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The Tour de France: An Updated Physiological Review

Alfredo Santalla, Conrad P. Earnest, José A. Marroyo, and Alejandro Lucia

From its initial inception in 1903 as a race premised on a publicity stunt to sell newspapers, the Tour de France had grown and evolved over time to become one of the most difficult and heralded sporting events in the world. Though sporting science and the Tour paralleled each other, it was not until the midlate 1980s, and especially the midlate 1990s (with the use of heart-rate monitors) that the 2 began to unify and grow together. The purpose of this brief review is to summarize what is currently known of the physiological demands of the Tour de France, as well as of the main physiological profile of Tour de France competitors.

Keywords: racing, cycling, mountain, time trial

In 1903 Maurice Garin's inaugural victory over 2428 km (94 h:33 min) in the Tour de France (Tour) established a 109-year legacy of bicycle racing. Today, 59 cyclists have won the Tour, in which, in its infancy, cyclists attended to their own maintenance, feeding, and hydration needs.¹ Today's modern Tour is well supported and composed of 3 stage types: flat (FT), high mountain (HM), and time trial (TT). While the first few Tours were <3000 km long, these soon evolved into the grueling, classic editions (>5000 km) composed of FTs divided into 14 to 17 stages (≈400 km/stage). This peaked in 1927 (5745 km, 17 stages, ~337-km stage) with each stage lasting ~14 hours. It was also during this time that HM stages were introduced in the Pyrenees (*Tourmalet* and *Aubisque*, 1910) and the Alps in 1911 (*Galibier*),¹ and 1934 saw the introduction of the more classic TT. The shorter prologue TT was introduced in 1967. In 1952, coinciding with the Tour's first television coverage, the Tour finished its HM stages on the top of respective climbs (*Alpe D'Huez*, *Puy de Dome*, and *Sestrières*), and in 1957, it was broadcast for the first time in its entirety, increasing the impact of the race among the general public.

The modern era of the Tour started in the 1980s with the inclusion of technological advances such as clip-on pedals and aerodynamic components (eg, TT helmets, aerobars, special bike frames, disc wheels).² Among the 59 Tour winners, 3 riders won the Tour 3 times, 4 riders won 5 times, and 1, Lance Armstrong, was able to

win the Tour 7 times. Paradoxically, it was not until the past 50 years that the level of specialization for cyclists increased and the great masters of the Tour emerged: Jacques Anquetil in the 60s, Eddie Merckx in the 70s, Bernard Hinault in the 80s, Miguel Indurain in the 90s, and Lance Armstrong after the year 2000.¹ Today, the Tour remains the largest sporting event that is free to most of those who attend, who line the roadsides from start to finish in the hope of catching a brief glimpse of their racing heroes.

Although the distance has gradually decreased from 1927, the Tour has maintained its current configuration of ~21 stages raced over 3 weeks¹ and allows for the analysis of changes in the estimated physiological requirements through the present day. Concordant with the decreased distance is an increase in the winner's average speed, reaching its zenith in 2005 (41,654 km/h; Figure 1).¹ Indeed, if the first 3 Tours are excluded (<3000 km), we observe a high correlation between the total race distance and the average speed of the winner ($r = -.889$, $P < .01$; Figure 2). This observation also suggests the obvious influence of the cyclist's ability to sustain high exercise intensities and greater speeds for prolonged periods of time (Figures 3 and 4). While the total race distance has varied less, in modern times (1985–2011) technological advances (modern bike frames, clip-on pedals, aerodynamic positioning, aerodynamic bike components, road surfaces, etc) have contributed to the improvements in racing speeds observed today despite the same physiological load ($r = -.511$, $P < .01$).²

Today's modern Tour begins with ~200 cyclists who cover an average distance of 3650 ± 208 km in an average of 92 ± 6 hours for the winner (data from 1990 to 2011).¹ FT stages now last ~200 km (4–5 h) and are ridden at high speeds (40–60 km/h) mostly in a group, known as the peloton, which demands high technical abilities. The TT stages, where specialists maintain high speeds (~50 km/h) without drafting, depend on a high, sustainable

