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Reanalysis of Power-Based $\dot{V}O_2max$ Estimation in Tadej Pogačar Reconstruction of the Record Power Performance Profile

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Abstract

Several recent studies have attempted to estimate the $\dot{V}O_2max$ of elite professional cyclists using models that relate the mechanical power output developed during uphill cycling to maximal oxygen uptake. A recent study by Berg proposed a $\dot{V}O_2max$ value of approximately 93 ± 3 $mL·min^{-1}·kg^{-1}$ for Tadej Pogačar, suggesting that his performances would fall within the upper range of human physiological variability. In addition to reconstructing the Record Power Profile (RPP), the present work provides a reanalysis of this estimation, based on a correction of the mechanical and physiological parameters used in the original model. The power outputs developed during several major climbs of the 2024 and 2025 seasons were recalculated using more realistic parameters, including the effective aerodynamic coefficient (CdA), air density, rolling resistance coefficient (Crr), total rider–bicycle system mass, drafting effects, and environmental conditions. An explicit analytical propagation of uncertainties was incorporated. Aerobic endurance was re-evaluated based on power–duration relationships observed in elite professional cyclists. Finally, the energetic equivalent of oxygen was recalculated using respiratory quotient values that are physiologically plausible for prolonged high-intensity efforts. The results indicate that Berg's initial model tends to overestimate mechanical power while underestimating the metabolic cost of the effort, primarily due to unrealistic assumptions regarding aerobic endurance and respiratory quotient. After correction, the $\dot{V}O_2max$ required to explain the observed performances is estimated at 100.7 ± 3 $mL·min^{-1}·kg^{-1}$, a value substantially higher than that originally reported. These findings suggest that the physiological demands associated with Tadej Pogačar's performances exceed the extreme upper bounds of $\dot{V}O_2max$ values currently documented in humans. This study highlights the importance of rigorous parameter calibration, realistic modeling of aerobic endurance, and explicit uncertainty analysis when interpreting power-based $\dot{V}O_2max$ estimations in professional cycling.

Keywords

$\dot{V}O_2max$; Power-based Modeling; Aerobic Endurance; Uncertainty Analysis; Professional Cycling; Record Power Profile

1 Introduction

$\dot{V}O_2$max has long been regarded as a major determinant of endurance performance,[1,2] although endurance performance also depends on fractional utilization and exercise economy/efficiency. In elite road cycling, $\dot{V}O_2$max has for decades remained one of the main physiological reference markers used to characterize performance level.[3,4] Although direct laboratory measurement remains the gold standard, such data are rarely available for professional riders competing in Grand Tours. As a result, a limited number of relatively recent studies[5] have sought to indirectly estimate $\dot{V}O_2$max from the mechanical power output developed during uphill cycling, using models that combine external work, assumed gross efficiency, and the energetic equivalents of oxygen.

Within this framework, Berg[6] recently proposed an estimation of Tadej Pogačar's $\dot{V}O_2$max based on race-derived power output, yielding a value of approximately 93 ± 3 mL·min^{-1}·kg^{-1}. The author concluded that, although exceptionally high, this value would remain compatible with the upper range of known human physiological variability[4,7] and could account for the performance observed during the 2024 and 2025 seasons. Given the magnitude of the reported value, a careful reanalysis is warranted to examine the physiological plausibility of the estimate and the validity of the assumptions used in its derivation.

However, the estimation of $\dot{V}O_2$max from external mechanical power is highly sensitive to the choice and calibration of both mechanical and physiological parameters.[8,9] In validated cycling power models, the predicted power requirement depends on drag area (CdA/SCx), air density, rolling resistance, total rider–bicycle system mass, gradient, and environmental conditions. In addition, drafting can materially reduce aerodynamic drag and the associated power requirement, including during uphill cycling. The subsequent conversion of mechanical power into metabolic demand depends on assumptions regarding gross efficiency and the energy equivalent of oxygen as a function of respiratory quotient. Finally, the interpretation of prolonged high-intensity performances is influenced by the power–duration relationship and critical power framework used to infer the sustainable aerobic contribution at a given duration.[10] Accordingly, even modest changes in CdA, drafting, gross efficiency, or the metabolic conversion equation can produce appreciable shifts in the final estimated $\dot{V}O_2$max.

The modelling of aerobic endurance represents an additional central component of these approaches, yet one that is often insufficiently constrained. While high fractions of $\dot{V}O_2$max can be sustained in running when expressed as speed, empirical power–duration data in professional cycling consistently show that a lower and remarkably stable fraction of short-duration maximal power can be maintained over efforts lasting 20 to 60 minutes. Neglecting these observations exposes power-based $\dot{V}O_2$max estimations to a systematic bias.

The aim of the present study is therefore to provide a reanalysis of the $\dot{V}O_2$max estimation proposed by Berg.[6] Based on recalculated power outputs from several reference climbs during the 2024 and 2025 seasons, this work reassesses the mechanical and physiological parameters of the original model, incorporates physiologically plausible respiratory quotient values, re-examines aerobic endurance using power–duration relationships observed in elite professional cyclists, and explicitly integrates an uncertainty analysis. The objective is to determine the level of estimated $\dot{V}O_2$max required to explain the observed performances when realistic assumptions and rigorous uncertainty propagation are applied.

2 Material and Methods

2.1 Calculation of Power and Mechanical Modelling

The mechanical power developed by Tadej Pogačar was recalculated for several major climbs during the 2024 and 2025 seasons, including key stages of the Tour de France and the Critérium du Dauphiné. Power estimation was based on classical cycling mechanics equations, incorporating gravitational, rolling resistance, and aerodynamic components. The same fundamental relationships as those used by Berg[6] were applied in order to ensure methodological consistency, while key parameters were re-evaluated.

The rider's body mass was set at 66 kg, in accordance with data communicated by the UAE Team Emirates and adopted by Berg.[6] Bicycle mass was fixed at 7 kg. An uncertainty of ± 1.2 kg was introduced for the combined cyclist–bicycle system to account for equipment, clothing, and uncertainties in reported rider and bicycle mass. Other sources suggest a body mass of approximately 64.5 kg for Tadej Pogačar.[11] However, potential errors related to rider mass have little influence on the results, as both power output and $\dot{V}O_2$max are expressed on a relative per-kilogram basis.

Aerodynamic drag was characterized using the effective aerodynamic coefficient (CdA). Unlike values derived from time-trial positions or heavily sheltered situations, an CdA of 0.30 ± 0.02[12] was adopted for climbs performed without drafting, consistent with values typically observed in road riding positions during uphill efforts. Drafting effects were explicitly taken into account when race conditions indicated prolonged riding in the slipstream of other riders in the peloton, with an approximate 50% reduction in aerodynamic drag during these phases.[13] In his study, Berg[6] employed a formula derived from two publications by Faria[14] and Heil,[15] which depends on rider height (1.76 m) and body mass (66 kg). In particular, the study by Heil,[15] based on analyses of hour record performances, was used by Berg.[6] The resulting CdA value is 0.218, which is exceptionally low and corresponds to parameters typically observed in time-trial positions or when riding in close draft behind other cyclists. Such a value is not applicable to all of the ascents analysed in the present study.

