Inverse relationship between $\dot{V}O_{2max}$ and economy/efficiency in world-class cyclists

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ABSTRACT

LUCÍA, A., J. HOYOS, M. PÉREZ, A. SANTALLA, and J. L. CHICHARRO. Inverse relationship between VO_{2max} and economy/efficiency in world-class cyclists. *Med. Sci. Sports Exerc*, Vol. 34, No. 12, pp. 2079–2084, 2002. **Purpose:** To determine the relationship that exists between VO_{2max} and cycling economy/efficiency during intense, submaximal exercise in world-class road professional cyclists. **Methods:** Each of 11 male cyclists (26 ± 1 yr (mean ± SEM); VO_{2max}: 72.0 ± 1.8 $mL \cdot kg^{-1} \cdot min^{-1}$) performed: 1) a ramp test for $\dot{V}O_{2max}$ determination and 2) a constant-load test of 20-min duration at the power output eliciting 80% of subjects' VO_{2max} during the previous ramp test (mean power output of 385 ± 7 W). Cycling economy (CE) and gross mechanical efficiency (GE) were calculated during the constant-load tests. **Results:** CE and GE averaged 85.2 ± 2.3 $W \cdot L^{-1} \cdot min^{-1}$ and 24.5 ± 0.7%, respectively. An inverse, significant correlation was found between 1) VO_{2max} ($mL \cdot kg^{-0.32} \cdot min^{-1}$) and both CE ($r = -0.71$; $P = 0.01$) and GE (-0.72; $P = 0.01$), and 2) $\dot{V}O_{2max}$ ($mL \cdot kg^{-1} \cdot min^{-1}$) and both CE ($r = -0.65$; $P = 0.03$) and GE (-0.64; $P = 0.03$). **Conclusions:** A high CE/GE seems to compensate for a relatively low $\dot{V}O_{2max}$ in professional cyclists. **Key Words:** PERFORMANCE, GROSS EFFICIENCY, POWER OUTPUT, PROFESSIONAL CYCLING, CYCLE ERGOMETRY

Previous studies have analyzed the main physiological determinants of performance in endurance sports. These include, among other variables, maximal oxygen uptake ($\dot{V}O_{2max}$), lactate/ventilatory thresholds, and economy/efficiency (11). Concerning the latter, a better economy or efficiency will decrease the percentage of $\dot{V}O_{2max}$ required to sustain a given mechanical work and thus might be advantageous to endurance performance. Previous research has indeed shown the importance of economy in endurance running performance (5,17,21,26,30). For instance, the superior performance of Kenyan runners during the last decades compared with their European counterparts is attributable, at least partly, to their greater running economy (26). Other variables such as $\dot{V}O_{2max}$ do not appear to differ between Europeans and Africans. The relatively low $\dot{V}O_{2max}$ values (~ 70 $mL \cdot kg^{-1} \cdot min^{-1}$) that sometimes are found in world-class male endurance runners can be compensated for by a great running economy (12,17,18). Furthermore, an inverse relationship has been reported in highly trained runners between $\dot{V}O_{2max}$ and running economy (18,23).

To the best of our knowledge, no previous study has analyzed whether $\dot{V}O_{2max}$ and economy/efficiency are inversely related in top-level cyclists (i.e., professional riders), as it occurs in elite runners. Although high $\dot{V}O_{2max}$ values (5.0 to 5.5 $L \cdot min^{-1}$ or 70–75 $mL \cdot kg^{-1} \cdot min^{-1}$) are usually found in world-class cyclists, $\dot{V}O_{2max}$ is not the main performance determinant in this sport (14,15). For instance, amateur, well-trained cyclists show similar $\dot{V}O_{2max}$ values to those of professional riders (14,15). Provided a minimum level of $\dot{V}O_{2max}$ is reached (e.g., > 65 $mL \cdot kg^{-1} \cdot min^{-1}$), cycling economy (CE) and gross mechanical efficiency (GE) might be especially important in top-level endurance cycling (9,14). Indeed, professional riders are considerably more economical and efficient than amateur riders despite similar $\dot{V}O_{2max}$ values in both groups (14,15).