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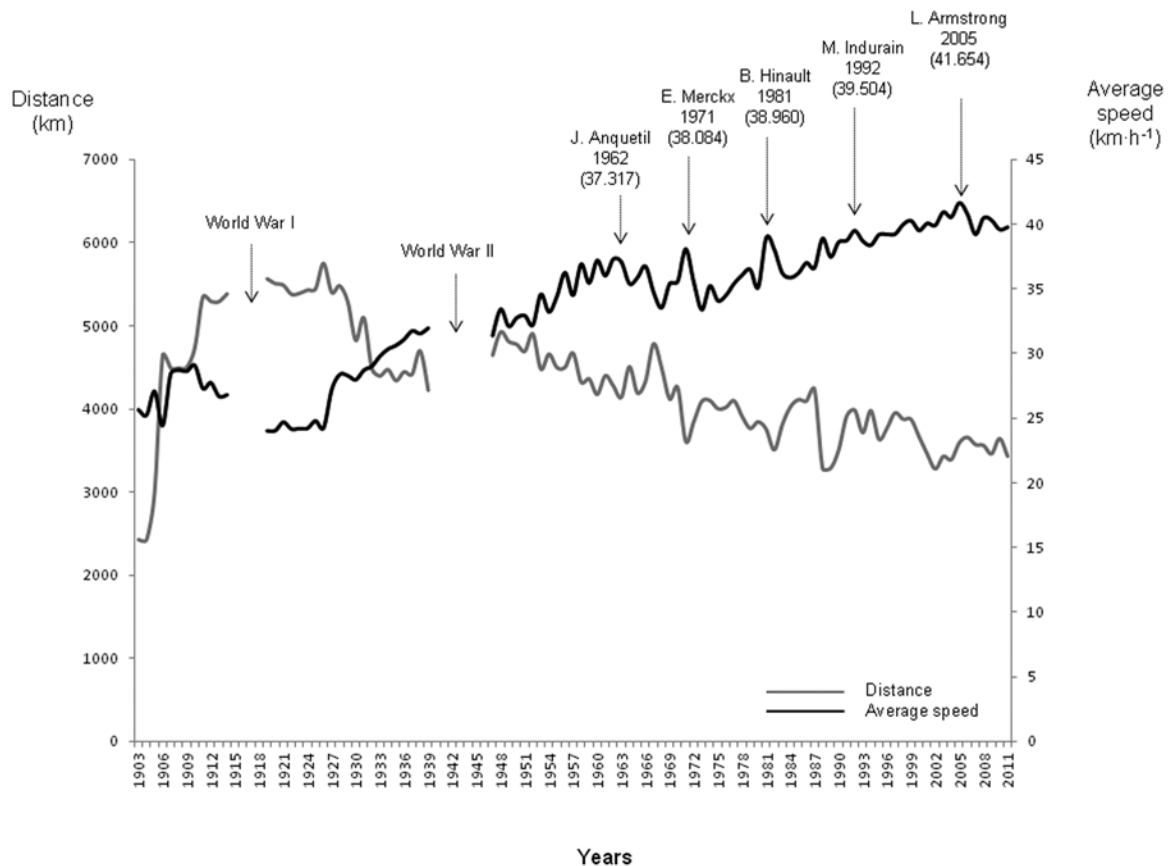


Figure 1 — Total distance covered and average speed of the winners of the Tour de France (1903–2011). Interruptions are the 2 periods of noncelebration due to World Wars I and II (1915–1918 and 1940–1946). The fastest wins of the Tour de France’s great dominators (≥ 5 victories) are also shown: cyclist’s name, year (speed in km/h).

power output and aerodynamics to be successful. Finally, the HM stages (~200 km, 5–6 h) often include eclipsing several mountain passes, thus demanding several bouts of 45 minutes or more at high intensities² (Table 1).

Anthropometric and Physiological Profile of Tour Cyclists

Stature

Most Tour participants are white,² with the winners being an average age of 28 ± 3 years old (range 20–36 y).¹ Recently (1985–2011) this age has narrowed to 29 ± 3 years (24–34 y),¹ which might denote a greater specialization for winners of the current generation of Tour winners. The anthropometric profile of Tour participants (body weight, height, body surface area, and body-mass index [BMI]) also appears to determine, at least in part, success during the different types of stages.³ For example, TT specialists are generally 180 to 185 cm tall, weigh 70 to 75 kg, and have a BMI ~22 kg/m². This anthropometry allows them to achieve higher *absolute* power outputs (W)

than climbers (175–180 cm, 60–66 kg, BMI 19–20 kg/m²), who are better able to maintain higher *relative* power outputs (W/kg).^{3,4} Although there are Tour winners with a climber-like anthropometry (eg, Marco Pantani, 173 cm and 57 kg), the profile of the 10 winners from the last 2 decades (Miguel Indurain to Cadel Evans) is much closer to that of TT specialists (179.1 ± 6 cm and 67.4 ± 7 kg).¹

Cardiorespiratory Capacity

The maximum oxygen uptake (VO_{2max}) of most Tour participants varies from 5.0 to 5.5 L/min or 70 to 80 mL · kg⁻¹ · min⁻¹.^{5–14} The highest values (~80 mL · kg⁻¹ · min⁻¹) usually correspond to climbers (body mass <70 kg), with the values of the top 10 riders ranging from 5.3 L/min (76 mL · kg⁻¹ · min⁻¹) to 5.8 L/min (82 mL · kg⁻¹ · min⁻¹). For race winners, the VO_{2max} has ranged from 6.1 L/min (81 mL · kg⁻¹ · min⁻¹)¹⁵ to 6.4 L/min (79 mL · kg⁻¹ · min⁻¹).¹⁶ We have registered a VO_{2max} of 86 mL · kg⁻¹ · min⁻¹ in a Tour winner.¹⁴ Collectively, these values suggest a minimum threshold of 80 mL · kg⁻¹ · min⁻¹ to win the Tour.