Air density was adjusted to reflect the actual environmental conditions encountered during the climbs, rather than using the standard sea-level value of 1.225 kg·m^{-3}. Air density was calculated based on the altitudes and temperatures of the climbs analysed using data collected from each Strava segment on the day of the race. In the absence of reliable data, a mean relative humidity of 50 ± 15% was assumed.

Rolling resistance was estimated using a rolling resistance coefficient (Crr) of 0.003 ± 0.0005,[16] which is typical of high-quality tyres.

Mechanical power during climbing was calculated as the sum of the power required to overcome gravitational forces, rolling resistance, and aerodynamic drag, in accordance with classical cycling mechanics models (Equation 1).[8]

P_{crank}	Mechanical power at the crank
P_{wheel}	Power applied at the wheel–ground interface
v	Speed in meters per second
m	Mass in kilograms
g	Gravitational acceleration in meters per second squared
Crr	Rolling resistance coefficient
Cd_a	Aerodynamic drag coefficient
ρ	Air density in kilograms per cubic meter
η_{trans}	Mechanical efficiency of the bicycle drivetrain
$P_{aero\ eff}$	Effective aerodynamic power accounting for drafting
$fabri$	Temporal fraction of time spent drafting
δ	Fractional reduction of aerodynamic drag due to drafting

$$P_{Crank} = \frac{P_{wheel}}{\eta_{trans}} = \frac{v(mg\ gradient + mg\ Crr) + 1/2\rho Cd_a v^3}{\eta_{trans}}$$

Equation (1)

2.1.1 Accounting for Aerodynamic Drafting

During the analysed ascents, the possible presence of aerodynamic drafting was accounted for by explicitly reducing the aerodynamic drag term in the power equation. The power associated with aerodynamic drag was therefore expressed as shown in Equation 2:

$$P_{aero\ eff} = 1/2 \cdot \rho Cd_a (1 - \delta) v^3$$

Equation (2)

where « ϱ » is the air density, CdA is the cyclist's effective aerodynamic coefficient, « v « is the travelling speed, and « δ » represents the fractional reduction in aerodynamic drag associated with drafting.

Based on experimental data available in the literature, drafting provided by one or more riders positioned ahead can reduce aerodynamic drag by approximately 30 to 50%,[12,13] depending on peloton configuration and rider proximity. In situations where race footage and tactical context indicated that the rider remained predominantly sheltered over a significant portion of the climb, a conservative value of δ = 0.40 ± 10% was adopted.

The calculations explicitly account for the fraction of time spent drafting during each ascent. Race footage allows a reliable qualitative assessment of drafting duration. For example, drafting is minimal during the climbs of Hautacam (7%) and Valmeinier (20%). Conversely, during the ascents of Mont Ventoux (95%) and the Col de la Couillole (95%), exposure to the wind is very limited, with only about 5% of the climb being performed without shelter. In the ascent of the Plateau de Beille, drafting persists for approximately two-thirds of the climb, while no drafting occurs during the Peyragudes individual time trial.

To account for the proportion of each ascent completed under aerodynamic shelter, the effective reduction in aerodynamic drag was calculated using Equation 3.

$$\delta_{eff} = f_{abri} \cdot \delta$$

Equation (3)

where « f_{abri} » represents the temporal fraction of the ascent during which the rider benefited from aerodynamic shelter.

Uncertainties associated with the estimation of drafting were incorporated into the overall uncertainty propagation of mechanical power by considering a variability of ± 10% on the value of « δ ». All assumptions related to aerodynamic drafting are thus explicitly stated, allowing independent reproduction of the calculations without reliance on the original computational tool.

The effect of wind was not explicitly included in the power calculations. For the analysed ascents, reported meteorological conditions indicated low wind speeds, making its influence on mechanical power of secondary importance compared with other sources of uncertainty. The effect of wind was not explicitly taken into account in the power calculations. For the climbs analysed, the reported weather conditions indicated low wind speeds, making its influence on mechanical power secondary compared with other sources of uncertainty. In addition, comparisons between the recalculated power outputs and the values published by several riders equipped with power meters did not reveal discrepancies exceeding the uncertainty interval associated with the calculation model (Tobias Johannessen, Oscar Onley, Kevin Vauquelin, Santiago Buitrago, Bruno Armirail, David Piganzoli, Ion Izagirre). Taking together, these elements suggest that omission of the wind-related term does not materially affect the estimates presented in this study.

2.1.2 Uncertainly Analysis

An explicit uncertainty analysis was incorporated at each step of the modelling process (Table 1). Uncertainties were assigned to mechanical parameters (CdA, Crr, air density, system mass), physiological parameters (gross efficiency, respiratory quotient), as well as temporal assumptions (typical effort duration at $\dot{V}O_2$max). Propagation of these uncertainties made it possible to derive confidence intervals for the recalculated power outputs and for the final $\dot{V}O_2$max estimate.

The standard uncertainty (standard deviation) of the mechanical power calculation was estimated using first-order analytical uncertainty propagation (Taylor series expansion).

Power calculations (including drafting adjustments) and uncertainty propagation were performed using an open-source tool (HTML/JavaScript) made available in a public repository.[17]

Table 1. Parameters and uncertainties considered for power calculation.

Parameters	Berg[6]	Uncertainty	Review	Uncertainty
Elevation gain (m)	STRAVA	-	STRAVA	± 10 m
Mass (kg)	66 + 7	-	66 + 7	± 1.2 kg
Distance (m)	STRAVA	-	STRAVA	± 100 m
Standard CdA (no drafting)	0.218	-	0.3	± 0.02
Drafting (CdA reduction during sheltered time)	-	-	- 40%	± 10 %
Crr (rolling resistance coefficient))	0.0026	-	0.003	± 0.0005
Air density (kg / m³)	1.225	-	1.012	± 0.02
Drivetrain mechanical efficiency	98%	-	98%	± 0.5 %
Derek Gee → Correction factor	1.04	-	-	-

2.2 Conversion of Power into $\dot{V}O_2$

Converting mechanical power into oxygen consumption can be achieved in three steps using the following fundamental equations:

- Conversion from Mechanical Power to Metabolic Power (Equation 4).
- Energetic Equivalent of Oxygen (QR $Joule\backslash cdotpL^{-1}$) (Equation 5).[18]
- $\dot{V}O_2$ at a Given Power Output (Equation 6).

P_{meca}	Mechanical power at the crank (W)
(η)	Metabolic efficiency (%)
P_{meta}	Metabolic power (W)
QR	Respiratory quotient
t	Duration (minutes)
t_{max}	Representative $\dot{V}O_2$max duration (≈ 4–8 min)
m	Body Mass (kg)
E_{O2}	Energetic equivalent of oxygen in joules per litre of oxygen (J)

$$P_{meta} = \frac{P_{meca}}{\eta}$$

Equation (4)

$$E_{O2} = (3{,}869 + 1{,}195 \cdot QR) \cdot 4184$$

Equation (5)

$$\dot{V}O_2\ (ml \cdot min^{-1} \cdot kg^{-1}) = \frac{P_{meta}\ (J \cdot s^{-1})}{E_{O2}\ (J \cdot L^{-1})} \times 60\ (s) \times \frac{1000}{m\ (kg)}$$

Equation (6)

2.3 Physiological Assumptions

The conversion of mechanical power into metabolic demand relies on assumptions regarding energetic efficiency and substrate utilization. Gross efficiency was set at 23%, with an uncertainty of ± 0.2%, a value located in the upper range of those reported in the literature for prolonged high-intensity cycling efforts. No reliable evidence of gross efficiency exceeding 23% for efforts lasting 30 to 40 minutes has been reported in the scientific literature.[19]

The energetic equivalent of oxygen was determined using physiologically plausible values of the respiratory quotient (RQ).[20] For prolonged efforts performed after several hours of racing, RQ values were assumed not to exceed 0.95, and the corresponding energy yields per litre of oxygen were calculated accordingly. Assumptions requiring RQ values ≥ 1.0 were considered physiologically unrealistic for the effort durations analysed.

