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Modeling the Power-Duration Relationship in Professional Cyclists During the Giro d'Italia

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Abstract

Vinetti, G, Pollastri, L, Lanfranconi, F, Bruseghini, P, Taboni, A, and Ferretti, G. Modeling the power-duration relationship in professional cyclists during the Giro d'Italia. *J Strength Cond Res* XX(X): 000–000, 2022—Multistage road bicycle races allow the assessment of maximal mean power output (MMP) over a wide spectrum of durations. By modeling the resulting power-duration relationship, the critical power (*CP*) and the curvature constant (*W′*) can be calculated and, in the 3-parameter (3-p) model, also the maximal instantaneous power (P_0). Our aim is to test the 3-p model for the first time in this context and to compare it with the 2-parameter (2-p) model. A team of 9 male professional cyclists participated in the 2014 Giro d'Italia with a crank-based power meter. The maximal mean power output between 10 seconds and 10 minutes were fitted with 3-p, whereas those between 1 and 10 minutes with the 2- model. The level of significance was set at $p < 0.05$. 3-p yielded *CP* 357 ± 29 W, *W′* 13.3 ± 4.2 kJ, and P_0 1,330 ± 251 W with a *SEE* of 10 ± 5 W, 3.0 ± 1.7 kJ, and 507 ± 528 W, respectively. 2-p yielded a *CP* and *W′* slightly higher (+4 ± 2 W) and lower (−2.3 ± 1.1 kJ), respectively ($p < 0.001$ for both). Model predictions were within ±10 W of the 20-minute MMP of time-trial stages. In conclusion, during a single multistage racing event, the 3-p model accurately described the power-duration relationship over a wider MMP range without physiologically relevant differences in *CP* with respect to 2-p, potentially offering a noninvasive tool to evaluate competitive cyclists at the peak of training.

Key Words: critical power, maximum mean power, power meter, road cycling, stage race

Introduction

The hyperbolic relationship between power (P) and duration (T_{lim}) is a well-established framework for human performance modeling (4,22,23). Commercially available power meters greatly expanded the knowledge on the P-T_{lim} relationship in competitive cycling by recording the maximal mean power output (MMP) over different durations and allowing the collection of a large amount of data from training, testing, and competition (14,25). Racing MMPs have been often collected without further modeling attempts, both in single-day events (6,18) and in multistage "Grand Tours" (7,26,30,37,38), with the main aim of quantifying the physical strain imposed by the race. When such modeling occurred, the 2-parameter (2-p) hyperbolic model was generally used, where the power asymptote (critical power [*CP*]) is the upper limit of the metabolic steady state (8,12), whereas the curvature constant (*W′*) is the amount of energy available above *CP* in the severe exercise-intensity domain (i.e., where maximal values of oxygen consumption, intramuscular metabolites, and blood lactate concentration are reached at exhaustion) (4,34).

In experienced cyclists, *CP* and *W′* estimates were comparable between laboratory tests and racing MMPs gathered from multiple national and international competitions (28). Moreover, higher MMP profiles—and a higher *CP*—were recorded during racing than training (15). Grand Tours are particularly suitable for this approach because they are characterized by numerous and various stages during which prolonged periods of submaximal cycling are interspersed with supramaximal bursts for intermediate and short durations, resulting in a wide-ranging P spectrum (30). However, the simplicity of the 2-p model (the time asymptote is constrained to 0, meaning that it predicts infinite P when $T_{lim} = 0$) makes it overestimate the performance below a T_{lim} of 1–2 minutes (14,23,35), which indeed may represent a great portion of the MMP profile expressed in a Grand Tour (30). A solution for this issue is offered by the 3-parameter (3-p) model, where the time asymptote is the third, unconstrained, parameter (*k*), so that the predicted P for $T_{lim} = 0$ takes a finite value (P_0), theoretically corresponding to the maximal instantaneous power (20). In so doing, performance with a T_{lim} below 1–2 minutes is no more overestimated, whereas estimations of *CP* are comparable with that of 2-p (35). This allows 3-p to accurately describe performance not only in the severe but also in the extreme exercise-intensity domain, i.e., where T_{lim} is so low that exhaustion occurs before of oxygen consumption and blood lactate concentration can reach their maximal values (4,35). Although only a few studies tested the 3-p in the extreme intensity domain, in particular with $T_{lim} < 60$ seconds (27,35), they promisingly showed a well-preserved goodness of fit to experimental data up

