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The Physiological Profile of a Multiple Tour de France Winning Cyclist

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ABSTRACT

BELL, P. G., M. J. W. FURBER, K. A. VAN SOMEREN, A. ANTÓN-SOLANAS, AND J. SWART. The Physiological Profile of a Multiple Tour de France Winning Cyclist. *Med. Sci. Sports Exerc.*, Vol. 49, No. 1, pp. 115–123, 2017. **Introduction**: This case study reports a range of physiological characteristics in a two-time Tour de France champion. **Methods**: After body composition assessment (dual-energy x-ray absorptiometry), two submaximal cycling step tests were performed in ambient (20°C, 40%) and hot and humid (30°C, 60% [HH]) conditions from which measures of gross efficiency (GE), lactate-power landmarks, and heart rate responses were calculated. In addition, thermoregulatory and sweat responses were collected throughout. $\dot{V}O_{2peak}$ and peak power output (PPO) were also identified after a separate ramp test to exhaustion. **Results**: $\dot{V}O_{2peak}$ and PPO were 5.91 L·min^{-1} (84 mL·kg^{-1}·min^{-1}) and 525 W, respectively, whereas mean GE values were 23.0% and 23.6% for ambient and HH conditions, respectively. In addition to superior GE, power output at 4 mmol·L^{-1} lactate was higher in HH versus ambient conditions (429.6 vs 419.0 W) supporting anecdotal reports from the participant of good performance in the heat. Peak core and skin temperature, sweat rate, and electrolyte content were higher in HH conditions. Body fat percentage was 9.5%, whereas total fat mass, lean mass, and bone mineral content were 6.7, 61.5, and 2.8 kg, respectively. **Conclusion**: The aerobic physiology and PPO values identified are among the highest reported for professional road cyclists. Notably, the participant displayed both a high $\dot{V}O_{2peak}$ and GE, which is uncommon among elite cyclists and may be a contributing factor to their success in elite cycling. In addition, performance in HH conditions was strong, suggesting effective thermoregulatory physiology. In summary, this is the first study to report physiological characteristics of a multiple Tour de France champion in close to peak condition and suggests what may be the prerequisite physiological and thermoregulatory capacities for success at this level. **Key Words**: CYCLING, PHYSIOLOGY, ENDURANCE, ELITE PERFORMANCE

The limits of human endurance performance and the nature of fatigue have been debated extensively (1,23,25,31,32,40), and cyclists competing in the Tour de France (TdF) represent the extremes of endurance performance characteristics. This can be attributed to unique physiological and morphological characteristics developed from extensive training-induced adaptations (21). To date, there is limited information on the physiological characteristics of TdF cyclists, and even less on the winners of the race who represent the elite of the elite endurance athletes. Widely recognized determinants of endurance cycling performance include gross efficiency (GE), peak oxygen uptake ($\dot{V}O_{2peak}$), peak power output (PPO), and numerous lactate landmarks that represent distinct changes in aerobic metabolism.

The TdF is a 3-wk stage race that covers variable terrain in which the winner is the cyclist who completes all the stages in the lowest overall cumulative time. The key stages that have been identified as the most relevant to overall performances are time trial (TT) stages and stages with uphill finishes (20). During TT stages, cyclists are required to produce a high absolute power output, usually in excess of 400 W, for prolonged periods (≤1 h) (35). A maximal 40-km TT power has been positively correlated with the power output produced at a blood lactate concentration of 4 mmol·L^{-1} and has additionally been shown to coincide with the average power output sustained during the hour record (2,33). Although this relationship is not universal, the measurement of sustained maximal power output for a duration of 1 h (also known as functional threshold power) is correlated to a blood lactate concentration of 4 mmol·L^{-1} when performing an incremental exercise test in the laboratory. Stages with uphill finishes similarly require very

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high sustained power outputs but, in addition, require a high power-to-weight ratio. The final climbs of these types of stages can range from 5 to 20 km in length, requiring maximal power outputs for periods of 10 min through to 1 h, during which the cyclist will be required to sustain a continuous power output of more than 6 $W \cdot kg^{-1}$ (20). A power-to-mass ratio in excess of 6 $W \cdot kg^{-1}$ coinciding with the blood lactate concentration of 4 $mmol \cdot L^{-1}$ is therefore a requirement for top performances during uphill finishes at the TdF.

GE is a measure of effective work and is expressed as a percentage of total energy expended that produces external work (12). In well-trained male cyclists, GE was reported as ranging from 10% to 25% (14), whereas in professional cyclists, GE was further elevated in the range of 22.0%–28.1% (22). Paradoxically, within professional level cyclists, $\dot{V}O_{2peak}$ and cycling efficiency have been found to be inversely related, and it has been hypothesized that a high efficiency might compensate for a relatively low $\dot{V}O_{2peak}$ (22). TdF cyclists typically demonstrate high GE values with the best cyclists in the TdF (top 10 overall finishes and stages winners) demonstrating GE values of ~24% and the winner as high as 25% (39).

A study of a multiple TdF winner measured maximal oxygen uptake on five separate occasions, four before the athlete's first TdF win and one in the year of his first TdF victory (8). These tests demonstrated large fluctuations in maximal oxygen uptake ranging from 5.29 to 6.10 $L \cdot min^{-1}$ between tests. The highest recorded value of 6.10 $L \cdot min^{-1}$ (81.2 $mL \cdot kg^{-1} \cdot min^{-1}$) was also recorded 6 yr before the first TdF win. Oxygen uptake at lactate threshold relative to $\dot{V}O_{2peak}$ was also highly variable and ranged from 76% to 85%. Interestingly, GE increased progressively from 21.2% to 23.1% during the 6-yr period. However, none of these data were recorded within the 3 months before or after the TdF victories. In addition, the study results were subsequently challenged based on the calculations used to derive efficiency and the equipment used during the investigations, claims that were refuted by the study's author (26). Lastly, the athlete was retrospectively stripped of his titles, and the results of all TdF wins were annulled based on evidence of the use of prohibited substances and methods. As a result, the observed results from this report should be reviewed with caution given the potential effect of performance-enhancing substance abuse during this period of testing.

