The power output/heart rate relationship in cycling: test standardization and repeatability

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ABSTRACT

GRAZZI, G., N. ALFIERI, C. BORSETTO, I. CASONI, F. MANFREDINI, G. MAZZONI, and F. CONCONI. The power output/heart rate relationship in cycling: test standardization and repeatability. *Med. Sci. Sports Exerc.*, Vol. 31, No. 10, pp. 1478–1483, 1999. **Purpose:** The purpose of this study was to update and standardize the test for determining the power output/heart rate (PO/HR) relationship in cycling. **Methods:** The current protocol was developed in the laboratory using a wind-load cycling simulator. Five hundred incremental tests were carried out by 290 male cyclists during a 2-yr period (1995–1997). The subjects' own bicycles, equipped with a standard crankset with a built-in power measuring system, were used for testing. The test protocol consisted of time-based increments in cadence that were uniform up to submaximal speeds and progressively greater in the final phase. **Results:** The PO/HR relationship obtained was linear at low to submaximal PO and curvilinear from submaximal to maximal PO. A method was developed for the mathematical identification of the point of transition from the linear to the curvilinear phase (deflection point or heart rate break point). In 484 of the 500 tests performed, the deflection was independent of the final acceleration (PO at deflection 318.4 ± 42.4 W, PO at final acceleration 351.6 ± 43.2 W, $P < 0.001$), whereas in 16 tests the deflection and the start of the final acceleration coincided. To evaluate test repeatability and precision, 15 subjects repeated the test twice within a few days. No significant differences were found for the heart rate at deflection, power output at deflection, or slope of the linear part of the PO/HR relationship obtained in the two tests. **Conclusion:** It is concluded that the deflection point obtained by determining the PO/HR relationship on a wind-load simulator is not an artifact dependent on the incremental test protocol but rather a repeatable physiological phenomenon. **Key Words:** HEART RATE DEFLECTION POINT, HEART RATE BREAK POINT, WIND-LOAD CYCLING ERGOMETER

In 1982 Conconi et al. (5) proposed a noninvasive test for identifying the anaerobic threshold through the determination of the speed/heart rate (S/HR) relationship in running. The S/HR relationship was subsequently determined in various sports, including cycling (4,6,11). Several authors have published data on the power output/heart rate (PO/HR) relationship in cycling during incremental exercise using different environmental conditions (outdoor cycling, indoor cycling, electrically braked cycle ergometers, and wind-load cycling simulators) and different test protocols (with diversities in test stage duration, PO increases from one stage to the next, and use of fixed or incremental cadences) (3,12,17,23,29,30).

Frictional air resistance increases relative to the square of the speed (10). In cycling, speeds are reached at which air resistance is considerable (e.g., at 60 km·h^{-1}, 90% of the total power output is used to overcome air resistance) (19,26). Therefore, even small changes in air density (due to variations in humidity, temperature, and atmospheric pressure) or the presence of wind will influence the cyclist' effort.

One purpose of our study was to demonstrate the precision and repeatability of the PO/HR relationship in cyclin when environmental conditions are standardized. First o all, the test was carried out on a wind-load simulator, device that enabled us to standardize air resistance, thereb avoiding the variability encountered outdoors. In additio we standardized the warm-up procedure, test protocol, an data analysis, employing a mathematical definition of th deflection point or heart rate break point.

A second objective of our study was to exclude th possibility that the deflection is an artifact caused by th incremental test protocol. To this end we examined th relationship between the deflection and the final accelera tion in 500 tests performed during the last 2 yr.

The final objective of this study was to verify the repeat ability of the PO/HR relationship. For this purpose, w tested 15 subjects twice within a week.

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METHODS

Subjects

The reported data were collected from 500 tests carrie out in the last 2 yr. These tests were performed in a lab

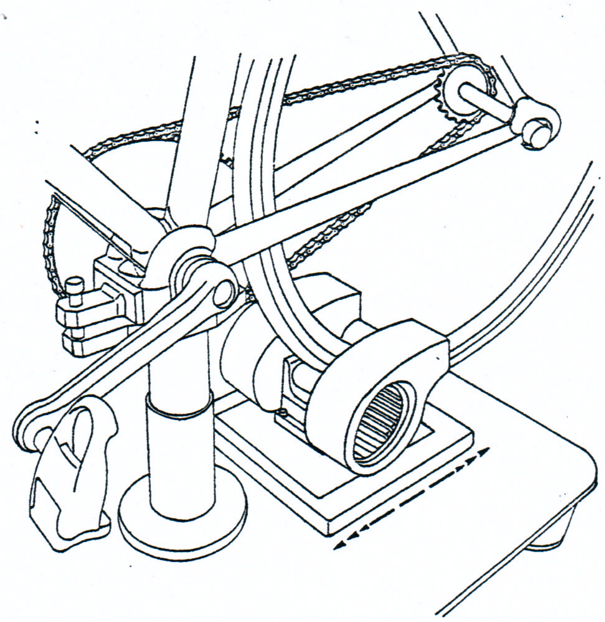

Figure 1—Schematic drawing of the wind-load simulator employed in our laboratory.

