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SCHOLARLY REVIEW

UCI Sports Nutrition Project: The Science of Successful Cycling Performance

Pedro L. Valenzuela,[1,2] Peter Leo,[3,4] Manuel Mateo-March,[5,6] Gabriele Gallo,[7,8] Stephen Seiler,[9] and Iñigo Mujika[10,11]

[1]GENUD Toledo Research Group, Faculty of Sport Sciences, University of Castilla-La Mancha, Toledo, Spain; [2]Department of Systems Biology, University of Alcalá, Madrid, Spain; [3]Department of Sport Science, University of Innsbruck, Innsbruck, Austria; [4]UniSA Allied Health & Human Performance, University of South Australia, Adelaide, SA, Australia; [5]Faculty of Sport Sciences, Universidad Europea de Madrid, Madrid, Spain; [6]Department of Sport Sciences, Sports Research Center, Universidad Miguel Hernández de Elche, Alicante, Spain; [7]Department of Neuroscience, Rehabilitation, Ophthalmology, Genetics, Maternal and Child Health, University of Genoa, Genoa, Italy; [8]Centro Polifunzionale di Scienze Motorie, University of Genoa, Genoa, Italy; [9]Department of Sport Science and Physical Education, University of Agder, Kristiansand, Norway; [10]Department of Physiology, Faculty of Medicine and Nursing, University of the Basque Country UPV/EHU, Leioa, Basque Country; [11]Exercise Science Laboratory, School of Kinesiology, Faculty of Medicine, Universidad Finis Terrae, Santiago, Chile

Cycling is one of the most popular sports worldwide, with competition events ranging from a few seconds (e.g., track sprint) to several days (e.g., road cycling 3-week Grand Tours). Professional cycling is arguably at the pinnacle of endurance sport demands due to the large number of events, range in durations, and variation in race conditions that these athletes must successfully negotiate. Numerous factors can affect performance in cycling, notably the type of event (e.g., track vs. road, single-day vs. multistage race); extrinsic conditions (e.g., race profile, weather conditions, altitude, team tactics); and individual variables (e.g., mental, physical, physiological, and technical attributes, nutritional strategies). In the present review, we aim to summarize the main factors underlying cycling performance. Particularly, we discuss current literature quantifying physiological and energetic demands imposed by races of different cycling modalities—albeit with a particular focus on road cycling—the factors associated with success in these races, the physical and physiological characteristics of elite/professional cyclists and their training regimens, and how these factors may be influenced by nutrition. Continued development in elite cycling requires a combination of traditional physiological markers with individual anthropometric and power–duration curve characteristics, as we move toward clustering of typologies and, ultimately, individual optimization of the training process.

Keywords: endurance, cyclists, physiology

The sport of cycling is broad and includes a variety of specialties such as mountain biking (MTB), track cycling, bicycle motocross, cyclo-cross, and road cycling. The physiological and biomechanical demands vary extensively between cycling modalities, as well as between events within each modality. These demands also determine the anthropometric and physiological characteristics, training methods, and nutritional strategies associated with optimal performance.

Road cycling includes multiday (typically five to eight stages) and single-day competitions. Among the former, the 3-week Grand Tours (Giro d'Italia, Tour de France, Vuelta a España), with their 21 stages and mix of flat, semimountainous, mountain stages, and individual time trials (TTs), are probably the most famous and physically demanding events. Even among World Tour (WT) level professional cyclists, the rigors of 3 weeks of daily racing are not well tolerated by everyone. Each of the eight riders carefully selected to race a Grand Tour from the ~30 members of a professional WT team will typically specialize in one or two stage types (e.g., sprinters, TT specialists, climbers, general classification contenders, all-rounders) based on their physique and physiological qualities. Apart from stage races, there are also prestigious single-day road races, notably the *Monuments* (i.e., Milan–San Remo, Tour of Flanders, Paris–Roubaix, Liège–Bastogne–Liège, and Il Lombardia), and some riders also focus their preparation to peak for these events. In addition, although road cyclists primarily represent their trade teams, they can also represent their national teams in events such as the World Championships and the Olympic Games, which usually consist of two separate events: a mass-start race and a TT. Typically, a WT level cyclist will start 55–80 races during a competitive season that spans from late January to mid-October. It is important to distinguish male professional cycling from female professional cycling here. As Figure 1 shows, men race over longer distances in both 1-day and stage races. The longest stage races on the female's side are currently nine stages, with most being three to four stages. For example, men's 1-day races in the WT category average ~225 km versus 145 km for women. During stage races, daily stage distances are typically shorter for both men and women compared to 1-day races. Overall, these differences result in average race duration for women being shorter by 1.5–2 hr.

Moving off the (mostly) paved roads of road cycling, track cycling encompasses all events that take place indoors and outdoors on a wooden-surfaced 250-m track. Track events can be divided between track sprint and track endurance. Those events range from a 200-m flying sprint of approximately 10 s to a >50-min event such as the Madison (see Table 1 and Craig and Norton (2001) for more details). In hilly and rocky forest landscapes, there are several MTB subdisciplines (e.g., downhill, four cross, enduro, E-MTB), although

Leo https://orcid.org/0000-0002-4501-7688
Mateo-March https://orcid.org/0000-0003-4418-8263
Gallo https://orcid.org/0009-0001-5481-7003
Seiler https://orcid.org/0000-0001-8024-5232
Mujika https://orcid.org/0000-0002-8143-9132
Valenzuela (Pedro. Valenzuela@uclm.es) is corresponding author, https://orcid.org/0000-0003-1730-3369

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the cross-country modality is probably the most popular after its inclusion in the 1996 Olympic Games, named in this first appearance as Olympic cross-country (see Impellizzeri & Marcora, 2007 for more details). However, shorter and longer events such as cross-country short circuit and cross-country marathon, respectively, are also popular. The general characteristics of the abovementioned cycling events are summarized in Table 1.

As outlined above, numerous factors can affect individual performance in cycling, notably the type of discipline and event, but also other extrinsic (e.g., race characteristics, environmental conditions, teams' tactics) and individual variables (e.g., mental, physical, physiological, and technical attributes, nutritional strategies; Phillips & Hopkins, 2020). In the present review, we aim to briefly summarize and connect current evidence on the physical demands of cycling races, the factors underlying performance in these events, the physical/physiological characteristics of elite/professional cyclists, their training routines, and how these factors may be influenced by nutrition. To make the length of this article manageable, we will mainly focus on the demands of road cycling, since this discipline encompasses many of the key performance influencing variables.

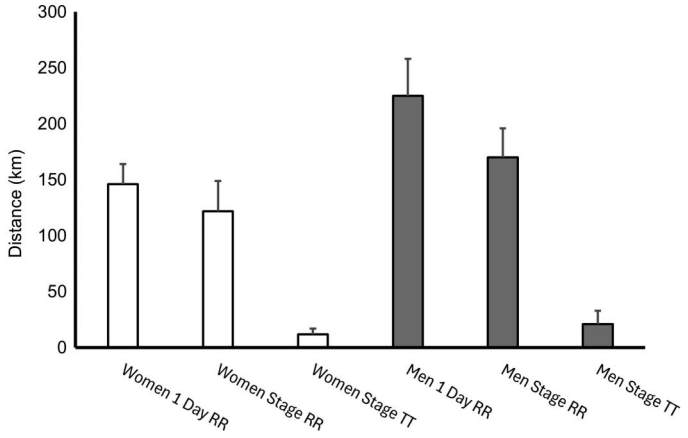


Figure 1 — Average distance of female and male World Tour level road races in 2024 (Stephen Seiler, unpublished data). Data are shown for 1-day RR as well as for TT and other stages within a multiday RR. RR = road races; TT = time trials.

Physical Demands of Professional Cycling Races

Three-week Grand Tours are often considered the epitome of endurance exercise performance. These races have been proposed as the ceiling of sustained daily energy expenditure in humans, with an estimated energy cost of approximately four to five times the daily basal metabolic rate throughout the 3-week period (Hammond & Diamond, 1997; Peterson et al., 1990; Thurber et al., 2019). In a classic study from the 1980s, Westerterp et al. (1986) used doubly-labeled water method (isotopes ^{2}H and ^{18}O, the gold standard method for free-living energy expenditure estimation) on four riders across 22 days during the >4,000 km and 21 stages of the Tour de France, and reported a total daily energy expenditure (TDEE) ranging from 6,931 to 8,604 kcal (Westerterp et al., 1986). Some years later, in a subsequent edition of the Tour de France but using different equations, the same research group estimated a TDEE of ~6,070 kcal (Saris et al., 1989). More recently, Van Hooren et al. (2022) estimated a TDEE of ~7,648 kcal for professional cyclists in the Vuelta a España (Van Hooren et al., 2022) and a similar TDEE (6,525 kcal) for a single-day race such as Ardennes classics. Grand Tour stages can be roughly classified as *flat, hilly, mountain stages,* or *time trial*. However, in Grand Tours, the term "flat" is somewhat of a misnomer as even relatively flat stages can have 1,000–2,000 m of total vertical climbing. "Mountain" stages are distinguished from "hilly" stages by typically having fewer but longer climbs and often mountain finishes. Figure 2 shows estimated TDEE for all eight male riders of a single team across all 21 stages of the 2024 Tour de France. Differences in rider body mass account for a ~2,000 Kcal variation in TDEE. Mountain stages tend to require the largest energy expenditures, with TTs being much less energetically

Table 1 Summary of the Characteristics of Some of the Main Cycling Events

	Road cycling						Track cycling			MTB		
	Grand tours (20–21 race stages, two rest days)				Non-Grand-Tour		Track sprint	Track endurance	Track sprint			
	Flat stages	SMT stages	200–1,000 m	Timed events	Single day	Multiday	200- to 1,000-m sprint	TT	Pursuit	XCO	XCC	XCM
Days	5–8	4–6	6–9	1–3	1	2–10	1–3	1–3	1–3	1	1	1
Distance	~150 to 220 km	~150 to 220 km	~150 to 200 km	<60 km	~200 to 300 km	~150 to 240 km	200–1,000 m	3,000–4,000 m	20–2,000 laps*	~30 km	~10 km	60–160 km
Time	~4 to 5 hr	~5 to 6 hr	~5 to 6 hr	<1 hr	~5 to 7 hr	~5 to 6 hr	~10 to 60 s	~3–4 min	~8 to 60 min	~1 to 2 hr	20–60 min	240–500 min
Mean speed (km/hr)	~45	~40	~35	~50	~40	~35 to 40	>70	>60	~50 to 60	~22.5	~30	~25
TEG (m)	<2,000	>2,000	>3,000	<1,000	~1,000 to 4,000	~2,000 to 2,500	n/a	n/a	n/a	~1,000 to 1,500	~250 to 500	~2,000 to 4,000

Note. Data obtained from Craig and Norton (2001), Impellizzeri and Marcora (2007), and Sanders et al. (2019). MT = mountainous stage; SMT = semimountainous stage; TEG = total elevation gain; TT = time trial; XCO = cross-country Olympic; XCC = cross country short circuit; XCM = cross-country marathon; n/a = nonapplicable.
*One lap corresponds to 250 m.