The purpose of the study was to determine if there exists a relationship between $\dot{V}O_{2max}$ and CE/GE during intense, submaximal exercise in a group of world-class cyclists.

METHODS

Subjects. Eleven professional male road cyclists (age (mean ± SEM): 26 ± 1 yr) were selected for this investigation. Written informed consent was obtained from each participant, and the institutional Ethics Committee (Complutense University of Madrid) approved the study. A previous physical examination (including ECG and echocardiographic evaluation within the previous month) ensured that each participant was in good health. Several of the present subjects are among the best cyclists in the world, according to the ranking of the International Cycling Union. To ensure that all of them could be really considered as

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"world-class" riders, they were required to meet the following requirements: 1) have participated in the mean competitions of the professional category (e.g., 3-wk tour races) and 2) have won at least one major professional race (e.g., one or more individual stages and/or final classification of a major 1-wk or 3-wk race (Giro d'Italia, Tour de France, or Vuelta a España), or Top 3 in World Championships). Hemoglobin and hematocrit levels were measured in each subject before participating in the experiments. Mean values of hemoglobin and hematocrit averaged 14.7 ± 0.3 $g \cdot dL^{-1}$ (range, 12.8–16.1) and 43.5 ± 0.7% (range, 39.9–46.5) and thus were within normal, physiological limits for endurance athletes (27).

Study protocol. Each subject reported to our laboratory on two consecutive days during the months of January or February, before the start of the competition season. During the days before testing and the test days, the subjects followed a similar type of high-carbohydrate (CHO) diet (~ 500 g $CHO \cdot d^{-1}$). On the first day, they performed a maximal exercise test (ramp protocol) for $\dot{V}O_{2max}$ determination, and on the second they performed a submaximal, constant-load test to measure CE and GE. Both tests were performed on the same electromagnetically braked cycle ergometer (Ergometrics 900, Ergo-line; Barcelona, Spain). The torque measuring unit was calibrated before each testing session (4–5 tests per session) with a known weight of 4.0 kg. All the components of the ergometer were checked by an experienced technician before the start of the study. Before this investigation, the ergometer was equipped with a new chain. This cycle ergometer has been used in numerous studies conducted in our laboratory with professional cyclists (13–15).

During the tests, the subjects adopted the conventional (upright sitting) cycling posture. This posture was characterized by a trunk inclination of ~ 75° and by the subject placing his hands on the handlebars with elbows slightly bent (~ 10° of flexion). All the tests were performed under similar environmental conditions (21–24°C, 45–55% relative humidity). Subjects were allowed to choose their preferred cadence within the range 70–90 rpm during both type of tests. This is known to better simulate actual cycling conditions compared with tests performed at a fixed cadence. During actual racing, indeed, the preferred pedalling cadence of professional riders ranges from 70 rpm (hill climbs) to 90 rpm (flat terrains or individual time trials) (13). A pedal-frequency meter was used by each subject to maintain his pedalling cadence within the aforementioned range. The subjects were cooled with a fan throughout the bouts of exercise.

Maximal exercise test. For the maximal test, a ramp protocol was followed until exhaustion. This type of protocol has been used for the $\dot{V}O_{2max}$ determination of professional cyclists in several previous studies (13–15). Starting at 20 W, the workload was increased by 25 $W \cdot min^{-1}$. The tests were terminated when pedal cadence could not be maintained at 70 rpm (at least). Verbal encouragement was given to the subjects to continue the test until they were exhausted. All the participants had previous experience with this type of protocol. Heart rates (HR, in bpm) were monitored during the tests from modified 12-lead ECG tracings (EK56; Hellige; Freiburg, Germany), and gas exchange data were collected continuously using an automated breath-by-breath system (CPX; Medical Graphics; St. Paul, MN). With this system, O_2 and CO_2 are measured with rapid analyzers, while a disposable flowmeter, which is based on the principle of differential pressure measurement by two sensitive differential pressure transducers, analyzes ventilatory flow. This type of flowmeter has been shown to be accurate (to within 2% of the target value obtained from Douglas bag collections) and reproducible for the measurement of minute ventilation during exercise (25). The mean percentage difference and the correlation coefficient between the $\dot{V}O_2$ measurements provided by the breath-by-breath system used in the present study and the Douglas bag method is 2.2% and 0.995 (P = 0.0001), respectively (unpublished data provided by the manufacturer from maximal tests performed in 15 subjects of varying fitness levels). The O_2 and CO_2 analyzers and the flowmeter were calibrated before each single test with reference gases (Praxair, Madrid, Spain) at a concentration of 15.99% for O_2 and 4.00% for CO_2, and a 3-L syringe (25), respectively. For each test, $\dot{V}O_{2max}$ was recorded as the highest $\dot{V}O_2$ value obtained for each 1-min interval, and the maximal power output (W_{max}) was computed as follows (22):