ratory using a wind-load simulator and the protocol described below.

The subjects included 290 male cyclists, ranging in age from 18 to 35 yr (mean = 28, SD = 3.7 yr). This group consisted of professional and amateur road racers who trained 300–600 km·wk^{-1}. Some of these subjects performed the test several times.

In 15 other cyclists, ranging in age from 23 to 34 (mean = 26, SD = 3), a laboratory cycling test was performed twice in the course of a week. Written informed consent was obtained before all tests.

Power Output and Heart Rate Measurement

A standard crankset with a built-in power measuring system (SRM Training System, Ingenierbüro Schoberer, Jülich-Welldorf, Germany) was mounted on the athlete's own bicycle and used for all tests. This instrument calculates the data of the torque and angular velocity and averages and records the power output of every complete revolution. It also monitors the heart beats and records the cyclist's heart rate every 5 s with the help of a pulse transmitter (Polar Electro, Kempele, Finland). Finally, it calculates the cycling speed by means of a magnet placed on the rear wheel. The precision of this power measuring system has been verified by others (14).

Wind-Load Simulator

The wind-load simulator used for the tests (Fig. 1) was specially constructed for our laboratory. The subject's bicycle (18), once mounted on the stand, was equipped with a heavy (2.8 kg) rear wheel to increase the inertia of rotation (wheel circumference 2.12 m). The tubular tire was inflated to a pressure of 8 atmospheres (117.6 psi). The bicycle's rear wheel was in contact with a freely rotating axle with two fans (Vetta Pro Beam VT100, O.M.A.S., San Lazzaro di Savena, Bologna, Italy) attached to either end. The rotating fans impelled air and created wind resistance. This roller with fans could be moved in a horizontal direction (see arrows in Fig. 1) with a micrometric screw and pressed against the tubular tire in such a way as to obtain variations in the rolling resistance. For purposes of the test, the pressure of the roller against the tire was regulated to obtain a resistance of 100 W at 60 rpm, with a gear ratio of 52 × 15.

The S/PO relationship documented using this wind-load simulator (Fig. 2) follows a curvilinear pattern of a parabolic type, as described for velodrome cycling (25,27). However, unlike velodrome tests in which wide oscillations in S and PO have been documented (unpublished observations), PO increases uniformly and presents negligible oscillations on the wind-load simulator. This absence of PO fluctuations allows for the performance of incremental tests with progressive increases and without sudden variations in PO that could cause early activation of the anaerobic mechanisms. Testing set-ups with wind-load simulators have been used by others (14,24).

Test Protocol

Warm-up. The test subjects were well rested and had not performed hard training sessions during the previous 48 h. Warm-up time and intensity were based upon the subject's habits, age, and physical condition. Trained athletes performed an incremental warm-up of at least 30 min.

The gear to use for the warm-up was selected after preliminary evaluations lasting 5 min, during which the subject, having chosen a certain gear, increased his cadence from 60 to 70 rpm (at a rate of 1 rpm every 30 s). If, during this preliminary test, the HR increments exceeded 8 bpm each minute (7), the subject switched to a lower gear. Professional cyclists generally used a 52 × 15 or a 52 × 14 gear. Following this procedure, when the cadence was increased by 1 rpm every 30 s, the PO increments per minute were