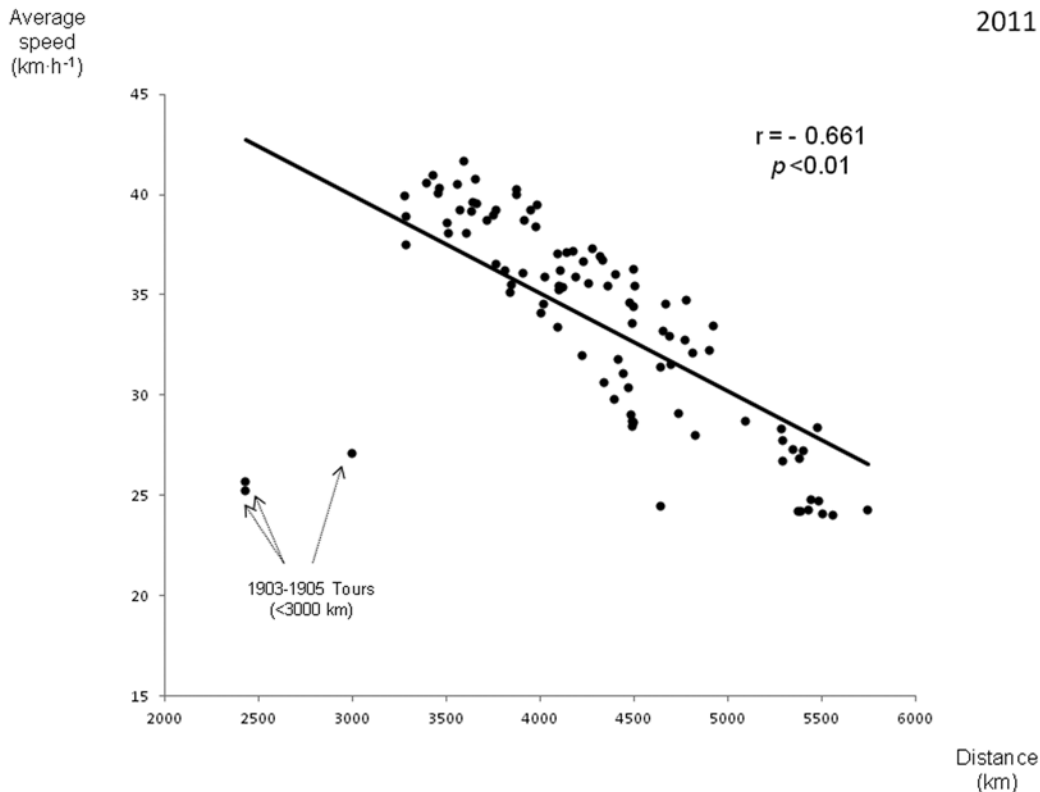
Years 1903-
2011

Figure 2 — Relationship between the total distance and winner's average speed in the Tour de France.

Power Output

The maximum power (W_{\max}) achieved by Tour cyclists during exercise testing varies by protocol. During ramp protocols (workload duration ≤ 1 min), W_{\max} ranges from 450 to 500 W (6.5–7.5 W/kg).^{4,8,9,11,17,18} For stage protocols (workload increments every 4 min), W_{\max} is usually 400–450 W (6.0–6.5 W/kg).^{3,14} Under both circumstances, higher values are generally observed in TT specialists,^{4,16} while the top-10 Tour cyclists can reach 500–550 W (7–7.7 W/kg) during ramp protocols⁸ and 572 W (~ 7.1 W/kg) during longer protocols such as those reported in 5-time winner Miguel Indurain.¹⁶

Submaximal Thresholds

The lactate threshold and the onset of blood lactate accumulation (denoting the workload eliciting a blood lactate concentration of ~ 4 mM/L) usually correspond to ~ 330 W (76% W_{\max} or 77% $VO_{2\max}$) and 386 W (87% W_{\max} or 86% $VO_{2\max}$), respectively.^{5,6,13,19,20} In ramp protocols, using ventilatory methods, Tour participants reach the first ventilatory threshold (VT, approximately equivalent in physiological terms to lactate threshold) at 315–370 W ($\sim 70\%$ W_{\max} or 70–75% $VO_{2\max}$) and the respiratory compensation point (RCP, approximately physiologically equivalent to onset of

blood lactate accumulation) at 400–450 W ($\sim 90\%$ W_{\max} or $\sim 90\%$ $VO_{2\max}$).^{6,7,19,21} These values are significantly higher than those reported in elite cyclists, who generally report lower VT ($\sim 60\%$ W_{\max} , $\sim 60\%$ $VO_{2\max}$) and RCP ($\sim 84\%$ W_{\max} , $\sim 80\%$ $VO_{2\max}$).^{9,10} The power output at the VT is correlated with performance in TT stages of the Tour,¹⁹ and the best TT specialists or Tour winners are able to maintain higher wattages at onset of blood lactate accumulation (eg, 505 W, 6.2 W/kg for Miguel Indurain¹⁶).

Efficiency

Tour cyclists also show high gross mechanical efficiency (GE) or delta efficiency and cycling economy (CE) at high loads of exercise.^{8,14} For example, the best cyclists in the Tour (top-10 and several stages winners) have GE and CE values of $\sim 24\%$ and ~ 85 W/L, respectively, measured during a constant-load test at 80% $VO_{2\max}$ (~ 385 W).⁸ The GE can be even higher in Tour winners, for example, 25% at ~ 500 W.¹⁶ Although GE generally depends on the percentage of type I fibers in the quadriceps muscle,²² there are no data on Tour cyclists supporting this premise with biopsies. However, it has been reported that professional cyclists (non-Tour competitors) have a higher percentage of type I fibers (64% in total), mitochondrial volume (4.3%), and capillary density for

