Critical Power and Anaerobic Capacity of Grand Cycling Tour Winners

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1. Introduction .

In order to evaluate the performances of top cyclists in the climbing stages of the great tours such as the Tour de France, the Giro de Italia and the Vuelta a España one should consider three historical fundamental findings.
First, intense or strenuous efforts can be sustained only for a limited time and low level efforts exercise are sustained much longer before the onset of fatigue and ultimately exhaustion. For all animal or human work done by skeletal muscles above a certain power level there is an almost universal relation between the produced mechanical power and the duration to exhaustion. This relation is indicated as the Power-Time or (P–t) relation, or the (P-t) curve when presented in graphic mode.

Second, work by skeletal muscles can be produced either by aerobic or anaerobic bio-chemical processes. Today this seems to be a redundant statement but it is was revolutionary when it was first published by the pioneer in sport physiology A.V. Hill. Hill and Otto Meyerhof received the 1922 Nobel Prize in Physiology or Medicine for their discovery of the aerobic-anaerobic energy systems. Meyerhof went on to discover the lactic acidosis accompanying anaerobic work, and the essential role of Phosphocreatine (PCr) was discovered in 1930. The role of ATP – Adenosine Tri Phosphate for aerobic muscle contraction was unveiled in 1950.

Third, skeletal muscles come in two varieties or types. Type I muscle fibers, the red fibers, or slow-twitch fibers obtain their capacity for contraction and producing work exclusively from the ATP-aerobic system. Type II muscle fibers, the white fibers, or fast-twitch fibers, work mainly on the PCr-anaerobic system. The necessary ATP for the aerobic system is continuously replenished by oxidation of stored and externally submitted glucose and/or stored lipids, the reserve of which are virtually unlimited in the human or animal body. Therefore pure Type I work can be sustained for very long times and type I muscles are not subject to fatigue. As an example, the heart muscle in a healthy being never stops working during a whole lifespan. A type-I bird such as the Stern will fly from Antarctica to the North Pole circle and back every year. At the other hand, anaerobic work relies on limited muscular storages of glycogen and PCr and further causes lactic acidosis. As a result a type-II bird such as a chicken will barely fly a hundred meters before exhaustion. Probably the most famous type-II animal is the Cheetah that can outrun all its prey on short bursts but will fail after a few hundred or so meters.
Monod and Scherrer introduced in 1965 the Critical Power (CP) model in order to describe the Power-to-exhaustion-time relation. The CP of a muscle or muscular group is the maximum rate of work that it can sustain for a very long time without fatigue. CP is mathematically defined as the power-asymptote of the hyperbolic relationship between power output and time-to-exhaustion.

The model has a very simple mathematical formulation;

Power to exhaustion = Critical Power + average anaerobic power

Or in shorthand ; $$P = CP + \frac{AEC}{t} \qquad (1)$$

Where CP is the critical power , AEC is the total anaerobic energy and t is the time to exhaustion. This relationship presents a hyperbola, but the relation can be transformed into a simple straight line by substituting the variable x = 1/t

Both hyperbolic and linear relations are presented in figure 1.

Physiologically, CP represents the boundary between the steady-state and the non-steady-state exercise intensity domains and may therefore provide a more meaningful index of performance than other parameters such as the Lactate Threshold LT, or the maximum oxygen consumption VO_{2max}. A proper analysis of the exhaustive (P-t) relationship will also provide the additional parameter of extreme importance, the Anaerobic Work Capacity (AEC) . The AEC is defined as the total amount of anaerobic work that can be performed at any intensity above CP.