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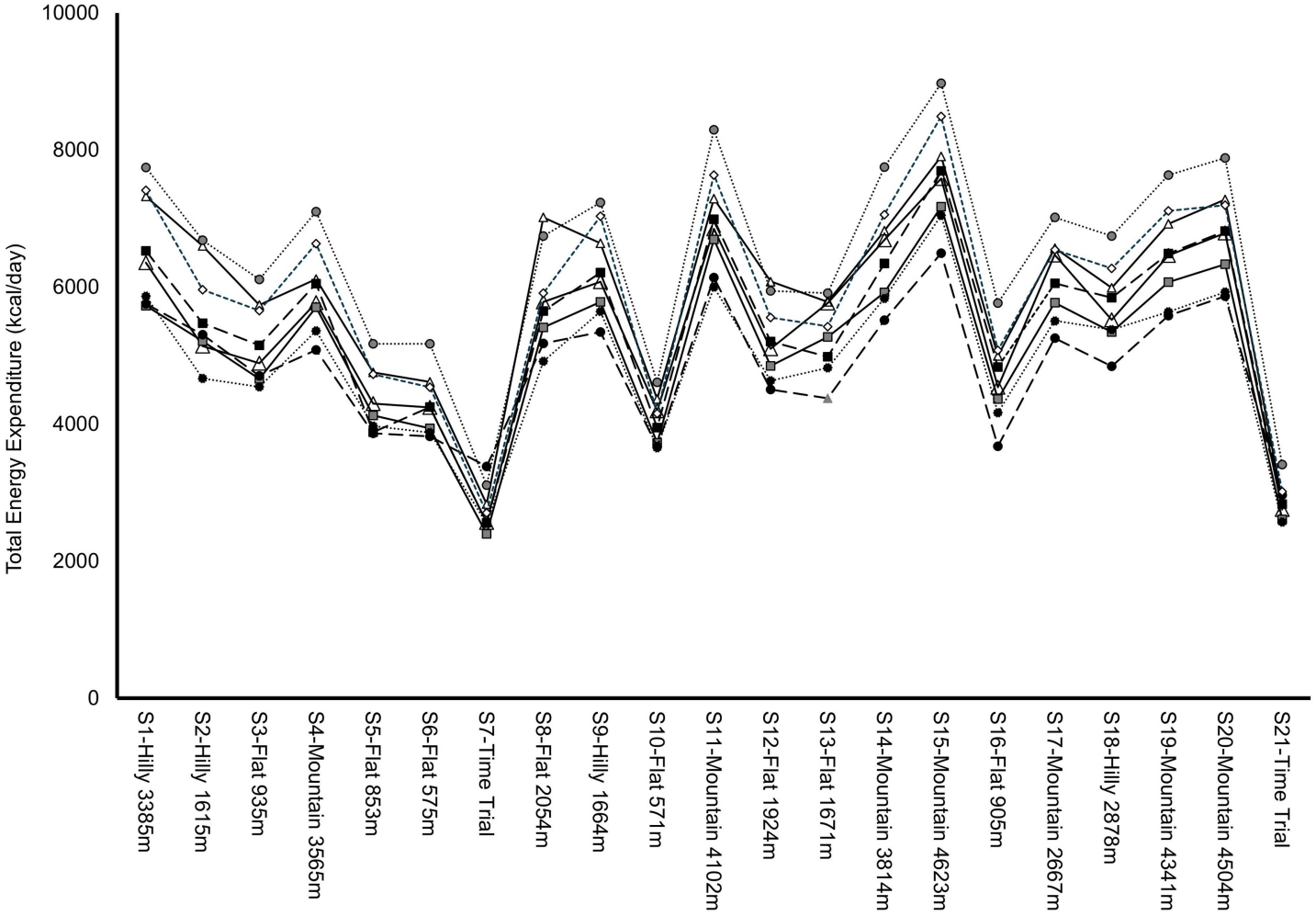


Figure 2 — Total daily energy expenditure estimated for eight male riders from a single team during the 2024 Tour de France (Stephen Seiler, unpublished data). Stages are classified as Flat, Hilly, Mountain, or Time Trial, with total vertical climbing meters for each stage. Riders' body mass ranged from ~60 to ~90 kg. Data were computed attending to resting metabolic rate estimations (Mifflin et al., 1990), mechanical work-derived energy expenditure assuming a 23% efficiency, and a conservative estimated factor of nonexercise physical activity levels (~1.4 times the resting metabolic rate, equivalent to little or no strenuous physical activity in adults; Shetty, 2005) adjusted on an individual and daily basis. Data were obtained from a professional cycling team.

demanding due to their comparatively short length. Although comparable data from professional female cyclists are still scarce, a recent case study also reported a TDEE of 7,572 kcal in a 29-year athlete competing in the 8-day Tour de France Femmes (Areta et al., 2024). Meeting these sustained high daily energy demands is therefore key for ensuring adequate performance.

Despite the length of single-day races, and the sustained load of stage races and Grand Tours, average power outputs (PO) can be astonishingly high. For instance, professional WT male cyclists reach an average PO of 3.8 W/kg across the ~80 cycling hours of a Grand Tour, with slightly lower values observed in ProTeam male cyclists (3.4 W/kg; Muriel et al., 2022). However, these values differ from stage to stage depending on the type of stage and cyclist's morphology (Sanders & Heijboer, 2019; Sanders & van Erp, 2021; Vogt et al., 2007). For instance, Sanders et al. (2019) reported an average PO of ~5.1 W/kg during TTs within a men's Grand Tour, whereas a lower PO was observed during mountainous stages (~3.5 W/kg) and particularly during semimountainous and flat stages (3.0 and 2.7 W/kg, respectively; Sanders & Heijboer, 2019). Moreover, the demands of both multistage and 1-day races depend on the race category. For instance, higher average PO values have been reported for *Monuments* compared to other single-day races such as WT or *Hors Category* (ProSeries) events (3.3 vs. 3.1 W/kg, respectively) in male cyclists (van Erp & Sanders, 2020).

While available data are less extensive, similar findings are observed in female road cyclists, albeit with smaller differences between race levels (van Erp & Lamberts, 2023). It is worth noting that male races are characterized by longer riding distance and time compared to female ones (Table 2; Sanders et al., 2019). A study comparing data from male and female WT cyclists during races reported that the latter attained an average PO of 2.8 W/kg, which represents a small difference with the relative PO observed in the male cyclists (3.0 W/kg), albeit differences enlarge when presented in absolute units (167 vs. 216 W, respectively; Table 2). Interestingly, and likely due to the shorter riding time of female races, this study also showed that female cyclists spend a greater proportion of time in high-intensity heart rate (HR) zones, and that female's races are associated with higher training load indicators when expressed relative to distance (e.g., training stress score or training impulses per kilometer; Sanders et al., 2019). A recent case study also

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Table 2 Average Volume and Intensity Characteristics of Road Races in Male and Female Professional Road Cyclists

	Female	Male
Distance (km)	116 ± 17	183 ± 32
Duration (min)	194 ± 30	285 ± 56
Mean PO (W)	167 ± 21	216 ± 34
Mean PO (W/kg)	2.8 ± 0.4	3.0 ± 0.5
IF (AU)	0.83 ± 0.07	0.73 ± 0.08
Mean HR (bpm)	152 ± 13	133 ± 12
Mean HR (% HR_{max})	79 ± 10	69 ± 6
Mean RPE (6–20 scale)	15.4 ± 1.5	15.4 ± 2.1
Total work (kJ)	1,958 ± 384	3,734 ± 918
TSS (AU)	224 ± 49	255 ± 68
TSS per km (AU)	1.92 ± 0.35*	1.40 ± 0.31

Note. Data are represented as mean ± SD. AU = arbitrary units; IF = intensity factor;HR = heart rate; HRmax = maximal heart rate; PO = power output; RPE = ratingof perceived exertion; TSS = training stress score; bpm = beats per minute. Table adapted from "Intensity and Load Characteristics of Professional Road Cycling: Differences Between Men's and Women's Races," by D. Sanders, T. van Erp, and J.J. de Koning, 2019, *International Journal of Sports Physiology Performance, 14*(3), pp. 296–302 (https://doi.org/10.1123/ijspp.2018-0190).

compared the race demands between a female and a male Grand Tour winners and reported overall similar relative power distributions (average PO of 3.5 and 3.6 W/kg for the female and the male cyclists, respectively) and pacing strategies, although the former competed at a higher relative intensity in some stages (e.g., in the initial kilometers of flat stages or in the final kilometers of mountainous stages; Lamberts et al., 2024).