1906-2011

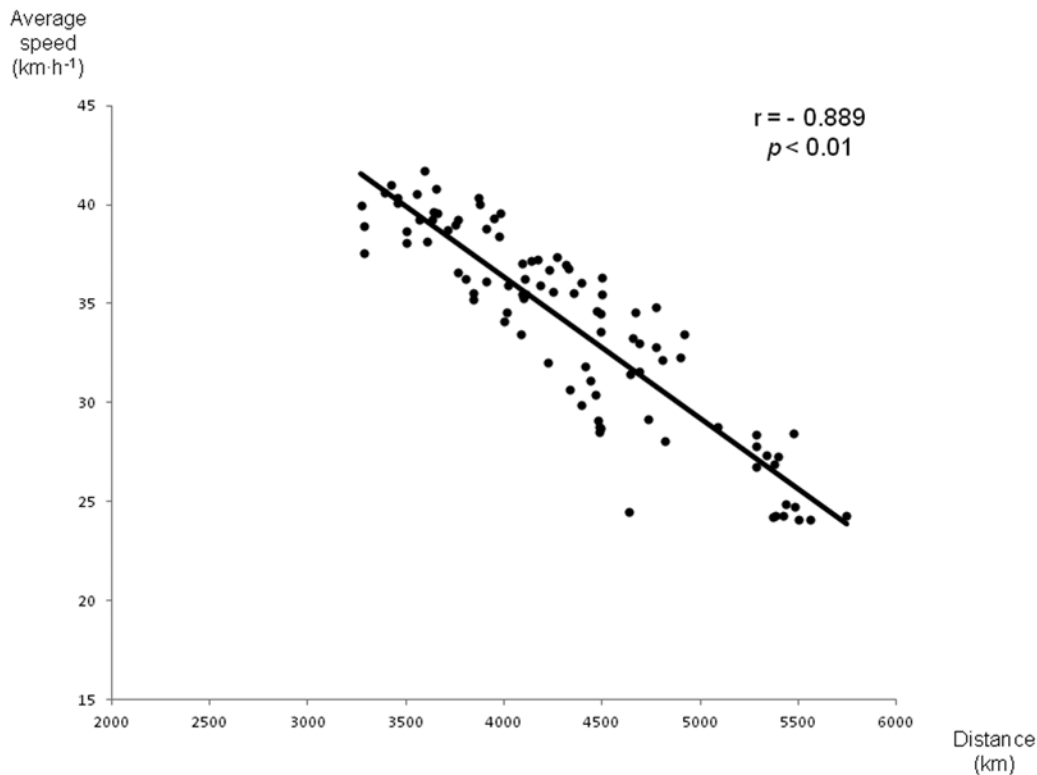


Figure 3 — Relationship between the total distance and winner's average speed in the Tour de France (except the first 3, which were less than 3000 km).

all types of fibers (mean of 589 capillaries/mm²) than their nonprofessional peers.²³ A high percentage of type I fibers has also been suggested as an important contributor to the high GE and CE values reported in Tour participants and winners.^{8,14,15} It has also been reported that muscle efficiency (expressed as delta efficiency) increases over the years in top-level Tour cyclists, especially in those with comparatively lower $\text{VO}_{2\text{max}}$.¹⁴ A good example of the performance advantage brought about by high muscle efficiency is the trend to adopt higher cadences (>90 rpm) by professional cyclists since Lance Armstrong began to adopt this pattern in the legendary ascents of *Sestriere* (1999), *Hautacam* (2000), and *Alpe d'Huez* (2001), where it is estimated that Armstrong maintained a power output of ~450 W during *Alpe d'Huez*.² Contrary to other athletes (including amateur cyclists), professional cyclists seem to be more efficient when pedaling at high cadences.¹² Indeed, when pedaling at a constant load (eg, ~370 W on average), GE has been shown to be 22.4%, 23.6%, and 24.2% at 60, 80, and 100 rpm, respectively, in top-level Tour cyclists.¹² It has been hypothesized that the lower muscle force exerted at high cadences could improve increasing venous return while decreasing the occlusion effect of quadriceps muscle on capillaries and arterioles.^{24,25}

Physiological Demands During the Tour de France

Although it is possible to estimate the physiological demands of the Tour based on history books, more robust advances in the scientific quantification of Tour demands began in the early 90s with the introduction of heart-rate monitors.^{2,26} Three different approaches have been described using this technology. The first method characterizes the absolute amount of time a cyclist spends at different intensities during each stage and race^{5,6,13,17,21,27,28} and is generally structured into zones corresponding to heart rates obtained in a previous maximal incremental cycle-ergometer test: zone 1 (HR < VT), <70% $\text{VO}_{2\text{max}}$, zone 2 (HR between VT and RCP, 70–90% $\text{VO}_{2\text{max}}$), and zone 3 (HR ≥ RCP, >90% $\text{VO}_{2\text{max}}$).² The physiological requirements of Tour have also been quantified in terms of power output (W) generated during the competition, with power output being estimated from the HR in competition and according to the HR–W relationship measured in the laboratory^{13,19,21,27–29} or measured directly during competition.³⁰ Finally, the third method, which accounts for the internal physiological load generated during the Tour,^{21,27,31} is quantified by recording training impulses (TRIMPs), whereby the first method's zones are