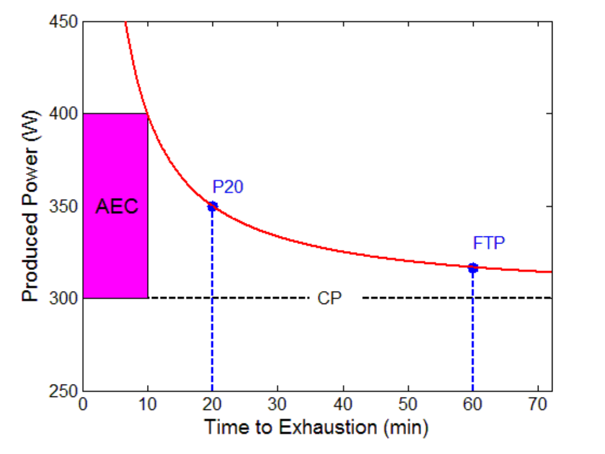

Figure 1a. Schematic presentation of the Power-Time (P-t) relationship for exhaustive exercise. The dotted horizontal line shows the asymptotic value CP of the hyperbolic relation. The surface of the magenta rectangle is the Total Anaerobic Capacity AEC

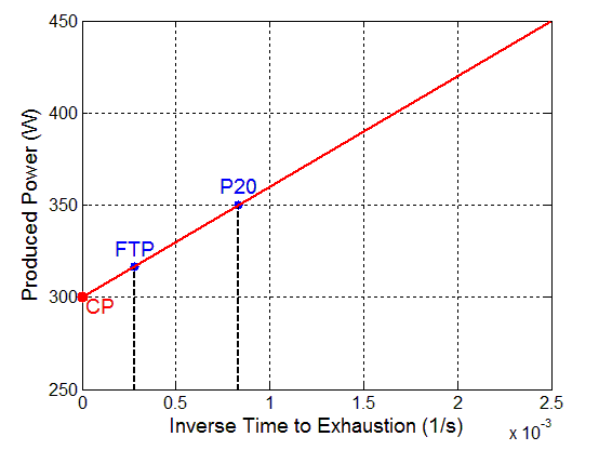

Figure 1b. Presentation of the same (P-t) model as in figure 1a, in function of the inverse of exhaustion time. The intersection of the straight line with the vertical axis is CP, the slope of the line is AEC. Also indicated are FTP and P20.

CP and AEC are often misinterpreted as purely mathematical constructs which lack physiological meaning but in recent years these concepts are emerging as valid and very useful indicators for evaluating endurance fitness and maximal short performance. From 1980 on CP was studied exclusively in laboratory settings. The power-time (P-t) curves are constructed using data obtained from three or more independent high-intensity constant-power bouts for which the time to exhaustion is between 2 and 20 minutes (ref.1). Testing at power outputs that would induce exhaustion at times less than 2 minutes are avoided because the hyperbolic relation predicts infinite power at zero time and obviously the model has to fail for short times. Therefore also the anaerobic energy production must include a power-limitation at short times. However in present study the shortest effort being considered takes approximately 15 minutes and this short-duration limitation is of no concern. Likewise, testing at lower power levels that would induce fatigue at times longer than 20 minutes are also avoided in laboratory settings because it seems impractical to motivate a tested individual for these longer times. Let us point out that the laboratory testing time interval 2 – 20 minutes is rather unrepresentative for predicting the real performance in a mountain stage of the grand tours with final climbs typical between ~15 minutes for a short steep climb such as the Peña Cabarga , and ~ 60 minutes for the longer climbs such as the Mont Ventoux or the Passo dello Stelvio. Nevertheless these laboratory tests have shown that CP is closely related but not equal to any of the physiological indicators such as power at the Gas Exchange Threshold (GET), at the Maximum Lactate Steady State (MLSS), or at the he maximum oxygen intake VO2max. In fact in most subjects the CP is situated at a power level that corresponds approximately to 80% of VO2max. Although laboratory testing might be useful the actual performances in the grand tours are unpredictable from these and therefore we set out to construct exhaustive (P-t) relations and their analysis on basis of real performances in the Grand Tours.

