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Can there be two speeds in a clean peloton? Performance strategies in modern road cycling

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ABSTRACT

In the history of professional cycling, riders have always sought competitive advantages. Throughout 20th century, many relied on performance-enhancing drugs (PEDs) which gave rise to a phenomenon called “two-speed cycling”. Throughout its modern era, professional cycling has seen anti-doping efforts repeatedly intensify on the heels of several large doping scandals. Over the past decade, the sport appears to have transitioned away from large-scale systematic doping and towards novel, legal performance-enhancing strategies, facilitated by a close relationship with scientific, technological, and engineering communities. The tools and technologies available to assess the demands of the sport, the capabilities of the riders, and the role of environmental factors such as wind resistance, altitude, and heat are more refined and comprehensive than ever. Teams and riders are now able to leverage these to improve training, recovery, equipment, race tactics and more, often from a very early age. This review explores several key developments in road cycling and their implications for the modern professional peloton.

Key Words: professional cycling; performance-enhancing drugs; marginal gains; performance analysis

INTRODUCTION

The main pack of riders navigating the road in a cycling race, known as the peloton, comprises a wide range of physiological, anthropometrical, technical, and strategical attributes. The role of each rider in a given race is typically based on strengths, weaknesses, and objectives, and can be modified by injuries, fitness level, personal goals, and unexpected in-race developments. The concept of “cycling at two speeds”, cyclisme à deux vitesses, has historically been used to distinguish between chemically enhanced riders and those who ride clean (134). However, despite increasingly stringent doping controls in professional cycling along with a clear shift in doping culture, the concept of two-speed cycling remains.

Given the well-documented benefits of performance-enhancing drugs (PEDs), there is an expectation that the intensification of anti-doping measures in professional cycling leads to more homogeneous performance levels in the peloton by reducing the number of artificially enhanced riders. Although this may be a reasonable assumption, it discounts the many substantial advances made in training, nutrition, technology, and strategy, as well as the growing talent pool of potential professionals and the early age at which they begin to seriously structure their training, racing, and recovery. These factors can differ greatly between teams and individual riders and thus help maintain the two-speed phenomenon. This review provides a brief history of the PED culture and use in professional cycling, followed by an examination of some of the key developments in the sport that has helped preserve the two-speed phenomenon in a peloton riding within an increasingly strict anti-doping framework.

The performance-enhanced past of the peloton

Drugs have been used to enhance athletic performance for millennia, stretching back to at least the ancient Olympic Games (16). Cycling as a profession emerged among working-class men who likened endurance sports to physically demanding jobs where the use of drugs to aid performance was considered the right thing to do (58). Indeed, doping has been pervasive in professional cycling for over 150 years, throughout most of which it was either legal or not subject to testing (34). For decades, riders doped to simply be able to do the job – faire le métier (33). Then, athlete health became a concern and a major driving force to regulate, if not outright ban the use of certain substances. Drug testing in the Tour de France (TdF), the most prestigious event on the race calendar, began in 1966. Despite this, amphetamines, cortisone, and steroids remained widespread in the professional peloton. It was also around this time that rumors about the use of blood transfusions in athletes began (60). The year after Raymond Poulidor underwent the first drug test in the TdF, Tom Simpson collapsed on the ascent of Mount Ventoux and later passed away due to an unfortunate combination of alcohol, amphetamines, intense heat, and extreme physical exertion. Although this event brought more attention to the use of stimulants and other drugs in cycling and in sports in general (69), doping would persist for decades to follow. Based on interviews with riders on a professional cycling team at the turn of the millennium, psychiatrist Jean-

Christophe Seznec (115) asserted that professional cyclists are not only prone to develop an addiction to PEDs, but also recreational drugs, noting the importance of explicitly acknowledging this risk in order to mitigate it.

When professional cycling entered the 90s, the banned yet at that time undetectable erythropoiesis-stimulating agent (ESA) recombinant human erythropoietin (rHuEPO) arrived in the peloton (101), and performances hit a new level. Increasing circulating erythropoietin (EPO) by illegal means has been perceived by some riders and coaches to give an estimated performance boost, without the term “performance” being strictly defined, of 3% to 20% (31, 100, 134, 138). Interestingly, despite its popularity in the peloton, the research literature on the effects of ESAs such as rHuEPO on endurance performance is equivocal. Its effects on hematological values like hemoglobin concentration ([Hb]) and clinical measurements of power and maximal oxygen uptake (VO2max) are well-established, but the real-world benefits are not always clear (116, 123).

There are several aspects of professional cycling that are difficult to account for in experimental studies on exogenous EPO, such as the extremely high fitness level of a peaked professional cyclist and the physiological impact of training and racing on parameters such as Hb. A recent randomized controlled trial found no apparent benefit of EPO on relevant performance markers has sometimes been cited to shed doubt on the true effects of the drug (47). However, this study was done in cyclists with an average VO2max of 55.6 mL/kg/min, which is substantially lower than their professional counterparts (124). By his own account, former professional Michael Rasmussen saw his hematocrit (Hct) drop from 41% to 36% following the 2002 Giro d’Italia (98), illustrating how blood composition can be severely perturbed by training and racing. Similar values have been observed in other professionals following participation in Grand Tours (17, 89). Using Rasmussen as an example, using rHuEPO to bring this up to 49%, just below the old 50% limit, would represent a relative Hct increase of 36% and result in improved ability to maintain a much higher intensity in training and racing, and consequently greater exercise-induced adaptations.

Throughout the 90s, Grand Tour riders with supraphysiological Hct would traverse France, Italy, and Spain at impressive speeds until it all seemingly came to an end in 1998. Three days before the start of the 85th edition of the TdF, a Festina team car carrying various PEDs was stopped by customs agents at the French-Belgian border. This event marked the start of what later became known as the Festina affair, a major catalyst in cycling’s transition to a cleaner sport. The wake of this scandal saw an increasing number of calls to action against doping, including by the driver of the Festina car (132), with claims of the sport dying unless drastic action is taken. Subsequent large-scale doping cases such as Operación Puerto and the contents of the USADA’s Reasoned Decision Report (10) served as reminders that PEDs were still present in the peloton and strengthened the resolve of those fighting for a cleaner sport.

Although riders are often blamed for the pervasive drug use in cycling, most entered a sport with a lack of top-down anti-doping efforts, leaving them with the difficult choice of either conforming to the culture or competing on unequal terms. One of the most crucial steps towards a cleaner sport is a change in culture among teams and riders. Much, if not most, of the credit should go to the riders themselves, many of which have actively pushed against the use of PEDs for years (46, 50, 59, 85, 130). Today, most doping cases in cycling are among semi-professional riders, whereas the number of riders testing positive at the highest level is approaching zero (88).

Although absence of evidence is not evidence of absence, fewer doping cases at the highest level of cycling suggests that overt, systematic drug use is a thing of the past. Given professional cycling's checkered history, it would be naïve to think that doping has been eliminated entirely, but the sport does appear to have evolved beyond doping being perceived as all but necessary to gain entry into the professional peloton. Generational shifts not only among riders, but also among governing bodies and team leadership have contributed to an overall firmer stance against doping, removing potentially significant contributors to anti-doping violations (6). There is also indications that the post-Armstrong generation, especially those who started their careers young, are less likely to use PEDs (5), although the evidence is equivocal (64). Additionally, anti-doping technology continues to improve, with recent advances such as gene expression analysis being able to extend the detection window of blood manipulations (28, 133).

Conceptual approaches to legal performance development

It could be argued that the extraordinary performances regularly being on display by the current generation of riders suggest that the dismantling of systematic doping practices has led to progression rather than regression of the sport of cycling. The transition away from prevalent PED use has forced teams and riders to seek out other areas of improvement, some with barely measurable effects, to keep up. Although seeking improvements in many areas is not a new phenomenon in professional cycling, it has received increasing attention over the past decade with the success of Team Sky, now INEOS Grenadiers, and team director, Dave Brailsford, who called this concept "marginal gains". Brailsford and his team set out to win the TdF within five years with a clean British rider (29). To achieve this, he brought with him the approach he used as a performance director for British Cycling, which had led to considerable success in track cycling. Team Sky was established on the back of British dominance in the Laoshan velodrome during the 2008 Beijing Olympics, where they took home seven gold medals. As he transitioned from the track to the road, Brailsford brought the idea that compiling enough marginal gains could provide a greater performance advantage than PEDs (87).

Although the marginal gain concept came to prominence with Team Sky during one of professional cycling's most recent avowed shift from banned to legal performance-enhancing strategies, it has been practiced by cyclists since at least the mid-1900s. Italian Fausto Coppi, who rode to multiple victories in the TdF and Giro d'Italia, as well as in one-day classics throughout the 40s and early 50s, was an early adopter of novel diet and training approaches. After World War II, the sport of cycling was anything but advanced and Coppi set out to change that. He worked with Bianchi to develop bikes and other equipment; he adapted his diet to better fuel his riding – not only its contents, but also the timing and amount; and he explored strategies for how to best race as a team (37). Some of these developments would later influence other greats, such as Eddie Merckx, who, among other things, was obsessed with proper bike fit (38). Current director of the French national team, Cyrille Guimard, has also long been known for his application of cutting-edge technology and training methods. One of his former riders, Laurent Fignon, described him as being “right up-to-date. He had files for everything. He was interested in all the lates training methods. Where his protégés were concerned, he would look at the very last detail and even the slightest defect would be corrected. He knew how to ensure everyone had the very best equipment that was on the market: made-to-measure bikes, the newest gadgets.” (32, p. 56).