When expressed in relative terms, both male and female road cyclists spend most of the racing time at low-to-moderate intensities (i.e., 70%–80% of the time below the first ventilatory threshold [VT]), with average HR below 75% HR_{max} in mass start events (Padilla et al., 2001; Sanders et al., 2019; Sanders & van Erp, 2021). In fact, careful inspection of second-by-second power data from WT level cycling races shows that 10%–20% of total race time can be spent at ~0 W, due to micro-pauses associated with riding in the draft of a peloton or during downhills. However, high-intensity efforts (i.e., above the second VT or respiratory compensation point [RCP]) seem key for attaining success in road cycling. Performance in most road cycling races is in fact misleading if summarized with average values for PO or HR. This is exemplified by a recent study that found no overall differences in most indicators of physical demands (including average PO and HR) when comparing successful (at least top-5) and less successful (at least top-15) cyclists during Grand Tours (Barranco-Gil et al., 2025). Indeed, top-5 cyclists spent a greater proportion of time at low PO values during races compared to less successful ones, which supports the notion that other factors (e.g., individual or team tactics) might have a great influence. Races are in fact most often won by being in a good position after several hours of cycling to then perform decisive efforts lasting seconds in a sprint, a few minutes on a cobbled sector, or 45 min up a decisive out of category climb with the finish line at 2,000 m. For example, although the PO values of top-5 finishes achieved by 18 professional male road cyclists in WT cycling races was "only" 2.5–3.7 W/kg, high-intensity short-duration efforts (<60 s) were decisive for success in flat and semi mountainous races with a sprint finish, whereas longer-duration PO (≥3 min and >10 min, respectively) were more important to be successful in semimountainous races with an uphill finish and in mountainous races (van Erp et al., 2022). Similarly, a study in female cyclists reported that high PO during short-duration efforts (≤1 min) were a differentiating factor in those races in which they attained a top-5 position (van Erp & Lamberts, 2022).

Apart from road cycling, the ability to perform single maximal or repeated near-maximal high-intensity efforts is also particularly relevant in other cycling modalities such as MTB and track cycling. Unlike road cycling races, where a high proportion of racing time is spent at submaximal exercise intensities, track cycling events are performed at high intensity (above the RCP or even above the maximal aerobic power [MAP]) and often require riders to maximally tax both the aerobic and anaerobic pathways. For instance, the aerobic and anaerobic energy contributions to a 1,000-m TT lasting ~60 s are close to a 50%–50% split, while the Madison event of 200 laps and ~50 min will be highly "aerobic" energetically, even though power surges are frequently interjected (Craig & Norton, 2001). Although average intensity is lower in MTB races than in track cycling, MTB races are also determined by the ability to repeatedly produce high-intensity efforts, with some studies reporting that 30%–40% of total race time is spent above the second lactate threshold (LT) (with 20% spent above the MAP; Impellizzeri et al., 2002; Stapelfeldt et al., 2004). Another feature of MTB races is the highly stochastic nature of PO, often oscillating dozens of times between ~600 and 1,000 W during steep uphills in an attempt to pass on narrow tracks, and then 0 W during a steep and technical downhill, all while HR remains elevated and essentially stable at well above 90% of maximal HR throughout a ~90-min race (Stapelfeldt et al., 2004). Thus, although average PO of 3.6 and 3.1 W/kg have been reported across several MTB races in male and female elite cyclists, respectively, the coefficient of variation for PO approaches 70% and averaged values say little about the actual race demands (Stapelfeldt et al., 2004). For this reason, nutritional strategies aimed at supporting performance during repeated high-intensity efforts seem key for performance in most cycling modalities. For instance, ensuring an optimal carbohydrate intake before and during races can help fuel high-intensity efforts (Podlogar & Wallis, 2022), and indeed professional road cyclists consume around ~90 g/hr of carbohydrates during races (up to 120 g/hr in some cyclists; Muros et al., 2019), which is in line with current recommendations (Jeukendrup, 2014; Podlogar & Wallis, 2022). Moreover, other strategies such as caffeine intake (Chen et al., 2024), creatine (Forbes et al., 2023), or bicarbonate supplementation (Dalle et al., 2021) might also attenuate fatigue or improve performance during high-intensity efforts (cross-reference to union cycliste internationale [UCI] review on Supplements; Whitfield et al., 2025).

Of note, successful cyclists are able to maintain high POs not only in the "fresh" state, but also in the last kilometers of a 6-hr race or during the final stages in multiday races, despite the inevitable accumulation of fatigue and depletion of energy reserves (Muriel et al., 2021, 2022). For example, Leo, Spragg, Mujika, Giorgi, et al. (2021) reported that professional cyclists presented an attenuated decline of their maximal PO values with accumulating levels of fatigue during a 5-day multistage race when compared to elite cyclists of lower caliber (U23, Continental cycling team; Leo, Spragg, Mujika, Giorgi, et al., 2021). Moreover, Muriel et al. (2022) found that, although WT and ProTeam cyclists attained similar maximal mean power (MMP) values during a Grand Tour (i.e., the highest values attained during the 3 weeks), WT

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maintained higher MMP values as the race progressed (i.e., during the second and third weeks; Muriel et al., 2022). Recently, a study reported that top-5 cyclists during Monuments (Milan-San Remo, Tour of Flanders, Paris-Roubaix, Liège-Bastogne-Liège, and Il Lombardia) not only presented higher MMP values in general for efforts lasting ≥5 min, but also a lower reduction of these MMP after large amounts of accumulated work (after 60 kJ/kg; Mateo-March et al., 2025). Based on more limited available data, female cyclists that attain a top-5 position also maintain higher PO values at the end of the race compared to those who rank lower (van Erp & Lamberts, 2022). Indeed, a recent case comparison study of a female and a male Grand Tour winner reported that they only had reductions in their MMP after 30 and 45 kJ/kg energy expenditure, respectively (i.e., after ~75%–80% of the total kJ expenditure in a stage for both; Lamberts et al., 2024). These findings reinforce the need for implementing nutritional strategies during stages to ensure an optimal performance in the final kilometers, particularly water and carbohydrate intake (Podlogar & Wallis, 2022) as well as caffeine supplementation during the stage (Cox et al., 2002; Talanian & Spriet, 2016). Moreover, some nutritional strategies implemented during or after exercise (e.g., glycogen reloading, protein supplementation) might also accelerate recovery between stages, thus improving durability in multistage races (Clauss et al., 2023; cross-reference to UCI reviews on Adaptations and Recovery by Morton et al., 2025, and on Supplements by Whitfield et al., 2025).

Physiological and Performance Indicators in Professional Cyclists

Simplistically summarized, successful performance in road cycling requires very high absolute and/or relative PO/MMP values across seconds to hours, and studies in large cohorts of professional male and female road cyclists confirm the primacy of this demand (Table 3). For instance, a study in 144 professional male cyclists analyzing training and racing PO data obtained over 8 years placed 90th percentile PO values at 14.2, 7.7, 6.6, and 5.8 W/kg for efforts lasting 30 s, 5 min, 20 min, and 1 hr, respectively (Valenzuela et al., 2022). Of note, WT cyclists attained higher PO values than ProTeam riders, particularly for long-duration efforts (60 and 240 min for relative PO values and ≥5 min for absolute PO; Valenzuela et al., 2022). In a similar study in 44 professional female cyclists, corresponding 90th percentile PO values were 11.8, 6.5, 5.5, and 4.9 W/kg, respectively (Mateo-March, Erp, et al., 2022). The 90th percentile PO values for female cyclists were 83%, 84%, 83%, and 84% of male PO for 30 s, 5 min, 20 min, and 1 hr, suggesting a generalizable downward shift in the power duration curve. It is also worth noting that sprinters presented the highest relative and absolute PO values for short-duration efforts (5–30 s), whereas general classification contenders and TT specialists presented the highest PO values for longer efforts among both male and female cyclists (Mateo-March, Erp, et al., 2022; Valenzuela et al., 2022).

Table 3 Field-Based Maximal Mean Power Output Values Attained by Male and Female Professional Cyclists During Racing or Training for Different Effort Durations

	Female			Male		
	p10	p50	p90	p10	p50	p90
30 s (W/kg)	9.0	10.2	11.8	10.9	12.6	14.2
5 min (W/kg)	5.1	5.8	6.5	6.5	7.1	7.7
20 min (W/kg)	4.3	5.0	5.5	5.5	6.3	6.6
1 hr (W/kg)	3.7	4.3	4.9	4.7	5.2	5.8

Note. Data are categorized in percentiles (i.e., p10, p50, and p90 correspond to the 10th, 50th, and 90th percentile). Data obtained from Mateo-March, Erp, et al. (2022) and Valenzuela et al. (2022).

From a classic physiological point of view, performance in road cycling is an integrated function of three major physiological determinants: maximal aerobic capacity (i.e., maximum oxygen uptake [VO_2max]), fractional utilization of VO_2max (linked to metabolic/LT phenomena), and economy or efficiency during submaximal exercise (i.e., the oxygen cost to generate a given cycling PO; Joyner & Coyle, 2008; Lucia et al., 2001).

Confirming the obligatory demand of high maximal aerobic capacity/power in cycling, classical studies using incremental laboratory testing (increases of 25 W/min) reported VO_2max and MAP values in professional cyclists ranging between 5.0–5.5 L/min (70–80 ml·kg^{-1}·min^{-1}) and 450–550 W (6.5–7.5 W/kg), with higher values usually observed in cyclists with greater performance (Lucía et al., 1998, 2001). For instance, a VO_2max of 5.9 L/min (84 ml·kg^{-1}·min^{-1}) and MAP of 525 W were reported in a multiple Tour de France winning cyclist during an incremental test (30 W/min) conducted 1 week before competing on a Grand Tour (Bell et al., 2017). Moreover, although controversy exists (e.g., Menaspà et al., 2010), a recent longitudinal study in U23 cyclists reported that VO_2max was a differentiating factor between those who transitioned to the professional category and those who did not (Valenzuela et al., 2023). Indeed, compared to cyclists of lower level (e.g., U23), professional cyclists present with higher absolute and relative MAP during an incremental test (7.3 vs. 6.9 W/kg), albeit no differences were observed for VO_2max (83 vs. 80 ml·kg^{-1}·min^{-1} in professional and U23 cyclists, respectively; Alejo et al., 2022).