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to a T_{lim} of 20 (35) to 1 second (27). Therefore, 3-p has the potential of encompassing a greater part of the P-T_{lim} spectrum expressed in a Grand Tour with respect to 2-p.

Extracting *CP*, *W′*, and P_0 from a single multiday event is attractive, as it can provide insights into the physiological characteristics of professional cyclists at their peak of physical fitness without subjecting them to impractical exhaustive tests near competitions. Therefore, the main aim of this study was to test the hypothesis that the power profile generated by professional cyclists during a multistage road bicycle race are compatible with a hyperbolic P-T_{lim} relationship, in particular the 3-p model. With this aim, we tested both models in the prediction of racing MMPs with longer T_{lim} than those used for curve fitting. Secondary aims were to further test the 3-p model with data points including $T_{lim} < 60$ seconds and to compare the obtained parameter estimates with the 2-p model and previously published data (7,15,28,31,35).

Methods

Experimental Approach to the Problem

Power output data from a professional cycling team competing in the 2014 Giro d'Italia (21 stages in 24 days: 3 time-trial, 6 flat, 7 medium mountain, and 5 mountain stages) partially published in a previous study (26) were retrospectively analyzed. The assumption was that the wide-ranging environmental conditions and team strategies of the Giro d'Italia allowed cyclists to perform a maximal effort particularly for middle and short durations (and thus selected time windows are assumed to reflect T_{lim}).

Subjects

The study involved a team of 9 professional road cyclists (age: 28 ± 5 years, range: 22-34, height: 176 ± 6 cm, average body mass throughout the race: 64.5 ± 3.3 kg). After being informed of the risks and the benefits, athletes gave signed written consent to participate. The study conformed to the Declaration of Helsinki and was approved by the Ethics Committee the University of Milano-Bicocca.

Procedures

All bicycles were equipped with a crank-based power meter (Power2Max, Chemnitz, Germany) with a precision within ±2% (16). Before each stage, power meters were calibrated according to manufacturer's recommendations, including the reset of their zero offset. Because of device malfunctions and the drop-out of 1 athlete after stage 17, 162 athlete × stage events were available (86%), with an average of 18 stages per athlete (range 14–21). Eight MMPs calculated over 8 predefined durations (10, 15, 30, 60, 300, 600, 1,200, and 1800 seconds) were available for each stage, whereas raw power output time courses were no longer available because of privacy restrictions. For the purposes of this study, we selected the athlete's highest MMPs for every duration (MMP_T, where T is the duration in seconds). Six P-T_{lim} points for each athlete (MMP_{10}, MMP_{15}, MMP_{30}, MMP_{60}, MMP_{300}, and MMP_{600}) were retained for the analysis of the P-T_{lim} relationship, as they were within the recommended T_{lim} range (12,23). MMP_{1200} and MMP_{1800} developed during time-trial stages, where the effort can be assumed steadily maximal, were used to test the models' predictions by means of the Bland-Altman plot.