The notion that modern riders can surpass past performances solely through legal performance strategies rests on the assumption that these strategies, particularly when combined, are highly effective. Furthermore, a larger pool of athletes and an earlier onset of structured athletic development might amplify these effects. The following section explores the degree of improvement that can be made in the areas of training, nutrition, and technology.

There is not a single anthropometric or physiological characteristic that is completely uniform across high-level cyclists (65, 111). Those with elite potential tend to have stand-out absolute measurements of aerobic fitness and power, but these are attributes that can also be found in cyclists of lower caliber. Elite riders also possess very high power-to-weigh ratios, typically expressed as watts per kilogram (W/kg). An emerging concept that may also distinguish riders of different caliber is durability, i.e., the point and degree of physiological decline during extended exercise (66, 79, 80). Laboratory measurements of key performance determinants such as power-to-weigh ratio, VO_{2max}, cycling economy, critical power, and peak power output provide a detailed physiological profile of each individual rider but cannot accurately predict real-life performance.

Training Strategies

Aided by technology, experience, and insights from a growing body of research, training is more refined, structured, and supervised than before, with most, if not all, training sessions serving a specific purpose. Each rider typically follows an individualized training plan that is carried out under comprehensive monitoring of variables such as heart rate, power output, climate, and terrain. These data, along with laboratory measurements, race outcomes, and even psychological variables, are used to adjust volume, frequency, intensity, and/or modality throughout the season. This allows each rider to absorb as much recoverable training volume as possible to optimize physiological adaptations and peak repeatedly for competition while avoiding overtraining. Whereas virtually every single pedal stroke of the modern rider is quantified and analyzed to guide training, racing, and recovery, riders of the past relied more on “feel”, often opting for subjective rather than objective measurements of output. During the 1987 TdF, Laurent Fignon declared his legs to be “functioning again, more or less”, but did not see the value in monitoring his heart rate, explaining that “I lost my temper with those blasted pulse monitors: I handed mine back so that it wouldn’t tell me anything anymore” (32, p. 182).

Although W/kg is often favored as an indicator of riding capacity and a way to quantify cycling performances, a large VO_{2max} has long been considered a basic requirement of entry into the professional peloton. Values reported for GC contenders are generally comparable between generations, with the lowest value found in the most dominant TdF rider of all time, albeit with an asterisk (**table 1**). There are a few caveats to these numbers, such as the validity of the actual measurement, most of which are not described in the research literature but rather in media. Moreover, oxygen uptake does not increase in proportion to body mass and scaling VO_{2max} to whole body mass is thus not appropriate when comparing athletes of different body sizes (71). Although some of these values may be exacerbated by PED use, both the baseline level and plasticity of VO_{2max} are under considerable genetic influence (15, 86, 135), and WorldTour levels can be reached without doping in those with sufficient genetic predisposition and appropriate stimulus.

Interestingly, there seems to be a physiological trade-off between efficiency and power, where adaptations towards the latter may attenuate the former (72, 113). This phenomenon was observed in Norwegian cyclist, Oskar Svendsen, who once had the highest VO2max ever recorded. Svendsen showed promise early by becoming junior time trial champion with less than three years of training and placing high in Tour de l’Avenir. However, despite an incredible VO2max of 96.7 ml/kg/min at 18 years of age, Svendsen never became a WorldTour rider. Although his early retirement at age 20 left his potential at the elite level largely unexplored, the reduction in cycling economy he experienced with increased training load could have been resolved as he matured as a rider, as cyclists appear to become more efficient over the span of their careers with little change in VO2max (112). If he remained active, Svendsen may eventually have been able to exploit his incredible baseline to reach the proverbial second speed in the modern peloton without chemical assistance. These insights into Svendsen’s physiological profile not only reveal some of the physiological complexities involved in high-level endurance performance, but also serve as an example of the scientific resources available to modern teams and riders that allows for a level of detail in the assessment and follow-up of athletes never seen before at that level of the sport.

Table 1. Reported maximal oxygen uptake ($\dot{V}O_{2max}$) of Tour de France (TdF) winners from the mid-1980s to present time

Rider	TdF victories	Body mass (kg)	BMI	$\dot{V}O_{2max}$ (ml/kg/min)	Ref.
Greg LeMond	1986, 1989 – 1990	67	21.1	92.5 – 95.0	(8, 42)
Miguel Indurain	1991 – 1995	79	22.4	78.0 – 95.0	(9, 61)
Lance Armstrong*	1999 – 2005	72	22.7	81.2 – 84.7	(20, 76)
Chris Froome	2013, 2015 – 2017	68	19.7	84.4 – 89.5	(11, 23)
Egan Bernal	2019	60	19.6	88.0 – 91.0	(2, 70)
Tadej Pogačar	2020 – 2021	66	21.3	85.0 – 89.4	(4, 136)
Jonas Vingegaard#	2022 – 2023	60	19.6	97.0	(122)

** Later stripped of all his TdF victories; # This number has been disputed by his own team (129). These $\dot{V}O_{2max}$ values should be interpreted with caution as most of them are reported without being substantiated by data from laboratory measurements. Both the true and reported values of each rider varies throughout a season and career as a function of fluctuating fitness level and body mass. Body mass and height (used to calculate body mass index [BMI]) values were derived from ProCyclingStats.com and are taken to represent approximate competition weight.*

Among the many training-related advances in the modern era is a more systematic approach to altitude training. Altitude-mediated erythropoiesis has long been recognized as an exposure that can produce adaptations that improves performance at sea level, as well as acclimatize athletes to sustain performance in hypobaric conditions. There are several ways to approach altitude training and care should be taken to avoid carrying the detrimental effects of prolonged hypoxic exposure, such as reduced cardiac output (Q) due to hypovolemia (117), into competition. Today, professional cycling teams rely on both experience as well as past and emerging research to use altitude as an important preparatory measure in various parts of the season. As the individual responses to hypoxic conditions can vary greatly (93), a large hematological response following real or simulated altitude exposure is an important attribute in modern riders. If done properly, altitude training can induce comparable hematological changes to rHuEPO use (table 2), making it a crucial performance-enhancing strategy in the modern peloton. Increasing [Hb] not only improves VO2max by improving the oxygen-carrying capacity of blood (43), it also enables sustained work at a higher fraction of maximal capacity (40) and faster VO2 kinetics (18), which can be hugely influential in a peloton with limited interindividual difference in VO2max.

Table 2. Comparison of physiological responses to rHuEPO use and altitude training

Outcome	rHuEPO	Hypobaric hypoxia
$\dot{V}O2_{max}$	6% – 10% (1, 18, 47)	3% – 8% (68, 84, 119)
[Hb]	8% – 12% (1, 18, 47)	14% – 15% (68, 114, 119)
Hct	8% – 16% (1, 18, 47)	4% – 13% (114, 119)
PPO	3% – 7% (1, 18, 47)	5% – 6% (84)

rHuEPO, recombinant human erythropoietin; $\dot{V}O_{2max}$, maximal oxygen uptake; [Hb], hemoglobin concentration; Hct, hematocrit; PPO, peak power output. The cited trials are of varying durations, with various outcome measures, and includes participants with heterogeneous baseline fitness levels and thus only provide rough estimations of the expected effects of each exposure on a group level.

A more recent strategy to legally induce hematological adaptations is heat acclimation. Prolonged exposure to heat is associated with both increased plasma volume, which can improve stroke volume and consequently Q and VO2max, as well as an expansion of total hemoglobin mass (Hbmass) (91). In fact, light exercise in a heated environment five times per week has been shown to increase Hbmass by 3% – 11% in endurance athletes (90, 103, 107). Due to the logistical challenges and cost related to with altitude camp designs such as live high-train low, heat acclimation training may offer a more accessible strategy for riders and teams with less resources, or an additional stimulus to regular stays at altitude.
The mechanistic similarities between synthetic and natural causes of erythropoiesis makes it physiologically possible to harness the benefits of EPO without doping. Voet (132) recounts that pre-scandal Festina riders did not even bring EPO to altitude camps because it was

going to be “useless”. Describing his first stay at altitude, formerly enhanced rider, Thomas Dekker, wrote that “[t]he altitude works its magic: the thin air jolts my body into producing extra red blood cells and the Swiss Tour is the first race in ages where I can stay with the pace on the climbs” (25, p. 135), expressing relief that he could hang with the peloton without PEDs. Michele Ferrari, Lance Armstrong’s coach during the height of his career, argues that the effects of EPO on hemoglobin concentration can be achieved through proper altitude training alone (31).