Because of its impact on sustainable metabolic energy expenditure rate, fractional utilization of VO_2max also plays a critical role in cycling performance (Joyner & Coyle, 2008). In addition to presenting a high VO_2max, cyclists must be able to sustain a high fraction, or percentage, of this upper limit oxygen uptake rate during long periods of time. This ability can be described through indicators such as lactate/aerobic turn points, the maximal lactate steady state, or the critical power. Thus, it has been proposed that highly-trained cyclists can sustain a higher fraction of their VO_2max without depleting intramuscular energy substrates (i.e., phosphocreatine and muscle glycogen) and postponing the accumulation of fatigue-related metabolites (e.g., H^+, adenosine diphosphate and P_i; Joyner & Coyle, 2008; Poole et al., 2016). For example, professional cyclists are typically reported to reach VT1/LT1 and VT2/LT2 at ~65%–75% and ~90%–95% of their VO_2max, respectively (Alejo et al., 2022; Lucía et al., 1998). It is worth noting, however, that the ability to sustain a high proportion of VO_2max per se does not explain endurance performance; instead, it is the combination of a high fractional utilization and a high VO_2max that determines athletes' ability to sustain a high exercise intensity without fatigue (e.g., PO at the LT; Støa et al., 2020).

Metabolic power is converted to mechanical power at the pedals during cycling. The total energetic cost of a given PO (mechanical work generated in kilojoules) relative to total metabolic cost in kilojoules is individually variable and termed gross efficiency. The ability to sustain high PO values for long periods can also be affected by cycling efficiency, as a greater efficiency will decrease the percentage of available metabolic power required

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to sustain a given mechanical work rate (Joyner & Coyle, 2008). Some studies suggest that professional cyclists can partially compensate for a relatively low VO_2max with very high cycling efficiency, as gross efficiency can improve modestly over time with accumulated training (Lucia et al., 2002; Santalla et al., 2009). For instance, a case report in a multiple Tour de France winning cyclist concluded that the combination of a high VO_2max with a high gross efficiency (23.0%–23.6%) seemed to be one of the main contributing factors to his success in elite cycling (Bell et al., 2017). However, other authors have reported no differences in cycling efficiency between world-class and recreational cyclists, which raises concerns on the validity of this indicator in isolation as a determinant of endurance performance (Moseley et al., 2004). Moreover, given that efficiency—as well as other physiological parameters—is usually measured in the lab under controlled conditions, it remains largely unknown how it evolves during prolonged exercise and under field conditions (Stevenson et al., 2022). Although their effectiveness remains unclear, nutritional interventions (e.g., nitrate supplementation) aimed at improving the efficiency of converting metabolic power to mechanical power have been investigated (Calvo et al., 2020; Lansley et al., 2011; cross-reference to UCI review on Supplements by Whitfield et al., 2025).

It is worth noting, however, that this three-component model proposed by Joyner and Coyle (2008) is founded on steady-state exercise. With few exceptions, cycling PO during races is highly stochastic in nature and success depends on the ability to produce high intermittent PO that is often above maximal lactate steady state or even MAP demarcations, and then recover rapidly during intermittent periods of "low" power demand. From this perspective, the fourth "minor" component of the traditional model of endurance physiology, "anerobic capacity" becomes an important dynamic buffer or "battery" that is partially depleted and recharged dozens to hundreds of times during a 6-hr road race or a 90-min MTB race. Indeed, as mentioned above, the ability to perform high-intensity efforts above the RCP (3–10 min) seems key in some types of events such as semimountainous races with an uphill finish, or mountainous races (van Erp et al., 2022; van Erp & Lamberts, 2022). Moreover, even shorter efforts (<60 s) are needed to succeed in sprint finishes (van Erp et al., 2022; van Erp & Lamberts, 2022), and indeed male sprinters have been reported to be able to sustain average PO values as high as 1,486 W (18.4 W/kg) or 1,085 W (13.6 W/kg) during efforts lasting 10 s and 30 s, respectively (Valenzuela et al., 2022). For this reason, as mentioned above, nutritional strategies aimed at improving cyclists' capability to perform high-intensity efforts might be recommended (cross-reference to UCI review on Performance Nutrition for Sprint and Endurance Track Cycling by Stanley et al., 2025).

The ability to perform high-intensity efforts is critical in other cycling modalities such as track cycling or MTB. In track sprint cycling, achieving high absolute PO values (1,500–2,000 W) over 15–60 s by optimizing the torque–cadence relationship is a key performance indicator (Douglas et al., 2021). However, from a standing start with a single gear, peak torque and relative PO values (20–22.5 W/kg) significantly influence acceleration and must also be considered (Gardner et al., 2007; Kordi & van Rijswijk, 2024). Track endurance events are divided into timed and bunch events. In timed events, the key differences between individual and team pursuits are related to PO demand undulation and delivery (Craig & Norton, 2001). In individual pursuit events, PO (500–600 W for males and 300–400 W for females) should ideally follow a smooth trend from start to finish. In contrast, PO requirements in team pursuits undulate as riders rotate from leading into "untouched air" to sitting on the wheel, with lead positions requiring higher PO values (600–700 W for males and 400–500 W for females) and follow positions requiring lower values (400–500 W for males and 300–400 W for females) at the same velocity (Broker et al., 1999; Heimans et al., 2017; Schumacher & Mueller, 2002). Athletes in both events experience PO and speed fluctuations depending on their position on the track, with the lowest PO values observed in the bends and the highest values observed at the beginning and middle of the straights. Besides the physical demands, these events require a high level of technical skill, including maintaining an aerodynamic position and closely following the black pursuit line on the track (Defraeye et al., 2014; Sigrist et al., 2017). Track endurance bunch events require performance characteristics similar to those in road cycling, particularly short criteriums, with stochastic PO delivery (~1,200 W peak PO and ~290 W average PO). Therefore, a strong aerobic base combined with the ability to execute repeated sprints and recover "on the fly" is fundamental. In addition to the physical demands, these events have a significant strategic and tactical component, including positioning, timing, and decision making (Gardner et al., 2007; Ofoghi et al., 2013; Sigrist et al., 2017; Stadnyk et al., 2022).

It is worth noting that the athletes' physiological and performance profile has been traditionally studied under controlled laboratory conditions and without accounting for the influence of fatigue, which is likely to accumulate with the duration and the intensity of the effort (Jones, 2024; Maunder et al., 2021). However, growing evidence points to the ability to attenuate the acute deterioration in physiological responses to exercise under fatigue and/or to maintain high PO levels after accumulated work—the so-called "durability" or "physiological resilience"—as a major determinant of cycling performance (Figure 3; Jones, 2024; Mateo-March, Valenzuela, et al., 2022; Maunder et al., 2021; van Erp et al., 2021). van Erp et al. (2021) observed that differences in the highest PO values (also known as MMP) attained during training sessions and competitions by professional cyclists classified as "successful" and those classified as "less successful" were larger under fatigue conditions, that is, after a greater accumulated mechanical work (van Erp et al., 2021). For example, a larger decline in the 20-min MMP (–9.0%) was found in nonsuccessful climbers versus –4.0% in their more successful peers when assessed after 50 kJ/kg compared with the "fresh" state (0 kJ/kg; van Erp et al., 2021). Similarly, a large study in male professional cyclists reported that, although WT cyclists might not necessarily be able to attain higher PO values than cyclists of a lower level (ProTeam) during training or racing when fatigue is not considered, differences enlarge with accumulating levels of fatigue (Mateo-March, Valenzuela, et al., 2022). Mateo-March et al. (2025) also showed that top-5 cyclists during Monuments showed an attenuated decline of PO values under fatigue (after 60 kJ/kg). In this regard, recent evidence suggests that high-intensity efforts (i.e., above the critical power) elicit greater fatigue compared with work-matched efforts of lower intensity (Barranco-gil et al., 2024; Mateo-March et al., 2024; Spragg et al., 2024) and the ability to attenuate such deterioration in performance after accumulated high-intensity work has been highlighted as a determinant of cycling performance (Leo et al., 2024).

Finally, apart from physiological characteristics, morphological characteristics (e.g., body mass and height, body surface and frontal area, adiposity, muscle mass) also play a major role. Performance in mountainous stages is strongly correlated with relative PO values due to the negative influence of body mass (particularly during steep climbs), while in other types of events such as TTs or flat stages, performance is more dependent on absolute

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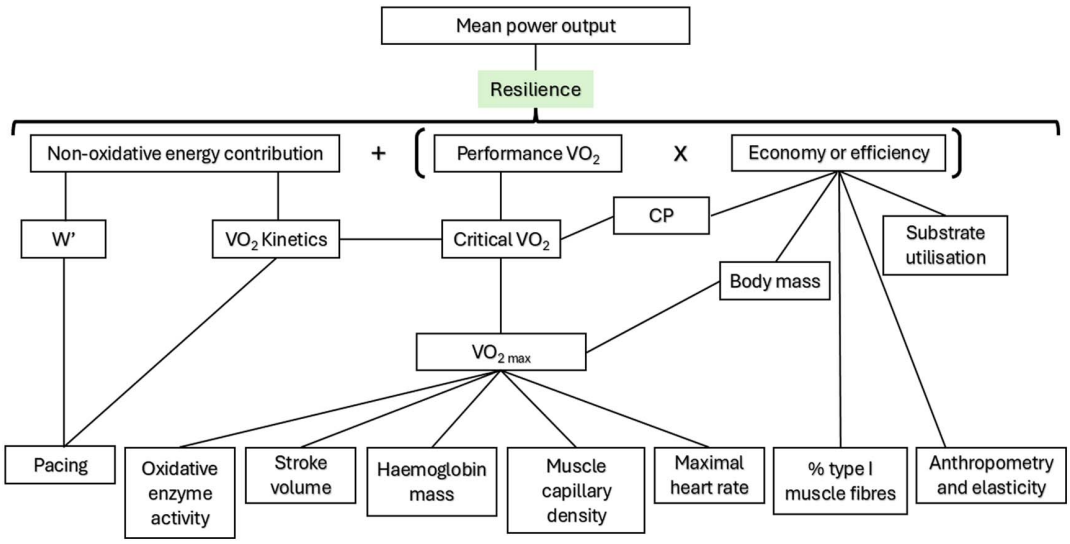


Figure 3 — Summary of the physiological determinants of cycling exercise performance and some of its contributing factors. Adapted from "The Fourth Dimension: Physiological Resilience As An Independent Determinant Of Endurance Exercise Performance," by A.M. Jones, 2024, *Journal of Physiology,* 602, pp. 4113–4128. CP = critical power; VO_2 = oxygen uptake.