Statistical Analyses

All 6 P-T_{lim} points were fitted with a 3-p model (20) by means of the nonlinear regression analysis. For comparison, the lowest 3 MMPs (MMP_{60}, MMP_{300}, and MMP_{600}) were fitted also with a 2-p model, as performed by Quod et al. (28). The general form of the fitted model was the 3-p (20):

$$T_{lim} = \frac{W'}{P - CP} + k \tag{1}$$

where *k* is the time asymptote (i.e., the extent of the shift of the hyperbola along the T_{lim} axis), which allows the curve to cross the P-axis at P_0 (Figure 1). Therefore, P_0 was calculated by setting $T_{lim} = 0$ s and solving for P. The 2-p was derived as a particular case of 3-p, by constraining $k = 0$ s, where P_0 cannot be determined because it becomes infinite. Contrary to the laboratory conditions, a random measurement error must be acknowledged not only for T_{lim} (biological variability of endurance time (22), plus the use of predefined time windows which may misestimate real T_{lim}) but also for P because outdoor conditions and the development of high P both affect the precision of power meter technology (16). Therefore, the geometric mean regression method (36) was used. The standard error of estimate (*SEE*) of *CP*, *W′*, and *k* was calculated by bootstrapping when fitting Equation 1, while that of P_0 when fitting the parameterization of Equation 1 that contains P_0 instead of *k* (36), obtained by setting $k = W'/(CP-P_0)$ (20). The 2-p and 3-p estimates of *CP* and *W′* were compared by means of the paired sample *t* test and Pearson product-moment correlation. The effect size was determined by Cohen's *d*, and with the Hopkin's criteria: 0–0.2 trivial, 0.2–0.6 small, 0.6–1.2 moderate, 1.2–2.0 large, and >2.0 very large (11). The level of significance was set at $p < 0.05$. The statistical package SPSS (Version 23.00, IBM Corp., Armonk, NY) was used.

Results

The P-T_{lim} relationship and the parameter estimates with their respective *SEE* of the 2 models are displayed in Figure 1 and Table 1, respectively. *CP* estimates were significantly lower in 3-p with respect to 2-p by a trivial amount (−4 ± 2 W or −1.0 ± 0.5% $p < 0.001$, $d = 0.13$), because of very small but systematically negative individual differences (range −0.2% to −1.8%), resulting in an almost perfect correlation ($r = 1.00$). *W′* estimates in the 3-p model were significantly higher than 2-p (2.3 ± 1.1 kJ or 21 ± 8%, $p < 0.001$, $d = 0.62$), with excellent correlation ($r = 0.98$). *CP* estimates of 2-p and 3-p were significantly related to MMP_{1200} ($r = 0.89$ and 0.90, respectively) and MMP_{1800} ($r = 0.71$ for both), being not significantly different between them. Bias ± 95% limits of agreement between 2-p and 3-p predictions and the longer MMPs developed during time-trial stages were, respectively, 2 ± 8 W and 0 ± 9 W for MMP_{1200}, whereas 10 ± 38 W and 12 ± 38 W for MMP_{1800} (Figure 2).

Discussion

The P-T_{lim} relationship obtained in the field from data collected during an extensive and multifaceted road bicycle race such as the Giro d'Italia resulted compatible with the hyperbolic model, both 2-p and 3-p. Short-term performance (10–60 seconds), which is usually analyzed separately (31,32), can be included in the same theoretical framework if the 3-p model is used instead of the 2-p. A strength of this study is having selected MMPs from a large amount of data generated in a relatively short period of time