Every rider in the professional peloton possesses rare abilities as cyclists. Given that the sport selects for individuals with above average baseline values of [Hb] and Hct, it may not take much stimulus to maintain a high level. However, compared to simply administering rHuEPO, strategies such as altitude training and heat acclimation are more complex undertakings, partly because of potential drawbacks with that must be accounted for, such as transiently reduced Q and altered dietary requirements. The financial cost associated with prolonged exposure to altitude and/or heat for a professional team is also a considerable barrier, as the finances of teams can differ greatly. In some cases, PED use might simply just be more practical than legal strategies, and not necessarily more powerful.

Improving oxygen delivery and utilization have been main training targets for cyclists throughout most of its history, while resistance training (RT) has been largely neglected. As the impact of both power output and oxygen consumption on cycling performance is intrinsically related to rider weight, maintaining a low body mass has been, and still is, imperative. However, RT with an emphasis on neural adaptations can substantially improve force-generating capacity and reduce the oxygen cost of exercise in athletes without adding unnecessary bulk (51-53, 140). It also helps maintain bone mineral density, which elite cyclists are prone to lose (48, 110). A recent study found that RT with traditional movements and individualized load improved bone mineral density and endurance performance in professional cyclists (126). Moreover, it appeared to improve strength, power, and body composition to a greater degree than short sprint training, a more traditional power training modality for cyclists, supporting the role of structured RT as a part of a professional cyclists overall training program. Indeed, evidence for the benefit of RT on cycling performance has been mounting over the past years (table 3) (62, 102, 104-106, 108, 109, 120, 131, 141). This has contributed to changing the way RT is perceived and applied in the.

Table 3. Effects of resistance training (RT) on performance markers in elite cyclists

Outcome	Improvement	Ref.
TT_{short}	4%	(106, 126, 141)
TT_{long}	7% – 8%	(104, 108, 141)
PPO	3% – 9%	(62, 104)
W_{max}	3%– 8%	(104, 105, 108)
Anaerobic capacity	2%	(109)
$OBLA_{power}$	3%	(108)
RFD	20%	(141)

TT, time trial; PPO, peak power output; W_{max}, peak aerobic power; $OBLA_{power}$, power at 4 mM lactate; RFD, rate of force development. TT duration varied slightly between trials. Intensity, duration, and frequency of RT were not uniform across the interventions; this table provides estimates of the effects appropriately designed RT can have on various attributes in cyclists with a very high baseline fitness level. Improvements on specific RT exercises are generally present in all trials but excluded from the table as they are not directly related to cycling performance.

An elite physiology is easier to perturb than improve. At the highest level of cycling, large adaptations to training are unlikely to occur in the short term. The full, natural potential of a rider can only be reached via the cumulative effects of proper training and recovery, both of which are highly dependent on proper fueling.

Nutrition, body composition, and supplementation

In Jørgen Leth's classic documentary, "A Sunday in Hell", Roger De Vlaeminck can be seen consuming a plate of meat with his team before setting out to defend his multiple Paris–Roubaix victories from the previous years in the 1976 edition, with the narrator explaining that "a rare steak is a good breakfast for what lies ahead" (67). This is in stark contrast to the low-residue diet often consumed by riders in the modern peloton (39). A low-residue diet is characterized by a very low fiber content, which can reduce rider weight and consequently improve race performance (36). This diet is usually combined with a very high carbohydrate intake throughout a race to ensure constant glucose availability, and the reduced satiety that can be associated with low-residue diets may even help a rider maintain energy intake during a race. The exact amount differs between riders, with numbers around 100 g of carbohydrate per hour being a rough estimate that may be exceeded considerably on hard days. The recognition of the added performance benefit of increased carbohydrate intake has given rise to the concept of gut training for athletes (56, 78). Racing hard for hours on end for multiple consecutive days with limited glucose availability is guaranteed to hamper performance compared to a well-fueled athlete; as red blood cells do not convert to adenosine triphosphate; blood doping cannot replace bioenergetic fuel.

There are some examples of riders that leveraged nutrition to increase their performance throughout history, such as Fausto Coppi (37), but in the modern era, all riders pay attention and have access to both nutritionists and chefs, both of which are roles that have become integral parts of professional teams. Riders also have access to more knowledge and tools, such as food apps powered by machine learning (121). The days of training hard during the day following by alcohol consumption in the evening and racing on the weekends are gone, but were reportedly common until fairly recently (25, 54). The culmination of evidence- and experience-based diets in professional cycling has led to better fueling strategies and lower body mass in the peloton and perhaps especially among the best riders.

Although described as “thin as rakes” (132, p. 63), the riders of the 90s were heavy by today’s standard. Laurent Fignon (32) explains that the importance of power-to-weight ratio did not become known among the riders before the mid-80s and that he, until that point, paid little attention to diet. Looking at the top 10 finishers of the TdF for the past four decades, starting with the latest edition, suggest that it is becoming more and more of a requirement for the overall GC placing (table 4). Notably, between 1992 and 2022, the average BMI of the top 10 decreased by 8.1%. This trend seems to generally hold across all Grand Tours for the past decades (118).

Table 4. Average height, weight, and body mass index (BMI) of the top 10 finishers in the Tour de France (TdF) in 1992, 2002, 2012, 2022

Year	Height (cm)	Weight (kg)	BMI (kg/m^2)	Relative BMI change
1992	178.0	70.3	22.2	–
2002	175.7	66.2	21.4	- 3.6%
2012	182.1	68.0	20.5	- 4.2%
2022	176.7	63.8	20.4	- 0.5%

Data selected to represent the field a decade apart, starting with the latest TdF and going back as far as the data is reliable. Data derived from ProCyclingStats.com.

Supplements such as creatine and beta-alanine have been shown to improve endurance performance, including in cycling (7, 12, 21, 49, 127, 128). Creatine was introduced to the peloton in the mid-90s but was very expensive at the time. Riders who had access to it could consume up to 30 g the day before a long time trial or a mountain stage in hopes of a performance boost (132). Creatine and beta-alanine are now both affordable and widely used, alongside other supplements such as caffeine, electrolytes, nitrates, various vitamins, and minerals, as well as macronutrient supplements such as protein and carbohydrate.

In recent years, a lot of attention has been devoted to exogenous ketones. It is a contentious supplement that has been embraced some of the strongest teams while being recommended against by the Union Cycliste Internationale (UCI) and the Movement for Credible Cycling (MPCC). Ketones, or ketone bodies, are acetyl-CoA-derived metabolites that are produced by the liver under conditions with reduced glucose availability, such as low-carbohydrate diets, fasting, and during or after hard exercise. Ketone bodies such as β-hydroxybutyrate can spare glycogen by inhibiting glycolysis and acting as an alternative fuel in oxidative phosphorylation, which in turn can improve endurance (19). As with the research on other legal and illegal enhancement strategies, the degree to which exogenous ketones translates to improved exercise performance remains to be fully elucidated (24, 92, 94, 96, 125, 139). Although there may be potential drawbacks with isolated ketone supplementation (82), in conjunction with sodium bicarbonate, which is a weak base that has been used for some time in endurance sports (45), ketone supplementation has been shown to improve power output towards the end of a race simulation by 5% (95), although this effect may be unreliable and warrants further study (97).

Much of the hype surrounding some of the proposed effect of ketones as an energy substrate appears unwarranted, but emerging evidence suggest that it may have intriguing properties as a signaling molecule. A few years ago, it was shown that infusion of ketone bodies increased circulating EPO levels in healthy adults (63). The impact of ketones on EPO is supported by the observation that adherence to a ketogenic diet can increase [Hb] and Hct by ~3%, with the caveat this effect is within the biological variation of these markers (83). Recently, Evans et al. (30) found that ingestion of ketone monoester after cycling exercise increased serum EPO concentration, providing further evidence that it may be the signaling effects rather than nutritional value of ketone supplements confers the greatest performance benefit for professional cyclists.

Technology and equipment

Science tends to be reductionistic by necessity, whereas a cycling race is much more open-ended. There is, however, a certain cycling event that is performed in highly controlled conditions and relies heavily on technological advances that can serves as a good example of marginal gains in modern road cycling: the hour record. In 1972, Eddy Merckx, perhaps the greatest cyclist of all time, rode a distance of 49.431 km to set a new hour record for the first time since the 1950s. Twelve years later, Francesco Moser breached 50 km with an effort totaling 51.151 km, aided by disc wheels and a skin suit. The following years would see various innovative approaches by riders such as Graeme Obree and Chris Boardman, until the UCI decided to revise the rules in 1994 and again in 2014 (table 5). To set his records, Boardman worked closely with Brailsford's predecessor in British Cycling, Peter Keen, and then later with Brailsford himself after his retirement, on what would be the beginning of British riders' marginal gains on the track and later in the peloton (14).

Table 5. The Men's Union Cycliste Internationale (UCI) hour record holders since the 2014 rule revision

Rider	Team	Date	Distance (km)	Increase (%)
Jens Voigt	Leopard Trek	18.09.2014	51.110	–
Matthias Brändle	IAM Cycling	30.10.2014	51.852	1.45
Rohan Dennis	BMC Racing	08.02.2015	52.491	1.23
Alex Dowsett	Movistar	02.05.2015	52.937	0.85
Bradley Wiggins	Team Wiggins	07.06.2015	54.526	3.00
Victor Campenaerts	Lotto Soudal	16.04.2019	55.089	1.03
Daniel Bigham	INEOS Grenadiers	19.08.2022	55.548	0.83
Filippo Ganna	INEOS Grenadiers	08.10.2022	56.792	2.24

All record holders are required to participate in UCI's anti-doping system and hold a biological passport.