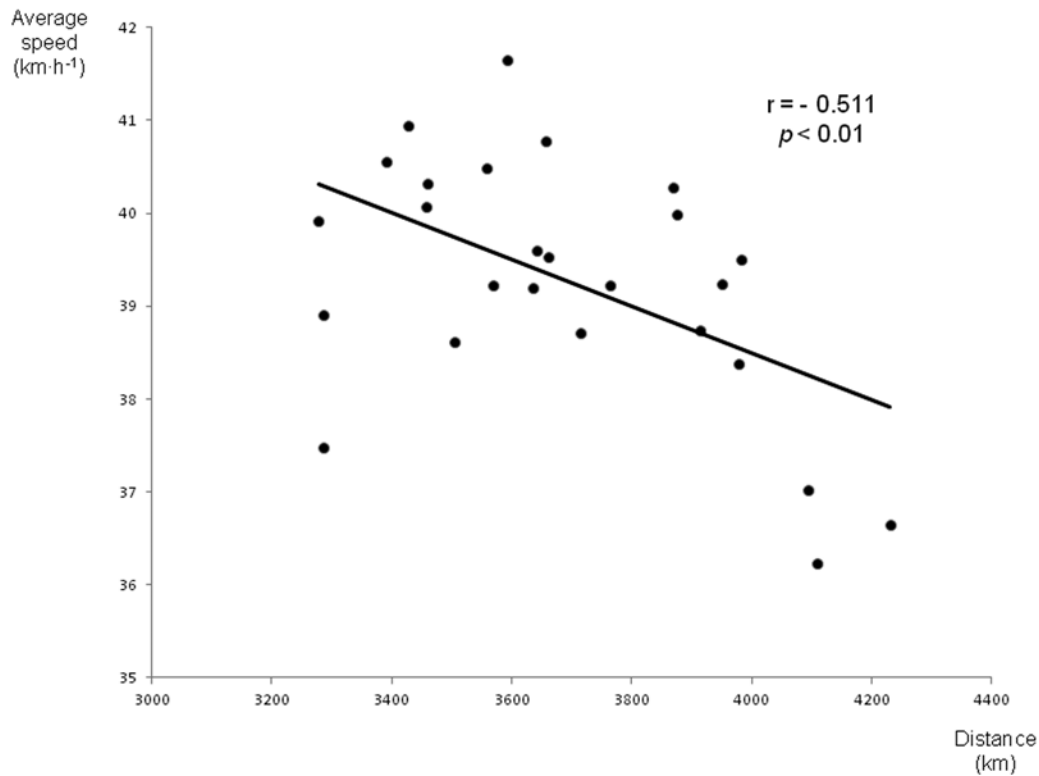


Figure 4 — Relationship between the total distance and winner’s average speed in the “modern” Tour de France, 1985–2011 (modern bicycle equipment was introduced in 1985).

Table 1 Characteristics of the 3 Main Competition Requirements of the Modern Tour de France (From the 1990s to Today)

	Flat stages	High mountain stages	Time-trial stages
Distance (km)	~200	~200	30–55
Exercise time (h)	4–5	5–6	≤1 ^a
Mean exercise intensity	Low to moderate (Zones 1–2)	Moderate to high (Zones 2–3 during ascents)	High (Zones 2–3).
Mean velocity (km/h)	~45	~20 (during ascents)	~50 (time-trial specialists)
Cycling position	Traditional (sitting)	Alternating (sitting and standing)	Aerodynamic (triathlon bars)
Main requirements	Technical	Physiological	Physiological and aerodynamic
Specific concerns	Crashes	Moderate hypoxia (altitude > 1500 m)	Aerodynamics
Estimated mean power output	200–250 W	≥6 W/kg in climbers	350 W (≥400 W in time trialists)
Physiological load (TRIMP) ^b	≤350	≥500	120–180

^a Dates from last 5 Tours (2007–2011), obtained from *Augendre* (Tour de France’s historical guide).

^b Dates from Lucía et al.²¹ and Earnest et al.¹⁹

multiplied by 1, 2, and 3 TRIMPs for each minute the cyclist performs in zones 1, 2 and 3 respectively, and then adding all zones to obtain total TRIMPs.²¹

FT Stages

On average, and, keeping in mind that cardiac drift will alter the HR–W relationship,² 70% of the total time during FT stages is spent in zone 1, 25% in zone 2, and only 5% in zone 3,^{5,27} or ~195, 82, and 21 min/d in each respective zone.⁵ The technical requirements during FT stages are very important,² as cyclists ride close together in the peloton trying to minimize air resistance by drafting as efficiently as possible.³² In these stages, pedal cadence is ~90 rpm²⁸ and cyclists typically maintain power outputs of 200–250 W.^{2,27}

HM Stages

HM stages range in difficulty from 1 to 4 (hardest to least difficult) but also contain *Hors*-category (translated as “outside” or other category) climbs, which represent the most difficult, and first-category climbs (hardest on to *Hors* on a scale of 1–4), each comprised of a distance often above 10 km. Climbs of this category can range up to 10 km in length, 5% to 10% in gradient,² and have an altitude of ~2000 m, so that reduced oxygen availability imposes an additional physiological challenge.² These climbs can demand work at intensities $\geq 90\%$ $\text{VO}_{2\text{max}}$ ³³ but should not surprise the reader. It should be remembered that the Tour was originally formed as a means of garnering publicity for the French newspaper *L’Auto*, by Henri Desgrange, who was no stranger to meting out punishing rides in order to gain publicity; this prompted the 1910 winner, Octave Lapize, to chastise officials—“You are assassins, yes, assassins!”—while climbing the first-ever HM stages of the Tour in the Pyrenees that day.