Measuring or estimating real performances is a tricky business, that could be extremely simple if riders would provide the data from their SRM, Powertap, or other on-bike power meters in a public database. For reasons that are not entirely clear riders, coaches, team managers are reluctant to do so. Analysts are forced to estimate average power developed during a climb from observed climbing times, climbing profiles, weather conditions, and other data such as weight of the riders and their apparel, frontal surface of the riders, whether a cyclist is climbing solo or protected in the pack etc…

Whether data from on-bike power meters, or from external observation and computation are used to construct an exhaustive (P-t) relation during the climbing stages of the Grand Tours, a number of conditions have to be fulfilled.

1. Data points for average climbing power and time must be obtained for final climbs with finish on the tops. An example of data to be rejected is e.g. the Climb of the col de Peyresourde when the finish line actually is situated in Bagnères de Luchon. Top riders will not go all-out because any time won on the ascent can still be lost in the descent.
2. Weather conditions have to be within reasonable limits of temperature and wind. Freezing temperatures, snow, torrential rainfall will lead to non-optimal performances. Stage 14 of the 2013 Vuelta a España ended on the Collada de le Gallina. Many riders, amongst whom Ivan Basso, had to abandon the stage because of severe under-cooling.
3. When a stage is a succession of climbs, the final ascent will only be valid if earlier climbs were done at “easy” or “controlling” pace. Stage 8 of the TDF-2013 went over the Port de Pailhères to Ax-les-Thermes and up to the climb of Ax-3-Domaines. Froome and his team rode calmly over the Pailhères and a fresh Froome won on the col AX-3-Domaines . In contrast, Nairo Quintana attacks on the Pailhères, consumes part of his anaerobic reserve and performs badly on the final climb. The data for Froome are valid for a (P-t) relation, the data for Quintana are not.

2. Data sources .

Valid data for historical and recent (P-t) studies of the Grand Tours are obtained from three possible sources.

1. Estimates of historical data by Frédéric Portoleau, published in “Pouvez-vous gagner Le Tour” (ref.2). These data correspond to the period 1989 – 2001. Estimates for the period 2002 to today can also be found on the website cyclisme-dopage.com and in a recent publication (ref.3). We must point

out that although we are using data from these sources, we do not accept unconditionally the conclusions of Mr. Vayer concerning the setting of radars of suspicion on individual climbs nor his conclusions concerning doping.

2. Our own observations of the Grand Tours in 2012-2013, and power computations with a Matlab program CyclingPower.m
The details of this program will be published elsewhere.

3. Occasional SRM-data files from the SRM website. Although these files never show the performance of the top-riders they can be used for cross-checking of our CyclingPower calculations

3. Observations and Analysis.

The performances of Miguel Indurain in the TDF 1994 and 1995, Alberto Contador in the TDF 2009 and 2013, Froome in TDF 2012-2013, Hesjedahl in the Giro 2012, and Horner in the Vuelta 2013 were analyzed with a two-parameter CP- model in accordance with formula (1). For each rider the Critical Power CP, and the Anaerobic Capacity AEC were obtained. Figures 2-5 show the corresponding (P-t) observations and the best-fit straight lines in the 1/t – presentation.

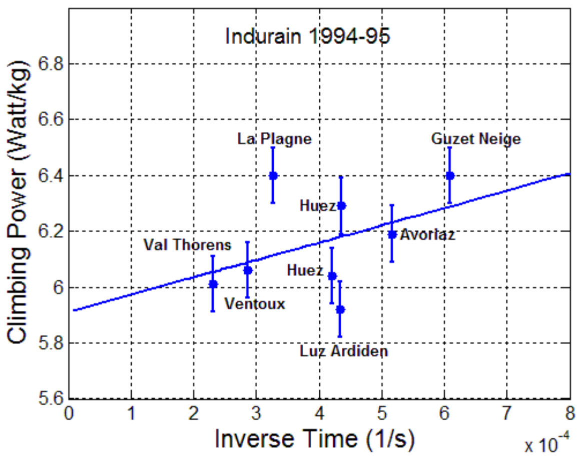

Figure 2. Climbing Power of Miguel Indurain in the TDF 1994 and 1995.