For the final $\dot{V}O_2$max calculation, an RQ of 1.00 was employed rather than 1.10 as proposed by Berg,[6] based on the tables of Peronnet and Massicotte.[21] Specifically, for interpolation at $\dot{V}O_2$max, the conversion was performed using RQ = 1.0 for the aerobic component. RER values greater than 1.0, which may be observed at maximal intensity, were not used as substrate RQ values because they include non-metabolic CO_2 associated with acid–base buffering. The anaerobic contribution was treated separately.

In order to estimate $\dot{V}O_2$max, only maximal-intensity efforts performed by Tadej Pogačar should be considered. However, most of these efforts occur under non-optimal conditions. They are frequently produced at the end of stages lasting several hours, leading to marked pre-fatigue, as observed in particular during the ascents of the Plateau de Beille and Valmeinier. This fatigue is compounded by moderate hypoxic stress related to altitude, as well as variable thermal stress depending on environmental conditions.

Under ideal conditions—absence of prior fatigue, sea-level altitude, and temperate ambient temperature—maximal physiological capacities would likely be higher. Consequently, the $\dot{V}O_2$max derived from these performances should be interpreted as a conservative (lower-bound) estimate, as a fraction of the maximal physiological potential is not fully expressed under such constrained conditions.

The effects of altitude and temperature were incorporated into the model. The reduction in aerobic power associated with altitude was estimated at approximately 6% between 1000 and 2000 m,[22] while thermal stress was accounted for using a conservative correction of a 0.25% loss of power per degree Celsius above 20°C.[23] Consequently, the power achieved under these conditions is slightly underestimated and should therefore be corrected to derive the theoretical maximal power used as the basis for $\dot{V}O_2$max estimation.

2.4 Calculation of $\dot{V}O_2$max

There are several indirect methods for estimating $\dot{V}O_2$max based on power output[24] or on the combination of power output and heart rate (HR).[25] A commonly used approach is based on the relationship between power and HR.[26] Their reliability remains a subject of considerable debate even today.[27] Whilst this method can yield satisfactory results when resting HR and maximum HR are well known, it is subject to significant uncertainty due to test conditions such as temperature, fatigue and hydration status. Although public statements and media reports have suggested approximate values for Pogačar's resting HR (37 bpm), maximal HR (200 bpm), and zone 2 power output (320–340 W at 150 bpm), these data were not considered sufficiently standardized to be used in the present analysis.

In the present study, $\dot{V}O_2max$ was instead derived from maximal aerobic power (MAP) using the power-to-oxygen conversion shown in Equation 7.

$$\dot{V}O2max = 60 \cdot \left(\frac{1000}{m}\right) \cdot \frac{MAP \div \eta}{(E_{O2}|RQ = 1)}$$

Equation (7)

2.4.1 *Estimating $\dot{V}O_2max$ from the Aerobic Endurance Index (AEI)*

For the final estimation of $\dot{V}O_2max$, this method allows maximal power to be interpolated over a duration of 6 ± 1 min, and the oxygen uptake required to sustain such a power output to be calculated. In accordance with the approach proposed by Pinot and Grappe,[28] this estimation is based on the relationship between power and the logarithm of time, fitted only over durations predominantly governed by aerobic metabolism and then mathematically extrapolated to a short duration considered representative of $\dot{V}O_2max$. The resulting power output is interpreted as a theoretical MAP, independent of specific anaerobic abilities.

The reference power profile (RPP) was reconstructed from the highest mean power outputs calculated in the present study across several exercise durations (e.g., 1, 3, 4, 20, 40, 60, and 120 min), derived from mechanical power calculations based on Tadej Pogačar's performances. In accordance with the approach proposed by Pinot and Grappe,[28] the decline in power with increasing duration can be described, over a wide range of exercise durations, by an approximately linear relationship between relative power, expressed as a percentage of MAP, and the natural logarithm of exercise duration (Equation 8).

$$P(t) = a \cdot \ln(t) + b$$

Equation (8)

where t is the duration (in minutes), and a (the slope) represents an aerobic endurance index (AEI), reflecting the athlete's ability to sustain a high fraction of MAP as exercise duration increases. This formulation is empirical and derives from fits applied to power profiles obtained under real-world ("field") conditions; it does not correspond to a mechanistic critical power–type model. Nevertheless, it enables robust interpolation of relative power over intermediate durations when multiple points of the RPP are available.

This method, by also analysing power outputs in two distinct ranges—between 1 and 10 minutes, and between 10 minutes and several hours—makes it possible to infer what Pinot and Grappe[29,30] refer to as time at MAP (T_MAP) and the associated MAP. This time and the corresponding power can be derived from the relationship shown in Equation 9.

$$\%MAP(t) = a \cdot \ln(t_{PMA}) + b$$

Equation (9)

However, the time at MAP derived from this model is short, often on the order of 3 to 4 minutes, and the associated power corresponds to a value that is unlikely to be unaffected by anaerobic capacity. It therefore appears reasonable to adopt an RQ of 1.1 if the MAP associated with this time at MAP derived from the Pinot and Grappe model is used.

Even though the resulting estimates are nearly identical, a duration of 6 ± 1 min and an RQ of 1.0 were retained as representative of a maximal aerobic effort in trained cyclists, in order to interpolate a $\dot{V}O_2max$-related power from the RPP. Accordingly, maximal 6-min power was calculated from two logarithmic equations describing the power–time relationship: the first fitted over the 1–10 min range, and the second over the 10 min to 2 h range.

The power corresponding to this duration, denoted $P_{6\pm1}$, was obtained from the RPP using the relative value %$MAP_{6±1}$ and then converted into watts based on the estimated MAP. This $P_{6±1}$ value was subsequently used as input for $\dot{V}O_2max$ estimation by combining the assumed mechanical efficiency with the energetic equivalent of oxygen as a function of the respiratory quotient.

2.4.2 *Aerobic Endurance and the Power-Duration Relationship*

Aerobic endurance was assessed from power–duration relationships observed in elite professional cyclists. Rather than if 85–90% of $\dot{V}O_2max$ can be sustained at critical power, endurance characteristics were constrained using real-world data showing that professional cyclists typically maintain approximately 80% of their 5-min maximal power during 30-min efforts, with limited interindividual variability among riders belonging to the top 10%.