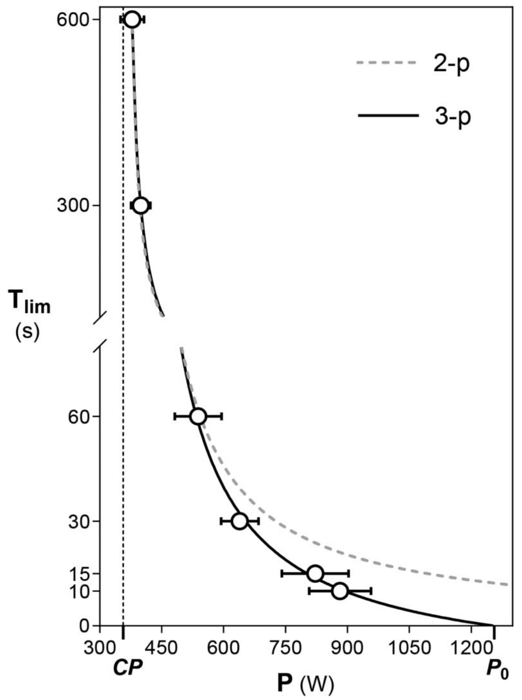

Figure 1. Average power (P)—time to exhaustion (T_{lim}) points and the related 2-parameter and 3-parameter hyperbolas (2-p, dashed gray curve and 3-p, continuous black curve). 2-p was fitted only to the highest 3 T_{lim} (1,200, 600 and 60 seconds), whereas 3-p to all data points. For clarity, the lower part of the T_{lim}-axis is magnified by 5 times. *CP* = critical power; P_0 = maximal instantaneous power.

(21 stages in 24 days), which represents a trade-off between homogenous testing conditions and a high probability of catching the "true" best performances. Model predictions highly agree with measured MMP_{1200} but overestimate MMP_{1800}, a reasonable finding given the environmental and tactical characteristics of the race that limit's the possibility to perform long-lasting maximal cycling bouts without planned, forced, or unexpected slowdowns. The present findings are restricted to male athletes; however, there is high likelihood that the model can be applied also to women's professional multistage races, where relative exercise intensities were found to be greater than for men (29).

A limitation of this study was the lack of access to raw power meter data, which restricted the number of available time windows, in particularly those of 2–3 and 12–15 minutes (23). Nonetheless, concerning the 2-p model, almost the same time windows (1, 4, and 10 minutes) were able to yield similar *CP* and *W′* estimates between racing and laboratory conditions (28) and were recently recommended when assessing *CP* from the power profile of a cyclist (24). Moreover, the 6 available P-T_{lim} data points were adequate for the 3-p model, in line with previous studies (average 6 data points, range 4–9) (2,3,5,9,10,17,20,35), as well as with the recent recommendation of one sprint effort 10–15 seconds long plus at least 3 maximal efforts between 2 and 15 minutes (14).

The fact that 3-p provides a slightly lower *CP* with respect to 2-p and a higher *W′* is a universal finding (2,3,5,9,10,17,20,35), and it has been ascribed to mathematical reasons as demonstrated elsewhere (35). In brief, because the 3-p shifts a portion of the curve in the negative T_{lim}-axis quadrant (Figure 1), the portion of *W′* with negative T_{lim} coordinates becomes nonavailable, thus, to fit the same data points, *W′* must take a higher value, and this occurs partly at the expense of *CP* (35). However, the observed *CP* decrease is more of statistical than practical relevance, given the trivial effect size and the fact that its relative size (1%) is lower than the precision of the power meter (2%). When compared with previous studies, the *CP* estimated from our data is among the highest values ever reported (15), much higher than that usually reported for noncyclists (34,35) and slightly higher than that estimated from racing data in non-professional–experienced cyclists (28), whereas the opposite trend appears for *W′* (Table 2). Under the assumption that the difference between the *CP* and the maximal aerobic power (MAP) is a constant (1), one might expect that athletes with elevated MAP also have elevated *CP*. Moreover, assuming a difference between MAP and *CP* similar to the one reported in a previous study (35), the MAP estimates are comparable with those measured in a similar athletic cohort of professional cyclists (7,31) (Table 2).

The use of 3-p instead of 2-p model also provides the P_0 estimate, which is a challenging factor to accurately establish. In fact, the local slope of the P-T_{lim} curve at extreme P (Figure 1) implies that a small uncertainty greatly influences the P-axis intercept; as a consequence, P_0 has a higher relative *SEE* compared with *CP* and *W′* (Table 1). Moreover, we lack external validators such as maximal instantaneous muscular power measurements, using either a force platform (35) or a cycle ergometer (33). Nonetheless, a comparison with previously published data has been