Although limited in scope, one study has described physiological data pertaining to blood lactate parameters in a TdF winner in close to peak condition (33). The tests were performed within 2 months of the athlete's 4th TdF victory and shortly before a successful World Hour Record performance. During a graded cycling ergometer step test protocol (35-W increments every 4 min) to exhaustion, a PPO of 572 W (7.06 $W \cdot kg^{-1}$) was recorded. The power output recorded at 4 $mmol \cdot L^{-1}$ blood lactate concentration was 505 W (6.23 $W \cdot kg^{-1}$). These authors also demonstrated that the power associated with 4 $mmol \cdot L^{-1}$ blood lactate concentration was highly predictive for the maximal effort that the athlete was able to sustain for 1 h during the Hour Record performance.

A study of a regular top 10 TdF finisher has described training loads and performance data collected in the field for a period of 6 yr (37). The highest recorded power outputs for durations of 45 and 60 min (which correspond closely to power outputs associated with 4 $mmol \cdot L^{-1}$ blood lactate) were 5.9 and 5.7 $W \cdot kg^{-1}$, respectively. These are considerably lower than the relative power values recorded for a previous TdF winner at 4 $mmol \cdot L^{-1}$ blood lactate before a World Hour Record attempt (33).

Despite extensive research into the physiological demands of professional cycling and the physiological characteristics of riders, there is a limited amount of data identifying the potentially unique characteristics of grand tour winners. Accordingly, we conducted a physiological assessment of a double TdF Champion, including peak oxygen consumption, peak and submaximal power output, blood lactate response, body composition, and thermoregulatory responses, during a period when he was close to maximal training status. These tests provide key insights into the physiological requirements to win a race of this magnitude.

METHODS

Participant. The participant was a 30-yr-old elite male cyclist competing in the UCI World Tour Series. At the time of testing, he was the reigning and two-time TdF champion. Testing was conducted 1 wk before competing in the final Grand Tour of the 2015 road cycling season (La Vuelta de España).

Informed consent and ethics statement. The participant completed written informed consent after a detailed explanation of all data collection procedures before the performance of any testing. Included in the written consent was a statement detailing permission for the publication of all collected data and the likelihood that their identity be evident irrespective of the anonymization of resulting published work. Approval by an independent ethics committee was not deemed necessary for several reasons, including the following: the participant approached the laboratory and requested that the tests be conducted on him and was therefore a volunteer with no recruitment process, the participant specifically requested that the results of the tests be published in a peer-reviewed scientific journal because of the general and scientific interest that these results would generate, and the data were collected as an observation on a single day, and no intervention, experimental method, or prospective nature was applied.

Pretesting procedures. On arrival at the laboratory, testing procedures and schedules were verbally communicated before the completion of written informed consent and a pretest health screening questionnaire. The sequence of the tests was as follows: body composition and bone mineral content (BMC), submaximal aerobic profile in ambient conditions, maximal aerobic profile in ambient conditions, and a submaximal aerobic profile in hot and humid (HH) conditions. All tests and procedures were conducted on the

same day and in accordance with GSK Medical Governance approval and GSK Human Performance Lab standard operating procedures.

Body composition and BMC. Body composition was measured using dual-energy x-ray absorptiometry (GE Lunar iDXA, GE Healthcare, Bucks, UK). The scan was performed after an overnight fast (>8 h), a morning urinary void, and with all metal artifacts removed. Fasted body mass was then measured using a digital column scale (seca 704; seca Ltd., Hamburg, Germany). The scan was performed in accordance with the manufacturer's guidelines for patient positioning and was analyzed using enCORE Software, version 14.10 (GE Healthcare). On the basis of the participant's size characteristics, the scan was undertaken using the "standard thickness" mode. In addition to regular machine calibration, a standard quality assurance (QA) procedure was performed and passed before the test (laboratory coefficient of variation for this QA procedure is 0.07%).

Aerobic profile and thermoregulatory response protocol (ambient conditions). Aerobic profiling (pulmonary gas exchange, heart rate, and blood lactate) was conducted 2 h postprandial (all food consumed by the participant was self-selected) to control for the blood glucose response and was subdivided into two parts: submaximal and maximal. In addition to aerobic profiling, several thermoregulatory responses (core temperature, skin temperature, sweat rate, and sweat electrolyte content [sodium; Na+]) were collected throughout the test. Preexercise temperature (°C), relative humidity (RH), and barometric pressure (mb) were 19.5°C, 49.3% RH, and 1016.2 mb, respectively. Fan cooling was provided for the participant throughout all cycle testing; a floor fan was positioned on the front right of the participant at a 45° angle and set to an air speed of $5.8~m \cdot s^{-1}$.