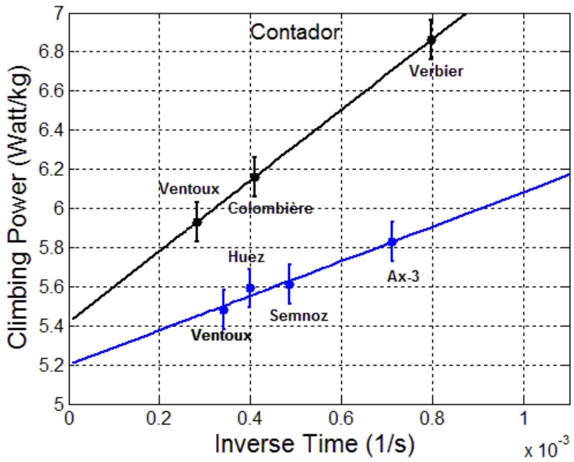

Figure 3: Climbing Power of Contador in the TDF of 2009 – Black markers, and in 2013 – Blue markers.

The climbing performances of Indurain show appreciable scattering of the data points around the best fitted straight line of the CP-analysis. This scatter is mainly caused by the climbing strategy of Indurain; He never attacked himself, and only responded to attacks of his adversaries. In fact he never won any mountain stage, except Time Trial stages (that are not considered in this graphics). Today we know that these were the first years of heavy EPO-abuse. As a consequence the CP is extremely high, but his AEC is moderately low when compared to later Grand Tour champions. The large scatter also lead to the largest error in the determination of CP and AEC.

Alberto Contador in his winning TDF of 2009 is quite a different rider from Contador in 2013. His critical power in 2009 was more than 4% higher than in 2013. Most notable in 2013 was his lack of anaerobic energy which is reflected in the low slope of the blue data and fitted line. His anaerobic capacity AEC was in 2013 less than half of his AEC in 2009.

The great variability of CP and AEC is illustrated by Hesjedahl vs Horner. Hesjedahls (P-t) curve lies fully below Horners which means that the former would have ended far behind Horner on all climbs, except on the short Alto del Naranco. Horner showed a high CP and low AEC, while in contrast Hesjedahl combined a very low aerobic power with a high anaerobic capacity. These results might give indications about possible doping abuse (see also 4.3)

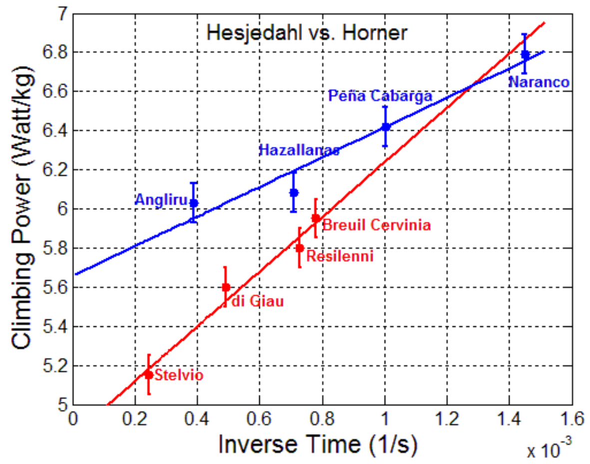

Figure 4: Climbing Power of Hesjedahl in the Giro 2012 (Red), and of Horner in the Vuelta 2013 (Blue).