Padilla et al¹³ analyzed the exercise intensity in climbs to mountain passes (68 *Hors* category, 172 first category, and 134 second category) of the 3 Grand Tours (Giro d’Italia, Vuelta a España, and Tour) and reported the average intensity (%HR reserve) during the ascents to be 77% in *Hors* and first-category passes and 74% in second-category mountain passes and always synonymous to the HR corresponding to onset of blood lactate accumulation. In addition, the authors described how the moment of the stage where the pass is located (first, second, or third part of the stage) strongly influences exercise intensity. Specifically, *Hors* and first-category passes in the second and final thirds of a stage are covered at higher intensities than those at the beginning.¹³ When just the Tour is analyzed, it has been reported that cyclists maintain approximately 158, 107, and 35 minutes in zones 1, 2, and 3, respectively, with a higher percentage of time spent in zone 3 than in the HM stages of the Vuelta.⁵ It has been estimated that riders maintain an average power output of 322 W during the climbs to the *Hors* and first-category mountain passes, with the highest values achieved in the ascents during the middle third of the stage (385 W and

345 W for *Hors* and first-category passes, respectively).¹³ Due to the fight against gravity, a high power:body-weight ratio (ie, ≥ 6 W/kg at $\text{VO}_{2\text{max}}$) is a prerequisite to perform successfully in these stages.^{3,4}

TT

The Tour also includes TT stages that include 1 prologue (5–10 km) and 2 long TTs (40–60 km). Occasionally a team TT stage is also included.² During the TT stages, the technical and aerodynamic requirements of the cyclist focus on posture in order to reduce frontal body surface area and bicycle componentry to maximize aerodynamic efficiency.³³ In fact, aerodynamic resistance represents 90% of the whole resistance encountered by the riders at speeds >30 km/h and, thus, is a major determinant of performance in TT stages.²⁶ In addition, TT stages require the cyclist to maintain high intensities of exercise for long periods of time, with high pedal cadences (90–100 rpm)^{2,26} such that TT specialists are able to maintain a higher percentage of time in zone 3. Thus, it has been estimated that TT specialists are able to maintain ~400 W for up to 60 minutes in long TTs (>40 km),²⁸ although on average, the estimated power output of most riders is lower, ~350 W.³¹ Recently, Earnest et al¹⁹ described the effort involved in TTs by analyzing HR data from 26 riders who competed in 35 TT stages from different editions of the Tour and Vuelta; results indicated that in the 21 long TTs (average distance ~48 km) and in 4 team TTs (average distance ~44 km), the cyclists who intended to contend for the stage victory or to reach a high position in the overall race standings were able to maintain >430 W for ~26 and ~20 minutes (in individual and team TTs, respectively).¹⁹

Lucia et al¹⁷ also described the estimated power maintained by cyclists in 3 long TTs in the Tour—2 of them held in the first week and 1 in the last week after 19 days of competition—thus with considerable fatigue accumulation. In 1 of the 2 first TTs (1999 Tour, 56.5 km), cyclists maintained an average power >402 W (6.2 W/kg) for ~40 minutes. In the other TT (1998 Tour, 58 km including a third-category mountain pass), the riders were able to maintain an average power >458 W (6.6 W/kg) for an average time of nearly 53 minutes,¹⁷ which today is the highest average power estimated for a TT during the Tour. Yet this value is considerably lower than the estimated average power output of 5-time winner Miguel Indurain during the 1-hour world record in a velodrome (that he set in 1994), that is, nearly 510 W (6.3 W/kg).¹⁶ Perhaps one of the most compelling examples of aerodynamic efficiency in the TT was in 1989 by Greg LeMond, who trailed Tour favorite Lauren Fignon by 50 seconds on the final day with just a relatively short TT (25.5 km) to go. While Fignon eschewed most modern technology, LeMond presented at the starting line with aerobars on his bike and proceeded to win the Tour by 8 seconds over Fignon. Despite a brilliant racing career, having won 3 Grand Tours (Giro once, Tour twice), the

fate of Fignon may rest as the man who lost the 1989 Tour to aerodynamic advances in the TT.¹

Actual Power Output Levels in the Tour de France

Both the rider's position on the bike (standing vs seated)²⁶ and cardiovascular drift, produced by dehydration and hyperthermia, can alter the cyclist's HR levels. Another potential confounder of using HR data to estimate exercise intensity during 3-week races comes from the fact that maximum HR tends to decrease during the event, especially during the last week of competition.² Now, power sensors (eg, SRM and PowerTap) can be used to quantify the physiological demands of 3-week races. These sensors have been validated^{34,35} and allow riders, coaches, and scientists to examine the external load (in watts) during cycling competitions,³⁶ as well as comparing wattage results with those derived from HR data in the aforementioned intensity zones.³⁶ To the best of our knowledge, no actual published data on power output are available during the Tour. However, there are examples from 5 to 6 FT stages of 1-week tour races, in which professional cyclists also experienced in Tour riding maintain, on average, a power output of 220 ± 22 W (3.1 ± 0.2 W/kg)³⁶ to 250 ± 30 W (3.8 ± 0.4 W/kg)³⁷ and during climbs and TT reach an average of 392 ± 60 W (5.5 ± 0.4 W/kg).³⁶