An electronically braked indoor cycle trainer (CompuTrainer™; RacerMate® Inc., Seattle) was used in conjunction with the participant's personal bicycle (Pinarello Dogma F8, Pinarello, Treviso, Italy) to complete the test. The CompuTrainer™ system was selected as it allows the participant to use their own bicycle and does not require a set cadence to elicit a constant power, allowing the participant to cycle at a self-selected cadence. The crank arm length was 175 mm, and an oval chain ring (Osymetric USA, Winston-Salem, NC) was used. After a 10-min self-selected warm-up, the cycle trainer rolling resistance was calibrated to reflect a tire-load generator pressure of 0.93 kg. The indoor cycle trainer software (RacerMate® One, RacerMate® Inc.) was programmed to elicit an incremental step test, starting at 250 W with increases in work rate of 25 W every 4 min. An online (i.e., continuously measured/real time) gas analyzer (Metalyzer 3B; Cortex, Leipzig, Germany) was used throughout the protocol to measure oxygen and carbon dioxide fractions and volume of gas in inspired and expired air. The analyzer was warmed up and calibrated for oxygen (17%) and carbon dioxide (5%) fractions and gas volume (3 L syringe) as per manufacturer's prescription. During the tests, the participant breathed through a low dead space (70 mL) mouth

piece, low resistance turbine ($<0.1~kPa \cdot L^{-1} \cdot s^{-1}$ at $16~L \cdot s^{-1}$), while inspired and expired gas was sampled continuously at 50 Hz. The analyzer rise time and the transit delay for O_2 and CO_2 were <100 ms and 800–1200 ms, respectively, using a dynamic calculation for each breath.

In addition to the continuous collection of expired gas, heart rate, and thermoregulatory data, in the final 30 s of each exercise step, blood lactate and rating of perceived exertion (5) were assessed. The submaximal test was terminated at the end of the step that produced a blood lactate concentration of $>4~mmol \cdot L^{-1}$. After completion of the submaximal test, a 15-min rest period was provided before commencing the maximal test. During this period, the participant was able to consume water *ad libitum* and cycle at <100 W. The indoor cycle trainer was recalibrated, and the software was programmed to elicit an incremental ramp test starting at 150 W, increasing at a rate equivalent to $30~W \cdot min^{-1}$. The participant was instructed to continue cycling for as long as possible and to maintain a cadence of >70 rpm. Expired gas and heart rate were collected throughout the test. The test was terminated when the participant was unable to maintain a cadence of >70 rpm.

Assessment of submaximal oxygen cost ($\dot{V}O_2$) and peak oxygen uptake ($\dot{V}O_{2peak}$). To assess for $\dot{V}O_2$ and $\dot{V}O_{2peak}$, expired gas data were averaged across 30-s intervals using the online gas analysis software (MetaSoft® Studio, Cortex) before downloading for subsequent assessment. $\dot{V}O_2$ was represented as the final 30 s of expired gas from each step in the submaximal test; $\dot{V}O_{2peak}$ was calculated as the highest 30 s average collected during the maximal test (19). Routine QA records demonstrated a laboratory coefficient of variation (mean) for $\dot{V}O_2$ data of 1.8% in the range of $2.05–3.94~L \cdot min^{-1}$.

Gross efficiency. Gross efficiency of the participant was assessed by calculating the amount of work completed relative to the amount of energy expended during each of the submaximal test stages using the following equation:

$$\text{gross efficiency}\,(\%) = \left[\text{work rate}\,(W)/\text{energy cost}\,(J \cdot s^{-1})\right] \times 100.$$

Work rate was converted to joules per second to quantify energy output, and the tables of Lusk (24), in accordance with stage RER and $\dot{V}O_2$ (average of last 60 s of stage [36]), were used to identify energy cost. Energy output as a percentage of energy cost was used to express GE. Stage and overall mean GE values were calculated (8,9) for the submaximal trials in ambient and HH conditions; however, it should be noted that GE data calculated for power outputs above steady-state exercise may be influenced by the $\dot{V}O_2$ slow component and as a result should be interpreted with a degree of caution.

PPO. PPO was calculated from the data collected in the maximal aerobic test. PPO was determined as the highest 30 s average from the incremental ramp test and subsequently

expressed relative to body mass. A comparison of the recorded power output data from the RacerMate® software was made with the data collected from the athlete's personal power meter (Stages Cycling, Kirchzarten, Germany) and the set ramp test power on the CompuTrainer™. This analysis demonstrated that power output was within 0.7% ± 2.2% according to the power meter and within 0.7% ± 0.8% of the programmed power during the maximal test according to the RacerMate® software.

Blood lactate sampling. Capillary blood samples were collected from the earlobe before warm-up and in the final 30 s of each stage during the submaximal aerobic test. Briefly, 20 μL of blood was collected into a capillary tube before being analyzed using an automated blood lactate analyzer (Biosen C-Line; EKF Diagnostics, Cardiff, UK). The coefficient of variation for blood lactate measurement in the laboratory was 0.27% in the range 2–18 mmol·L^{-1}.

Heart rate. Heart rate was collected continuously via a wireless telemetry system (Polar T34; Polar Electro (UK) Ltd., Warwick, UK). In the submaximal aerobic test, heart rate data from the final 30 s of each stage were used for further analysis, whereas in the maximal test, heart rate data collection was incomplete because of a signal dropout midway through the test.

Power and heart rate at landmarks associated with blood lactate thresholds. Because of the lack of a "gold standard" measure and conjecture surrounding the use of a single landmark to define lactate thresholds (3), several landmarks were calculated. Blood lactate concentrations and heart rates collected during the ambient and HH submaximal trials were inserted into validated software (Lactate-E [29]), which subsequently calculated the predicted power and heart rates at the following reported landmarks: 1 mmol·L^{-1} above baseline, DMAX (6), modified DMAX (3), 2 mmol·L^{-1}, and 4 mmol·L^{-1}. Subsequently, the predicted power at these landmarks was expressed relative to current and predicted race body mass (W·kg^{-1}).