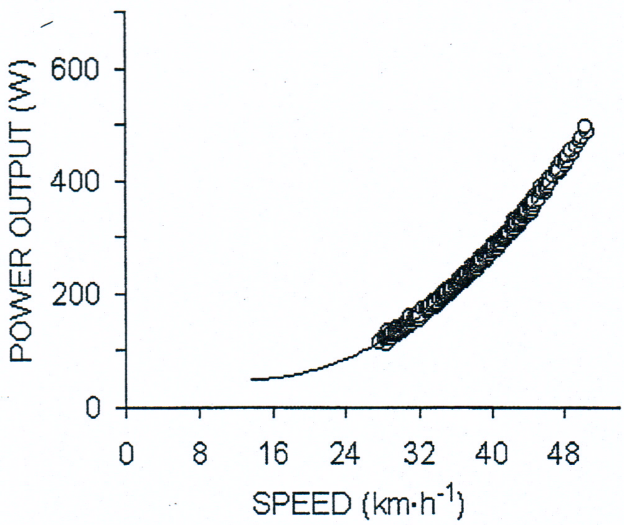

Figure 2—Speed/power output relationship for a professional cyclist during an incremental test performed on the wind-load simulator shown in Figure 1.

between 10 and 15 W for elite athletes, whereas smaller PO increments were observed in athletes of lower level. In sedentary individuals, PO increments per minute are generally less than 5 W (personal observation).

Once the gear had been selected, the athlete pedaled for 1 min at 60 rpm. The cadence was then increased by 1 rpm every minute until a cadence of 90–95 rpm was reached. After a 5-min recovery period of slow pedaling, the warm-up was completed with variations at higher cadences (e.g., 110 rpm) of short duration (5–10 s), repeated 3–5 times. After another 5-min recovery, the subject was ready to begin the test.

Test procedure. Using the gear selected for the warm-up, the athlete rode his bicycle in the racing position. The test was started at 60 rpm, and the cadence was increased by 1 rpm every 30 s. When the subject (or test assistant) became aware of physical signs of near-maximal effort, such as "burning muscles" or breathing difficulties (9), the uniform increases in cadence were substituted by a faster acceleration that was regulated by the test subject himself. In this phase, the increase in cadence occurred after progressively shorter time intervals and continued up to the subject's maximal cadence, which was reached in 2–3 min, depending on the subject. In the cyclists examined, maximal cadence on the wind-load simulator ranged from 120 to 150 rpm, being higher in sprinters. It has been shown that the HR reached at the end of the final acceleration coincides with the HR_{max} reached in competition (7).

Data Analysis

The PO and HR values memorized by the power measuring system during the incremental test were transferred to a personal computer, and the PO/HR relationship was graphed and the correlation coefficient (r), intercept on the *y*-axis (*a*), and slope (*b*) of the straight-line equations formed by the data points were calculated. The first values of r, *a*, and *b* were calculated for the straight-line equation formed by the first 20 data points; the subsequent values were for the straight-line equations obtained with the addition of each subsequent data point. The so-called deflection point (7), that is, the passage from the linear phase of the PO/HR relationship to the curvilinear phase, corresponds to the point at which *b* starts to decrease.

As previously reported for the running test (7), we considered to be unsuccessful those cycling tests that showed any of the following characteristics:

1. straight-line equation of the PO/HR relationship having r lower than 0.98,
2. increases in HR exceeding 8 bpm each minute, or
3. start of acceleration of the final phase at PO of deflection (POd) rather than above POd.

Test Repeatability

Fifteen athletes performed the wind-load test twice in the course of a week (minimal time lapse between the two tests was 1 d, maximal 7 d). Temperature, humidity, and the time of day for the two tests were very similar. Test subjects were

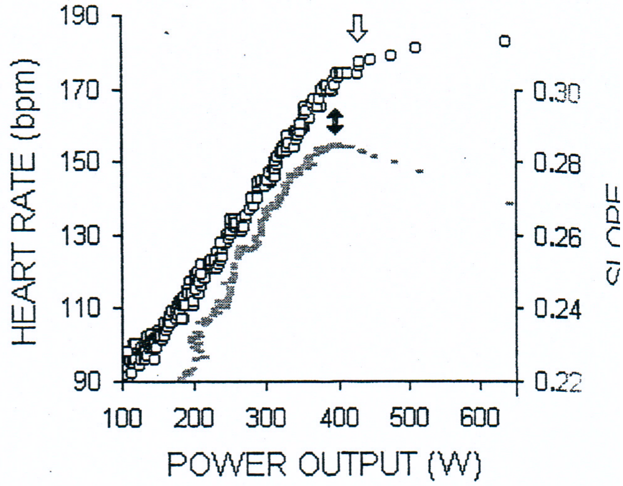

Figure 3—Power output/heart rate relationship (○) during an incremental test on a wind-load simulator for a professional cyclist. The data points represent average PO and HR of 5-s intervals. The slope values (−) of the straight-line equations calculated on the data points (see Methods) are also presented. *Solid arrows:* deflection point. *Open arrow:* start of final acceleration.

asked not to change their usual diet and training habits during the period between tests. An incremental test preceded by a 30-min warm-up was carried out as described above. Slope (*b*) of the straight-line equation of the PO/HR relationship, PO and HR at deflection (POd and HRd), and PO and HR at the beginning of the final acceleration (POac and HRac) were calculated and compared for the two tests.