One case study conducted during the 2005 Giro reported mean power output levels of 132 ± 26 W (2 ± 0.2 W/kg) during FT stages versus 235 ± 30 W (3.5 ± 0.1 W/kg) in HM stages, with peak values of 367 W that were maintained for 30 minutes in the HM stages.³⁸ Another finding of that case study was that FTs were characterized by a large variability of power output, with short bursts of high power and long periods with reduced intensity of exercise, whereas HM mostly required submaximal, constant power output over longer periods. These fluctuations in power during FS likely occur relative to the degree a cyclist rides in the midst of the peloton, versus near the front, where more work is required. While we are unaware of any published data to the contrary, other case studies using the SRM in a few cyclists allow us to hypothesize that the aforementioned published values in 1 cyclist during the Giro fall below those achieved by the best Tour contenders. For instance, in the 2011 Tour, the average power maintained by several *domestique* (eg, servant or helper) cyclists in HM stages ranged from 249 to 331 W, with peaks of 337 to 417 W (maintained for 20 min).³⁰ Moreover, an average power of 383 W (6.0 W/kg) was maintained by 1 cyclist for more than 32 minutes during the ascent to *Galibier* in stage 19.³⁰ One rider rode with the overall victory candidates for 26 seconds in the ascent to *Galibier*; keeping pace with the best riders required that he maintain 471 W (7.3 W/kg) during this short period of time.³⁰ In the same Tour (2011), another cyclist (who finished the stage 4 min:20 s behind the stage winner) maintained 397 W for ~1 hour.³⁹ While

more data are needed to support these individual observations, these case studies suggest that the strong men of the Tour may be able to maintain even higher power levels than those observed in the *domestiques*. Keeping in mind that these are individual data, these power output values do not differ essentially from published estimates based on the HR:W ratio obtained in the laboratory.^{19,28,31} Although several cycling teams use power meters during training and competitions, the lack of published studies with these devices implies that, still, in order to estimate the actual power output during the Tour, we must rely on studies that quantify power output according to the HR–W relationship.^{2,19,20,27,28,31}

Physiological Load of the Tour (TRIMPs)

The physiological load (in terms of TRIMPs) of the Tour has been studied together to that of the Vuelta and Giro,^{13,19,21,27,29,31} or together with that of shorter (1-wk) tour races.³¹ As for the Tour, the mean TRIMP value is 7112 ± 289 for a mean total race duration of ~91 hours and 51 minutes.²¹ Lucia et al²¹ first described the actual requirement of the Tour by analyzing the internal load of 7 cyclists in 4 Tours and Vueltas (1997, 1999, 2000, and 2001). Although the 2 races were different, with a greater total distance in the Tour and a less clear differentiation between “pure” FT and “pure” HM in the Vuelta, the typical FT stages were less demanding (≤ 350 TRIMPs) in the Tour than in the Vuelta, yet the total TRIMP load was similar in both races.²¹ Nevertheless, the HM and TT stages, in which the cyclists spend long periods of time in zone 3^{2,5,6,27,31,33} and which decide the final outcome of the race,² are those that characterize the Tour as the hardest race. The HM stages are more demanding in the Tour (≥ 500 TRIMPs) than in the Vuelta (~380 TRIMPs).²¹ This is because in the Tour, HM stages are longer and have more mountain passes and *Hors*-category parts,²¹ whose ascents impose a greater load; that is, each ascent involves a load of 115, 72, or 41 TRIMPs for *Hors*- and first- and second-category ascents, respectively.¹³ In fact, HMs are so demanding that the largest loads, ~600 TRIMPs, are recorded in these stages (total duration >5 h and ~2 h in zone 3, corresponding to 3–4 ascents of ~30–40 min each).

The TRIMP value seems to be the limit of daily energy expenditure that can be tolerated by humans, because 2 consecutive days of 600 TRIMPs have never been recorded²¹ despite the fact that there are 2 or more consecutive HM stages in every Tour de France. Keeping in mind that the demand of a marathon is ~300 TRIMPs,²¹ the high TRIMP values of the Tour, that is, ≥ 500 TRIMPs for several consecutive stages and an average of 350 to 400 TRIMPs/d over the total 3-week period, would suggest that the Tour is arguably the hardest endurance race in the world. It seems that these limits (~600 TRIMPs/d and a total of ~7100 TRIMPs) may be regulated at the

level of a “central controller” in order to prevent potentially dangerous body disturbances such as hormonal exhaustion. In effect, decreases in testosterone, cortisol, luteinizing hormone, and melatonin have been described in the third week of the Vuelta.^{40,41} In this sense, there are no individual differences in either total load (TRIMPs) or accumulated load (~2000 TRIMPs/wk) between the Tour and the Vuelta.²⁹ In addition, the pattern of daily TRIMP accumulation in 3-week races for a given cyclist is similar over the years,²⁹ suggesting a maximal threshold limit in the human ability to tolerate strenuous endurance exercise. Such a limit would be “predetermined”; that is, an anticipation capacity in the regulation of daily energy expenditure exists, based both on the cyclist’s previous experience (from the past 3-wk races completed) and on daily sensory feedback.²⁹ In long TTs (40–60 km), the physiological load is ~120 to 180 TRIMPs.^{19,21} Similar to the time spent in each intensity zone, the internal load depends largely on the role each rider has in the team. Thus, in TTs, the total load (TRIMP) and the percentage of TRIMP corresponding to zone 3 (>RCP or >90% $\text{VO}_{2\text{max}}$) are higher in cyclists who are really competing at their best (ie, contenders) than in those without aspirations to victory.¹⁹ This difference remains significant even in the long team TTs.¹⁹