$$W_{max} = W_f + [(t/60 \times 25)]$$

where W_f is the value of the last completed workload (in W), t is the time the last uncompleted workload was maintained (in s), 60 is the duration of each completed workload (in s), and 25 is the power output difference between the last two workloads.

Constant-load test at 80% $\dot{V}O_{2max}$. The submaximal, constant-load tests were performed over a 20-min period at a fixed power output. For each subject, the latter was identified on the $\dot{V}O_2$ (average for each 1-min interval): power output curve of the previous ramp test by straight linear interpolation, as shown in Figure 1. Each 20-min test was preceded by a 15-min warm-up period, consisting of 5 min at 70 W, 3 min at 60% of the maximal power output reached during the previous ramp test, and 2 min of gradual workload increases until the target power output was attained. Gas exchange data and HR were monitored as in the maximal tests. In addition, blood variables were determined as detailed below.

Before the start of the experimental protocol, a 21-gauge butterfly needle was inserted into the antecubital vein of each subject. The catheter was kept patent by periodic flushing with a heparinized saline solution. Blood samples were collected every 5 min during the tests. During each sampling period (~ 15 s), a 1-mL aliquot was initially withdrawn to clear the catheter, and a 1.5-mL blood sample was subsequently collected using a heparinized syringe for the immediate estimation of PCO_2 and pH using an automated blood gas analyzer (ABL5; Radiometer; Copenhagen, Denmark). Bicarbonate concentration $[HCO_3^-]$ was calculated using the pH and PCO_2 values. Capillary blood

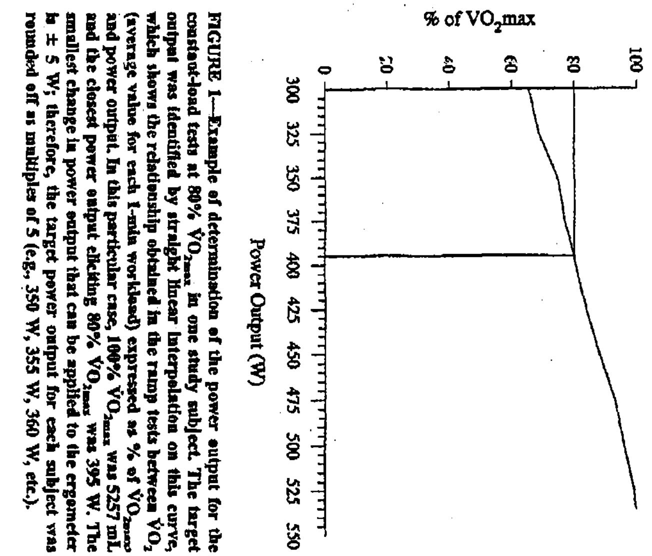

FIGURE 1—Example of determination of the power output for the constant-load tests at 80% $\dot{V}O_{2max}$ in one study subject. The target output was identified by straight linear interpolation on this curve, which shows the relationship obtained in the ramp tests between $\dot{V}O_2$ (average value for each 1-min workload) expressed as % of $\dot{V}O_{2max}$, and power output. In this particular case, 100% $\dot{V}O_{2max}$ was 5257 mL and the closest power output eliciting 80% $\dot{V}O_{2max}$ was 395 W. The smallest change in power output that can be applied to the ergometer is ± 5 W; therefore, the target power output for each subject was rounded off as multiples of 5 (e.g., 350 W, 355 W, 360 W, etc.).

samples were taken from fingertips (25 μL) every 5 min during the tests and immediately after exercise for the determination of blood lactate concentration (BLa) using an electro-enzymatic analyzer (YSI 1500; Yellow Springs, OH).