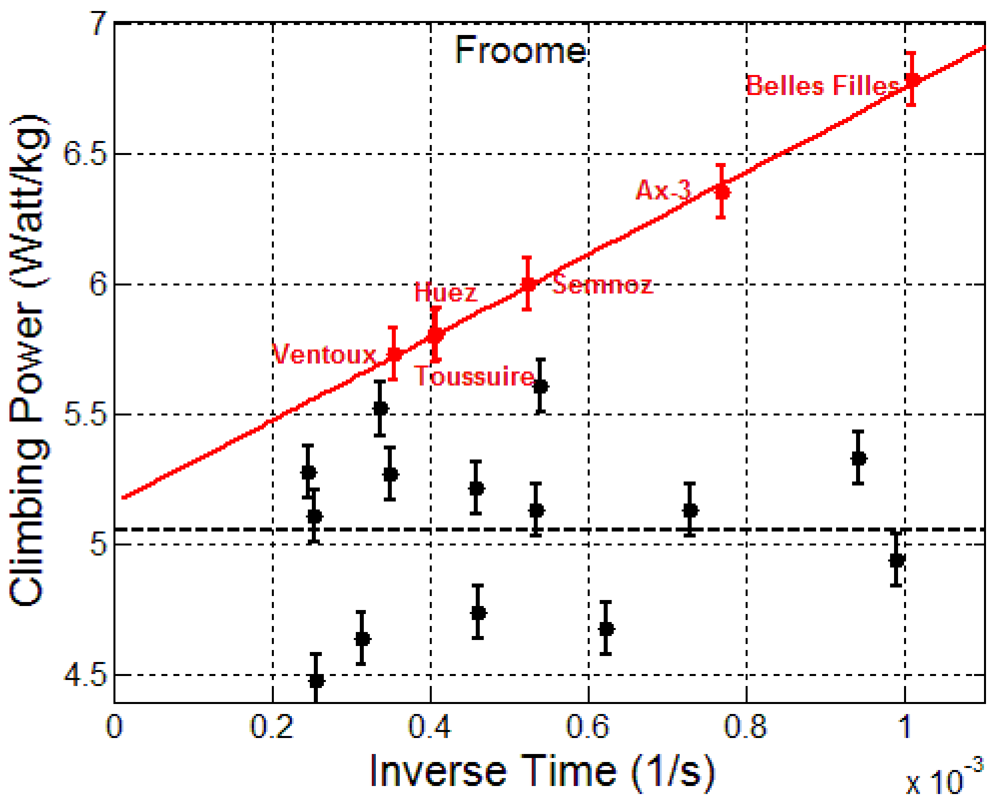

Figure 5: Climbing Power of Froome in the TDF 2012 and 2013.

Christopher Froome shows a remarkable constancy in his performances, to the extent that his performances in two Tours, 2012 and 2013, can be presented in one single exhaustive

(P-t) curve. The red data present his climbs of 2012 on Planche des Belles Filles and on La Toussuire exactly on the line corresponding to the 4 climbs of the Tour 2013. Also the climbs of the Alpe d'Huez and La Toussuire coincide in climbing time and climbing power. The black data correspond to 14 non-final climbs of 1st category and HC. The large spread of these points indicate clearly the effect of the modern strategy of least possible effort in controlling conditions. No matter how long the stage, and how many climbs, the leading teammates will try to ride a pace that stays below the CP of their team leader, and respond only to potentially dangerous attacks. The weighted average power of these non-final climbs is indeed lower than the extrapolated CP deduced from the final climbs.

4. Discussion.

All our presented data show an enormous variation in climbing power versus duration of the climb. This is in agreement with the well-known hyperbolic (P-t) relationship that is described the two parameters Critical Power (CP) and Anaerobic Capacity (AEC). A particular performance has to be evaluated by considering both these aerobic and anaerobic contributions. Because climbing performances may vary between short climbs of ~ 15 minutes , and longer climbs of ~60 minutes, with strong variations in the anaerobic contribution it is unreasonable to average climbing power over the ascends of the Tour, the Giro or the Vuelta. For the same reason it is unwise to put "radars" of suspicion on individual climbs.