Table 1

Individual and average parameter estimates and standard errors (SEEs).*

	CP (W)		*SEE* (W)		*W′* (kJ)		*SEE* (kJ)					
	2-p	**3-p**	**2-p**	**3-p**	**2-p**	**3-p**	**2-p**	**3-p**	***k* (s)**	***SEE* (s)**	**P_0 (W)**	***SEE* (W)**
A	372	369	3	7	9.9	11.5	0.8	2.1	−9.8	4.5	1,542	394
B	347	342	6	9	8.5	11.0	1.6	3.3	−12.5	10.2	1,223	301
C	367	363	2	6	10.8	13.4	0.8	1.0	−17.6	2.7	1,126	79
D	365	364	5	6	7.9	8.4	1.3	2.1	−5.6	4.1	1865	1888
E	328	323	12	15	18.3	21.8	3.1	5.3	−20.0	10.4	1,413	372
F	323	320	10	9	11.2	12.8	2.6	2.7	−12.6	7.1	1,335	395
G	414	410	4	16	8.6	10.7	1.1	2.7	−12.5	6.3	1,263	444
H	343	340	1	6	9.9	12.2	0.2	1.4	−16.6	4.3	1,072	366
I	386	379	8	20	14.0	18.4	0.7	6.1	−24.5	12.0	1,129	323
Mean	361	357†	6	10†	11.0	13.3†	1.4	3.0†	−14.6	6.8	1,330	507
SD	29	29	4	5	3.3	4.2	0.9	1.7	5.7	3.3	251	528

*2-p = 2-parameter; 3-p = 3-parameter; CP = critical power; *k* = time asymptote constant; P_0 = theoretical maximal instantaneous power; *SEE* = standard error of estimate = *W′* = curvature constant.
†Significantly different from 2-p.

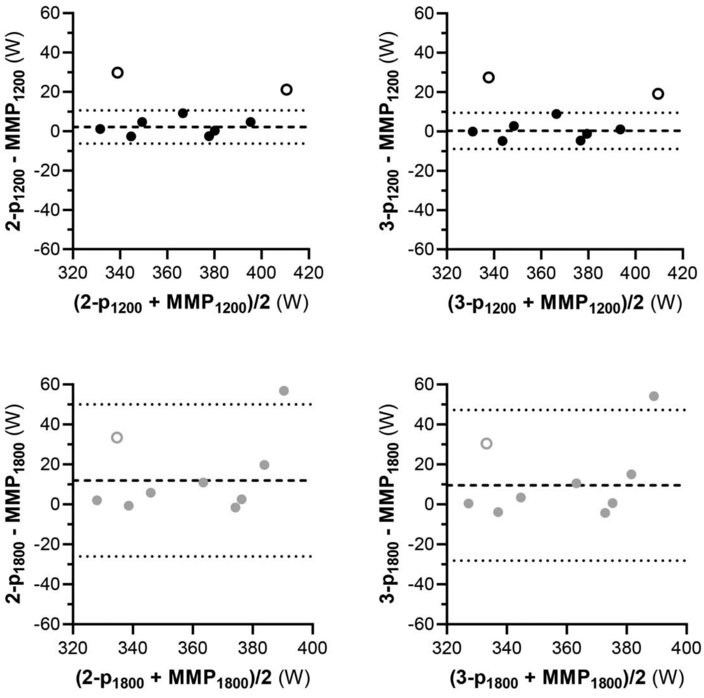

Figure 2. Bland-Altman plots comparing the prediction of the 2-parameter (2-p) and 3-parameter model (3-p) with the measured maximal mean power output for 20 minutes (MMP$_{1200}$, black dots) and for 30 minutes (MMP$_{1800}$, gray dots). The maximal mean power output from stages other than time trials were excluded from the analysis (open dots). Dashed line, bias; dotted lines, 95% limits of agreement. MMP = maximal mean power output.