Average values of CE and GE during the constant-load test were calculated. CE was expressed in ($W \cdot L^{-1} \cdot min^{-1}$) (7), and GE was calculated as the ratio of work accomplished$\cdot min^{-1}$ (i.e., W converted to $kcal \cdot min^{-1}$) to energy expended$\cdot min^{-1}$ (i.e., in $kcal \cdot min^{-1}$), as described elsewhere (7). Energy expended was calculated from $\dot{V}O_2$ and respiratory exchange ratio (RER) using the tables of Lusk (16).

Statistical analysis. Pearson product-moment correlation coefficients were calculated to determine whether there was a significant relationship between $\dot{V}O_{2max}$ and both CE and GE. $\dot{V}O_{2max}$ was expressed in absolute units ($L \cdot min^{-1}$) and in relative units ($mL \cdot kg^{-1} \cdot min^{-1}$ and $mL \cdot kg^{-0.32} \cdot min^{-1}$). The later was performed following the recommendation by Padilla et al. (22) to express physiological values relative to mass exponents of 0.32 and 1 in order to adequately evaluate level and uphill cycling ability, respectively, in elite cyclists. The level of significance was set at 0.05. To discard any possible influence of individual variations in pedalling cadence on CE/GE, correlation coefficients were also calculated between these variables. Results are expressed as means ± SEM.

RESULTS

Individual characteristics of the subjects (demographic and physical characteristics, history of cycling performance in the professional category) and the results of both ramp

TABLE 1. Individual characteristics of the subjects: age, physical characteristics, data from ramp and constant-load tests at 80% $\dot{V}O_{2max}$, and history of cycling performance in the professional category.

	Demographics Data			Ramp Tests			Constant-Load Tests								Racing Performance History	
					$\dot{V}O_{2max}$		Power Output									
Subject	Age (yr)	Height (cm)	Mass (kg)	W_{max} (W)	($mL \cdot min^{-1}$)	($mL \cdot kg^{-1} \cdot min^{-1}$)	(W)	($W \cdot kg^{-1}$)	(%W_{max})	Cadence (rpm)	GE (%)	CE ($W \cdot L^{-1} \cdot min^{-1}$)	Bla (mM)	HR (bpm)	Specialty	Most Remarkable Victories in International Professional Races
1.	29	178	69.6	515	5744	82.5	375	5.4	73	88	22.0	76.6	3.6	168	Complete	1 race
2.	25	185	84.4	585	5531	65.5	415	4.9	71	80	22.6	78.8	3.8	170	Rouleur	2 stages in 3-wk tour races
3.	21	184	69.6	505	5099	73.3	375	5.4	74	83	24.0	83.8	3.1	181	Complete	1 stage in 3-wk tour races, several races
4.	22	175	64.9	500	5339	82.3	345	5.3	69	86	20.9	72.1	3.5	180	Climber	Top 10 in Tour, several races
5.	32	185	74.6	465	5128	68.7	360	4.8	77	73	24.2	84.5	3.3	176	Rouleur	1 stage in 3-wk tour races, several races
6.	26	180	72.0	515	4962	68.9	380	5.3	74	83	26.0	89.3	2.1	163	Climber	5 stages, twice top 10 in Tour and Vuelta
7	23	187	76.8	550	5841	76.1	400	5.3	73	84	24.1	84.0	2.9	181	Rouleur	1 race
8.	28	183	75.8	535	5257	69.3	395	5.2	74	85	27.0	94.2	2.7	163	Time-trialist	World champion (RR and TT), top 4 in Giro, Tour, and Vuelta
9	27	175	69.0	490	4798	69.5	375	5.4	77	86	28.1	97.9	3.5	165	Complete	2 races
10.	26	186	79.8	580	5224	65.5	415	5.2	72	81	26.1	91.0	1.9	157	Time-trialist	Several races (including TT)
11.	27	188	74.0	500	5230	70.7	400	5.4	80	71	24.3	84.7	2.0	158	Complete	2 races
Mean (SEM)	26 (1)	182 (1)	73.7 (1.7)	522 (11)	5287 (95)	72.0 (1.8)	385 (7)	5.2 (0.1)	74 (1)	82 (2)	24.5 (0.7)	85.2 (2.3)	2.9 (0.2)	169 (3)		