Table 1 shows a compilation of all the obtained CP and AEC in this study. Column 4 shows P_{20}, the interpolated power for a reference time of 20 minutes. Column 5 is the Functional Threshold Power i.e. the power to exhaustion during 60 minutes, and column 6 shows an estimated maximal oxygen intake VO_{2max}

	AEC (kJ/kg)	CP (W/kg)	P_{20} (W/kg)	FTP (W/kg)	VO_{2max} $\frac{ml}{min.kg}$
Indurain	0.95 ± 0.78	5.81 ± 0.34	6.47	6.09	91.8
Froome	1.58 ± 0.04	5.16 ± 0.02	6.48	5.60	81.5
Contador 09	1.81 ± 0.04	5.42 ± 0.01	6.92	5.92	85.6
Contador 13	0.86 ± 0.14	5.20 ± 0.07	5.92	5.44	82.2
Horner	0.75 ± 0.15	5.62 ± 0.15	6.29	5.86	88.8
Hesjedahl	1.42 ± 0.21	4.82 ± 0.13	6.00	5.22	76.2

Tabel 1. Compilation of CP, AEC and related power parameters for all riders

We see that of all these grand tour champions Miguel Indurain presents the highest CP of 5.81 W/kg, while Hesjedahl had 4.82 W/kg in his winning Giro in 2012. More interesting are the CP- values of Froome and Contador in the TDF 2013. They have identical values within the limits of error, and these values are way below Indurain. The main difference between Froome and Contador in the TDF2013 is their AEC, 1.58 kJ/kg for Froome and barely half as much for Contador. Could Froome have won the TDF of 2009 against Contador? Absolutely not because in 2009 both CP and AEC of Contador were much higher than Froome's in 2013. Also remarkable is the high CP of Horner in his winning Vuelta, which is second only to Indurain.

4.1. CP and Maximal Oxygen uptake

Of all the power-related parameters only CP can be considered to elucidate maximal steady-state aerobic power, because any effort at a higher intensity level will inevitably lead to ventilatory exhaustion and blood lactate acidosis.

For pure aerobic metabolism the volume of oxygen consumed to produce an amount of work P is given by

$$\dot{V}O_2 = \frac{60}{r.Ee} P = \alpha\, P \quad \text{with} \quad \alpha = 12.63\, \frac{ml}{W.min} \qquad (2)$$

Where $\dot{V}O_2$ is calculated in $\frac{ml}{min.kg}$, P is in W/kg, r is the mechanical efficiency of cycling which is typically 23%, and Ee is the energetic equivalent of 1 liter of oxygen. Astrand (ref.4) shows that at high work intensity the aerobic metabolism consumes ~ 20% of fat versus ~80% of glucose. Thus the energy production of 1 liter of oxygen at this level is a proper average of the burning of fat (= 20.95 kJ/l) and of sugars (= 19.45 kJ/l) and will yield an effective aerobic energy of 20.65 kJ/liter.

Poole et al. (ref.1) estimated that the oxygen intake at CP, VO_{2CP} is approximately 80 % of VO_{2max}

Thus we may estimate $\dot{V}O_{2max}$ from the critical power ;

$$\dot{V}O_{2max} = 1.25\, \dot{V}O_{2CP} = 15.8\, CP \qquad (3)$$

From column 6 we see that Hesjedahl in his winning Giro 2012 presented the lowest VO_{2max} of all riders in this study and that Indurain had the highest all-time VO_{2max} of 91.8 $\frac{ml}{kg.min}$.

Although Contador had to concede time to Froome on every climb in the TDF 2013 they had almost identical CP and $\dot{V}O_{2max}$, from which it is clear that superior aerobic (endurance) power and $\dot{V}O_{2max}$ cannot be considered being the only physiological quality of the grand tour winners. The secret, if any, of the supremacy of Froome over Contador lies in his higher AEC, 1.58 kJ/kg for Froome versus 0.86 kJ/kg for Contador.

We also have to remark an enormous difference between the performances of Contador in his winning tour of 2009 and in the tour 2013. His CP was a full 4.25 % higher in 2009, and most notably his AEC in 2009 was more than double of his AEC in 2013! Because AEC is related to the ability of accelerating in the climb and suffocating his adversaries it seems that Contador's best weapon of the past has now become his greatest weakness.

Probably the most surprising and alarming performance is due to Horner in the Vuelta 2013. Horner's CP and $\dot{V}O_{2max}$ are only superseded by Indurain in his top years 1994-1995. In the words of A. Vayer, Indurain was a "fully loaded mule", and indeed it is known now that the years 1994 – 1999 were the years of unlimited use Epo.