attempted (Table 2). Although it is likely that P_0 is inherently lower than maximal instantaneous muscular power, as demonstrated for untrained subjects (35), the predicted P for $T_{\text{lim}} = 1$ second (P_1) does not underestimate actual measurements in similar élite cyclists cohorts (7,31). Thus, as previously hypothesized (35), the validity of the 3-p model can be extended up to T_{lim} of few seconds, but not near instantaneous. Interestingly, although the absolute values of CP and P_0 are clearly higher than those observed in untrained subjects, the difference ($P_0 - CP$) is not and tends to be even lower (Table 2). This could be explained by the fact that the higher relative proportion of type I muscle fiber in élite road cyclists contributes to the enhancement of CP (19) but decreases the peak power per unit of muscle mass. Of course, whole-body P_0 is still enhanced, thanks to higher quadriceps muscle volume and pennation angle (13), but by a lower extent with respect to CP. This increase of CP "at the expense" of other parameters could be responsible also for the lower W' with respect to untrained subjects (Table 2), but the physiological explanation of this difference is less clear, and the role of muscle fiber composition as a determinant of W' is unproven to date (19).

Table 2

Comparison of selected parameters with literature data.*†

	Model estimates			Measurements	
	Current study	**Road racing data (15,28)**	**Noncyclists (35)**	**Professional cyclists (7,31)**	**Noncyclists (35)**
CP (W kg^{-1})	5.4 ± 0.4	5.5 ± 0.4 (15) 5.0 ± 0.4 (28)	2.6 ± 0.5		
W' 2-p(J kg^{-1})	166 ± 49	178 ± 31 (28)	236 ± 69		
W' 3-p (J kg^{-1})	201 ± 63		251 ± 66		
MAP (W kg^{-1})	6.1 ± 0.4‡			6.5 ± 0.1 (7) 6.4 ± 0.4 (31)	3.4 ± 0.6
P_0 (W kg^{-1})	20.0 ± 3.8		17.7 ± 4.7	—	22.9 ± 3.3§
P_1 (W kg^{-1})	18.9 ± 2.9			17.4 ± 2.5 (7) 17.4 ± 1.8 (31)	
$P_0 - CP$ (W kg^{-1})	14.7 ± 3.8		15.1 ± 4.5		
k (s)	−14.6 ± 5.7		−18.6 ± 9.0		

*2-p = 2-parameter; 3-p = 3-parameter; CP = critical power; W' = curvature constant; MAP = maximal aerobic power; P_0 = theoretical maximal instantaneous power; P_1 = maximum mean power for 1 s duration; k = time asymptote constant.

†Numerical values of CP 2-p and 3-p are equal to the first decimal when normalized per body mass.

‡Estimated as CP + 50 W (average difference between CP and MAP in (35)).

§Single leg (halved) maximal instantaneous power measured by the force platform.