Statistical Analysis

The fit for the regression line of the linear section of the PO/HR relationship (r) was calculated with the Pearson product moment correlation. Significance of the values of PO at deflection versus PO at the beginning of final acceleration was determined by the two-sided paired Student's *t*-test.

To determine test repeatability, one-way ANOVA with repeated measures was applied for the five variables considered. Intraclass correlation coefficient (ICC) and technical error of measurement (TEM; Knapp (21)) were calculated for each variable. A *P*-value of 0.05 or less was considered statistically significant.

RESULTS

The Power Output/Heart Rate Relationship

The PO/HR relationship obtained for a professional cyclist tested on the wind-load simulator is shown in Figure 3. At low to submaximal PO, the data points form a straight line. At higher PO, the points deviate from linearity and form a curvilinear pattern. The values of the slope (*b*) of the PO/HR relationship rise in the initial phases of the test, remain stationary in the central phases, and descend in the final phases. The point at which *b* begins to decrease (indicated by solid arrows) corresponds to the deflection point and can be used to determine both POd and HRd. A

TABLE 1. Test repeatability; the data considered in the two tests are the slope of the linear section of the PO/HR relationship, the values at deflection (POd and HRd) and the values at the beginning of final acceleration (POac and HRac).

	Slope (*b*)	POd (W)	HRd (bpm)	POac (W)	HRac (bpm)
1st Test	0.328 ± 0.074	272.0 ± 32.7	163.9 ± 9.9	304.7 ± 30.1	169.6 ± 12.1
2nd Test	0.333 ± 0.076	269.1 ± 34.5	163.7 ± 10.1	307.9 ± 31.2	170.2 ± 11.5
*P**	0.435	0.122	0.854	0.280	0.542
ICC	0.87	0.98	0.92	0.94	0.95
TEM	0.0155	7.85	0.55	9.4	2.4

Values are means ± SD.
* Probability of ANOVA with repeated measures.
ICC, intra-class correlation coefficient; TEM, technical error of measurement (21. Knapp, T.R. Technical error of measurement: a methodological critique. *Am. J. Phys. Antropol.* 87:235–236, 1992.).

indicated by the open arrow in Figure 3, the final acceleration, that is the phase in which the gradual acceleration is substituted by increases in cadence occurring after progressively shorter time intervals, begins after the deflection point has been reached.

Test Acceptability

Of the 500 tests conducted on the wind-load simulator, 484 were immediately successful, satisfying the three acceptability criteria listed in Methods. In particular, POd was lower than PO at the beginning of the final acceleration in all 484 cases (318.9 ± 42.6 W vs 351.1 ± 43.5 W, Student's *t*-test for paired data, $P < 0.001$). In the 16 remaining cases, instead, POd and POac coincided; these tests were successfully repeated on a second occasion.

Test Repeatability

Table 1 shows the test repeatability values of the five variables considered obtained in two tests performed by 15 subjects within 1 wk. The values obtained in the two tests were not significantly different. As in the 484 successful tests reported previously, in the 30 tests performed to determine test repeatability, PO at deflection was significantly lower than PO at the beginning of the final acceleration (Student's *t*-test for paired data, $P < 0.001$).

DISCUSSION

As in the original (5) and subsequent articles (4–7,11), the PO/HR relationship obtained by application of the present protocol on the wind-load simulator is linear at low to submaximal PO and curvilinear from submaximal to maximal PO. The point of passage from the linear to the curvilinear phase is called the deflection point. This deflection point, previously shown to coincide with the anaerobic threshold (5,11), can be identified mathematically by the decrease in slope of the straight line that describes the PO/HR relationship (7). Such mathematical identification avoids the errors inherent in subjective data evaluation (1).

Some authors have maintained that the deflection is not a physiological phenomenon but, rather, an artifact produced through execution of the incremental test protocol. They have criticized, for example, the fact that in the original test protocol (5) the speed increments were distance-based (e.g., every 200 m in running tests). Given the increase in speed of the test subject, the duration of the various intervals became progressively shorter. Hypothetically, this shortening of interval duration could have caused the deflection, in that beyond a certain phase of the test, the duration of each speed could have been insufficient for cardiocirculatory adaptation to the new speed. However, in the current protocol, the athlete's acceleration is based on time and not on distance, and the time available for HR adaptation is the same for the various PO. Yet the deflection occurs as before.