W_{max}, maximal power output; GE, gross mechanical efficiency; CE, cycling economy; BLa, capillary blood lactate; HR, heart rate; RR, road race; TT, time trial; Giro, Giro d'Italia; Tour, Tour de France; Vuelta, Vuelta a España; 'Rouleur', specialist in flat terrains; 'Time-trialist', specialist in individual time-trials (usually held on flat terrains); Climber, specialist in high mountain ascents; Complete, able to achieve good performance in both mountain ascents and flat terrains.

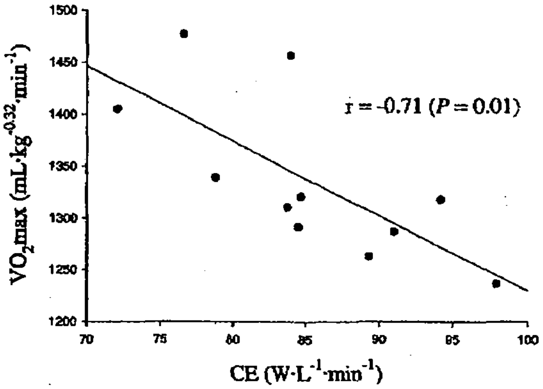

FIGURE 2—Relationship between $\dot{V}O_{2max}$ (mL·kg$^{-0.32}$·min^{-1}) and cycling economy (CE).

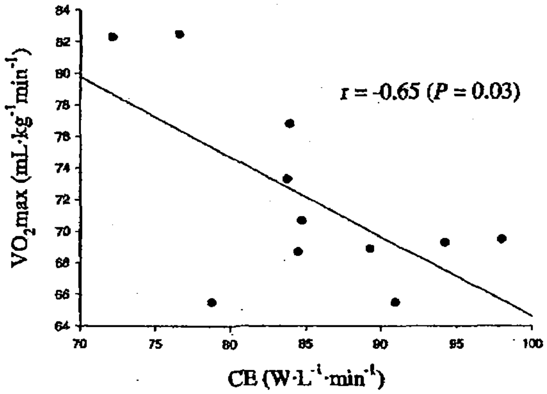

FIGURE 4—Relationship between $\dot{V}O_{2max}$ (mL·kg^{-1}·min^{-1}) and cycling economy (CE).

and constant-load tests are shown in Table 1. The mean values of pH and [HCO_3^-] obtained during the constant-load tests averaged 7.38 ± 0.01 (range, 7.30–7.45) and 19.1 ± 0.9 mM (17.2–21.4), respectively.

The following significant, inverse correlations were found: $\dot{V}O_{2max}$ (mL·min^{-1}) versus both CE ($r = -0.61$; $P = 0.047$) and GE (-0.63; $P = 0.04$); $\dot{V}O_{2max}$ (mL·kg$^{-0.32}$·min^{-1}) versus both CE ($r = -0.71$; $P = 0.01$) and GE (-0.72; $P = 0.01$) (Figs. 2 and 3); and $\dot{V}O_{2max}$ (mL·kg^{-1}·min^{-1}) versus both CE ($r = -0.65$; $P = 0.03$) and GE (-0.64; $P = 0.03$) (Figs. 4 and 5). No significant correlation ($P > 0.05$) was found between pedalling cadence and either CE ($r = 0.02$) or GE ($r = 0.002$).

DISCUSSION

The main finding of our study was that, in professional world-class cyclists, both CE and GE are inversely correlated to $\dot{V}O_{2max}$ (either expressed in absolute or relative units). It follows that a high CE/GE could compensate for a relatively low $\dot{V}O_{2max}$ in these athletes. Although comparable findings have been obtained in highly trained distance runners (12,17,18,23), to the best of our knowledge, no previous study has assessed the possible relationship between $\dot{V}O_{2max}$ and CE/GE in cyclists of this high fitness level. In addition, no data are available about the CE or GE of humans able to tolerate such high power outputs during prolonged endurance cycling (i.e., average of ~ 400 W in our subjects and ≥ 400 W in four of them) before significant lactic acidosis occurs (average values of BLa were relatively low and pH was maintained within normal limits).