Core temperature. Core temperature (T_c) was recorded using a noninvasive technique. During breakfast, the participant opened a sealed package containing a core temperature sensor pill (CorTemp®, Palmetto, FL) and consumed it with water after the removal of the magnet that activates the pill. A CorTemp® data recorder (CorTemp®) wirelessly received the signal from the pill (sampling rate was 0.1 Hz) and converted it into a digital format, displaying temperature in real time and saving for subsequent analysis. Manufacturer documentation reports the CorTemp® sensor to be accurate to within ±0.1°C. The sensor was consumed 2 h before the aerobic profiling session to ensure the pill was settled in the participant's digestive tract, minimizing the influence of fluid consumption.

Skin temperature. Skin temperature (T_s), using a single site measurement, was monitored using a medical grade thermal validation system (E-Val Flex; Ellab, Hileroed, Denmark) at a sampling rate of 60 Hz and a resolution of 0.01°C (manufacturer reported accuracy is ±0.05°C). Once the participant was in a comfortable position on the bike, a skin thermistor (MHD Flexible Plast Foil, Ellab) was affixed to the center of the left scapular region using surgical tape (Micropore; 3M, Loughborough, UK), after which T_s was recorded continuously until the end of each cycling test. A single site measurement was selected because of wire placement logistics and participant comfort. This positioning also allowed the thermistor to be shielded from airflow of the cooling fan.

Sweat rate and electrolyte content. During aerobic profiling sessions, the participant's sweat was collected for analysis of electrolyte content using absorbent patches. The patches (Tegaderm, 3M) were affixed to four regions on the right side of participant's body: forearm (middorsal), chest (superior to the nipple, ~5 cm lateral from the sternum), back (spine of the scapula and ~7 cm lateral from the vertebral column), and thigh (midventral). Each site was cleaned and dried before the application of patches, using distilled water, gauze, and latex free gloves to avoid contamination of the collection area. After testing, each patch was removed using sterile disposable tweezers and placed in to a vial for later extraction. Sweat was extracted from the patch using centrifugation (Heraeus Multifuge 3S-R; Thermo Scientific, Waltham, MA) at 3600 rpm for 10 min. Sweat electrolyte (Na^+) concentration was measured using flame photometry (Sherwood Scientific Model 420 Dual Channel Flame Photometer, Cambridge, UK). Subsequently, absolute sweat electrolyte losses were calculated by multiplying the concentration of each electrolyte (mmol·L^{-1}) by the volume of fluid loss (L) during the session and time corrected to attain electrolyte loss per hour. To determine sweat rate, changes in pre- and postexercise body mass were measured and corrected for fluid consumption. The participant showered after completing the ambient aerobic profile, and before and after the HH testing session, the same patching and analysis process was followed.

Submaximal aerobic profile and thermoregulatory response (HH conditions). To determine the responses of the participant in HH conditions, which are regularly encountered during UCI World Tour cycle racing, the submaximal aerobic test was repeated in an environmental chamber (TIS Services, Alton, UK). The test was completed 2 h postprandial and followed the same procedures described previously. The chamber was set to provide the environmental conditions of 30.0°C, 60.0% RH, and 1015.0 mb. As per the previous submaximal test, heart rate, expired gas, and thermoregulatory data were continuously collected, whereas blood lactate and rating of perceived exertion were collected in the final 30 s of each exercise step. The termination criterion for the test was also replicated.

RESULTS

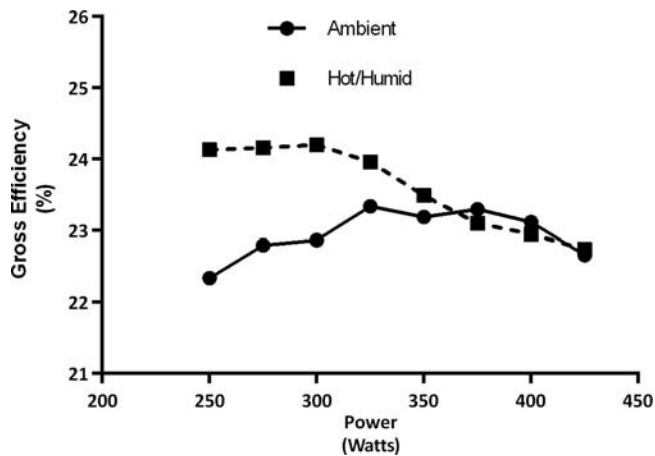**Body composition and BMC.** Fasted body mass was 70.0 kg, as measured using the digital column scale, and the

FIGURE 1—Comparison of GE across submaximal aerobic profile in ambient (19.5°C, 49.5% RH, 1016.2 mb) and HH (30°C, 60.0% RH, 1015.0 mb) conditions.

participant's body fat percentage was 9.5%. Total fat, lean mass, and BMC were 6.7, 61.5, and 2.8 kg, respectively. (NB Body composition values are calculated based on the body mass estimated by the GE Lunar iDXA [71.0 kg].) Soft tissue body composition was further analyzed in three distinct body regions: arms, legs, and trunk. Regional fat mass was 0.9, 2.0, and 3.0 kg and lean mass was 7.0, 20.6, and 30.7 kg for arms, legs, and trunk, respectively.

Submaximal $\dot{V}O_2$, $\dot{V}O_{2peak}$, and GE. $\dot{V}O_2$ increased linearly with increases in stage power across the submaximal tests in both ambient ($R^2 = 0.99$; [$y = 0.0122x + 0.1473$]) and HH ($R^2 = 0.99$; [$y = 0.0132x - 0.2217$]) conditions, with similar absolute $\dot{V}O_2$ recorded for each stage. $\dot{V}O_{2peak}$ was 5.91 L·min^{-1}, which expressed relative to body mass was 84 mL·kg^{-1}·min^{-1}. We were unable to determine peak heart rate because of a signal dropout at 11 min 31 s into the test, at which point heart rate was 154 bpm (self-reported maximum heart rate in competition was ~170 bpm). Mean GE values were 23.0% and 23.6% for ambient (range; 22.3%–23.3%) and HH (range; 22.7%–24.2%) conditions, respectively

(Fig. 1). Mean cadence values were 95.9 ± 2.2 and 96.3 ± 1.9 rpm for ambient and HH conditions, respectively.