Indeed, several studies show that the best professional cyclists competing for the general classification in Grand Tours can sustain between 80% and 83% of their 5-min maximal power (P5) for 30 minutes.[31–33] It is therefore not appropriate to recalculate $\dot{V}O_2max$ by assuming that critical power represents 85–90% of power at $\dot{V}O_2max$ in cycling. This constitutes an important critical point in the study by Berg.[6]

Even in the absence of direct physiological data, it appears highly unlikely that Tadej Pogačar could sustain 85–90% of his $\dot{V}O_2max$ for 40 min. The calculated power outputs over durations from 3 to 40 min indicate a record power profile (RPP) consistent with that typically observed in elite professional cyclists, without any marked singularity in the 20–40 min range. If such a capacity were present, one would expect a relatively small decline in power from short efforts to 20–40 min efforts, together with a more specific dominance in the 20–60 min range. Instead, Pogačar dominates elite cycling across the full spectrum of exercise durations from 3 to 60 min, rather than within this range alone.

Pogačar's power–duration profile was constructed from recalculated performances over durations of approximately 1, 3, 4, 20, 40, 60, and 120 minutes. These data made it possible to establish a representative curve and to interpolate the typical power associated with $\dot{V}O_2max$, estimated over a maximal effort duration of 6 ± 1 minutes.

For the final $\dot{V}O_2max$ calculation, it is essential to rely on Tadej Pogačar's best performances rather than averaging across all selected ascents. Indeed, some climbs were not performed at full offensive power, but rather in a defensive tactical context, which does not guarantee that the effort was truly maximal.

3 Results

3.1 Recalculated Mechanical Power Outputs

Recalculation of mechanical power outputs across all analysed ascents reveals systematic discrepancies relative to the values reported by Berg[6] (Table 2). When realistic aerodynamic, environmental, and rolling resistance parameters are applied, the recalculated power outputs are consistently lower than those obtained using Berg's original parameter set.[6]

For the Plateau de Beille ascent[34] (distance: 15630 m; elevation gain: 1235 m; mean altitude: 1162 m; temperature: 32°C at the bottom and 28°C at the summit; air density: 1.005 $kg \cdot m^{-3}$), the recalculated mechanical power is estimated at 430 ± 6 W after accounting for drafting over approximately two thirds of the climb, corresponding to 6.5 $W \cdot kg^{-1}$. This value contrasts with the power of 453 W (6.9 $W \cdot kg^{-1}$) reported in the initial analysis.

Comparable discrepancies are observed for the Hautacam ascent[35] (distance: 13420 m; elevation gain: 1052 m; mean altitude: 988 m;

temperature: 34°C at the bottom and 28°C at the summit; air density: 1.025 $kg \cdot m^{-3}$), with a recalculated power of 417 ± 6 W (6.3 $W \cdot kg^{-1}$), compared with an adjusted value of 441 W in the initial study. Temperatures on that day were particularly oppressive, reaching 34°C at the foot of the climb.

For the Mont Ventoux ascent[36] (distance: 20740 m; elevation gain: 1569 m; mean altitude: 1103 m; temperature: 27°C at the summit and 19°C at the base; air density: 1.03 $kg \cdot m^{-3}$), the recalculated mechanical power is estimated at 400 ± 6 W (6.1 $W \cdot kg^{-1}$), consistent with prolonged drafting behind other riders for at least 90% of the ascent. The initial analysis by Berg reported a value of 421 W.[6]

During the Peyragudes individual time trial[37] (distance: 7550 m; elevation gain: 564 m; mean altitude: 1230 m; temperature: 28°C at the bottom and 26°C at the summit; air density: 1.0065 $kg \cdot m^{-3}$), the recalculated power on the uphill section reaches 453 ± 7 W (6.9 $W \cdot kg^{-1}$), a value close to that reported by Berg,[6] namely 462 W. This agreement is consistent with the minimal influence of drafting and the adoption of aerodynamic positions specific to time-trial efforts.

The ascent of the Col de la Couillole[38] (distance: 15700 m; elevation gain: 1156 m; mean altitude: 1098 m; temperature: 31°C at the bottom and 27°C at the summit; air density: 1.015 $kg \cdot m^{-3}$) exhibits lower recalculated power outputs, estimated at 410 ± 6 W (6.2 $W \cdot kg^{-1}$), reflecting a non-maximal racing context. This value differs significantly from the 428 W reported by Berg.[6]

The Valmeinier climb[39] during the 2025 Critérium du Dauphiné (distance: 16230 m; elevation gain: 1176 m; mean altitude: 1283 m; temperature: 34°C at the bottom and 28°C at the summit; air density: 0.99 $kg \cdot m^{-3}$), which was not included in the initial study, yields a recalculated power of 432 ± 6 W (6.55 $W \cdot kg^{-1}$), sustained for 39 min 12 s under conditions of high temperature and moderate altitude. This value is comparable to that observed for the Plateau de Beille ascent under similar thermal conditions. Together with the Plateau de Beille climb, this represents Tadej Pogačar's highest performance records over the 2024 and 2025 seasons.

The Passo di Ganda ascent[40] during the 2025 Tour of Lombardy (distance: 9250 m; elevation gain: 660 m; mean altitude: 723 m; temperature: 21°C at the summit and 16°C at the base; air density: 1.11 $kg \cdot m^{-3}$) is also of particular interest, as it corresponds to an effort in which Pogačar rode sheltered for approximately 3.6 km before completing the final 5.6 km alone. The recalculated power yields a value of 458 ± 7 W sustained for 20 min 57 s, representing a performance essentially identical to that achieved during the Peyragudes individual time trial at the 2025 Tour de France.

The recalculated power outputs are markedly lower, with a mean value of 423 ± 6 W compared with 442 W reported by Berg.[6] These values appear more realistic.

Within the scope of the present work, four short-duration maximal power efforts by Tadej Pogačar were also recalculated over durations of approximately 1, 3, 4, and 12 minutes. This allows completion of the reconstruction of his RPP.

A first estimate concerns a maximal effort of approximately 1 minute performed during his attack on the Mont-Dore climb. The power of this effort was calculated dynamically from second-by-second data published on Strava. The result of this simulation yields a power output of 11.5 $W \cdot kg^{-1}$.[41]

A second estimate was obtained during the ascent of the Saint-Hilaire ramp[42] (distance: 1250 m; elevation gain: 114 m; time: 2 min 50 s), where the developed power is estimated at 562 ± 10 W sustained over 2 min 50 s.

The third power output was calculated for the Côte de la Redoute[43] during Liège–Bastogne–Liège 2025 and 2026 (distance: 1510 ± 10 m; elevation gain: 153 ± 2 m; air density: 1.17 ± 0.01 kg·m^{-3}; Crr: 0.003 ± 0.0005; CdA: 0.35 ± 0.02; $f_{(abri)}$ = 40%). Pogačar launched his attack 906 m from the summit, spending only 40% of the effort within the peloton and being exposed to a slightly unfavourable headwind, justifying the use of an CdA value of 0.35. The resulting power calculation yields 540 ± 8 W sustained for 3 min 58 s for 2025 and 572 ± 8 W for 3 min 45 s for 2026. All these calculations are consistent with power values directly reported by riders who have publicly shared their power data on Strava.

These short-duration power estimates are consistent with values observed in other professional cyclists who have made their power data publicly available, notably via the Strava platform, thereby supporting the plausibility of the calculations performed.

Furthermore, the power output sustained during the final two hours of Tadej Pogačar's solo ride at the World Championships in Kigali was also recalculated by the Velo2max association. Over this segment, the rider maintained an average power of approximately 360 ± 10 W[44] at a mean altitude of 1450 m, while sustaining an average speed of 43.4 km·h^{-1} over nearly 90 km, with a total positive elevation gain of approximately 1650 m. Given the environmental conditions of this effort, it is entirely reasonable to consider that a power output of around 375 W could be sustained for two hours by Tadej Pogačar under more favourable conditions.