The values of GE obtained in the present study (~ 24%) are similar to those recently reported in professional riders at the power outputs eliciting the lactate threshold (LT) and the respiratory compensation point (RCP) during a ramp test (14), and higher than those previously measured in not highly trained cyclists (average of ~ 20%) (19,20). Although GE is not an accurate measure of muscle efficiency (7), it is a good indicator of whole body efficiency and thus might be relevant from a practical point of view (3). In addition, GE measurements performed during laboratory testing have been proved to be reliable (19). Although the physiological

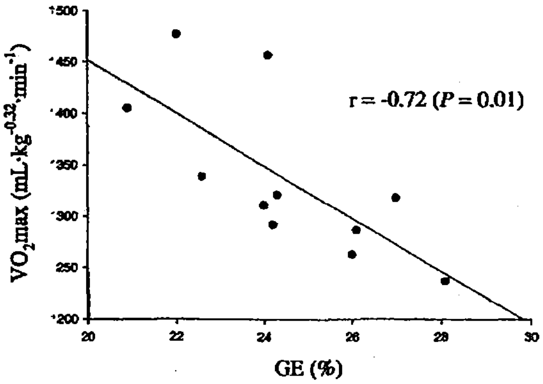

FIGURE 3—Relationship between $\dot{V}O_{2max}$ (mL·kg$^{-0.32}$·min^{-1}) and gross mechanical efficiency (GE).

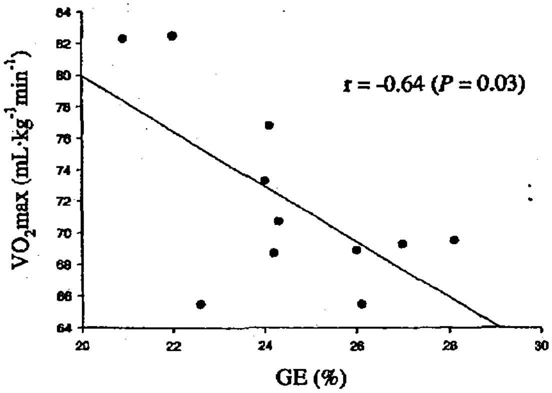

FIGURE 5—Relationship between $\dot{V}O_{2max}$ (mL·kg^{-1}·min^{-1}) and gross mechanical efficiency (GE).

and metabolic determinants of this variable remain to be fully understood (19), several factors can have an influence on GE, such as pedalling cadence (4), diet (24), overtraining (1), genetics (2), or fiber type distribution (7). It is unlikely that the three first factors could have significantly influenced the present results given that 1) we found no significant correlation between pedalling cadence and GE ($r = 0.002$; $P > 0.05$) and individual values of preferred pedaling cadence ranged within relatively narrowed limits (71–88 rpm; 2) the diet of the subjects was standardized as specified in the Methods section; and 3) all the subjects were tested before the competition period, and none of them showed symptoms or signs of overtraining. At the present moment, it is not possible to determine the influence of the remaining two factors, genetics and fiber type distribution, on the GE of professional road cyclists. For instance, scarce data are available in the literature showing the results of muscle biopsies in professional riders of the highest competition level. Nevertheless, the GE of humans is positively related to the percentage distribution of Type I fibers in exercising muscles. Previous research with endurance trained cyclists has shown that a higher percentage of Type I fibers in one of the main muscles involved in cycling (vastus lateralis) is associated with a greater GE during prolonged (1 h) exercise of either high (>LT) or moderate intensity (<LT) (7), and short bouts (5 min) of two-legged knee extension exercise (9). Thus, one could speculate that, in the natural selection process to succeed in world-class cycling, a relatively low $\dot{V}O_{2max}$ (a parameter mainly limited by the maximal capacity of the cardiac pump) could be compensated for, at least partly, by a especially high percentage distribution of efficient Type I fibers in knee extensor muscles. On the other hand, no well-controlled studies have been published to determine the specific influence of training interventions on the GE of elite endurance athletes such as the present ones. Indirect evidence from cross-sectional studies comparing professional and well-trained amateur riders of a lower performance level nevertheless suggests that one of main adaptations to high-volume endurance training in this sport (e.g., average of 35,000 $km \cdot yr^{-1}$ in professional riders versus 25,000 $km \cdot yr^{-1}$ in amateur ones) is an increase in GE (14). Such adaptation is required at the highest competition level to sustain extremely high power outputs (>400 W) during prolonged periods at the lowest possible metabolic cost. Moreover, once a certain fitness level is reached (e.g., the amateur category), submaximal variables such as GE at the LT (~ 70%$\dot{V}O_{2max}$) or at the RCP (~ 90%$\dot{V}O_{2max}$) are more important determinants of cycling performance than $\dot{V}O_{2max}$ (14).