PO values, with body mass exerting less negative influence but with aerodynamic drag (e.g., frontal surface area) increasing exponentially with net windspeed. Consequently, anthropometric variables differ depending on the cyclist's specialty (Lucia et al., 2001; Padilla et al., 1999; Sánchez-Muñoz et al., 2023). Although all professional cyclists seem to present low levels of fat mass (5%–10% depending on the equation used), a recent study in WT cyclists reported that climbers had a lower muscle mass, height, and body mass compared to all-rounders and particularly flat specialists (average height of 175, 181, and 183 cm and average body mass of 63.8, 68.8, and 74.5 kg for climbers, all-rounders, and flat bunch sprint specialists, respectively; Sánchez-Muñoz et al., 2023). In turn, achieving high absolute PO values along with a reduced frontal surface area seems paramount in other riders such as flat specialists. For this reason, appropriate bike fitting and aerodynamic testing is of relevance, particularly given that a correct balance between an aerodynamic position (e.g., low hip and torso angle) and PO production capacity should be sought (Faulkner & Jobling, 2021; Fintelman et al., 2015).

The role of muscle mass on cycling performance is particularly controversial. Increases in lean mass (and consequently body mass) have been traditionally regarded by road cyclists as a detrimental adaptation because of the negative influence of gravity on performance (i.e., speed), particularly during uphill cycling (Mujika et al., 2016). In support of this, a recent study by Leo, Spragg, Mujika, Menz, et al. (2021) reported that performance improvements across one season in professional cyclists were mostly associated with reductions in body mass and not to increases in absolute PO values (Leo, Spragg, Mujika, Menz, Lawley, 2021). Similarly, another study showed that Junior cyclists who signed a contract with an U23 development team did not show higher absolute values of VTs, PPO, or VO_2max compared to those failing to sign such a contract; in turn, differences were found when expressing these values relative to cyclists' body mass (Hovorka et al., 2023). It must be noted, however, that a higher muscle mass can result in a higher absolute PO and consequently a higher speed, at least under those conditions in which gravity exerts a smaller influence (i.e., on flat roads). Indeed, quadriceps' muscle mass has been identified as one of the main determinants of peak power production capacity in cyclists, which would be of relevance for high-intensity efforts (e.g., track cyclists, sprinters; Douglas et al., 2021; Kordi et al., 2018, 2020; Miura et al., 2002). Moreover, TT performance has been reported to improve with strength training along with concomitant increases in muscle mass, with the improvement of both variables correlated (Vikmoen et al., 2016). Therefore, evidence overall suggests that modest muscle mass gains through focused strength training can be beneficial for overall cycling performance (Llanos-Lagos et al., 2025; Mujika et al., 2016). Ensuring an optimal protein intake might be key for promoting muscle mass gains in some cyclists (e.g., sprinters), or to at least prevent muscle catabolism in periods of high energy demands (e.g., during strenuous training periods of multistage races; Cintineo et al., 2018; Moore et al., 2014; Witard et al., 2025; cross-reference to UCI review on Adaptations and Recovery by Morton et al., 2025).

Training Characteristics in Cyclists

To sustain the physical demands of cycling races and attain the astonishing physiological characteristics mentioned above, cyclists undergo strenuous training regimens. Scarce evidence exists on the best training methods for professional cyclists (for which randomized controlled trials would be needed). Indeed, although a recent systematic review aimed to summarize the main characteristics of the training strategies used by trained cyclists (Galán-Rioja et al., 2023), only one of the included studies (which was a case report) was performed in an elite cyclist (Rønnestad & Hansen, 2018).

Accepting the lack of peer-reviewed studies, observational evidence allows us to at least describe the most common training strategies applied by world-class professional cyclists. As in other long-duration endurance sports, cyclists have been reported to spend most of their training time at low intensity, with ~65% of the time in Z1 (i.e., below the VT), ~29% in Z2 (i.e., between the VT and the RCP), and ~6% in Z3 (i.e., above the RCP; Sperlich et al., 2023). However, the proportion of time in high-intensity zones seems to increase in the competitive phase compared to the preparatory phase of the season (Sperlich et al., 2023). Two recent case series studies reported the week-by-week training

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characteristics of world-class male professional road cyclists leading up to a top-5 position in the final general classification of Giro d'Italia and Tour de France (Gallo et al., 2022, 2023). Average weekly volume ranged between 15 and 22 hr, with cyclists adopting a pyramidal intensity distribution where the proportion of low, medium, and high-intensity volume was 81%–91%, 6%–14%, and 2%–6% respectively. Interestingly, two distinct patterns of periodization were observed depending on the phase of the season. There was a "high-intensity races-based block periodization," characterized by an increased proportion of volume performed at moderate and high intensity due to 1-week stage races that served as preparation for the Grand Tour, but also periods during which there was a switch to a more polarized intensity distribution (less medium-intensity and more high-intensity training) when not competing for at least 4 weeks. Other components such as strength training and altitude training broadly differed between athletes. Some cyclists performed no resistance training whereas others strength-trained two times per week in the first 2 months of the preparation period (November and December). Regarding altitude training, some cyclists did not perform it at all, while others performed between two and three training camps (each lasting 2–3 weeks) above 1,800 m above sea level in preparation before a Grand Tour.

Another recent case study reported the day-by-day (instead of week-by-week) training characteristics of a world-class road cyclist who reached the podium of Giro d'Italia final general classification (Gallo et al., 2024). A pattern alternating "hard" and "easy days" was observed, with strenuous training sessions (i.e., high amounts of medium- or high-intensity training, or large amounts of work) not performed for more than two consecutive days. Specifically, "easy days" usually corresponded to less than 2 hr/1,000 kJ and little or no high-intensity training (above the functional threshold power, critical power or RCP), while "hard days" corresponded to more than 4 hr/3,000 kJ, including at least 30 min of high-intensity training.

Thus, the abovementioned data suggest that nutritional demands (e.g., energy intake, macronutrient requirements) could require periodization both at macrocycle (different weeks) and microcycle level (different days; cross-reference to UCI review on Energy availability by Burke et al., 2025). Moreover, although more research is needed, training characteristics also seem to differ between male and female cyclists, with the latter having lower training volume (particularly due to lower time in low- and moderate-intensity zones) despite similar relative training loads (e.g., similar training stress score; Table 4; Van Erp et al., 2020).

Table 4 Average Daily Training Characteristics of Male and Female Professional Road Cyclists

	Female	Male
Distance (km)	64.1 ± 38.1	91.9 ± 48.1
Duration (min)	145 ± 72	182 ± 96
Mean PO (W)	138 ± 22	191 ± 32
Mean PO (W/kg)	2.30 ± 0.37	2.64 ± 0.45
Mean HR (bpm)	136 ± 16	125 ± 12
Mean HR (% HRmax)	69.8 ± 6.7	65.5 ± 6.3
Mean RPE (6–20 scale)	12.1 ± 2.2	12.2 ± 2.3
Total work (kJ)	1,223 ± 645	2,151 ± 1,238

Note. Data are mean ± SD. Table adapted from Van erp, Sanders, and de Koning (2019) and Van Erp et al. (2020). HR = heart rate; HR_{max} = maximal heart rate; PO = power output; RPE = rating of perceived exertion; bpm = beats per minute.

However, given the rapid rate of development in female professional cycling, it is possible that training characteristics of top female cyclists will evolve as female athletes receive professional contracts that enable them to train full time.

Conclusions

Although large differences exist between modalities, professional cycling—especially the 3-week Grand Tours—epitomizes extreme endurance exercise, demanding an exceptional physical effort. Despite the enormous energy demands imposed by races, professional cyclists achieve impressive performance levels. Numerous extrinsic and intrinsic factors influence success in professional cycling. Among the latter, "traditional" physiological markers of endurance performance and anthropometric parameters (which might differ between cyclists' typologies) play a major role, but also does the ability to generate high PO values at critical moments and the capacity to sustain performance under fatigue, recently termed as "durability." Thus, training and nutritional strategies should aim to improve these performance indicators.

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References

Alejo, L.B., Montalvo-Pérez, A., Valenzuela, P.L., Revuelta, C., Ozcoidi, L.M., Calle, V.De, Mateo-March, M., Lucia, A., Santalla, A., & Barranco-Gil, D. (2022). Comparative analysis of endurance, strength and body composition indicators in professional, under-23 and junior cyclists. *Frontier in Physiology, 13*, Article 945552. https://doi.org/10.3389/fphys.2022.945552

Areta, J.L., Meehan, E., Howe, G., & Redman, L.M. (2024). Energetics of a world-tour female road cyclist during a multistage race (Tour de France Femmes). *International Journal of Sport Nutrition and Exercise Metabolism, 34*(5), 253–257.