PPO. PPO, the highest 30 s power output from the maximal aerobic test, was determined as 525 W, equating to 7.5 W·kg^{-1} when expressed relative to body mass (69.9 kg immediately pretest). Mean ± SD, minimum, and maximum cadence were 97 ± 2.9, 62, and 104 rpm, respectively.

Submaximal lactate profile and associated power and heart rate values. Absolute power output, relative power output, and race mass relative power output at the following blood lactate landmarks were calculated: 1 mmol·L^{-1} above baseline, DMAX (6), modified DMAX (3), 2 mmol·L^{-1}, and 4 mmol·L^{-1} for both ambient and HH submaximal trials (Table 1). In addition, associated heart rates and blood lactate values are presented. A graphical representation of the submaximal lactate profile is presented in Figure 2.

Submaximal T_c and T_s responses. T_c increased steadily with increases in stage power across the submaximal tests in both ambient and HH conditions (Fig. 3). T_c increased more rapidly and to a higher peak temperature in the HH conditions (38.6°C vs 38.2°C).

Starting T_s was 1.0°C higher in HH compared with ambient conditions (33.1°C vs 34.1°C) (Fig. 3) and was elevated above ambient values throughout the test. T_s increased rapidly to a peak of 35.4°C in the early stages of the HH test, whereas in ambient conditions, T_s peaked in the final stage and at a lower temperature (33.5°C).

Sweat analysis. Sweat rates during the submaximal aerobic tests were 1.42 and 1.70 L·h^{-1} in the ambient and HH conditions, respectively. After sweat composition analysis, the rate of Na$^+$ loss was calculated as 1.64 g·h^{-1} (50.3 mmol·L^{-1}) in ambient and 1.92 g·h^{-1} (58.9 mmol·L^{-1}) in HH conditions.

DISCUSSION

To our knowledge, we present the first data from a winner of the TdF that includes peak oxygen consumption, PPO,

TABLE 1. Power and heart values at selected lactate landmarks.

Blood Lactate Landmark	Power (W)[a]	Relative Power (W·kg^{-1})[b]	Race Weight Relative Power (W·kg^{-1})	Heart Rate (bpm)	Lactate (mmol·L^{-1})
Baseline					
Ambient	N/A	N/A	N/A	N/A	1.09
HH	N/A	N/A	N/A	N/A	0.99
1 mmol·L^{-1} above baseline[c]					
Ambient	382	5.4	5.7	128	2.09
HH	390	5.5	5.8	139	1.99
DMAX					
Ambient	356	5.0	5.3	121	1.36
HH	357	5.2	5.5	131	1.11
Modified DMAX					
Ambient	385	5.4	5.8	129	2.22
HH	392	5.5	5.9	139	2.04
Fixed blood lactate (2 mmol·L^{-1})					
Ambient	379	5.4	5.7	127	2.00
HH	390	5.5	5.8	139	2.00
Fixed blood lactate (4 mmol·L^{-1})					
Ambient	419	5.9	6.3	138	4.00
HH	430	6.1	6.4	149	4.00

[a]Calculated using Lactate-E software (8).
[b]Ambient weight = 70.8 kg; HH weight = −71.0 kg.
[c]Values derived using third-order polynomials (lactate vs power, lactate vs heart rate).
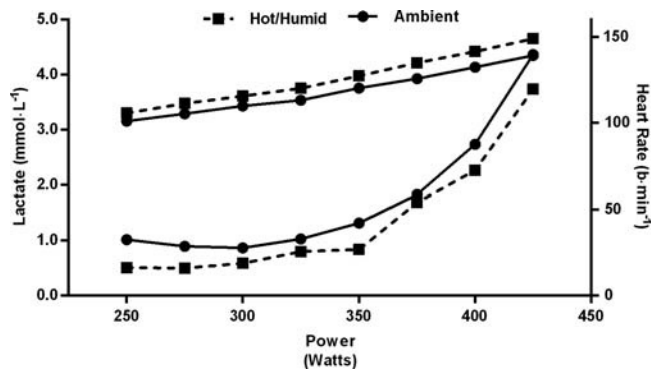
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FIGURE 2—Lactate and heart rate responses to submaximal step tests in ambient and HH environmental conditions.

submaximal power output, and blood lactate data, collected when the athlete was close to peak physical condition. The participant had won the TdF 22 d before the testing and was in preparation for the final 3-wk stage race of the year, which started 5 d after the testing date and was therefore arguably, excluding the increase in body mass, in peak physical condition.

An unexpected finding was the higher than anticipated body fat percentage of 9.5%. Previous work in male U.S. Cycling Federation athletes reported a mean body fat of 4.7% in male road cyclists (44), although these measures were collected via an alternate method (seven site skinfolds [16]), which has previously been reported to underestimate fat percentage when compared with dual-energy x-ray absorptiometry (7,10). Conversely, a mean body fat of 10.2% was reported in professional road cyclists (43); however, these measurements were taken in preseason where the condition of the athletes is unlikely to be optimal. Anecdotally, the athlete in this case study reported that in the 3 wk after the TdF (i.e., immediately before testing), they had gained 3–4 kg of body mass. Aside from the potential differences in mass because of changes in hydration status and glycogen stores, a large amount of this added mass might be represented by added body fat.

