds prevented this.

Nonetheless, some more concrete link to the physiological basis of this new index seems warranted for the purposes of basic understanding and appropriate use of this new assessment tool. The units we report (1/beat) can be converted to an approximate mass-specific O_2 pulse by multiplying by 0.18 ml O_2/kg, the average cost coefficient measured for all the runners in this study. This calculation provides a reasonable approximation of the volume of O_2 consumed per kilogram of body weight per beat of the heart during running (thus 0.18·AFI = ml $O_2 \cdot kg^{-1} \cdot beat^{-1}$), a variable more intuitively related to the maximal aerobic power of the runner.

Independence of the Aerobic Fitness Index From Running Speed

The independence of individual $1/t_c$·HR values from running speed, which enhances the practicality of our new assessment technique, was not a foregone conclusion at the outset of this study. This result was unlikely if either the amount of O_2 consumed per heartbeat or the energy cost of applying ground force (C) changed appreciably as a function of running speed. Although we did find values of $1/t_c$·HR to be consistently independent of speed, this occurred, despite significant speed-induced increases in both of the aforementioned variables. However, because the increases in mass-specific O_2 pulses and C were largely parallel, values for the aerobic fitness index were statistically

Table 3. *Techniques for estimating $\dot{V}O_{2max}$*

	Accuracy	Convenience	Exertion Required
Åstrand-Rhyming	Good	Average	Intermediate
Harvard step test	Average	Good	Intermediate
Cooper 12-min run	Fair	Average	Maximal
Shuttle run	Good	Fair	Maximal
AFI	Good	Good	Modest

Accuracy and convenience rankings are based on a 5-category scale (poor, fair, average, good, excellent). Convenience rankings incorporate time and equipment required to obtain estimates.

unchanged across speed in 31 of our 36 subjects. Although a causal explanation for these results is more appealing than a noncausal one, such an explanation would not be correct. The stance limb mechanics responsible for the increases in the energy cost of applying ground force at higher speeds (4, 31) are not directly linked to the cardiovascular changes responsible for the increases in mass-specific O_2 pulses.

Utility of the Aerobic Fitness Index as a Field Test of Maximal Aerobic Power

The accuracy of the $\dot{V}O_{2\,max}$ predictions provided by the aerobic fitness index are as good as or better than those reported for other predictive tests. Although some individual studies have reported marginally higher correlations from running (7, 26) or other tests (3, 23), the predictions generally reported in the literature for these tests (25, 35) are equally or less accurate than those we report here. As with many of the existing tests, the greatest source of error in the predictions resulted from individual variation from estimated mass-specific rates of oxygen uptake, which in this case were estimated from rates of ground force application ($1/t_c$). For any given subject running at any speed, $\dot{V}O_2/W_b$ predicted from $1/t_c$ differed from the measured value by an average of 7.7%, similar to the error reported for subjects performing mechanical work at the same rates (25).

A sense of the error introduced into the predictions of $\dot{V}O_{2\,max}$ as a result of the individual variability in the energetic cost of applying ground force (C) is provided by the relationship between the rates of ground force application ($1/t_c$) and $\dot{V}O_2/W_b$ illustrated in Fig. 4. The aerobic fitness index consistently underpredicted $\dot{V}O_{2\,max}$ values for subjects that had relatively low $\dot{V}O_2/W_b$ for any given value for $1/t_c$, and vice versa. Predictions for those subjects whose $\dot{V}O_2/W_b$ values were close to the group mean with respect their rates of ground force application were the most accurate.

The influence of factors other than individual variability in C that might have weakened the relationship between $\dot{V}O_{2\,max}$ and the aerobic fitness index was small. Adding maximal HR or gender to the aerobic fitness index as copredictors of $\dot{V}O_{2\,max}$ with the use of a multiple-regression analysis increased the proportion of variance in $\dot{V}O_{2\,max}$ accounted for by 7 and 8%, respectively. In contrast, when measured values for mass-specific O_2 pulses were used as a single predictor of $\dot{V}O_{2\,max}$, rather than $1/t_c \cdot$HR, the proportion of variance accounted for in the measured maximums for aerobic power for the subjects in our validation group increased by 21%, from 69 to 90%. Although variability in maximal HR and other factors may have a greater effect on predictions of aerobic power from our ambulatory index in more heterogenous populations, the influence of these factors among a population of healthy adults in the age range tested here was modest.

We anticipate that the accuracy of predictions of $\dot{V}O_{2\,max}$ provided by the aerobic fitness index during treadmill running in health club and other settings should be similar to those reported here. However, we cannot know how accurate predictions from overground running on a level surface will be. Running at volitional speeds in the field, rather than controlled speeds on a treadmill, may weaken the predictive ability of our index. Further work to determine the accuracy of values obtained during overground running is warranted, as is an assessment of how well our index will track individual changes in aerobic fitness over time. The close relationship between training-induced changes in $\dot{V}O_{2\,max}$ and the HR elicited by any given submaximal exercise intensity (8, 14) suggests that aerobic fitness index estimates of changes in $\dot{V}O_{2\,max}$ over time may be more accurate than estimates of absolute values.

Ease of use is an appealing aspect of this new technique for assessing aerobic fitness. Given the ambulatory monitors necessary and a level running surface, any person fit enough to jog can gain an estimate of aerobic fitness with modest exertion in a matter of minutes. The elimination of cumbersome procedures and the high levels of exertion required by existing field tests offers an assessment technique that is more practical for widespread public use and equally accurate (Table 3). The simplicity of the procedure and the minimally obtrusive nature of the monitors required should, ultimately, place the capability for the personal assessment of aerobic fitness within the reach of most of the individuals in the developed world. Convenience makes our new index a potentially powerful tool for the modification of sedentary behavior and the improvement of aerobic fitness and health.

We conclude that simultaneous measurements of foot-ground constant times and heart rates during level running at a freely chosen steady speed can be used to estimate maximal aerobic power.

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