Taken together, these data—spanning efforts ranging from one minute to several hours—allow a tighter constraint on the reconstruction of Tadej Pogačar's RPP and improve the overall coherence of the associated physiological estimates.

Table 2. Calculation of mechanical power for long ascents and comparison with Berg.[6]

Climb	Minutes of exercise	Calculated Power Output Berg[6]		Calculated Power Output (This study 2026)		Temperature
		W	W / kg	W	W / kg	
Plateau de Beille : TDF 2024	39	453	6.86	430 ± 6	6.51 ± 0.09	32-28°
Hautacam : TDF 2025	35	441	6.68	417 ± 6	6.32 ± 0.09	34-28°
Mont Ventoux : TDF 2025	54	421	6.38	400 ± 6	6.06 ± 0.09	27-19°
CLM de Peyragude : TDF 2025	23	462	7.00	453 ± 6	6.86 ± 0.09	28-26°
Col de la Couillole : TDF 2024	39	428	6.48	410 ± 6	6.21 ± 0.09	31-27°
Passo Di Ganda : Lombardi 2025	21	NC	NC	458 ±7	6.94 ± 0.1	21-16°
Valmeinier : Dauphiné 2025	39	NC	NC	432 ± 6	6.55 ± 0.09	34-28°
Isola 2000 : TDF 2024	36	446	6.75	NC	NC	-

3.2 Record Power Profile and Aerobic Endurance

The recalculated performances were used to construct a representative power–duration profile covering efforts of approximately 1 to 120 minutes (Table 3).

To further inform the power profile, we also examined data made publicly available by Tadej Pogačar. On 8 September 2024, he shared an Instagram[45] video showing a screenshot of a training ride that was also uploaded to Strava.[46] The session corresponded to a 240 km training ride completed in 6 h 20 min, at an average speed of 37.9 km·h^{-1}, with a normalized power of 326 W and a mean raw power of 277 W. The reported Training Stress Score (TSS) of 390 allows an approximate

Functional Threshold Power (FTP) of about 415 W to be inferred (Equation 10). However, because these data originate from public, non-standardized sources, they are not treated here as validation data in the strict scientific sense, but only as contextual elements for secondary corroboration.

$$FTP = NP \times \sqrt{\frac{Time\ (h) \times 100}{TSS}}$$

Equation (10)

This provides a reliable indication of Tadej Pogačar's power output over a 1-hour effort and can therefore be considered a robust data point.

This record performance profile (Figure 1) is similar to that observed across the datasets analysed by Valenzuela[31] and van Erp.[33] These authors showed that the power sustained during 30- to 40-min efforts corresponds to approximately 78–83% of maximal 5-min power.

It should be emphasized that the RPP was reconstructed from efforts performed in competition settings, under conditions that are rarely optimal for the full expression of maximal power. Cumulative fatigue related to race dynamics, as well as environmental constraints such as temperature and altitude, are likely to impair aerobic performance. In this context, the retained power values are most probably underestimated, on the order of up to ~2%. Consequently, the estimated MAP, ranging between 513 and 527 W, could reasonably lie at a slightly higher level, on the order of an additional ten watts.

Fitting the Pogačar RPP allows estimation of two characteristic log-linear relationships of the endurance index, one for the short-duration domain (1 to 10 minutes) and the other for the long-duration domain (10 to 240 minutes) (Table 4). Their intersection suggests that from approximately 3 min 48 s onward, the aerobic contribution becomes predominant in performance. However, the corresponding power (572 W) cannot be retained for $\dot{V}O_2max$ estimation, as it lies outside the dispersion band of the aerobic model, with a residual of ±10 W, corresponding to 1.53% standard deviations indicating a still substantial non-aerobic component. Accordingly, it is more appropriate to consider a duration of 6 ± 1 min as the representative window of MAP associated with $\dot{V}O_2max$, and, based on the reconstructed RPP and aerobic endurance modelling, to estimate MAP at 521 ± 7 W.

Table 3. Reconstruction of Tadej Pogačar's Record Power Profile. Power values normalized to a body mass of 66 kg.

Duration	Gross Power (W)	Power / kg	Intensity Zone
1 minute (acceleration at Mont-Dore)	759 ± 15 W	11.3 $W \cdot kg^{-1}$	Zone 6
3 minutes (Rampe St Hilaire)	562 ± 10 W	8.5 $W \cdot kg^{-1}$	Zone 5 - 6
4 minutes (Côte de la Redoute)	540 and 572 ± 8 W	8 $W \cdot kg^{-1}$	Zone 5
MAP (6 minutes) (recalculated)	520 ± 7 W	7.8 $W \cdot kg^{-1}$	Zone 5
10 minutes (recalculated)	490 ± 7 W	7.4 $W \cdot kg^{-1}$	Zone 5
20 minutes (Passo Di Ganda, Peyragudes)	458 ± 6 W	6.9 $W \cdot kg^{-1}$	Zone 4 - 5
40 minutes (Beille, Valmeinier)	432 ± 6 W	6.5 $W \cdot kg^{-1}$	Zone 4
60 minutes (FTP) (recalculated)	415 ± 6 W	6.3 $W \cdot kg^{-1}$	Zone 4
120 minutes (Kigali) (recalculated)	375 ± 6 W	5.7 $W \cdot kg^{-1}$	Zone 3
240 à 360 minutes (recalculated)*	320 à 340 W	4.8 à 5.1 $W \cdot kg^{-1}$	Zone 2 (upper limit)

* Power reported by Tadej Pogačar in an interview. Zone 2 riding consisting of 4 to 5 hours of cycling between 320 and 340 W.