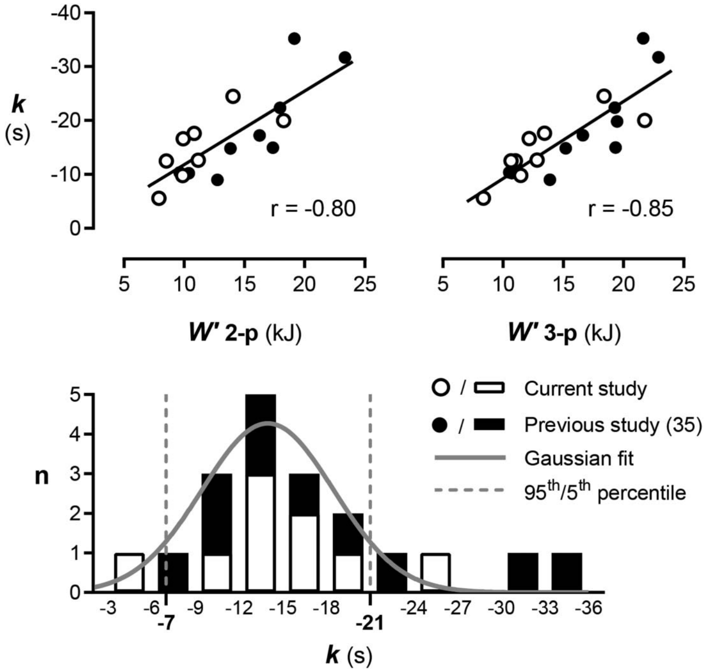

Figure 3. Top panel: Relationship between the time asymptote (*k*) and the curvature (*W*′) obtained with the 2-parameter (2-p) and the 3-parameter (3-p) critical power model. Lower panel: Frequency distribution of *k* values and the corresponding Gaussian distribution obtained with nonlinear regression. The calculated 95th and fifth percentiles are also shown. Data of the current study are pooled with those of a previous study (35) to increase statistical power and generalizability.

Since W' has both anaerobic and aerobic components (34), we interpret these results as a relative reduction of the former with respect to the latter.

From a physiological perspective, k remains the most enigmatic parameter of the 3-p model. Starting from the observation that the utilization of anaerobic energy reserves has finite kinetics, Morton introduced this parameter to account for a linear feedback control system on the availability of W' (21). Therefore, when P is high (and T_{lim} is short), W' cannot be entirely exploited. In this context, k represents the amount of decrease in the available W' per every increment of P above CP, as formally demonstrated by Equation 10 of Vinetti et al. (35). It seems to be less negative in élite cyclists with respect to normal subjects (35), probably as an effect of the correlation that exists between k and W' (Figure 3). Strikingly, this correlation holds also with the W' calculated from the 2-p model, where k is absent. Therefore, it seems that k is dependent on the intrinsic curvature of experimental data, so that its correlation with W' is more than a mere statistical artifact, possibly reflecting different athletic phenotypes. We speculate that the higher the maximal anaerobic lactic capacity (i.e., the higher W'), the lower is its "exploitability" at short T_{lim} (i.e., the more negative is k), because the maximal rate of anaerobic lactic energy release (maximal lactic power) is finite. Vice versa, subjects with a low maximal lactic capacity (lower W') have "less to lose" at short T_{lim} (k is less negative). Moreover, k seems to have a narrow acceptable "physiological" range: the Gaussian distribution of current and previous data shows that the 95th and fifth percentiles of k estimates are -7 and -21 seconds, respectively (Figure 3). However, when the quality or quantity of data points with $T_{\text{lim}} < 60$ seconds is scarce, the 3-p model can generate unreliable k and P_0 estimates, with negative repercussions also on the other parameters (35). This is well exemplified in Table 1, subject D, where the only value of k beyond the proposed upper limit of -7 was associated with an exceptionally high *SEE* of P_0. In this setting, constraining k into this "physiological" range during the fitting procedure may avoid excessive distortions, although, at least with data of Figure 3, this will not abolish, but only attenuate, the correlation with W'. Future studies should better define the "physiological" range of k, possibly including highly specialized athletes of both sexes.

In conclusion, the 3-p model can efficiently describe MMPs in the 10 seconds—10 minutes duration range collected in a single multistage road bicycle race, with acceptable predictions up to 1 second and 20 minutes. Although the uncertainty regarding P_0 remains high, the time asymptote of the power-duration relationship (k) shows a Gaussian distribution; therefore, it can be potentially constrained to a "normal" range to reduce the variability of P_0. The resulting parameter estimates offer an objective and noninvasive assessment of cyclists' physical fitness and performance.

Practical Applications

With the methods and limitations described above, it is possible to reasonably assess the power-duration relationship during a multistage racing event. Using such an approach, the resulting parameter estimates are representative of the peak in physical fitness of élite cyclists (in particular, CP for the maximal sustainable aerobic power, whereas W' and P_0 for the short-term maximal power output), a condition where multiple time-to-exhaustion tests are intolerable or impractical. These findings may be useful for coaches and sports scientists to obtain a "snapshot" of a cycling team's condition.

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