The PPO of 525 W is considerably greater than data published for 10 internationally competitive male cyclists (445 ± 52 W) (30). However, this is lower than that recorded for another TdF winner in peak condition (572 W) (33) and also lower than the highest PPO recorded from a group of professional cyclists (585 W) using a similar ramp protocol (22). This can primarily be attributed to the large variations in body mass and somatotype among elite cyclists (13). The standardization of power data is therefore best expressed as power relative to body mass. When expressed in relative terms, the PPO of 7.5 $W \cdot kg^{-1}$ is among the highest recorded for any professional cyclist. Relative to other TdF winners, this value is considerably higher than previously recorded (7.06 $W \cdot kg^{-1}$) (33). However, the comparative data were collected using differing protocols, which can significantly influence these results, for example, higher ramp rates yielding higher PPO (39). It is, however, lower than the best

value recorded from a group of European professional cyclists (7.70 $W \cdot kg^{-1}$) who used a similar ramp protocol (22). If calculated using the athlete's self-reported race mass (67 kg), the relative peak power of 7.84 $W \cdot kg^{-1}$ would be the highest recorded to date.

The workload at 4 $mmol \cdot L^{-1}$ has been well correlated with professional cycling performance in the field in TT stages and uphill cycling, two characteristics required to excel at stage racing (34). Submaximal power at 4 $mmol \cdot L^{-1}$ (6.1 $W \cdot kg^{-1}$) was significantly higher than that reported for top international road cyclists who excel at TT stages (5.7 ± 0.2 $W \cdot kg^{-1}$) and uphill cycling (5.7 ± 0.5 $W \cdot kg^{-1}$) (28). However, this value is very close to that recorded for another TdF winner when tested in peak condition (6.2 $W \cdot kg^{-1}$) (34). Once again, if calculated using the athlete's self-reported race mass, the relative power at 4 $mmol \cdot L^{-1}$ (6.4 $W \cdot kg^{-1}$) would be the highest value reported to date. Comparisons to other studies of submaximal workloads in relation to blood lactate concentrations are confounded by the multiple differing methods, lack of reporting of the methods, and a lack of standardization with respect to the methods used to analyze blood lactate concentrations.
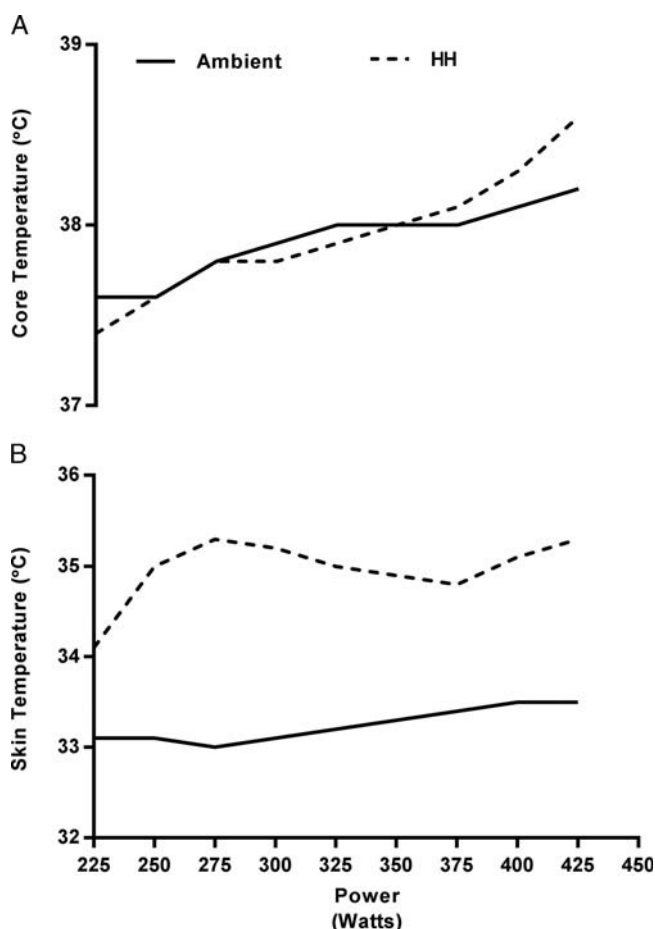

FIGURE 3—Comparison of core temperature (A) and skin temperature (B) during submaximal aerobic profile in ambient (19.5°C, 49.5% RH, 1016.2 mb) and HH conditions (30.0°C, 60.0% RH, 1015.0 mb).

Mean GE across both ambient and HH conditions (23.3%), as well as the mean GE for the two submaximal trials at 80% of $\dot{V}O_{2peak}$ (23.2%), compared favorably to the values described previously (22). All of the athletes tested in this report that recorded a GE greater than 22% also recorded $\dot{V}O_{2peak}$ values less than 77 mL·kg^{-1}·min^{-1} (22). The results presented in this case study therefore demonstrate a uniquely high $\dot{V}O_{2peak}$ in combination with a high GE, two characteristics that are required to sustain the very high submaximal power outputs required to win the TdF (Fig. 4).

The GE in HH conditions declined as a function of work rate in keeping with previously published data (14), whereas in normal ambient conditions, efficiency initially increased at low work rates and declined above work rates of 360 W. GE at lower work rates (<350 W) was greater in HH conditions than that in ambient conditions, whereas at higher work rates, the GE was similar for both ambient and HH conditions. The differences between the values recorded exceeded the typical error of measurement for GE (27) by a considerable margin. This increased efficiency at lower work rates in HH conditions is in contrast to the study by Hettinga et al. (15), who demonstrated that GE for a group of well-trained cyclists in hot conditions (35.5°C, 15.5% RH) was on average 0.9% lower than that in cool conditions (15.6°C, 20.0% RH). Similarly, submaximal power output values recorded at various blood lactate landmarks were higher in HH than in ambient conditions, which may be directly attributable to the improved GE. The mechanism underpinning higher GE in HH conditions is difficult to ascertain. Potentially, an efficient thermoregulatory response allowed the maintenance of lower muscle temperatures, which has been shown to allow higher degrees of glycolysis (4) and subsequently may allow for more efficient energy production.