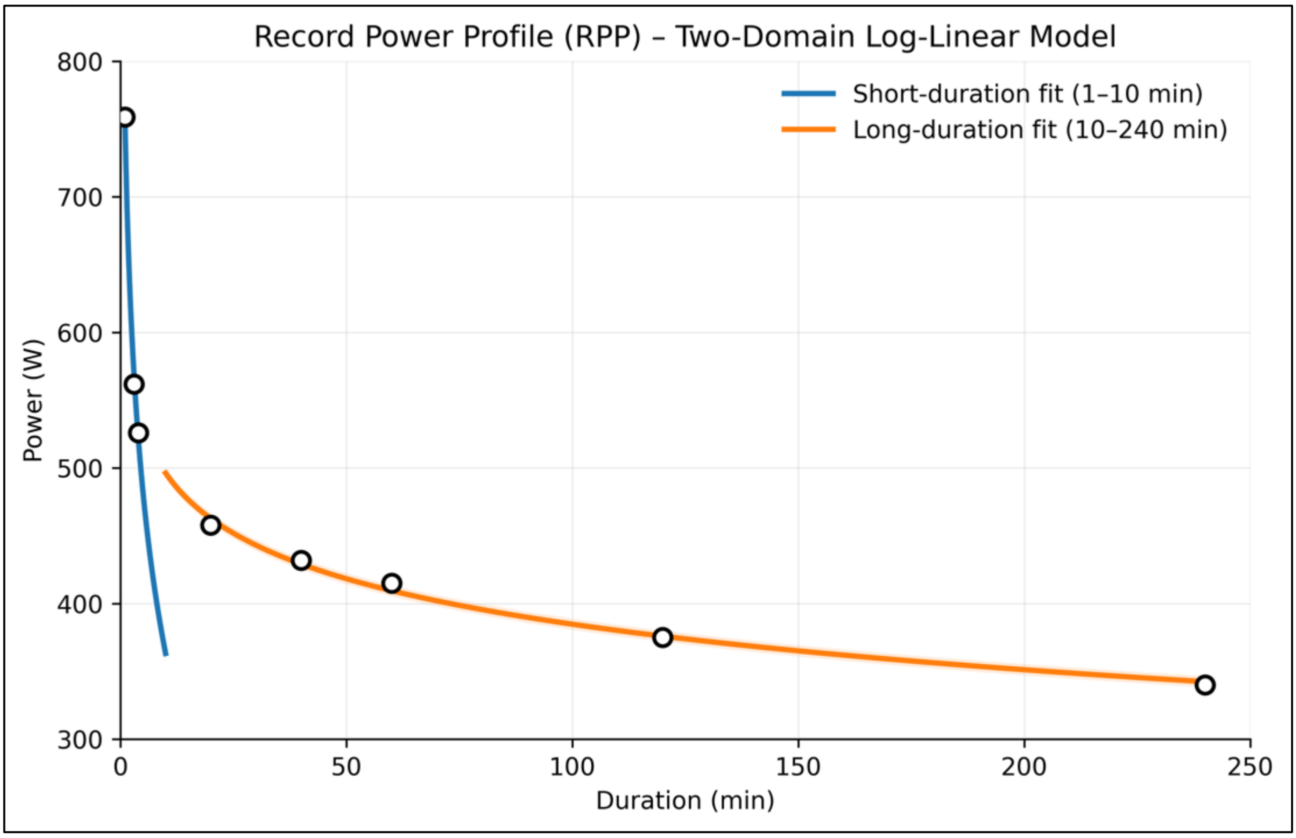

Figure 1. Pogačar Record Power Profile (RPP) reconstructed from best observed mean power outputs. The solid line represents a smooth interpolation fitted on Ln(time), displayed on a linear time scale.

Table 4. Short- and long-duration Aerobic Endurance Index equations (Pinot and Grappe modeling).

Aerobic Endurance Index (AEI)	Equation	Standard Dispersion	R^2
Equation IEA $T_{1\text{-}10\ minutes}$	$P = -116.1 \pm 18.1 \times Ln(t) + 749.4$	29.7 W	97.4 %
Equation IEA $T_{10\text{-}240\ minutes}$	$P = -46.11 \pm 4.54 \times Ln(t) + 599.4$	5.0 W	98.6 %
Equation %MAP in function of duration	$\%MAP = -9.63 \pm 0.62 \times \text{Ln}(t) + 111.1$	1.53 %	98.8 %
T_{MAP} (intersection aera) / Watts	3 minutes 48 seconds / 572 W		
MAP for 6 minutes ± 1	521 ± 7 W		

3.3 $\dot{V}O_2$max calculation

Based on the recalculated mechanical power outputs, the reconstructed power–duration profile, physiologically plausible respiratory quotient values (≤ 0.95) for a 40-min effort, and a gross efficiency of 23 ± 0.2%,[48–50] the oxygen uptake required to sustain the observed performances was calculated.

After correction for environmental factors, including altitude and thermal stress, the $\dot{V}O_2$max required to sustain, for example, an effort of 432 W for approximately 40 minutes under conditions comparable to the Valmeinier climb is estimated at 100.7 ± 3 mL·min^{-1}·kg^{-1}. This value integrates all mechanical recalibrations, endurance constraints, and uncertainty propagation applied in the present analysis.

These results can be placed in perspective by comparison with the observed power outputs and $\dot{V}O_2$max estimation of Thibaut Pinot, for whom a complete RPP has been published.[51] Whereas Tadej Pogačar is capable of sustaining power outputs on the order of 430 W during prolonged efforts, the corresponding power observed for Thibaut Pinot is approximately 400 W. Based on this RPP, the estimated $\dot{V}O_2$max for Thibaut Pinot is 88 ± 3 mL·min^{-1}·kg^{-1}. This estimate is consistent with a laboratory measurement performed at the beginning of the 2013 season, which reported a $\dot{V}O_2$max of 85 mL·min^{-1}·kg^{-1}—a value that may have been slightly underestimated due to the non-maximal physiological condition typically observed early in the season.

Other studies on Grand Tour-winning cyclists provide useful points of comparison for the results obtained here. For example, van Erp[52] showed that Tom Dumoulin was able to sustain 6.2 and 5.6 W·kg^{-1} over durations of 20 to 60 min, respectively, corresponding to approximately 5.9 ± 0.1 W·kg^{-1} for a 40-min effort comparable to Pogačar's performance at Valmeinier, for example. However, Tom Dumoulin's $\dot{V}O_2$max is not available. It can only be noted that this level of power is nearly 10% lower than that of the Slovenian rider Tadej Pogačar.

Another study by Bell et al.[48] reported a MAP of 525 W in Christopher Froome, associated with a $\dot{V}O_2$max of 5.91 L·min^{-1}, i.e. 84.1 mL·kg^{-1}·min^{-1}. However, within the framework of the present analysis, this study does not allow a direct relationship to be established between RPP and $\dot{V}O_2$max, unlike the case of Thibaut Pinot, for whom both a RPP and a $\dot{V}O_2$max measurement obtained early in the season are available. Indeed, the value reported by Bell et al. was obtained using a different exercise protocol, based on long stages with 25-W increments every 4 min, during which oxygen uptake was measured. Under these conditions, the power attained cannot be directly equated with a reference value derived from a RPP, and the measured $\dot{V}O_2$ may furthermore not strictly correspond to a true $\dot{V}O_2$max according to the usual validation criteria.

4 Discussion

4.1 Sensitivity of the Model Assumptions and Physiological Implications of the Required $\dot{V}O_2$max

The limitation of this interpretation nevertheless lies in the commonly accepted assumption of a quasi-linear relationship between mechanical power output and oxygen consumption. However, several studies[53,54] have shown that during severe or prolonged exercise, $\dot{V}O_2$ kinetics may exhibit a slow component and fail to reach a true steady state, calling into question the validity of directly inferring $\dot{V}O_2$ from mechanical power alone. These observations suggest that the power–$\dot{V}O_2$ relationship may be altered when exercise is pushed to extreme intensities for several tens of minutes, and they argue in favour of direct measurements of gas exchange under ecological (field-based) conditions to validate such assumptions.

Nevertheless, this does not call into question our estimation of the power associated with $\dot{V}O_2$max, which is based on a short effort duration that does not allow sufficient time for a drift in the power–$\dot{V}O_2$ relationship to occur. By contrast, it is possible that the $\dot{V}O_2$ calculated for a 40-min effort is underestimated, thereby highlighting a potential alteration in metabolic efficiency under prolonged high-intensity conditions.

The present reanalysis highlights the strong sensitivity of $\dot{V}O_2$max estimates derived from power output to the mechanical and physiological assumptions adopted. While the general methodological framework proposed by Berg[6] is theoretically coherent, the results show that small variations in parameter selection can lead to substantial differences in the inferred $\dot{V}O_2$max values. This sensitivity is particularly pronounced when mechanical power, aerobic endurance, and metabolic cost are not constrained by empirical, real-world observations from professional cycling.