From Voigt's first attempt to Ganna's latest, the modern hour record has been improved by over 11%. Although Ganna is a multiple World Time Trial champion and likely one of the most suitable riders to attempt the record, the last person to hold the record before him was Daniel Bigham, the only rider on the list that was never a WorldTour rider. Although an accomplished cyclist in his own right, Bigham's record is a prime example of how far and fast you can get by maximizing the margins, with his record being set at an average power output approximately 100 watts less than Wiggins. Bigham himself puts his performance down to 50% physiology and 50% equipment (137). One of the main aspects Bigham exploited was aerodynamics; his coefficient of aerodynamic drag (CdA) was ~0.15, which is considerably below what is commonly seen in cyclists, including professionals (41).

Aerodynamics is not only relevant when riding fast around a velodrome for an hour, but also one of the most important things to consider when trying to ride fast on a bike in general. At a riding speed of about 54 km/h, close to the average on a flat TdF stage, approximately 90% of the total resistance is aerodynamic resistance (13, 44). Most of the resistance is caused by the rider himself, with common estimates ranging from 60-82% (74), and the rest by other factors such as equipment (22, 73, 77). The importance of minimizing CdA underlies much of the development of modern bike frames, wheels, handlebars, helmets, clothing, and more. In recent years, there has been less emphasis from manufacturers on getting their bikes down to the UCI weight limit of 6.8 kg in favor of more aerodynamic optimizations. This approach is supported by findings showing that simply opting for aerodynamic rather than light wheels will reduce climbing time on 3% – 6% grade hills (57). Steeper hills favor lighter wheels and WorldTour riders often make specific selections of wheelset, gear ratio, and even frameset based on race or stage profile. Some teams take it a step further, such as Jumbo-Visma, who use a portable aero sensor to measure exact wind conditions on race day and make equipment selections accordingly (81).

Since the inception of professional cycling there have been numerous technological advances and there is still a steady flow of innovations reaching the peloton. Some of these become widely adopted, such as aero-optimized gear; some are providing new alternatives without replacing old ones, such as tubeless tires (riders still use a variety of tubed, tubeless, and tubular tires); and others are replacing without immediately improving a function, such as disc brakes. Technology has also enabled more extensive monitoring of athletes, both on and more recently off the bike. For instance, several teams are now measuring body temperature and hydration status, and by analyzing the individual sodium composition sweat, can select the appropriate supplementary amount of sodium for each rider. During very hot days, riders are often seen wearing cooling gear to keep body temperature down. This can not only keep the riders comfortable, but may also benefit their performance in the race by lowering thermal strain (75).

Although professional cycling continues to benefit from science, technology, and engineering, the UCI have rules and regulations in place that ensures that cycling does not, for better or worse, stray too far away from its origins. Although these are subject to change based on new developments, they sometimes can become more restrictive, such as the recent ban on handlebars narrower than 350mm. Riders with the ability and resources to combine effective performance strategies from training, nutrition, recovery, and technology – perhaps especially strategies with small effects that are more likely to be ignored by others – may find themselves able to ride at a different speed than the rest of the peloton.

Merging the margins

Imagine a gifted and durable athlete with an exceptional ability to consume oxygen across all intensity domains, maintain a low body mass, effectively utilize lactate, absorb and recover from a high training load without injury or illness, handle training and race nutrition, thermoregulate in various climates, and respond well to altitude and heat exposure finding his or her way into cycling early in life. Suppose this young cyclist learns to maintain an aerodynamic position on the bike, pedal with an efficient cadence, move seamlessly through the peloton, avoid accidents, calmly handle the pressure of competition, and execute winning moves. Professional cycling selects for individuals with supraphysiological potential from environments that have allowed this potential to be expressed. Then, it awards those who have made it to the starting line and are able make as many performance determinants as possible come together on race day.

Increased professionalism at the highest level of the sport trickles down to the amateur and junior ranks, exposing up-and-coming cyclists to favorable conditions at an earlier age, leading to greater improvements in physiology, psychology, and race craft. Some riders may show incredible promise in some aspects of racing and struggle with others. Oskar Svendsen, VO2max world record holder, undoubtedly had one of the greatest physiological potentials ever seen in a rider. However, he admittedly also had technical and tactical challenges: “Cycling is a monotonous sport, yet so complex and driven by tactics that you won’t win races unless you deliver on all those qualities. I came into the sport with good physical qualities, but I struggled most with the tactics and patterns. I did learn a lot in my senior years on Team Joker though, even if I still had a long way to go. Descending down hills was also something I struggled a lot with, and it sapped much of my energy in races.” (99) Svendsen’s career serves as an example of how cycling is not only a physiological sport, but also technical, tactical, and psychological. Recently retired rider, Richie Porte, described former TdF GC winners Chris Froome and Tadej Pogačar as “psychological beasts” and noted that cycling has become increasingly scientific, which does not suit all riders (35). Modern riders are more methodical, data driven, and regimented than before. This reduces the human element of the sport, to the dismay of those claiming that this will increase predictability. Some researchers in the field have also warned against measuring just for the sake of measuring, and advise that rider data should serve a specific purpose (55).

The widely established routine of constant fueling during training and racing not only acutely increase work capacity but also improves subsequent recovery by preventing the rider from becoming completely depleted. This is in stark contrast to the days when reaching for your bottle during a hard training ride, even if it only contained water, was considered a weakness. Paul Köchli, former coach of riders such as Bernard Hinault and Greg Lemond, once said that the art of cycling is to do the right thing at the right moment (27). This is true not only in the context of a race, but indeed for the professional cyclist’s career as a whole. The effects of proper training, nutrition, and recovery accumulate not only throughout a season, but a whole career, benefitting those who consistently do the right things from early on.

Conclusion and future perspectives

In some ways, modern approaches to improving cycling performance represent a first principles approach to cycling and a fundamental challenge of conventions, within the rules and regulations of UCI. It seems to have restored some of the faith in the sport that was once lost with various doping scandals. Given the measurable impacts of legal performance-enhancing strategies, many of which were previously unknown or overlooked, it could be argued that combining these effects can bring a clean rider’s performance close to, or even surpass, that of an enhanced cyclist, assuming a gifted baseline and sufficient degree of adaptability.

Suggesting that it is possible to win at the highest level in cycling without the use of PEDs is not the same as claiming that the sport is completely clean. As others have pointed out, periods that have previously been perceived as clean have later been shown to be anything but (26). This paper covers some of the key legal advances in road cycling that has contributed to elite performances in the modern peloton, while at the same time acknowledging that illegal strategies may still be present.

Much of what was once considered “marginal gains” have now become common in all professional cycling teams. This represents a shift from a culture of doping to a culture of exhaustive continuous improvement, a lot of which is kept under wraps and some that may even be considered a grey area. Effective anti-doping measures contribute to a more level playing field, but not entirely level. The teams with the most resources often get the most talented riders, allowing them to combine the greatest potential with the best strategies. And even still, there are some who favor optimizing riders and their equipment for weight rather than aerodynamics, ignoring the latter to the extent that it becomes a considerable detriment. In an era of professional cycling where individual performances are influenced by a multitude of human and nonhuman factors, which in combination can have profound effects, the existence of two-speed cycling in a clean peloton is not only logical – it should be expected.

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REFERENCES

1. Annaheim, S., Jacob, M., Krafft, A., Breymann, C., Rehm, M., & Boutellier, U. (2016). RhEPO improves time to exhaustion by non-hematopoietic factors in humans. European Journal of Applied Physiology, 116(3), 623-633. https://doi.org/10.1007/s00421-015-3322-6
2. Arnold, R. (2018, 18 January 2018). Egan Bernal: A VO2max of 91… “it’s just a number”. Ride Media. Retrieved 10 January 2023 from https://www.ridemedia.com.au/features/egan-bernal-vo2max-91-just-number
3. Astolfi, T., Crettaz von Roten, F., Kayser, B., Saugy, M., & Faiss, R. (2021). The Influence of Training Load on Hematological Athlete Biological Passport Variables in Elite Cyclists. Frontiers in Sports and Active Living, 3. https://doi.org/10.3389/fspor.2021.618285
4. Attia, P., & San-Millán, I. (2022, 1 April 2022). How often should you be doing Zone 5 training? | Iñigo San-Millán, Ph.D. & Peter Attia, M.D. YouTube. Retrieved 10 January 2023 from https://www.youtube.com/watch?v=xuqURs4auc8
5. Aubel, O., Lefèvre, B., Le Goff, J.-M., & Taverna, N. (2018). Doping risk and career turning points in male elite road cycling (2005–2016). Journal of Science and Medicine in Sport, 21(10), 994-998. https://doi.org/10.1016/j.jsams.2018.03.003