Barranco-Gil, D., Alejo, L.B., Revuelta, C., Paz, S.De, Ibañez, M., Lucia, A., & Valenzuela, P. (2024). Intensity matters: Effect of different work-matched efforts on subsequent performance in cyclists. *International Journal of Sports Physiology and Performance, 19*(10), 1006–1011. https://doi.org/10.1123/ijspp.2023-0287

Barranco-Gil, D., Mateo-March, M., Muriel, X., Pallarés, J.G., Lucia, A., & Valenzuela, P.L. (2025). What does it take to reach the podium? Power output and heart rate-derived racing demands of top cyclists during grand tours. *Scandinavian Journal of Medicine and Science in Sports, 35*(5), Article e70074. https://doi.org/10.1111/sms.70074

Bell, P.G., Furber, M.J.W., Van Someren, K.A., Antón-Solanas, A., & Swart, J. (2017). The physiological profile of a multiple tour de france winning cyclist. *Medicine and Science in Sports and Exercise, 49*(1), 115–123. https://doi.org/10.1249/MSS.0000000000001068

Broker, J.P., Kyle, C.R., & Burke, E.R. (1999). Racing cyclist power requirements in the 4000-m individual and team pursuits. *Medicine and Science in Sports and Exercise, 31*(11), 1677–1685. https://doi.org/10.1097/00005768-199911000-00026

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Burke, L.M., Gonzalez, J.T., Areta, J.L., Kuikman, M., Coates, A.M., Bailey, D.M., Moran, J., & Dolan, E. (2025). UCI sports nutrition project: Body composition, energy requirements and energy availability in cycling. *International Journal of Sport Nutrition and Exercise Metabolism*. In review.

Calvo, J.L., Alorda-Capo, F., Pareja-Galeano, H., & Jiménez, S.L. (2020). Influence of nitrate supplementation on endurance cyclic sports performance: A systematic review. *Nutrients, 12*(6), Article 1796. https://doi.org/10.3390/nu12061796

Chen, B., Ding, L., Qin, Q., Lei, T., Girard, O., Cao, Y., & Girard, O. (2024). Effect of caffeine ingestion on time trial performance in cyclists: A systematic review and. *Journal of the International Society of Sports Nutrition, 21*(1), Article 2363789. https://doi.org/10.1080/15502783.2024.2363789

Cintineo, H.P., Arent, M.A., Antonio, J., & Arent, S.M. (2018). Effects of protein supplementation on performance and recovery in resistance and endurance training. *Frontiers in Nutrition, 5*, Article 83. https://doi.org/10.3389/fnut.2018.00083

Clauss, M., Skattebo, Ø., Rasen DÆhli, M., Ditta Valsdottir, T., Ezzatkhah Bastani, N., Ivar Johansen, E., Jensen Kolnes, K., Steen Skålhegg, B., & Jensen, J. (2023). Carbohydrate ingestion during prolonged cycling improves next-day time trial performance and alters amino acid concentrations. *Medicine and Science in Sports and Exercise, 55*(12), 2228–2240. https://doi.org/10.1249/MSS.0000000000003264

Cox, G.R., Desbrow, B., Montgomery, P.G., Anderson, M.E., Bruce, C.R., Macrides, T.A., Martin, D.T., Moquin, A., Roberts, A., Hawley, J.A., & Burke, L.M. (2002). Effect of different protocols of caffeine intake on metabolism and endurance performance. *Journal of Applied Physiology, 93*(3), 990–999. https://doi.org/10.1152/japplphysiol.00249.2002

Craig, N.P., & Norton, K.I. (2001). Characteristics of track cycling. *Sports Medicine, 31*(7), 457–468. https://doi.org/10.2165/00007256-200131070-00001

Dalle, S., Koppo, K., & Hespel, P. (2021). Sodium bicarbonate improves sprint performance in endurance cycling. *Journal of Science and Medicine in Sport, 24*(3), 301–306. https://doi.org/10.1016/j.jsams.2020.09.011

Defraeye, T., Blocken, B., Koninckx, E., Hespel, P., Verboven, P., Nicolai, B., & Carmeliet, J. (2014). Cyclist drag in team pursuit: Influence of cyclist sequence, stature, and arm spacing. *Journal of Biomechanical Engineering, 136*(1), Article 011005. https://doi.org/10.1115/1.4025792

Douglas, J., Ross, A., & Martin, J.C. (2021). Maximal muscular power: Lessons from sprint cycling. *Sports Medicine—Open, 7*(1), Article 48. https://doi.org/10.1186/s40798-021-00341-7

Faulkner, S., & Jobling, P. (2021). The effect of upper-body positioning on the aerodynamic-physiological economy of time-trial cycling. *International Journal of Sports Physiology & Performance, 16*(1), 51–58. https://doi.org/10.1123/ijspp.2019-0547

Fintelman, D.M., Sterling, M., Hemida, H., & Li, F.X. (2015). The effect of time trial cycling position on physiological and aerodynamic variables. *Journal of Sports Sciences, 33*(16), 1730–1737. https://doi.org/10.1080/02640414.2015.1009936

Forbes, S.C., Candow, D.G., Neto, J.H.F., Kennedy, M.D., Forbes, J.L., Machado, M., Bustillo, E., Gomez-Lopez, J., Zapata, A., & Antonio, J. (2023). Creatine supplementation and endurance performance: Surges and sprints to win the race. *Journal of the International Society of Sports Nutrition, 20*(1), Article 2204071. https://doi.org/10.1080/15502783.2023.2204071

Galán-Rioja, M.Á., Gonzalez-Ravé, J.M., González-Mohíno, F., & Seiler, S. (2023). Training periodization, intensity distribution, and volume in trained cyclists: A systematic review. *International Journal of Sports Physiology and Performance, 18*(2), 112–122. https://doi.org/10.1123/ijspp.2022-0302

Gallo, G., Mateo-March, M., Fuk, A., Faelli, E., Ruggeri, P., Codella, R., & Filipas, L. (2024). The day-by-day periodization strategies of a giro D'italia podium finisher. *International Journal of Sports Physiology and Performance, 19*(5), 505–509. https://doi.org/10.1123/ijspp.2023-0224

Gallo, G., Mateo-March, M., Gotti, D., Faelli, E., Ruggeri, P., Codella, R., & Filipas, L. (2022). How do world class top 5 Giro d'Italia finishers train? A qualitative multiple case study. *Scandinavian Journal of Medicine and Science in Sports, 32*(12), 1738–1746. https://doi.org/10.1111/sms.14201

Gallo, G., Mateo-March, M., Gotti, D., Maunder, E., Codella, R., Ruggeri, P., Faelli, E., & Filipas, L. (2023). The weekly periodization of top 5 tour de france general classification finishers: A multiple case study. *International Journal of Sports Physiology and Performance, 18*(11), 1313–1320. https://doi.org/10.1123/ijspp.2023-0142

Gardner, A.S., Martin, J.C., Martin, D.T., Barras, M., & Jenkins, D.G. (2007). Maximal torque- and power-pedaling rate relationships for elite sprint cyclists in laboratory and field tests. *European Journal of Applied Physiology, 101*(3), 287–292. https://doi.org/10.1007/s00421-007-0498-4

Hammond, K., & Diamond, J. (1997). Maximal sustained energy budgets in humans and animals. *Nature, 386*(6624), 457–462. https://doi.org/10.1038/386457a0

Heimans, L., Dijkshoorn, W.R., Hoozemans, M.J.M., & De Koning, J.J. (2017). Optimizing the team for required power during track-cycling team pursuit. *International Journal of Sports Physiology and Performance, 12*(10), 1385–1391. https://doi.org/10.1123/ijspp.2016-0451

Hovorka, M., Leo, P., Simon, D., Rumpi, C., & Nimmerichter, A. (2023). Physiological characteristics of competitive male junior cyclists transitioning to the under-23 level: A retrospective comparative study. *International Journal of Sports Physiology & Performance, 18*(8), 874–877. https://doi.org/10.1123/ijspp.2022-0496

Impellizzeri, F., & Marcora, S. (2007). The physiology of mountain biking the physiology of mountain biking. *Sports Medicine, 37*(1), 59–71. https://doi.org/10.2165/00007256-200737010-00005

Impellizzeri, F., Sassi, A., Rodriguez-Alonso, M., Mognoni, P., & Marcora, S. (2002). Exercise intensity during off-road cycling competitions. *Medicine and Science in Sports and Exercise, 34*(11), 1808–1813. https://doi.org/10.1097/00005768-200211000-00018

Jeukendrup, A. (2014). A step towards personalized sports nutrition: Carbohydrate intake during exercise. *Sports Medicine, 44*, 25–33. https://doi.org/10.1007/s40279-014-0148-z

Jones, A.M. (2024). The fourth dimension: Physiological resilience as an independent determinant of endurance exercise performance. *Journal of Physiology, 602*(17), 4113–4128. https://doi.org/10.1113/JP284205

Joyner, M.J., & Coyle, E.F. (2008). Endurance exercise performance: The physiology of champions. *The Journal of Physiology, 586*(1), 35–44. https://doi.org/10.1113/jphysiol.2007.143834

Kordi, M., Folland, J., Goodall, S., Haralabidis, N., Maden-Wilkinson, T., Sarika Patel, T., Leeder, J., Barratt, P., & Howatson, G. (2020). Mechanical and morphological determinants of peak power output in elite cyclists. *Scandinavian Journal of Medicine and Science in Sports, 30*(2), 227–237. https://doi.org/10.1111/sms.13570

Kordi, M., Menzies, C., & Parker Simpson, L. (2018). Relationship between power–duration parameters and mechanical and anthropometric properties of the thigh in elite cyclists. *European Journal of Applied Physiology, 118*(3), 637–645. https://doi.org/10.1007/s00421-018-3807-1

Kordi, M., & van Rijswijk, I. (2024). Performance analysis and mechanical determinants of the opening lap of the team sprint in elite-level track

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cycling. *European Journal of Sport Science, 24*(9), 1240–1246. https://doi.org/10.1002/ejsc.12158

Lamberts, R.P., Vleuten, A.Van, Dumoulin, T., Delahaije, L., & Erp, T.Van. (2024). Racing demands for winning a grand tour: Differences and similarities between a female and a male winner. *International Journal of Sports Physiology & Performance, 19*(11), 1209–1217. https://doi.org/10.1123/ijspp.2023-0476