Nutrition and Hydration in the Tour

During early Tours, cyclists had to be self-sufficient in all aspects of their racing, including mechanical repairs, feeding, and hydration. Per the former, it was in 1913 that Eugene Christophe was penalized an insulting 3 minutes for enlisting the aid of a 7-year-old boy to pump billows after spending nearly 5 hours seeking out a blacksmith and making his own bike-fork repairs when he merely needed an extra set of hands to keep up the flames. As for feeding and hydration, cyclists often had to obtain food in bars along the way and get water from fountains.² At this time, cyclists were not aware of the effects of carbohydrate intake on preexercise glycogen, fat oxidation, and performance, so the occurrence of exercise-induced hypoglycemia (known as “heating the bunk”) was frequent.² Today, carbohydrate intake during stages is still rather low (mean 25 g/h), below values that allow maximizing the rate of carbohydrate oxidation during exercise (30–60 g/h).² Nevertheless, the daily calorie intake of participants in the Tour is high enough (23–25 MJ/d) to match the tremendous energy cost of competition.⁴² The cyclists’ carbohydrate intake (>12–13 $\text{g} \cdot \text{kg}^{-1} \cdot \text{d}^{-1}$) seems sufficient to replenish glycogen stores within 18 hours—the period that elapses from the end of a stage to the time the next day’s stage begins (from ~5 PM to noon). Especially important is the carbohydrate intake (1.1 g/kg) during the first 6 hours after the stage. This carbohydrate intake is complemented with protein (0.35 g/kg) to increase muscle glycogen resynthesis in these first hours of recovery.⁴³ A remarkable aspect is also the high protein intake (3 $\text{g} \cdot \text{kg}^{-1} \cdot \text{d}^{-1}$) observed during

Grand Tour events.³³ In general terms, during 3-week tour races (eg, Vuelta) the daily energy intake corresponds to ~840 g of carbohydrates, ~200 g of protein, and ~158 g of fat.⁴³ Today, hydration levels vary from 3.3 L/d⁴³ to 6.7 L/d,⁴² depending on the amount of carbohydrates consumed in liquid form (sports drinks).³³

Hematological Variables and Blood Doping

From the beginning of Tour various means have been used to improve performance. In the first decades, cyclists used wine mixed with strychnine, ether-soaked handkerchiefs, or chloroform rubbed into their gums to reduce pain and perception of fatigue.² In 1967, the Tour saw the death of British cyclist Tom Simpson on the slopes of Mont Ventoux after he drank a mixture of alcohol and amphetamines in extremely hot weather conditions.¹ Probably the most epic disaster of the Tour was in 1998 when a Festina team car was intercepted carrying recombinant human erythropoietin (rhEPO) and other doping substances, leading to not only the expulsion of the team but also nearly the demise of the Tour itself.

rhEPO increases blood hemoglobin concentration ([Hb]), $\text{VO}_{2\text{max}}$, and performance.² Despite its early use and attempts by the International Cycling Union’s establishment of a 50% hematocrit (HCT) level as the upper limit to compete, rhEPO was not detectable until 2000. To date, several riders have exceeded this upper limit and have also been removed from the Tour. Research suggests that normal HCT values are $43.0\% \pm 0.02\%$ (range 39–48%) as reported by Saris et al,⁴⁴ who obtained 353 samples during Tours from 1980 to 1985 and before the marketing of rhEPO. Later studies have reported slightly higher values for HCT and [Hb] in 177 participants—at the beginning of the 2011 Tour being 43.5% to 46.9% and 14.6 to 15.0 g/dL, respectively.⁴⁵ Morkeberg et al⁴⁶ analyzed hematological and urine variables for blood doping, steroids, autologous blood transfusions, and rhEPO in a cycling team over an entire racing season. Using 661 samples from training, precompetition (1–3 d before the meeting), and competition periods including the 3 Grand Tours and World Championship, the authors observed that HCT and [Hb] fell from 45% and 15.2 g/dL from December 2006 to 40.7% and 14.0 g/dL on September 2007. These values then “recovered” to 44.7% and 15.3 g/dL by November 2007. During the Tour, there was a decrease of 11.5% in [Hb] (range 7.0–20.6%), which expresses the hematologic adaptation involved the Tour.⁴⁶ Paradoxically, the cyclists who participated in that Tour showed increases in HCT and [Hb] during the tapering period before the Tour,⁴⁶ making it difficult to determine whether these effects were due to doping or tapering alterations. In January 2008 the International Cycling Union and the World Anti-Doping Agency established the biological passport as a control method for hematological variations on individual patterns recorded for years. Today, this method controls 850 cyclists intensively (eg,

~20,000 samples in 2008–2009)⁴⁷ and is more accurate than previous methods.⁴⁸

Summary and Future Perspectives

From its initial inception as a race premised on a publicity stunt to sell newspapers, the Tour de France has grown and evolved over time to become one of the most difficult and heralded sporting events in the world. Rich in history, heroism, high jinks, and controversy, the Tour has continued to survive and thrive over the years. Though sporting science and the Tour paralleled each other, it was not until the midlate 1980s that the 2 began to unify and grow together. It is our hope that, with the development of technology allowing scientists to measure power output, continued scientific inquiry would follow the historical precedent of determining the capabilities and potential limitations of human endurance. However, such aspirations take coordinated research efforts, and to date few teams have been willing to take on such an agenda. Finally, as with much scientific inquiry, insights into molecular biology will surely help in the pursuit of linking the physiology of those who are highly trained and those experiencing various metabolic diseases.

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