6. Aubel, O., Lefèvre, B., Le Goff, J. M., & Taverna, N. (2019). The team effect on doping in professional male road cycling (2005-2016). Scandinavian Journal of Medicine & Science in Sports, 29(4), 615-622. https://doi.org/10.1111/sms.13384
7. Baguet, A., Koppo, K., Pottier, A., & Derave, W. (2010). Beta-alanine supplementation reduces acidosis but not oxygen uptake response during high-intensity cycling exercise. Eur J Appl Physiol, 108(3), 495-503. https://doi.org/10.1007/s00421-009-1225-0
8. Bailey, M. (2016, 6 May 2016). Greg LeMond: Interview. Cyclist. Retrieved 10 January 2023 from https://www.cyclist.co.uk/in-depth/115/greg-lemond-interview
9. Bailey, M. (2016, 31 May 2016). Miguel Indurain: the record Tour winner. Cyclist. Retrieved 10 January 2023 from https://www.cyclist.co.uk/in-depth/423/miguel-indurain-the-record-tour-winner
10. Bell, P., Ten Have, C., & Lauchs, M. (2016). A case study analysis of a sophisticated sports doping network: Lance Armstrong and the USPS Team. International Journal of Law, Crime and Justice, 46, 57-68. https://doi.org/10.1016/j.ijlcj.2016.03.001
11. Bell, P. G., Furber, M. J., van Someren, K. A., Antón-Solanas, A., & Swart, J. (2017). The Physiological Profile of a Multiple Tour de France Winning Cyclist. Med Sci Sports Exerc, 49(1), 115-123. https://doi.org/10.1249/mss.0000000000001068
12. Bemben, M. G., & Lamont, H. S. (2005). Creatine supplementation and exercise performance: recent findings. Sports Med, 35(2), 107-125. https://doi.org/10.2165/00007256-200535020-00002
13. Blocken, B., van Druenen, T., Toparlar, Y., & Andrianne, T. (2018). Aerodynamic analysis of different cyclist hill descent positions. Journal of Wind Engineering and Industrial Aerodynamics, 181, 27-45. https://doi.org/10.1016/j.jweia.2018.08.010
14. Boardman, C. (2017). Triumphs and Turbulence: My Autobiography. Ebury Press.
15. Bouchard, C., An, P., Rice, T., Skinner, J. S., Wilmore, J. H., Gagnon, J., Pérusse, L., Leon, A. S., & Rao, D. C. (1999). Familial aggregation of VO(2max) response to exercise training: results from the HERITAGE Family Study. J Appl Physiol (1985), 87(3), 1003-1008. https://doi.org/10.1152/jappl.1999.87.3.1003
16. Bowers, L. D. (1998). Athletic drug testing. Clin Sports Med, 17(2), 299-318. https://doi.org/10.1016/s0278-5919(05)70082-x
17. Chicharro, J. L., Hoyos, J., Bandrés, F., Terrados, N., Fernández, B., & Lucía, A. (2001). Thyroid hormone levels during a 3-week professional road cycling competition. Horm Res, 56(5-6), 159-164. https://doi.org/10.1159/000048112
18. Connes, P., Perrey, S., Varray, A., Préfaut, C., & Caillaud, C. (2003). Faster oxygen uptake kinetics at the onset of submaximal cycling exercise following 4 weeks recombinant human erythropoietin (r-HuEPO) treatment. Pflugers Arch, 447(2), 231-238. https://doi.org/10.1007/s00424-003-1174-0

19. Cox, Pete J., Kirk, T., Ashmore, T., Willerton, K., Evans, R., Smith, A., Murray, Andrew J., Stubbs, B., West, J., McLure, Stewart W., King, M. T., Dodd, Michael S., Holloway, C., Neubauer, S., Drawer, S., Veech, Richard L., Griffin, Julian L., & Clarke, K. (2016). Nutritional Ketosis Alters Fuel Preference and Thereby Endurance Performance in Athletes. Cell Metabolism, 24(2), 256-268. https://doi.org/10.1016/j.cmet.2016.07.010
20. Coyle, E. F. (2005). Improved muscular efficiency displayed as Tour de France champion matures. J Appl Physiol (1985), 98(6), 2191-2196. https://doi.org/10.1152/japplphysiol.00216.2005
21. Crisafulli, D. L., Buddhadev, H. H., Brilla, L. R., Chalmers, G. R., Suprak, D. N., & San Juan, J. G. (2018). Creatine-electrolyte supplementation improves repeated sprint cycling performance: A double blind randomized control study. J Int Soc Sports Nutr, 15, 21. https://doi.org/10.1186/s12970-018-0226-y
22. Crouch, T. N., Burton, D., LaBry, Z. A., & Blair, K. B. (2017). Riding against the wind: a review of competition cycling aerodynamics. Sports Engineering, 20(2), 81-110. https://doi.org/10.1007/s12283-017-0234-1
23. CyclingTips. (2016, 15 August 2016). Chris Froome’s lab results analysed: just how good is the three-time Tour de France champion? CyclingTips. Retrieved 10 January 2023 from https://cyclingtips.com/2016/08/chris-froomes-lab-results-analysed-just-how-good-is-the-three-time-tour-de-france-champion
24. Dearlove, D. J., Harrison, O. K., Hodson, L., Jefferson, A., Clarke, K., & Cox, P. J. (2021). The Effect of Blood Ketone Concentration and Exercise Intensity on Exogenous Ketone Oxidation Rates in Athletes. Medicine & Science in Sports & Exercise, 53(3). https://doi.org/10.1249/MSS.0000000000002502
25. Dekker, T. (2018). The Descent. Ebury Press.
26. Dimeo, P. (2014). Why Lance Armstrong? Historical Context and Key Turning Points in the ‘Cleaning Up’ of Professional Cycling. The International Journal of the History of Sport, 31(8), 951-968. https://doi.org/10.1080/09523367.2013.879858
27. Dower, J. (2014). Slaying the Badger ESPN.
28. Durussel, J., Haile, D. W., Mooses, K., Daskalaki, E., Beattie, W., Mooses, M., Mekonen, W., Ongaro, N., Anjila, E., Patel, R. K., Padmanabhan, N., McBride, M. W., McClure, J. D., & Pitsiladis, Y. P. (2016). Blood transcriptional signature of recombinant human erythropoietin administration and implications for antidoping strategies. Physiological Genomics, 48(3), 202-209. https://doi.org/10.1152/physiolgenomics.00108.2015
29. Edworthy, S., & Brailsford, D. (2012). 21 Days to Glory: The Official Team Sky Book of the 2012 Tour de France. HarperSport.
30. Evans, E., Walhin, J.-P., Hengist, A., Betts, J. A., Dearlove, D. J., & Gonzalez, J. T. (2022). Ketone monoester ingestion increases post-exercise serum erythropoietin concentrations in healthy men. American Journal of Physiology-Endocrinology and Metabolism. https://doi.org/10.1152/ajpendo.00264.2022
31. Ferrari, M. (2013, 22 January 2013). A bit of history. 53×12. Retrieved 27 December 2022 from https://www.53×12.com/a-bit-of-history

32. Fignon, L. (2010). We Were Young and Carefree. Yellow Jersey Press.
33. Fincoeur, B. (2009). Lutte antidopage et cyclisme à deux vitesses: Évolution du rapport au dopage chez les cyclistes belges depuis l'affaire Festina. Revue internationale de criminologie et de police technique, 62.
34. Fincoeur, B., Gleaves, J., & Ohl, F. (2019). Doping in Cycling: Interdisciplinary Perspectives. Routledge.
35. Fletcher, P. (2022, 23 December 2022). Richie Porte: Pogacar and Froome are psychological beasts. Cyclingnews. Retrieved 18 January 2023 from https://www.cyclingnews.com/news/richie-porte-pogacar-and-froome-are-psychological-beasts
36. Foo, W. L., Harrison, J. D., Mhizha, F. T., Langan-Evans, C., Morton, J. P., Pugh, J. N., & Areta, J. L. (2022). A Short-Term Low-Fiber Diet Reduces Body Mass in Healthy Young Men: Implications for Weight-Sensitive Sports. Int J Sport Nutr Exerc Metab, 32(4), 256-264. https://doi.org/10.1123/ijsnem.2021-0324
37. Fotheringham, W. (2010). Fallen Angel: The Passion of Fausto Coppi. Yellow Jersey Press.
38. Fotheringham, W. (2013). Half Man, Half Bike: The Life of Eddy Merckx, Cycling's Greatest Champion. Yellow Jersey Press.
39. Freeman, R. (2018). The Line: Where Medicine and Sport Collide. Wildfire.
40. Fritsch, J., Winter, U. J., Reupke, I., Gitt, A. K., Berge, P. G., & Hilger, H. H. (1993). [Effect of a single blood donation on ergo-spirometrically determined cardiopulmonary performance capacity of young healthy probands]. Z Kardiol, 82(7), 425-431. (Einfluss einer einmaligen Blutspende auf die ergospirometrisch bestimmte kardiopulmonale Leistungsfähigkeit bei jungen gesunden Probanden.)
41. García-López, J., Rodríguez-Marroyo, J. A., Juneau, C.-E., Peleteiro, J., Martínez, A. C., & Villa, J. G. (2008). Reference values and improvement of aerodynamic drag in professional cyclists. Journal of Sports Sciences, 26(3), 277-286. https://doi.org/10.1080/02640410701501697
42. Gifford, B. (July 2008). Greg LeMond vs. The World. Men's Journal. Retrieved 10 January 2023 from https://www.mensjournal.com/health-fitness/greg-lemond-vs-the-world-20130318
43. Gledhill, N., Warburton, D., & Jamnik, V. (1999). Haemoglobin, blood volume, cardiac function, and aerobic power. Can J Appl Physiol, 24(1), 54-65. https://doi.org/10.1139/h99-006
44. Grappe, F., Candau, R., Belli, A., & Rouillon, J. (1298). Aerodynamic drag in field cycling with special reference to the Obree's position. Ergonomics, December 1, 1299-1311. https://doi.org/10.1080/001401397187388