Lansley, K.E., Winyard, P.G., Bailey, S.J., Vanhatalo, A., Wilkerson, D.P., Blackwell, J.R., Gilchrist, M., Benjamin, N., & Jones, A.M. (2011). Acute dietary nitrate supplementation improves cycling time trial performance. *Medicine and Science in Sports and Exercise, 43*(6), 1125–1131. https://doi.org/10.1249/MSS.0b013e31821597b4

Leo, P., Mateo-March, M., Giorgi, A., Muriel, X., Javaloyes, A., Barranco-Gil, D., Pallarés, J.G., Lucia, A., Mujika, I., & Valenzuela, P.L. (2024). The influence of high-intensity work on the record power profile of under-23, pro team, and world tour cyclists. *International Journal of Sports Physiology and Performance, 19*(6), 545–549. https://doi.org/10.1123/ijspp.2023-0451

Leo, P., Spragg, J., Mujika, I., Giorgi, A., Lorang, D., Simon, D., & Lawley, J. (2021). Power profiling, workload characteristics, and race performance of U23 and professional cyclists during the multistage race tour of the alps. *International Journal of Sports Physiology & Performance, 16*(8), 1089–1095. https://doi.org/10.1123/ijspp.2020-0381

Leo, P., Spragg, J., Mujika, I., Menz, V., & Lawley, J.S. (2021). Power profiling in U23 professional cyclists during a competitive season. *International Journal of Sports Physiology and Performance, 16*(6), 881–889. https://doi.org/10.1123/ijspp.2020-0200

Llanos-Lagos, C., Rodrigo, L., Campillo, R., & Villarreal, E.S.De. (2025). Heavy strength training effects on physiological determinants of endurance cyclist performance: A systematic review with meta-analysis. *European Journal of Applied Physiology,* Advance online publication. https://doi.org/10.1007/s00421-025-05883-2

Lucia, A., Hoyos, J., & Chicharro, J.L. (2001). Physiology of professional road cycling. *Sports Medicine, 31*(5), 325–337. https://doi.org/10.2165/00007256-200131050-00004

Lucia, A., Hoyos, J., Pérez, M., Santalla, A., & Chicharro, J. (2002). Inverse relationship between VO2max and economy/efficiency in world-class cyclists. *Medicine & Science in Sports & Exercise, 34*(12), 2079–2084. https://doi.org/10.1249/01.MSS.0000039306.92778.DF

Lucía, A., Pardo, J., Durántez, A., Hoyos, J., & Chicharro, J.L. (1998). Physiological differences between professional and elite road cyclists. *International Journal of Sports Medicine, 19*(5), 342–348. https://doi.org/10.1055/s-2007-971928

Mateo-March, M., Erp, T.Van, Muriel, X., Valenzuela, P.L., Zabala, M., Lamberts, R.P., Lucia, A., Barranco-Gil, D., & Pallarés, J.G. (2022). The record power profile in professional female cyclists: Normative values obtained from a large database. *International Journal of Sports Physiology & Performance, 17*(5), 682–686. https://doi.org/10.1123/ijspp.2021-0372

Mateo-March, M., Leo, P., Muriel, X., Javaloyes, A., Mujika, I., Barranco-Gil, D., Pallarés, J.G., Lucia, A., & Valenzuela, P.L. (2024). Is all work the same? Performance after accumulated work of differing intensities in male professional cyclists. *Journal of Science and Medicine in Sport, 27*(6), 430–434. https://doi.org/10.1016/j.jsams.2024.03.005

Mateo-March, M., Moya-Ramón, M., Sánchez-Jiménez, J., Peña-González, I., & Javaloyes, A. (2025). Decoding victory in cycling's grand monuments: A performance analysis of top-5 versus top-6-30 finishers. *Scandinavian Journal of Medicine & Science in Sports, 35*(5), Article e70057.

Mateo-March, M., Valenzuela, P.L., Muriel, X., Gandia-Soriano, A., Zabala, M., Lucia, A., Pallares, J.G., & Barranco-Gil, D. (2022). The record power profile of male professional cyclists: Fatigue matters. *International Journal of Sports Physiology and Performance, 17*(6), 926–931. https://doi.org/10.1123/ijspp.2021-0403

Maunder, E., Seiler, S., Mildenhall, M.J., Kilding, A.E., & Plews, D.J. (2021). The importance of "durability" in the physiological profiling of endurance athletes. *Sports Medicine, 51*(8), 1619–1628. https://doi.org/10.1007/s40279-021-01459-0

Menaspà, P., Sassi, A., & Impellizzeri, F.M. (2010). Aerobic fitness variables do not predict the professional career of young cyclists. *Medicine and Science in Sports and Exercise, 42*(4), 805–812. https://doi.org/10.1249/MSS.0b013e3181ba99bc

Mifflin, M.D., St Jeor, S.T., Hill, L.A., Scott, B.J., Daugherty, S.A., & Koh, Y.O. (1990). A new predictive equation for resting energy expenditure in healthy individuals. *American Journal of Clinical Nutrition, 51*(2), 241–247. https://doi.org/10.1093/ajcn/51.2.241

Miura, A., Endo, M., Sato, H., Sato, H., Barstow, T.J., & Fukuba, Y. (2002). Relationship between the curvature constant parameter of the power-duration curve and muscle cross-sectional area of the thigh for cycle ergometry in humans. *European Journal of Applied Physiology, 87*(3), 238–244. https://doi.org/10.1007/s00421-002-0623-3

Moore, D.R., Camera, D.M., Areta, J.L., & Hawley, J.A. (2014). Beyond muscle hypertrophy: Why dietary protein is important for endurance athletes. *Applied Physiology, Nutrition, and Metabolism = Physiologie Appliquee, Nutrition et Metabolisme, 39*(9), 987–997. https://doi.org/10.1139/apnm-2013-0591

Morton, J.P., Hearris, M., Fell, M.J., Owens, D.J., Halson, S., & Trommelen, J. (2025). UCI sports nutrition project: Nutritional periodisation: Strategies to enhance training adaptation and recovery. *International Journal of Sport Nutrition and Exercise Metabolism*. Advance online publication. https://doi.org/10.1123/ijsnem.2025-0073

Moseley, L., Achten, J., Martin, J.C., & Jeukendrup, A.E. (2004). No differences in cycling efficiency between world-class and recreational cyclists. *International Journal of Sports Medicine, 25*(5), 374–379. https://doi.org/10.1055/s-2004-815848

Mujika, I., Rønnestad, B.R., & Martin, D.T. (2016). Effects of increased muscle strength and muscle mass on endurance-cycling performance. *International Journal of Sports Physiology and Performance, 11*(3), 283–289. https://doi.org/10.1123/ijspp.2015-0405

Muriel, X., Mateo-March, M., Valenzuela, P.L., Zabala, M., Lucia, A., Pallares, J.G., & Barranco-Gil, D. (2021). Durability and repeatability of professional cyclists during a grand tour. *European Journal of Sport Science, 22*(12), 1797–1804. https://doi.org/10.1080/17461391.2021.1987528

Muriel, X., Valenzuela, P., Mateo-March, M., Pallarés, J., Lucia, A., & Barranco-Gil, D. (2022). Physical demands and performance indicators in male professional cyclists during a grand tour: WorldTour vs ProTeam category. *International Journal of Sports Physiology & Performance, 17*(1), 22–30. https://doi.org/10.1123/ijspp.2021-0082

Muros, J.J., Sánchez-Muñoz, C., Hoyos, J., & Zabala, M. (2019). Nutritional intake and body composition changes in a UCI World Tour cycling team during the Tour of Spain. *European Journal of Sport Science, 19*(1), 86–94. https://doi.org/10.1080/17461391.2018.1497088

Ofoghi, B., Zeleznikow, J., Dwyer, D., & Macmahon, C. (2013). Modelling and analysing track cycling Omnium performances using statistical and machine learning techniques. *Journal of Sports Sciences, 31*(9), 954–962. https://doi.org/10.1080/02640414.2012.757344

Padilla, S., Mujika, I., Cuesta, G., & Goiriena, J. (1999). Level ground and uphill cycling ability in professional road cycling. *Medicine and Science in Sports and Exercise, 31*(6), 878–885. https://doi.org/10.1097/00005768-199906000-00017

Padilla, S., Mujika, I., Santisteban, J., Impellizzeri, F.M., & Goiriena, J.J. (2001). Exercise intensity and load during uphill cycling in

Unauthenticated | Downloaded 05/10/26 08:45 PM UTC

professional 3-week races. *Medicine & Science in Sports & Exercise, 33*(5), 796–802. https://doi.org/10.1097/00005768-200105000-00019

Peterson, C.C., Nagy, K.A., & Diamond, J. (1990). Sustained metabolic scope. *Proceedings of the National Academy of Sciences of the United States of America, 87*(6), 2324–2328. https://doi.org/10.1073/pnas.87.6.2324

Phillips, K.E., & Hopkins, W.G. (2020). Determinants of cycling performance: A review of the dimensions and features regulating performance in elite cycling competitions. *Sports Medicine—Open, 6*(1), Article 23. https://doi.org/10.1186/s40798-020-00252-z

Podlogar, T., & Wallis, G.A. (2022). New horizons in carbohydrate research and application for endurance athletes. *Sports Medicine, 52*, 5–23. https://doi.org/10.1007/s40279-022-01757-1

Poole, D., Burnley, M., Vanhatalo, A., Rossiter, H.B., & Jones, A.M. (2016). Critical power: An important fatigue threshold in exercise physiology. *Medicine & Science in Sports & Exercise, 48*(11), 2320–2334. https://doi.org/10.1249/MSS.0000000000000939

Rønnestad, B.R., & Hansen, J. (2018). A scientific approach to improve physiological capacity of an elite cyclist. *International Journal of Sports Physiology and Performance, 13*(3), 390–393. https://doi.org/10.1123/ijspp.2017-0228