A first major finding concerns the modelling of aerobic endurance. The assumption that 85–90% of $\dot{V}O_2$max can be sustained at critical power—although sometimes observed in running when expressed in terms of speed—does not appear to be supported by power–duration data in professional cycling. The data analysed here, as well as numerous independent datasets, show that elite cyclists consistently sustain approximately 80–83% of their 5-min maximal power during 30–40 min efforts, with limited interindividual variability among leading riders. Overestimating this fraction mechanically leads to an underestimation of the $\dot{V}O_2$max required to explain prolonged performances.

A second key factor concerns the energetic equivalent of oxygen and the respiratory quotient values assumed for prolonged high-intensity efforts. Using values corresponding to respiratory quotients close to or exceeding 1.0 implies an almost exclusive reliance on carbohydrate metabolism, or even a contribution from anaerobic pathways. Such conditions appear poorly compatible with efforts lasting 30–50 minutes performed after several hours of racing. Experimental data instead show a progressive decrease in respiratory quotient as exercise duration increases, reflecting a growing contribution of lipid oxidation. Restricting the respiratory quotient to physiologically plausible ranges therefore have a major impact on estimating the metabolic cost of exercise.

The recalculated mechanical power outputs further illustrate the importance of realistic parameterization of aerodynamic and environmental effects. Assumptions derived from time-trial conditions, laboratory-based rolling resistance measurements, or standard sea-level air density values can lead to biased estimates of climbing power. Explicit integration of drafting effects, altitude, and thermal stress results in lower mechanical power estimates, but these reductions are largely offset by the increased metabolic cost associated with realistic modelling of endurance and substrate utilization.

When all these factors are considered, the $\dot{V}O_2$max required to sustain the analysed performances converges toward a value on the order of 100.7 ± 3 $mL{\cdot}min^{-1}{\cdot}kg^{-1}$. Such a value lies beyond the upper limits of $\dot{V}O_2$max currently documented in the scientific literature.

Direct laboratory measurements exceeding 95 $mL{\cdot}min^{-1}{\cdot}kg^{-1}$ in cyclists are extremely rare and rely on an isolated case.[55] The case of the young cyclist Oskar Svendsen, for whom a $\dot{V}O_2$max of approximately 96 $mL{\cdot}min^{-1}{\cdot}kg^{-1}$ has been reported, represents a rare observation in the available scientific literature. However, this isolated case cannot be used as a robust upper bound of human physiological capacity for at least two reasons.

First, the longitudinal measurements presented in this publication show a prior plateau of $\dot{V}O_2$max around 85 $mL{\cdot}min^{-1}{\cdot}kg^{-1}$ over the three preceding tests, followed by an abrupt increase of more than 13.6%, whereas the maximal power achieved during testing increased only modestly (less than 5%), rising on average from 504 W to 525 W. Such a decoupling between the evolution of measured maximal power and the reported increase in $\dot{V}O_2$max warrants discussion, as it may reflect either methodological variability or an atypical physiological change.

Second, haematocrit values ranged from 45.0% to 48.8% over the follow-up period, yet the authors did not specify when these variations occurred. However, in many endurance-training settings, plasma volume expansion typically leads to a relative reduction in haematocrit as aerobic adaptations become consolidated.[56] Although such variation cannot be interpreted on its own, it nonetheless provides an additional reason why this single case should not be used as a normative reference. Moreover, the authors acknowledged a possible measurement error of 3% and noted that the subject underwent a further test in another laboratory the following year, yielding a value of 91 $mL \cdot kg^{-1} \cdot min^{-1}$.

Thus, despite its scientific interest, all these considerations argue for a cautious interpretation: this isolated case cannot, on its own, be regarded as a reliable upper bound of human $\dot{V}O_2max$ physiology.

Another remarkable observation has been reported in an Olympic gold medal-winning cross-country skier, for whom a $\dot{V}O_2max$ of 90.6 $mL \cdot kg^{-1} \cdot min^{-1}$ was documented in the scientific literature. In addition, self-reported values of a similar magnitude have been mentioned by some world-class athletes, notably 88–92 $mL \cdot kg^{-1} \cdot min^{-1}$ in the case of Kilian Jornet[57] and 92–93 $mL \cdot kg^{-1} \cdot min^{-1}$ in that of Greg LeMond[58] and David Gaudu.[59] Although such declarations do not arise from a published and standardized scientific protocol, they nonetheless provide contextual indications that extremely high $\dot{V}O_2max$ values have been claimed in a few exceptional athletes.

More recently, the case of Kristian Blummenfelt attracted substantial media attention after a value of 101.1 $mL \cdot kg^{-1} \cdot min^{-1}$ was circulated on social media.[60] This value should, however, be interpreted with caution. The publicly circulated image was discussed as displaying an RER of 0.93; if that reading is correct, it would be difficult to reconcile with the secondary criteria commonly used to support a valid $\dot{V}O_2max$ determination, for which an RER ≥ 1.10 is often expected. Under these conditions, this recent value cannot be regarded as established with the same degree of robustness as a published measurement accompanied by a full description of the protocol.

Moreover, available data suggest an inverse relationship between $\dot{V}O_2max$ and gross efficiency in elite cyclists,[61] which makes the coexistence of very high $\dot{V}O_2max$ values with exceptionally high sustainable power outputs even more singular.

It should be emphasized that the present study does not aim to establish a single causal explanation for the observed performances. Rather, it shows that, under realistic mechanical and physiological constraints, explaining these performances implies a $\dot{V}O_2max$ that exceeds the values currently documented in the scientific literature. This observation highlights the need for great caution when interpreting power-based models, particularly when they are used to normalize or contextualize exceptional performances without an explicit analysis of uncertainties.

Several limitations must be acknowledged. The analysis relies on indirect estimates of mechanical power rather than data obtained from on-bike power meters for the primary subject, and some environmental parameters were inferred from available information. Nevertheless, the explicit integration of uncertainties and the use of conservative parameter ranges limit the impact of these constraints. The conclusions remain robust with respect to reasonable variations in the main underlying assumptions.

Beyond the physiological interpretation of the estimated $\dot{V}O_2max$, the present results also raise a broader question regarding the statistical structure of exceptional performances within an elite field.

4.2 Exceptional Performances and Statistical Discontinuity

Beyond the absolute value of the $\dot{V}O_2max$ estimated in this reanalysis, the results raise a more general question regarding the interpretation of exceptional performances in elite sport. When examining the distribution of performances within homogeneous populations of world-class athletes, extreme values are generally expected to fall within a statistical continuity of the distribution. However, several of the performances analysed here appear to depart from this expectation, as illustrated by the unusually pronounced separation observed during certain key events, notably the Peyragudes individual time trial (Figure 2).

The panels in Figure 2 illustrate a clear departure from a Gaussian distribution of finishing times in the 2025 Peyragudes individual time trial. Two riders clearly stand out with a very pronounced dominance. Over an effort lasting only 23 minutes, the third-ranked rider is already relegated to 1 min 20 s behind, while the fifth-ranked rider is more than 2 minutes back.