A single climbing performance can never yield information about the relative contributions of the aerobic and the anaerobic components. Rather the full exhaustive (P-t) curve is needed with climbs of different lengths and slopes. Disregarding this full analysis can lead to extremely erroneous estimates of CP and oxygen intake. The most problematic case can be ascribed to Vayer's estimate of Contador on the Verbier climb in the TDF 2009. Vayer stated a value of $\dot{V}O_2 = 99.5\, \frac{ml}{kg.min}$ by assuming that the developed power was 100% aerobic. From our figure 3 we see that Contador's Verbier climb is a perfect extrapolation of his climbs on the Mont Ventoux and on the Colombière and that the his (P-t) curve is consistent with a $\dot{V}O_{2max} = 85.6\, \frac{ml}{kg.min}$. Contador derived 79% of his power from aerobic metabolism. The remaining 21% came from his anaerobic reserve.

4.2. Determination of FTP

Because it is not always practical or feasible to obtain full (P-t) data for the determination of CP and AEC, it has become practice to replace CP by the concept of Functional Threshold Power. FTP corresponds to the mean maximal power that can be sustained during a 1 hour effort. Because FTP is supposedly only 1 to 2% above CP it has become a practice to use FTP as a threshold power from which different effort intensities and training zones are defined. A first step for this purpose is to obtain a reasonable estimate of FTP without the need of an all-out field performance of 1 hour duration. Also a laboratory test is not easily translated into real-life performance, and it is also impractical to have a cyclist highly motivated during a full 1 hour test. Therefore an exhaustive test of 20 minutes can be used to predict FTP. According to Andrew Coggan subtracting 5% from the P20 value yields FTP, and most power training centers and training software are based on this P20/FTP relationship. This relation might provide a reasonable estimation of FTP for the modal cyclist, but it is not adequate for the evaluation of grand tour champions. In the first place there is a fundamental objection to this P20-rule because stating any fixed value of the FTP/P20 ratio eliminates the independent role of the anaerobic contribution and reduces the two-parameter analysis of the (P-t) curve to a single-parameter analysis.

Indeed accepting the P20 rule corresponds to stating that $0.95\ P_{20} = FTP$ or in detail

$$0.95\left(CP + \frac{AEC}{1200}\right) = CP + \frac{AEC}{3600} \qquad (3)$$

From which results that $AEC = \beta.CP$ with $\beta = 97\ s$, and it would mean that AEC is altogether useless.

In the second place, the vast variation in the values for AEC obtained in this study contradict the P20 rule. We present the actual relations FTP/P20 and CP/FTP for our grand tour champions in table 2.

	$\left(1 - \frac{FTP}{P20}\right)$ %	$\left(1 - \frac{CP}{FTP}\right)$ %
Indurain	5.9	4.6
Froome	13.6	7.8
Contador 09	14.5	8.4
Contador 13	8.1	4.4
Horner	6.8	4.1
Hesjedahl	13.0	7.7
P20 - Rule	5.0	2.6

Table 2. Fractional difference between FTP-P20 and CP-FTP for grand tour winners.

Whereas the naive P20-rule states a 5% difference between P20 and FTP, none of the grand tour winners accuses a value close to 5%. All values are substantially higher, although there are great variations, from a maximum of 14.5% for the very explosive Contador in the TDF2009 to a minimum for Indurain in his Tours 1994-95. Also the fractional difference between CP and FTP is systematically underestimated by the P20-rule

The third column in table 2 in fact indicates the fraction of the anaerobic contribution on a long climb such as the Ventoux, the Colombière, Val Thorens or the Stelvio. As an example, on his winning climb on the Mont Ventoux Christopher Froome had to produce 7.8% of his power from his anaerobic reserve.