The participant expressed anecdotally that he performs well in hot environmental conditions. The improved GE and submaximal power outputs in HH conditions appear to support this; however, it should be noted that because both ambient and HH trials were performed on the same day, we were unable to control for circadian rhythm and any associated fluctuations in physiology (41). Despite the higher than anticipated body fat percentage for an elite cyclist, the athlete's low body mass index (19.4 kg·m^{-2}) and ectomorphic somatotype may predispose to maintenance of performance or reduced decrement in performance in the heat (11,18,42). Furthermore, in line with other highly trained athletes, the participant's sweat rate was relatively high in both ambient and HH conditions, suggesting an efficient thermoregulatory response to exercise (38). Interestingly, the sweat Na$^+$ concentrations in both conditions were similar and of moderate magnitude (50–60 mmol·L^{-1}), which is also indicative of well-developed acclimation to HH environments.

Before the tests conducted for this case study, the participant had only undergone performance laboratory testing on one previous occasion in 2007 (an interval of 8 yr between tests). A longitudinal analysis of the two data sets may well be confounded by the use of different methodologies and protocols, and at the time of publication, we were unable to establish the specific methods used to collect the data in 2007. However, taking into account these confounding factors, some differences are clear, providing some interesting insight. The participant's mass recorded in 2007 was 75.6 kg. This is 4.8 kg greater than that recorded on the day of testing (70.8 kg) and approximately 8 kg greater than the self-reported race mass of the participant (67 kg). This equates to a change in mass of 10.5%. The reduction in mass appears to have been predominantly through the loss of body fat mass. The recorded body fat percentage was 16.9% in 2007 in comparison with 9.5% for the more recent test; however, differing methodologies may result in significant differences in the determination of body fat percentage (17). It is therefore not possible to conclude definitively whether the mass lost by the participant was predominantly fat mass, muscle mass, or a combination of both. Such a large reduction in mass would have an equivalent or greater performance-enhancing effect during uphill racing provided that the ability to produce power was not adversely effected. The PPO of 525 W compares favorably to the PPO of 540 W reported in 2007 when expressed relative to body mass (7.5 vs 7.1 W·kg^{-1}).

CONCLUSION

In conclusion, we present a broad range of physiological variables from a two-time TdF winner. These values were recorded at close to peak condition and therefore arguably represent the extremes of human endurance performance characteristics. The values for PPO, $\dot{V}O_{2peak}$, submaximal power outputs, and GE are among the highest reported for professional road cyclists.

Body fat was higher than previously reported for professional cyclists, which may be explained by the athlete's self-reported 4 kg increase in body mass since his second TdF win. When recalculated, relative values using the reported
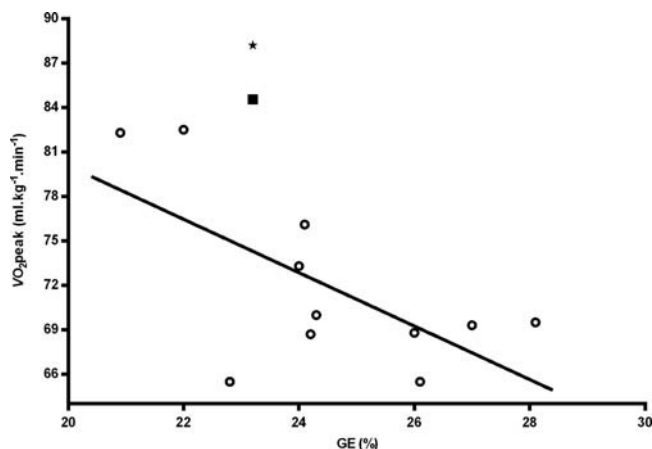

FIGURE 4—GE (%) at 80% of $\dot{V}O_{2peak}$ (mean of ambient and HH) vs $\dot{V}O_{2peak}$ from this case study (■, recorded mass; ★, self-reported race mass) in comparison with those from a group of professional cyclists (○) modified from Lucia et al. (22).

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competition body mass, PPO, and submaximal power at 4 mmol·L^{-1} blood lactate concentration are the highest values published to date.

Two unique characteristics of this case report are the high GE in relation to $\dot{V}O_{2peak}$ when compared with that reported for other professional cyclists, and the potential for strong performance in HH conditions owing to higher GE and lower submaximal blood lactate versus those presented in ambient conditions. This may in part be explained by efficient thermoregulatory processes as well as by the higher GE recorded during the first half of the exercise bout conducted in HH conditions. The characteristics of a high $\dot{V}O_{2peak}$ and high GE are critical to sustaining high power outputs. Such traits are a requirement to excel in TT and uphill stages finishes, two areas where time is usually gained over other stage race competitors. The TdF takes place in midsummer and usually experiences high temperatures and humidity on many stages. The ability to maintain performance in the heat may therefore be an important contributing characteristic to performance in this race and is reflected in the athlete's TdF performances to date.

In summary, these data provide a unique insight into the characteristics required to succeed at the TdF, the sport of cycling's leading event.