45. Grgic, J., Pedisic, Z., Saunders, B., Artioli, G. G., Schoenfeld, B. J., McKenna, M. J., Bishop, D. J., Kreider, R. B., Stout, J. R., Kalman, D. S., Arent, S. M., VanDusseldorp, T. A., Lopez, H. L., Ziegenfuss, T. N., Burke, L. M., Antonio, J., & Campbell, B. I. (2021). International Society of Sports Nutrition position stand: sodium bicarbonate and exercise performance. J Int Soc Sports Nutr, 18(1), 61. https://doi.org/10.1186/s12970-021-00458-w
46. Hamilton, T., & Coyle, D. (2012). The Secret Race: Inside the Hidden World of the Tour de France. Bantam Press.
47. Heuberger, J. A. A. C., Rotmans, J. I., Gal, P., Stuurman, F. E., van 't Westende, J., Post, T. E., Daniels, J. M. A., Moerland, M., van Veldhoven, P. L. J., de Kam, M. L., Ram, H., de Hon, O., Posthuma, J. J., Burggraaf, J., & Cohen, A. F. (2017). Effects of erythropoietin on cycling performance of well trained cyclists: a double-blind, randomised, placebo-controlled trial. The Lancet Haematology, 4(8), e374-e386. https://doi.org/10.1016/S2352-3026(17)30105-9
48. Hilkens, L., van Schijndel, N., Weijer, V., Boerboom, M., van der Burg, E., Peters, V., Kempers, R., Bons, J., van Loon, L. J. C., & van Dijk, J.-W. (2022). Low Bone Mineral Density and Associated Risk Factors in Elite Cyclists at Different Stages of a Professional Cycling Career. Medicine & Science in Sports & Exercise. https://doi.org/10.1249/MSS.0000000000003113
49. Hill, C. A., Harris, R. C., Kim, H. J., Harris, B. D., Sale, C., Boobis, L. H., Kim, C. K., & Wise, J. A. (2007). Influence of beta-alanine supplementation on skeletal muscle carnosine concentrations and high intensity cycling capacity. Amino Acids, 32(2), 225-233. https://doi.org/10.1007/s00726-006-0364-4
50. Hincapie, G., & Hummer, C. (2014). The Loyal Lieutenant: Leading Out Lance and Pushing Through the Pain on the Rocky Road to Paris. HarperCollins.
51. Hoff, J., Berdahl, G. O., & Bråten, S. (2001). Jumping height development and body weight considerations in ski jumping. In Science and skiing II : Second International Congress on Science and Skiing ; St. Christoph a. Arlberg, Austria, January 9-15, 2000. Hamburg: Kovač (Verlag), 2001, S. 403-412, Lit.
52. Hoff, J., Gran, A., & Helgerud, J. (2002). Maximal strength training improves aerobic endurance performance. Scand J Med Sci Sports, 12(5), 288-295. https://doi.org/10.1034/j.1600-0838.2002.01140.x
53. Hoff, J., Helgerud, J., & Wisløff, U. (1999). Maximal strength training improves work economy in trained female cross-country skiers. Med Sci Sports Exerc, 31(6), 870-877. https://doi.org/10.1097/00005768-199906000-00016
54. Hushovd, T., & Ravnåsen, J. (2014). Thor. Schibsted Forlag AS.
55. Javaloyes, A., & Mateo-March, M. (2022). Only what is necessary: The use of technology in cycling and concerns with its selection and use. Journal of Science & Cycling, 11(3), 1-2. https://doi.org/10.28985/1322.jsc.16
56. Jeukendrup, A. E. (2017). Training the Gut for Athletes. Sports Med, 47(Suppl 1), 101-110. https://doi.org/10.1007/s40279-017-0690-6

57. Jeukendrup, A. E., & Martin, J. (2001). Improving Cycling Performance. Sports Medicine, 31(7), 559-569. https://doi.org/10.2165/00007256-200131070-00009
58. Johnson, M. (2016). Spitting in the Soup: Inside the Dirty Game of Doping in Sports. VeloPress
59. Kimmage, P. (2007). Rough Ride. Yellow Jersey Press.
60. Klein, H. G. (1985). Blood transfusion and athletics. Games people play. N Engl J Med, 312(13), 854-856. https://doi.org/10.1056/nejm198503283121311
61. Kolata, G. (2005, 24 July 2005). Super, Sure, but Not More Than Human. The New York Times. Retrieved 10 January 2023 from https://www.nytimes.com/2005/07/24/weekinreview/super-sure-but-not-more-than-human.html
62. Kordi, M., Folland, J. P., Goodall, S., Menzies, C., Patel, T. S., Evans, M., Thomas, K., & Howatson, G. (2020). Cycling-specific isometric resistance training improves peak power output in elite sprint cyclists. Scand J Med Sci Sports, 30(9), 1594-1604. https://doi.org/10.1111/sms.13742
63. Lauritsen, K. M., Søndergaard, E., Svart, M., Møller, N., & Gormsen, L. C. (2018). Ketone Body Infusion Increases Circulating Erythropoietin and Bone Marrow Glucose Uptake. Diabetes Care, 41(12), e152-e154. https://doi.org/10.2337/dc18-1421
64. Lentillon-Kaestner, V., Hagger, M., & Hardcastle, S. (2011). Health and doping in elite-level cycling. Scandinavian Journal of Medicine & Science in Sports, 22, 596-606. https://doi.org/10.1111/j.1600-0838.2010.01281.x
65. Leo, P., Simon, D., Hovorka, M., Lawley, J., & Mujika, I. (2022). Elite versus non-elite cyclist – Stepping up to the international/elite ranks from U23 cycling. Journal of Sports Sciences, 40(16), 1874-1884. https://doi.org/10.1080/02640414.2022.2117394
66. Leo, P., Spragg, J., Mujika, I., Giorgi, A., Lorang, D., Simon, D., & Lawley, J. S. (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 and Performance, 16(8), 1089-1095. https://doi.org/10.1123/ijspp.2020-0381
67. Leth, J. (1977). A Sunday in Hell Steen Herdel Filmproduktion.
68. Levine, B. D., & Stray-Gundersen, J. (1997). “Living high-training low”: effect of moderate-altitude acclimatization with low-altitude training on performance. J Appl Physiol (1985), 83(1), 102-112. https://doi.org/10.1152/jappl.1997.83.1.102
69. Ljungqvist, A. (2017). Brief History of Anti-Doping. Med Sport Sci, 62, 1-10. https://doi.org/10.1159/000460680
70. Llamas, F. (2016, 24 January 2016). La ‘bestia’ que viene. Marca. Retrieved 10 January 2023 from https://www.marca.com/ciclismo/2016/01/24/56a4fa71ca474159048b45c4.html
71. Lolli, L., Batterham, A. M., Weston, K. L., & Atkinson, G. (2017). Size Exponents for Scaling Maximal Oxygen Uptake in Over 6500 Humans: A Systematic Review and Meta-Analysis. Sports Med, 47(7), 1405-1419. https://doi.org/10.1007/s40279-016-0655-1