From a statistical standpoint, the existence of such discontinuities calls into question the assumption that the full set of observed performances can be explained solely by natural interindividual variability within a stable physiological distribution. While exceptional talent and genetic determinants may account for part of this variability, such sharp breaks in performance coherence warrant specific scientific scrutiny rather than implicit normalization.

It should be emphasized that this observation does not, in itself, constitute evidence for any particular mechanism. It nevertheless highlights the need to clearly distinguish an expected statistical extreme from a potential deviation requiring additional explanatory hypotheses. Failing to make this distinction risks conflating physiological limits, methodological artifacts, and unexamined external factors.

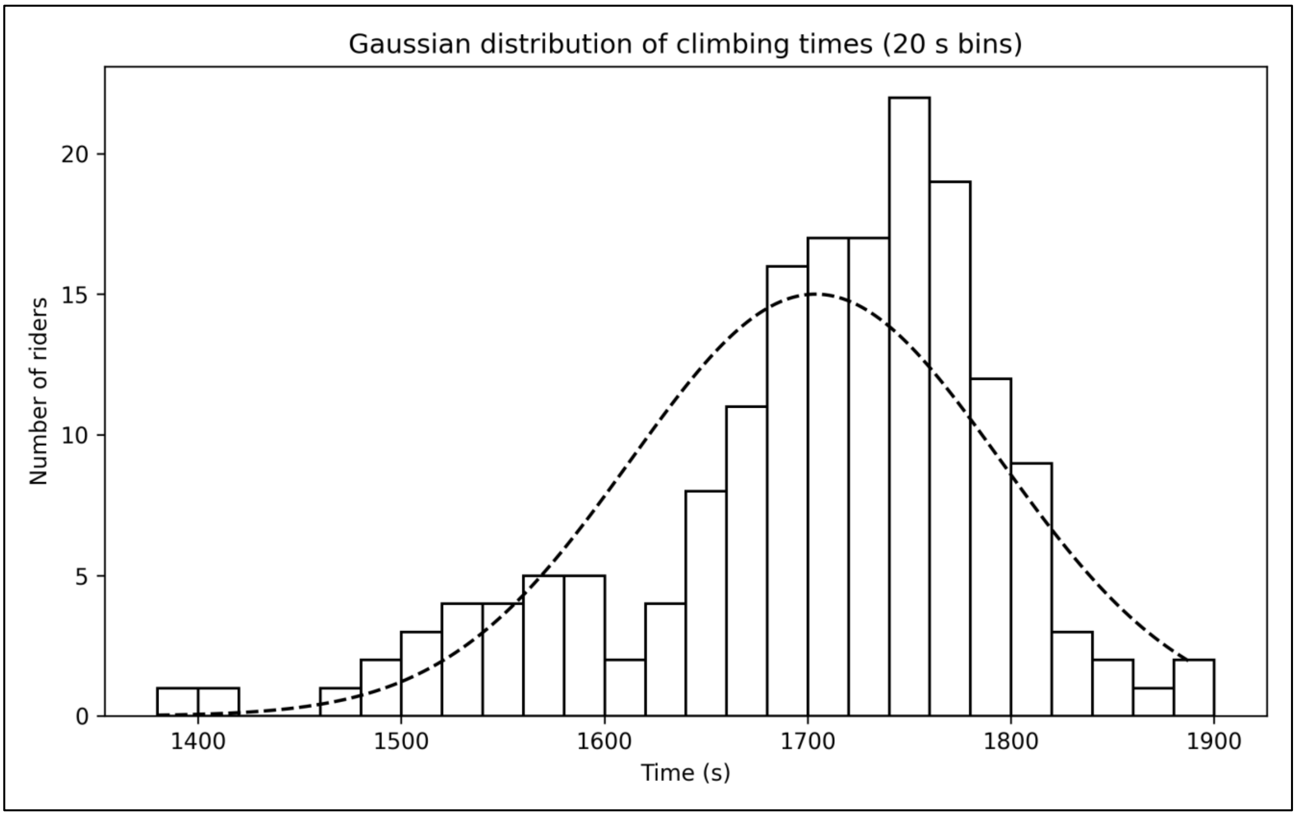

Figure 2. Peyragudes individual time trial, Tour de France 2025. Distribution of climbing times for the 171 participants, shown as a histogram with 20-second bins. The dashed curve represents the fitted Gaussian distribution. Winner: 23:00.00. Mean: 28:23.88. SD: 91.22 s. Bin width: 20 s.

5 Practical Applications

For cycling performance analyses, this study proposes a reproducible procedure to estimate mechanical power during climbs and to infer the associated aerobic demand, in a manner compatible with field data (Strava segments and environmental information). Concretely, the user can:

1. Recalculate power for a given ascent from speed, gradient, and resistive forces (gravity, rolling resistance, aerodynamic drag), using realistic parameter ranges (CdA, Crr, mass, air density);
2. Apply a race-context correction when drafting can be identified (reduction of the aerodynamic term);
3. Reconstruct the RPP when enough maximal efforts between 3 and 120 minutes are available;
4. Compute $\dot{V}O_2max$ calibrated on the RPP, using a representative effort duration for $\dot{V}O_2max$ with coherent parameters, while introducing uncertainty related to respiratory quotient, gross efficiency, time at $\dot{V}O_2max$, and MAP.

This approach provides a standardizable framework with explicit uncertainty calculation to compare ascents, document the effects of conditions (altitude, temperature, drafting), and limit biases arising from arbitrary parameter choices.

These results are not intended to establish a causal explanation for the observed performances, nor to challenge the principle of power-based $\dot{V}O_2max$ estimation per se. Rather, they underscore the critical importance of rigorous parameter calibration, realistic modelling of aerobic endurance, and explicit consideration of uncertainties when interpreting such estimates. In the absence of these precautions, power-based models may lead to an underestimation of the physiological demands associated with exceptional performances.

6 Conclusions

This study provides a quantitative reanalysis of a recent power-based estimate of Tadej Pogačar's estimated $\dot{V}O_2max$. By reassessing the main mechanical and physiological parameters, constraining aerobic endurance using power-duration relationships observed in elite professional cyclists, and explicitly incorporating an uncertainty analysis, the present work indicates that Berg's estimated mechanical power was very likely overestimated.[6] In contrast, the level of estimated $\dot{V}O_2max$ required to explain the performances analysed appears substantially higher than that previously reported by Berg.[6]

When realistic assumptions are applied, the $\dot{V}O_2max$ required to sustain the observed power outputs converges toward a value of approximately 100.7 ± 3 $mL·min^{-1}·kg^{-1}$. This value lies beyond the extreme upper limits of $\dot{V}O_2max$ currently documented in the scientific literature and exceeds those reported in most studies based on direct laboratory measurements in elite cyclists.

More broadly, this reanalysis highlights the need for great caution when normalizing and contextualizing extraordinary sporting performances using simplified physiological models. Future work combining high-resolution power data, direct physiological measurements, and transparent quantification of uncertainties will be essential to better characterize the limits of performance in elite professional cycling.

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Data Availability: The data used in this study were obtained exclusively from publicly available sources (race data, timed segments, and publicly accessible environmental information). No private or confidential datasets were used.

Ethical Considerations: This study involved no experimentation with human or animal subjects and relied solely on secondary analysis of publicly available data. Therefore, no ethical approval was required.

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Conflicts of Interest: The authors declare no conflict of interest.

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