CE averaged ~ 85 $W \cdot L^{-1} \cdot min^{-1}$ in our subjects, although a considerable variability existed among subjects (range, 72–98). This mean value is clearly above those values (mean of ~ 75 $W \cdot L^{-1} \cdot min^{-1}$) previously reported by Coyle and coworkers (6) in amateur highly trained riders of a lower competition level, during a simulated time trial of 1-h duration at power outputs ranging between 325 and 376 W. In line with our findings, CE also showed important variations among subjects. Biomechanical/anatomical factors can have a significant influence on running economy (26). In contrast, the variations of CE and GE that occur among elite riders of a lower fitness level than the present subjects are largely attributable to variations in the percentage distribution of Type I fibers in knee extensor muscles. The best rider in the present study (e.g., two-time world champion) showed a relatively low $\dot{V}O_{2max}$ value (slightly below 70 $mL \cdot kg^{-1} \cdot min^{-1}$) but very high values of both CE and GE (clearly above 90 $W \cdot L^{-1} \cdot min^{-1}$ and 25%, respectively).

The 20-min constant-load bouts were performed at the power output eliciting 80% of the subjects' $\dot{V}O_{2max}$ during the previous ramp tests. Average exercise intensity increased up to ~ 86%$\dot{V}O_{2max}$ throughout the constant-load bouts because of the so-called "$\dot{V}O_2$ slow component"—that is, the gradual increase in $\dot{V}O_2$ that inevitably occurs in all humans during intense, submaximal exercise, and that largely reflects an increased recruitment of inefficient Type II fibers (8). Most fibers (including both Types I and II) of the main muscles involved in pedalling are indeed recruited at the relative intensity at which the constant-load tests were performed, as shown in previous research (10,28). The most important phases of endurance cycling races (mountain ascents, time trials) are also held at high, submaximal intensities, i.e. around the RCP (14). On the other hand, both the time duration of the constant-load tests and the selected work rate (slightly below the subjects' RCP, within the so-called "isocapnic buffering phase" (29)) were well tolerated by the cyclists. For this reason, we propose that the type of constant-load exercise protocol used here could be included in the "routine" evaluation of competitive cyclists. Although thorough research has been conducted on those predictors of cycling performance that can be evaluated during more conventional gradual tests (e.g., $\dot{V}O_{2max}$, LT, or RCP), to date, less is known about the possible influence of GE and CE on top-level performance in this sport. Similarly, little data are available concerning the potential trainability of GE/GE in elite cyclists and the influence of genetic endowment on both variables.

In summary, both CE and GE are inversely correlated to $\dot{V}O_{2max}$ in world-class endurance cyclists. As it occurs in elite runners, a high CE/GE could compensate for a relatively low $\dot{V}O_{2max}$. Further research is needed in this field, particularly to determine which aspects of training (e.g., technique modification, high-intensity intervals versus low-intensity training, etc.) have the greatest impact on CE/GE. We propose that constant-load exercise protocols as the one used in this study could be included in the "routine" tests that most competitive cyclists perform several times over the season. The information provided by constant-load bouts (particularly CE and GE) is of practical applicability and complementary to that obtained from the more conventional gradual tests to exhaustion (e.g., $\dot{V}O_{2max}$, LT, or RCP).

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