4.3. What is normal ?

It is beyond the scope of this study to state definite conclusions concerning possible doping abuses of the concerned champions. Comparisons with past performances, particularly the ones from the pre-EPO period are difficult. The influence of improved diets, food supplements, and training techniques , better roads and cycling materials, and the “sum of marginal gains”, over a period of almost 30 years cannot be evaluated. However it is remarkable that Froome’s critical power of 5.16 W/kg is significantly lower than the 5.45 W/kg of average total climbing power of past champions such as Lemond, Hinault, Roche, Delgado and even Indurain in his first two wins. Therefore we, consider Froome ‘s CP to be an acceptable landmark for a performance free of any blood-oxygen doping or other illegal techniques. Defining a safe reference value for AEC is more difficult because to our knowledge this is the first study addressing the issue and it is not possible to re-analyze the historical data. Also, little is known about te influence of modern anaerobic training and of AEC-boosting diets such as creatine-loading (ref. 5). Therefore we also consider the AEC = 1.58 kJ/kg of Froome as a reference value. In figure 6 we have presented both performance parameters with reference to Christopher Froome. Of the other grand tour winners all but 1 (Hesjedahl) have equal or higher aerobic power expressed as CP. However also all but 1 (Contador in 2009) have lower AEC, and the differences in AEC are much more pronounced than the differences in CP.

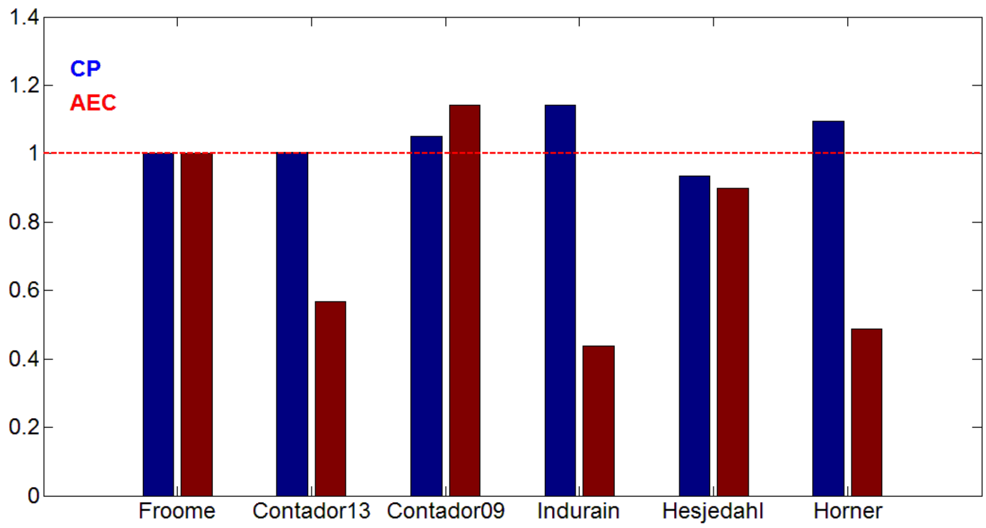

Figure 6. Comparing the performance parameters with reference to the TDF of Froome in 2013.

Conclusions

To our knowledge this is the first study of exhaustive climbing performances by the winners of the grand tours TDF, Giro and Vuelta, with the Monod-Scherrer critical power model. Within the climbing time interval 15 – 60 minutes the model adequately describes the performances, and values for the critical power and the anaerobic capacity are obtained.
In modern cycling the anaerobic component is more important than generally accepted and the practice of estimating the functional threshold power and critical power with a single maximal test over 20 minutes is invalid. The maximal oxygen uptake for all winners is below

90 $\frac{ml}{min.kg}$, with the exception of Indurain in his uncontrolled EPO-years 1994-1995.
As to individual cases, the data give indications for anomalous high CP values and hence possible oxygen-boosting practices for Contador in his winning TDF of 2009, and for Horner in his 2013 Vuelta a España. More investigation of the 2 parameter CP model of the grand tours are necessary and might lead to a performance passport as a supplement to the existing biological passport. Future studies could be facilitated and could gain in public acceptance and credibility with the creation of a public database containing power the data files (SRM, Powertap and others) of all top riders,

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