Another criticism regards the acceleration with which the incremental test is concluded. In fact, it could be hypothesized that the deflection is caused by the progressively greater increments in PO of the final phase, in which the subject's PO could increase faster than heart rate. This is not the case, however, because we have shown previously (7) and also in the present article that for the great majority (96.8%) of tests performed, the athlete begins the final rapid acceleration when the deflection has already occurred. The subjective sensations of near-maximal effort that lead the subject to begin the final acceleration are perceived, therefore, well above POd, the work intensity above which a sharp accumulation of blood lactate has been shown to occur (4–6,11,28,33). In addition, the POd and HRd values obtained in tests carried out within a short time and under the same experimental conditions show only negligible differences. Moreover, in this test-retest experiment the PO and HR values at the beginning of the final acceleration were repeatable and always well above the deflection values. Given the repeatability and precision (indicated by TEM values) of the information provided, the test can be employed for monitoring longitudinal variations in cycling performance.

Among the difficulties encountered in reproducing our test, some are related to protocols that maintain small increments in speed also in the final phase of the test (30). When the gradual uniform increments of the initial phase are maintained up until exhaustion, a situation of lactacid exercise lasting several minutes is obtained. This could lead to a proton concentration exceeding the capacity of the local buffering system, lower muscle pH, reduce muscular efficiency, and consequently PO (8) and, finally, lead to an anomalous PO/HR relationship. Whipp (32) and Hansen et al. (16) have shown that when a speed above the anaerobic threshold is maintained for a prolonged period, one can observe a decrease in PO relative to O_2 consumption, an observation that can be partially explained in terms of reduced muscular efficiency because of acidification. With our protocol, the anaerobic phase is not so severe as to reduce muscle efficiency. In fact test subjects can increase PO up to the very end of the test.

Incremental Tests at Constant versus Increasing Cadence

In the test on the wind-load simulator described in this article, the increments in PO are obtained primarily by increasing cadence, following a physiological rule that holds true for all mammals (2,13,20,22). Incremental tests on a cycle ergometer are often performed at a fixed cadence, and the PO is augmented solely by increasing the force applied to each single pedal stroke. The difference in applied force between protocols at an increasing cadence and those at a fixed cadence becomes greater with increasing exercise intensity. Under conditions of maximal effort, the muscular power required by tests at a fixed cadence is more than twice that required by tests at an increasing cadence or under actual cycling conditions. In fact, competitive cyclists reach their maximal speeds at cadences that exceed 160 rpm (as compared with the 60–80 rpm called for in the usual cycle ergometer tests). If a cyclist capable of reaching 60 $km \cdot h^{-1}$ were asked to attain this speed at a cadence of 60 rpm, he would have to use a gear with a development of 16.7 m. A gear this high is never used in training or racing. It may be presumed that employment of the high muscular power required by tests at a fixed cadence leads to an early and progressive activation of the anaerobic lactacid mechanisms (15,31). These important differences make it difficult to compare the PO/HR relationships produced by incremental protocols at a constant cadence with those produced at an increasing cadence. This may explain the problems encountered by several authors in reproducing the data of the Conconi test (3,12,17,23,29). For example, Heck et al. (17) clearly identified deflection in only 71% of the tests performed, whereas with tests at an increasing cadence, the percentage of failures to identify the deflection is negligible (7). In our experience, incremental tests at a fixed cadence are performed more easily, and the deflection can be more easily identified in subjects who are fast (sprinters) and are endowed with great muscular power (personal data), and who presumably have high percentages of fast-twitch muscle fibers.

In conclusion, the incremental test described in this article enables determination of the PO/HR relationship and identification of the deflection, that is, of the exercise intensity above which increases in HR are no longer proportional to the increase in PO. If the test is performed following the directions provided here, the deflection is nearly always identifiable and cannot be attributed to the experimental protocol. We maintain, therefore, the previously advanced hypothesis (5) that the deflection is a physiological phenomenon caused by activation of the anaerobic lactacid mechanisms of ATP production, as indicated by the sharp accumulation of blood lactate above the deflection (4,5,6,11,28,33). For its repeatability and for its only slight test-to-test variations in POd and HRd, this test can be used to advantage in designing and modifying training programs and for checking the modifications in cycling performance that may follow.

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