72. Lucía, A., Hoyos, J., Pérez, M., Santalla, A., & Chicharro, J. L. (2002). Inverse relationship between VO2max and economy/efficiency in world-class cyclists. Medicine & Science in Sports & Exercise, 34(12). https://doi.org/10.1249/01.MSS.0000039306.92778.DF
73. Lukes, R. A., Chin, S. B., & Haake, S. J. (2005). The understanding and development of cycling aerodynamics. Sports Engineering, 8(2), 59-74. https://doi.org/10.1007/BF02844004
74. Malizia, F., Druenen, T., & Blocken, B. (2021). Impact of wheel rotation on the aerodynamic drag of a time trial cyclist. Sports Engineering, 24. https://doi.org/10.1007/s12283-021-00341-6
75. Marino, F. E. (2002). Methods, advantages, and limitations of body cooling for exercise performance. British Journal of Sports Medicine, 36(2), 89. https://doi.org/10.1136/bjsm.36.2.89
76. Martin, D. T., Quod, M. J., & Gore, C. J. (2005). Has Armstrong's cycle efficiency improved? Journal of Applied Physiology, 99(4), 1628-1629. https://doi.org/10.1152/japplphysiol.00507.2005
77. Martin, J. C., Milliken, D. L., Cobb, J. E., McFadden, K. L., & Coggan, A. R. (1998). Validation of a Mathematical Model for Road Cycling Power. Journal of Applied Biomechanics, 14(3), 276-291. https://doi.org/10.1123/jab.14.3.276
78. Martinez, I. G., Mika, A. S., Biesiekierski, J. R., & Costa, R. J. S. (2023). The Effect of Gut-Training and Feeding-Challenge on Markers of Gastrointestinal Status in Response to Endurance Exercise: A Systematic Literature Review. Sports Med, 53(6), 1175-1200. https://doi.org/10.1007/s40279-023-01841-0
79. Mateo-March, M., Valenzuela, P. L., Muriel, X., Gandia-Soriano, A., Zabala, M., Lucia, A., Pallarés, J., & Barranco-Gil, D. (2022). The Record Power Profile of Male Professional Cyclists: Fatigue Matters. International Journal of Sports Physiology and Performance, 17, 1-6. https://doi.org/10.1123/ijspp.2021-0403
80. 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
81. Mc Laughlin, R. (2022, 3 August 2022). Has Aerosensor finally cracked at-home aero testing? CyclingTips. Retrieved 17 January 2023 from https://cyclingtips.com/2022/08/has-aerosensor-finally-cracked-at-home-aero-testing
82. McCarthy, D. G., Bostad, W., Powley, F. J., Little, J. P., Richards, D. L., & Gibala, M. J. (2021). Increased cardiorespiratory stress during submaximal cycling after ketone monoester ingestion in endurance-trained adults. Appl Physiol Nutr Metab, 46(8), 986-993. https://doi.org/10.1139/apnm-2020-0999
83. McKay, A. K. A., Peeling, P., Pyne, D. B., Welvaert, M., Tee, N., Leckey, J. J., Sharma, A. P., Ross, M. L. R., Garvican-Lewis, L. A., Swinkels, D. W., Laarakkers, C. M., & Burke, L. M. (2019). Chronic Adherence to a Ketogenic Diet Modifies Iron Metabolism in Elite Athletes. Medicine & Science in Sports & Exercise, 51(3). https://doi.org/10.1249/MSS.0000000000001816

84. Meeuwsen, T., Hendriksen, I. J. M., & Holewijn, M. (2001). Training-induced increases in sea-level performance are enhanced by acute intermittent hypobaric hypoxia. European Journal of Applied Physiology, 84(4), 283-290. https://doi.org/10.1007/s004210000363
85. Millar, D. (2012). Racing Through the Dark. Orion Publishing Group.
86. Miyamoto-Mikami, E., Zempo, H., Fuku, N., Kikuchi, N., Miyachi, M., & Murakami, H. (2018). Heritability estimates of endurance-related phenotypes: A systematic review and meta-analysis. Scandinavian Journal of Medicine & Science in Sports, 28(3), 834-845. https://doi.org/10.1111/sms.12958
87. Moore, R. (2012). Sky's the Limit: British Cycling's Quest to Conquer the Tour de France. HarperSport.
88. Movement for Credible Cycling. (2022). Credibility figures: Continental teams tarnished [Internet; cited 2023 August 2]. Retrieved from: https://www.mpcc.fr/en/credibility-figures-continental-teams-tarnished/.
89. Mørkeberg, J. S., Belhage, B., & Damsgaard, R. (2009). Changes in blood values in elite cyclist. Int J Sports Med, 30(2), 130-138. https://doi.org/10.1055/s-2008-1038842
90. Nybo, L., Rønnestad, B., & Lundby, C. (2022). High or hot-Perspectives on altitude camps and heat-acclimation training as preparation for prolonged stage races. Scand J Med Sci Sports. https://doi.org/10.1111/sms.14268
91. Oberholzer, L., Siebenmann, C., Mikkelsen, C. J., Junge, N., Piil, J. F., Morris, N. B., Goetze, J. P., Meinild Lundby, A.-K., Nybo, L., & Lundby, C. (2019). Hematological Adaptations to Prolonged Heat Acclimation in Endurance-Trained Males. Frontiers in Physiology, 10. https://doi.org/10.3389/fphys.2019.01379
92. Pinckaers, P. J., Churchward-Venne, T. A., Bailey, D., & van Loon, L. J. (2017). Ketone Bodies and Exercise Performance: The Next Magic Bullet or Merely Hype? Sports Med, 47(3), 383-391. https://doi.org/10.1007/s40279-016-0577-y
93. Płoszczyca, K., Langfort, J., & Czuba, M. (2018). The Effects of Altitude Training on Erythropoietic Response and Hematological Variables in Adult Athletes: A Narrative Review. Frontiers in Physiology, 9. https://doi.org/10.3389/fphys.2018.00375
94. Poffé, C., Ramaekers, M., Bogaerts, S., & Hespel, P. (2020). Exogenous ketosis impacts neither performance nor muscle glycogen breakdown in prolonged endurance exercise. Journal of Applied Physiology, 128(6), 1643-1653. https://doi.org/10.1152/japplphysiol.00092.2020
95. Poffé, C., Ramaekers, M., Bogaerts, S., & Hespel, P. (2021). Bicarbonate Unlocks the Ergogenic Action of Ketone Monoester Intake in Endurance Exercise. Medicine & Science in Sports & Exercise, 53(2). https://doi.org/10.1249/MSS.0000000000002467
96. Poffé, C., Robberechts, R., Podlogar, T., Kusters, M., Debevec, T., & Hespel, P. (2021). Exogenous ketosis increases blood and muscle oxygenation but not performance during exercise in hypoxia. American Journal of Physiology-Regulatory, Integrative and Comparative Physiology, 321(6), R844-R857. https://doi.org/10.1152/ajpregu.00198.2021

97. Poffé, C., Wyns, F., Ramaekers, M., & Hespel, P. (2021). Exogenous Ketosis Impairs 30-min Time-Trial Performance Independent of Bicarbonate Supplementation. Med Sci Sports Exerc, 53(5), 1068-1078. https://doi.org/10.1249/mss.0000000000002552
98. Rasmussen, M., & Wivel, K. (2013). Gul Feber. People'sPress.
99. Redford, P. (2018, 2 April 2018). The Fittest Human Ever Quit Sports, Found Happiness. Deadspin Retrieved 10 January 2023 from https://deadspin.com/the-fittest-human-ever-quit-sports-found-happiness-1823998288
100. Riis, B., & Pedersen, L. S. (2012). Riis: Stages Of Light And Dark. Vision Sports Publishing.
101. Robinson, N., Giraud, S., Saudan, C., Baume, N., Avois, L., Mangin, P., & Saugy, M. (2006). Erythropoietin and blood doping. Br J Sports Med, 40 Suppl 1(Suppl 1), i30-34. https://doi.org/10.1136/bjsm.2006.027532
102. Rønnestad, B. (2022). Case Report: Effects of Multiple Seasons of Heavy Strength Training on Muscle Strength and Cycling Sprint Power in Elite Cyclists. Front Sports Act Living, 4, 860685. https://doi.org/10.3389/fspor.2022.860685
103. Rønnestad, B., Hamarsland, H., Hansen, J., Holen, E., Montero, D., Whist, J. E., & Lundby, C. (2021). Five weeks of heat training increases haemoglobin mass in elite cyclists. Exp Physiol, 106(1), 316-327. https://doi.org/10.1113/ep088544
104. Rønnestad, B., Hansen, E. A., & Raastad, T. (2010). Effect of heavy strength training on thigh muscle cross-sectional area, performance determinants, and performance in well-trained cyclists. Eur J Appl Physiol, 108(5), 965-975. https://doi.org/10.1007/s00421-009-1307-z
105. Rønnestad, B., Hansen, E. A., & Raastad, T. (2010). In-season strength maintenance training increases well-trained cyclists' performance. Eur J Appl Physiol, 110(6), 1269-1282. https://doi.org/10.1007/s00421-010-1622-4
106. Rønnestad, B., Hansen, E. A., & Raastad, T. (2011). Strength training improves 5-min all-out performance following 185 min of cycling. Scandinavian Journal of Medicine & Science in Sports, 21(2), 250-259. https://doi.org/10.1111/j.1600-0838.2009.01035.x
107. Rønnestad, B., Hansen, J., Bonne, T., & Lundby, C. (2021). Case Report: Heat Suit Training May Increase Hemoglobin Mass in Elite Athletes. International Journal of Sports Physiology and Performance, 17, 1-5. https://doi.org/10.1123/ijspp.2021-0033
108. Rønnestad, B., Hansen, J., Hollan, I., & Ellefsen, S. (2015). Strength training improves performance and pedaling characteristics in elite cyclists. Scand J Med Sci Sports, 25(1), e89-98. https://doi.org/10.1111/sms.12257
109. Rønnestad, B., Hansen, J., & Nygaard, H. (2017). 10 weeks of heavy strength training improves performance-related measurements in elite cyclists. J Sports Sci, 35(14), 1435-1441. https://doi.org/10.1080/02640414.2016.1215499