Sánchez-Muñoz, C., Mateo-March, M., Muros, J.J., Javaloyes, A., & Zabala, M. (2023). Anthropometric characteristics according to the role performed by World Tour road cyclists for their team. *European Journal of Sport Science, 23*(9), 1821–1828. https://doi.org/10.1080/17461391.2022.2132879

Sanders, D., & Heijboer, M. (2019). Physical demands and power profile of different stage types within a cycling grand tour. *European Journal of Sport Science, 19*(6), 736–744. https://doi.org/10.1080/17461391.2018.1554706

Sanders, D., & van Erp, T. (2021). The physical demands and power profile of professional Men's cycling races: An updated review. *International Journal of Sports Physiology and Performance, 16*(1), 3–12. https://doi.org/10.1123/ijspp.2020-0508

Sanders, D., van Erp, T., & de Koning, J.J. (2019). Intensity and load characteristics of professional road cycling: Differences between men's and women's races. *International Journal of Sports Physiology and Performance, 14*(3), 296–302. https://doi.org/10.1123/ijspp.2018-0190

Santalla, A., Naranjo, J., & Terrados, N. (2009). Muscle efficiency improves over time in world-class cyclists. *Medicine and Science in Sports and Exercise, 41*(5), 1096–1101. https://doi.org/10.1249/MSS.0b013e318191c802

Saris, W.H.M., Van Erp-Baart, M.A., Brouns, F., Westerterp, K.R., & Ten Hoor, F. (1989). Study on food intake and energy expenditure during extreme sustained exercise: The Tour de France. *International Journal of Sports Medicine, 10*, S26–S31. https://doi.org/10.1055/s-2007-1024951

Schumacher, Y.O., & Mueller, P. (2002). The 4000-m team pursuit cycling world record: Theoretical and practical aspects. *Medicine and Science in Sports and Exercise, 34*(6), 1029–1036. https://doi.org/10.1097/00005768-200206000-00020

Shetty, P. (2005). Energy requirements of adults. *Public Health Nutrition, 8*(7a), 994–1009. https://doi.org/10.1079/PHN2005792

Sigrist, S., Maier, T., & Faiss, R. (2017). Qualitative video analysis of track-cycling team pursuit in world-class athletes. *International Journal of Sports Physiology & Performance, 12*(10), 1305–1309. https://doi.org/10.1123/ijspp.2016-0596

Sperlich, B., Matzka, M., & Holmberg, H.C. (2023). The proportional distribution of training by elite endurance athletes at different intensities during different phases of the season. *Frontiers in Sports and Active Living, 5*, Article 1258585. https://doi.org/10.3389/fspor.2023.1258585

Spragg, J., Leo, P., Giorgi, A., Gonzalez, B.M., & Swart, J. (2024). The intensity rather than the quantity of prior work determines the subsequent downward shift in the power duration relationship in professional cyclists. *European Journal of Sport Science, 24*(4), 449–457. https://doi.org/10.1002/ejsc.12077

Stadnyk, A.M.J., Impellizzeri, F.M., Stanley, J., Menaspà, P., & Slattery, K.M. (2022). Testing, training, and optimising performance of track cyclists: A systematic mapping review. *Sports Medicine, 52*(2), 391–401. https://doi.org/10.1007/s40279-021-01565-z

Stanley, J., Leo, P., Haakonssen, E., & Leckey, J.J. (2025). UCI sports nutrition project: Performance nutrition for sprint and endurance track cycling. *International Journal of Sport Nutrition and Exercise Metabolism*. Advance online publication. https://doi.org/10.1123/ijsnem.2025-0043

Stapelfeldt, B., Schwirtz, A., Schumacher, Y.O., & Hillebrecht, M. (2004). Workload demands in mountain bike racing. *International Journal of Sports Medicine, 25*(4), 294–300. https://doi.org/10.1055/s-2004-819937

Stevenson, J.D., Kilding, A.E., Plews, D.J., & Maunder, E. (2022). Prolonged cycling reduces power output at the moderate-to-heavy intensity transition. *European Journal of Applied Physiology, 122*(12), 2673–2682. https://doi.org/10.1007/s00421-022-05036-9

Støa, E.M., Helgerud, J., Rønnestad, B.R., Hansen, J., Ellefsen, S., & Støren, Ø. (2020). Factors influencing running velocity at lactate threshold in male and female runners at different levels of performance. *Frontiers in Physiology, 11*, Article 585267. https://doi.org/10.3389/fphys.2020.585267

Talanian, J., & Spriet, L.L. (2016). Low and moderate doses of caffeine late in exercise improve performance in trained cyclists. *Applied Physiology, Nutrition and Metabolism, 41*(8), 850–855. https://doi.org/10.1139/apnm-2016-0053

Thurber, C., Dugas, L.R., Ocobock, C., Carlson, B., Speakman, J.R., & Pontzer, H. (2019). Extreme events reveal an alimentary limit on sustained maximal human energy expenditure. *Science Advances, 5*(6), Article eaaw0341. https://doi.org/10.1126/sciadv.aaw0341

Valenzuela, P.L., Alejo, L.B., Lucia, A., & Barranco-Gil, D. (2023). What does it take to become a professional cyclist? A laboratory-based longitudinal analysis in competitive young riders. *International Journal of Sports Physiology and Performance, 18*(11), 1275–1282. https://doi.org/10.1123/ijspp.2023-0083

Valenzuela, P.L., Muriel, X., Van Erp, T., Mateo-March, M., Gandia, A., Zabala, M., Lamberts, R.P., Lucia, A., Barranco-gil, D., & Pallarés, J.G. (2022). The record power profile of male professional cyclists: Normative values obtained from a large database. *International Journal of Sports Physiology & Performance, 17*(5), 701–710. https://doi.org/10.1123/ijspp.2021-0263

van Erp, T., & Lamberts, R.P. (2022). Performance characteristics of TOP5 Versus NOT-TOP5 races in female professional cycling. *International Journal of Sports Physiology and Performance, 17*(7), 1070–1076. https://doi.org/10.1123/ijspp.2021-0488

van Erp, T., & Lamberts, R.P. (2023). Demands of professional female cycling races: Influence race level and race duration (single or multi-day events). *European Journal of Sport Science, 23*(8), 1463–1471. https://doi.org/10.1080/17461391.2022.2111277

van Erp, T., Lamberts, R.P., & Sanders, D. (2022). Power profile of top 5 results in world tour cycling races. *International Journal of Sports Physiology and Performance, 17*(2), 203–209. https://doi.org/10.1123/ijspp.2021-0081

van Erp, T., & Sanders, D. (2020). Demands of professional cycling races: Influence of race category and result. *European Journal of Sport Science, 21*(5), 666–677. https://doi.org/10.1080/17461391.2020.1788651

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van Erp, T., Sanders, D., & Lamberts, R.P. (2021). Maintaining power output with accumulating levels of work done is a key determinant for success in professional cycling. *Medicine & Science in Sports & Exercise, 53*(9), 1903–1910. https://doi.org/10.1249/MSS.0000000000002656

Van Erp, T., Sanders, D., & De Koning, J.J. (2020). Training characteristics of male and female professional road cyclists: A 4-year retrospective analysis. *International Journal of Sports Physiology and Performance, 15*(4), 534–540. https://doi.org/10.1123/ijspp.2019-0320

Van Hooren, B., Cox, M., Rietjens, G., & Plasqui, G. (2022). Determination of energy expenditure in professional cyclists using power data: Validation against doubly labeled water. *Scandinavian Journal of Medicine and Science in Sports, 33*(4), 407–419. https://doi.org/10.1111/sms.14271

Vikmoen, O., Ellefsen, S., Trøen, Ø., Hollan, I., Hanestadhaugen, M., Raastad, T., & Rønnestad, B.R. (2016). Strength training improves cycling performance, fractional utilization of VO_2max and cycling economy in female cyclists. *Scandinavian Journal of Medicine and Science in Sports, 26*(4), 384–396. https://doi.org/10.1111/sms.12468

Vogt, S., Schumacher, Y.O., Roecker, K., Dickhuth, H.H., Schoberer, U., Schmid, A., & Heinrich, L. (2007). Power output during the Tour de France. *International Journal of Sports Medicine, 28*(9), 756–761. https://doi.org/10.1055/s-2007-964982

Westerterp, K., Saris, W., Van Es, M., & Ten Hoor, F. (1986). Use of the doubly labeled water technique in humans during heavy sustained exercise. *Journal of Applied Physiology, 61*(6), 2162–2167. https://doi.org/10.1152/jappl.1986.61.6.2162

Whitfield, J., Egan, B., Del Coso, J., Derave, W., Saunders, B., & Burke, L.M. (2025). UCI sports nutrition project: Considerations and applications for the use of sports foods and supplements to improve performance in cycling. *International Journal of Sport Nutrition and Exercise Metabolism*. Advance online publication. https://doi.org/10.1123/ijsnem.2025-0111

Witard, O.C., Hearris, M., & Morgan, P.T. (2025). Protein nutrition for endurance athletes: A metabolic focus on promoting recovery and training adaptation. *Sports Medicine, 55*(6), 1361–1376. https://doi.org/10.1007/s40279-025-02203-8

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Nontechnical Summary

In the present review, we summarize the main factors underlying cycling performance. Although large differences exist between modalities, professional cycling especially the 3-week Grand Tours—epitomizes extreme endurance exercise, demanding an exceptional physical effort. Despite the enormous energy demands imposed by races, professional cyclists achieve impressive performance levels. Numerous extrinsic (e.g., race profile, weather conditions, altitude, team tactics) and intrinsic factors (e.g., mental, physical, physiological, and technical attributes, nutritional strategies) influence success in professional cycling. Among the latter, "traditional" physiological markers of endurance performance (e.g., maximum oxygen uptake, lactate threshold, pedaling efficiency) and anthropometric parameters (e.g., body mass, surface area) play a major role, but also the ability to generate high power output values at critical moments and the capacity to sustain performance under fatigue, recently termed as "durability." Thus, training and nutritional strategies should aim to improve these performance indicators.

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