110. Sabo, D., Reiter, A., Pfeil, J., Güssbacher, A., & Niethard, F. U. (1996). [Modification of bone quality by extreme physical stress. Bone density measurements in high-performance athletes using dual-energy x-ray absorptiometry]. Z Orthop Ihre Grenzgeb, 134(1), 1-6. https://doi.org/10.1055/s-2008-1037409 (Beeinflussung der Knochenqualität durch extreme körperliche Belastung. Knochendichtemessungen bei Hochleistungssportlern mit der Dual-Energie-Röntgen-Absorptionmetrie.)
111. Sánchez-Muñoz, C., Mateo-March, M., Muros, J. J., Javaloyes, A., & Zabala, M. (2022). Anthropometric characteristics according to the role performed by World Tour road cyclists for their team. European Journal of Sport Science, 1-8. https://doi.org/10.1080/17461391.2022.2132879
112. Santalla, A., Naranjo, J., & Terrados, N. (2009). Muscle efficiency improves over time in world-class cyclists. Med Sci Sports Exerc, 41(5), 1096-1101. https://doi.org/10.1249/MSS.0b013e318191c802
113. Schiffer, T. A., Ekblom, B., Lundberg, J. O., Weitzberg, E., & Larsen, F. J. (2014). Dynamic regulation of metabolic efficiency explains tolerance to acute hypoxia in humans. The FASEB Journal, 28(10), 4303-4311. https://doi.org/10.1096/fj.14-251710
114. Schuler, B., Thomsen, J. J., Gassmann, M., & Lundby, C. (2007). Timing the arrival at 2340 m altitude for aerobic performance. Scand J Med Sci Sports, 17(5), 588-594. https://doi.org/10.1111/j.1600-0838.2006.00611.x
115. Seznec, J. C. (2002). Toxicomanie et cyclisme professionnel. Annales Médico-psychologiques, revue psychiatrique, 160(1), 72-76. https://doi.org/10.1016/S0003-4487(01)00133-0
116. Sgrò, P., Sansone, M., Sansone, A., Romanelli, F., & Di Luigi, L. (2018). Effects of erythropoietin abuse on exercise performance. The Physician and Sportsmedicine, 46(1), 105-115. https://doi.org/10.1080/00913847.2018.1402663
117. Siebenmann, C., Hug, M., Keiser, S., Müller, A., van Lieshout, J., Rasmussen, P., & Lundby, C. (2013). Hypovolemia explains the reduced stroke volume at altitude. Physiol Rep, 1(5), e00094. https://doi.org/10.1002/phy2.94
118. Smith, A., Wijnkoop, M. v., Colangelo, J., Buadze, A., & Liebrenz, M. (2023). Body Mass Index trends in men's Grand Tour cycling events from 1992-2022: Implications for athlete wellbeing and regulatory frameworks. Research Square. https://doi.org/10.21203/rs.3.rs-2568920/v1
119. Stray-Gundersen, J., Chapman, R. F., & Levine, B. D. (2001). "Living high-training low" altitude training improves sea level performance in male and female elite runners. J Appl Physiol (1985), 91(3), 1113-1120. https://doi.org/10.1152/jappl.2001.91.3.1113
120. Sunde, A., Støren, Ø., Bjerkaas, M., Larsen, M. H., Hoff, J., & Helgerud, J. (2010). Maximal Strength Training Improves Cycling Economy in Competitive Cyclists. The Journal of Strength & Conditioning Research, 24(8). https://doi.org/10.1519/JSC.0b013e3181aeb16a

121. Team Jumbo-Visma. (2021, 21 January 2021). Must-have for all riders: the Jumbo Foodcoach app. TeamJumboVisma.com. Retrieved 16 January 2023 from https://www.teamjumbovisma.com/article/material/must-have-for-all-riders-the-jumbo-foodcoach-app/
122. Thewlis, T. (2023). Chords to cols: How Jonas Vingegaard went from guitars to Grand Tours [Internet]. 2023 July 6 [cited 2023 August 2]; Retrieved from: https://www.cyclingweekly.com/racing/holidays-in-the-mountains-to-hard-graft-in-hantsholm-harbour-the-making-of-jonas-vingegaard.
123. Trinh, K. V., Diep, D., Chen, K. J. Q., Huang, L., & Gulenko, O. (2020). Effect of erythropoietin on athletic performance: a systematic review and meta-analysis. BMJ Open Sport Exerc Med, 6(1), e000716. https://doi.org/10.1136/bmjsem-2019-000716
124. Valenzuela, P. L., Alejo, L. B., Ozcoidi, L. M., Lucia, A., Santalla, A., & Barranco-Gil, D. (2023). Durability in Professional Cyclists: A Field Study. Int J Sports Physiol Perform, 18(1), 99-103. https://doi.org/10.1123/ijspp.2022-0202
125. Valenzuela, P. L., Castillo-García, A., Morales, J. S., & Lucia, A. (2021). Perspective: Ketone Supplementation in Sports-Does It Work? Adv Nutr, 12(2), 305-315. https://doi.org/10.1093/advances/nmaa130
126. Valenzuela, P. L., Gil-Cabrera, J., Talavera, E., Alejo, L. B., Montalvo-Pérez, A., Rincón-Castanedo, C., Rodríguez-Hernández, I., Lucia, A., & Barranco-Gil, D. (2021). On- Versus Off-Bike Power Training in Professional Cyclists: A Randomized Controlled Trial. Int J Sports Physiol Perform, 16(5), 674-681. https://doi.org/10.1123/ijspp.2020-0305
127. Van Thienen, R., Van Proeyen, K., Vanden Eynde, B., Puype, J., Lefere, T., & Hespel, P. (2009). Beta-alanine improves sprint performance in endurance cycling. Med Sci Sports Exerc, 41(4), 898-903. https://doi.org/10.1249/MSS.0b013e31818db708
128. Vandebuerie, F., Vanden Eynde, B., Vandenberghe, K., & Hespel, P. (1998). Effect of creatine loading on endurance capacity and sprint power in cyclists. Int J Sports Med, 19(7), 490-495. https://doi.org/10.1055/s-2007-971950
129. Vandecapelle, B. (2023). FACTCHECK. “Toen hij 17 was, had hij VO_2max van 97”: waanzinnige cijfers doen de ronde over Vingegaard, maar kloppen ze wel? [Internet]. 2023 July 19 [cited 2023 August 2]; Retrieved from: https://www.hln.be/tour-de-france/factcheck-toen-hij-17-was-had-hij-vomax-van-97-waanzinnige-cijfers-doen-de-ronde-over-vingegaard-maar-kloppen-ze-wel~a340e8a6/.
130. Vaughters, J. (2019). One-Way Ticket: Nine Lives on Two Wheels. Quercus Editions Ltd.
131. Vikmoen, O., Ellefsen, S., Trøen, Ø., Hollan, I., Hanestadhaugen, M., Raastad, T., & Rønnestad, B. (2016). Strength training improves cycling performance, fractional utilization of VO2max and cycling economy in female cyclists. Scand J Med Sci Sports, 26(4), 384-396. https://doi.org/10.1111/sms.12468
132. Voet, W. (2002). Breaking the Chain: Drugs and Cycling: The True Story. Random House.

133. Wang, G., Durussel, J., Shurlock, J., Mooses, M., Fuku, N., Bruinvels, G., Pedlar, C., Burden, R., Murray, A., Yee, B., Keenan, A., McClure, J. D., Sottas, P.-E., & Pitsiladis, Y. P. (2017). Validation of whole-blood transcriptome signature during microdose recombinant human erythropoietin (rHuEpo) administration. BMC Genomics, 18(8), 817. https://doi.org/10.1186/s12864-017-4191-7
134. Whittle, J. (2009). Bad Blood: The Secret Life of the Tour de France. Yellow Jersey Press.
135. Williams, C. J., Williams, M. G., Eynon, N., Ashton, K. J., Little, J. P., Wisloff, U., & Coombes, J. S. (2017). Genes to predict VO2max trainability: a systematic review. BMC Genomics, 18(Suppl 8), 831. https://doi.org/10.1186/s12864-017-4192-6
136. Witts, J. (2022, 1 August 2022). Rouleur Retrieved 10 January 2023 from https://www.rouleur.cc/blogs/rouleur-performance/recover-like-a-grand-tour-rider
137. Witts, J. (2022, 1 September 2022). Behind the scenes of Dan Bigham's Hour Record: Part one Rouleur. Retrieved 17 January 2023 from https://www.rouleur.cc/blogs/the-rouleur-journal/behind-the-scenes-of-dan-bighams-hour-record-part-one
138. Zenovich, M. (2020). Lance Part 1 ESPN.
139. Øvretveit, K. (2023). Metabolic and moral effects of exogenous ketones. Norwegian journal of nutrition, 21(2), 33-36. https://doi.org/10.18261/ntfe.21.2.6
140. Øvretveit, K., & Tøien, T. (2018). Maximal Strength Training Improves Strength Performance in Grapplers. J Strength Cond Res, 32(12), 3326-3332. https://doi.org/10.1519/jsc.0000000000002863
141. Aagaard, P., Andersen, J. L., Bennekou, M., Larsson, B., Olesen, J. L., Crameri, R., Magnusson, S. P., & Kjær, M. (2011). Effects of resistance training on endurance capacity and muscle fiber composition in young top-level cyclists. Scandinavian Journal of Medicine & Science in Sports, 21(6), e298-e307. https://doi.org/10.1111/j.1600-0838.2010.01283.x

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