REFERENCES

1. Amann M, Dempsey JA. Locomotor muscle fatigue modifies central motor drive in healthy humans and imposes a limitation to exercise performance. *J Physiol*. 2008;586(1):161–73.
2. Amann M, Subudhi AW, Foster C. Predictive validity of ventilatory and lactate thresholds for cycling time trial performance. *Scand J Med Sci Sports*. 2006;16(1):27–34.
3. Bishop D, Jenkins DG, Mackinnon LT. The relationship between plasma lactate parameters, W$_{peak}$ and 1-h cycling performance in women. *Med Sci Sports Exerc*. 1998;30(8):1270–5.
4. Blomstrand E, Essén-Gustavsson B. Influence of reduced muscle temperature on metabolism in type I and type II human muscle fibres during intensive exercise. *Acta Physiol Scand*. 1987;131(4):569–74.
5. Borg G. Perceived exertion as an indicator of somatic stress. *Scand J Rehabil Med*. 1970;2(2):92–8.
6. Cheng B, Kuipers H, Snyder AC, Keizer HA, Jeukendrup A, Hesselink M. A new approach for the determination of ventilatory and lactate thresholds. *Int J Sports Med*. 1992;13(7):518–22.
7. Clark RR, Kuta JM, Sullivan JC. Prediction of percent body fat in adult males using dual energy x-ray absorptiometry, skinfolds, and hydrostatic weighing. *Med Sci Sports Exerc*. 1993;25(4):528–35.
8. Coyle EF. Improved muscular efficiency displayed as Tour de France champion matures. *J Appl Physiol (1985)*. 2005;98(6):2191–6.
9. Coyle EF, Sidossis LS, Horowitz JF, Beltz JD. Cycling efficiency is related to the percentage of type I muscle fibers. *Med Sci Sports Exerc*. 1992;24(7):782–8.
10. Duz S, Kocak M, Korkusuz F. Evaluation of body composition using three different methods compared to dual-energy X-ray absorptiometry. *European Journal of Sport Science*. 2009;9(3):181–90.
11. Epstein Y, Shapiro Y, Brill S. Role of surface area-to-mass ratio and work efficiency in heat intolerance. *J Appl Physiol Respir Environ Exerc Physiol*. 1983;54(3):831–6.
12. Faria EW, Parker DL, Faria IE. The science of cycling: factors affecting performance - part 2. *Sports medicine*. 2005;35(4):313–37.
13. Foley JP, Bird SR, White JA. Anthropometric comparison of cyclists from different events. *Br J Sports Med*. 1989;23(1):30–3.
14. Gaesser GA, Brooks GA. Muscular efficiency during steady-rate exercise: effects of speed and work rate. *J Appl Physiol*. 1975;38(6):1132–9.
15. Hettinga FJ, De Koning JJ, de Vrijer A, Wüst RC, Daanen HA, Foster C. The effect of ambient temperature on gross-efficiency in cycling. *Eur J Appl Physiol*. 2007;101(4):465–71.
16. Jackson AS, Pollock ML. Generalized equations for predicting body density of men. *Br J Nutr*. 1978;40(3):497–504.
17. Johansson AG, Forslund A, Sjodin A, Mallmin H, Hambraeus L, Ljunghall S. Determination of body composition–a comparison of dual-energy x-ray absorptiometry and hydrodensitometry. *Am J Clin Nutr*. 1993;57(3):323–6.
18. Kakitsuba N, Mekjavic IB, Katsuura T. Individual variability in the core interthreshold zone as related to body physique, somatotype, and physical constitution. *J Physiol Anthropol*. 2009;28(6):275–81.
19. Lamberts RP, Lambert MI, Swart J, Noakes TD. Allometric scaling of peak power output accurately predicts time trial performance and maximal oxygen consumption in trained cyclists. *Br J Sports Med*. 2012;46(1):36–41.
20. Lucia A, Earnest C, Arribas C. The Tour de France: a physiological review. *Scand J Med Sci Sports*. 2003;13(5):275–83.
21. Lucia A, Hoyos J, Chicharro JL. Physiology of professional road cycling. *Sports Med*. 2001;31(5):325–37.
22. Lucia A, Hoyos J, Perez M, Santalla A, Chicharro JL. Inverse relationship between $\dot{V}O_{2max}$ and economy/efficiency in world-class cyclists. *Med Sci Sports Exerc*. 2002;34(12):2079–84.
23. Lundby C, Robach P. Performance enhancement: what are the physiological limits? *Physiology (Bethesda)*. 2015;30(4):282–92.
24. Lusk G. Animal calorimetry: analysis of the oxidation of mixtures of carbohydrate and fat. *J Biol Chem*. 1924;59:41–2.
25. Marcora SM, Staiano W. The limit to exercise tolerance in humans: mind over muscle? *Eur J Appl Physiol*. 2010;109(4):763–70.
26. Martin DT, Quod MJ, Gore CJ, Coyle EF. Has Armstrong's cycle efficiency improved? *J Appl Physiol (1985)*. 2005;99(4):1628–9; author reply 9.
27. Moseley L, Jeukendrup AE. The reliability of cycling efficiency. *Med Sci Sports Exerc*. 2001;33(4):621–7.
28. Mujika I, Padilla S. Physiological and performance characteristics of male professional road cyclists. *Sports Med*. 2001;31(7):479–87.
29. Newell J, Higgins D, Madden N, et al. Software for calculating blood lactate endurance markers. *J Sports Sci*. 2007;25(12):1403–9.
30. Nimmerichter A, Eston RG, Bachl N, Williams C. Longitudinal monitoring of power output and heart rate profiles in elite cyclists. *J Sports Sci*. 2011;29(8):831–40.
31. Noakes TD. Maximal oxygen uptake: "classical" versus "contemporary" viewpoints: a rebuttal. *Med Sci Sports Exerc*. 1998;30(9):1381–98.
32. Noakes TD. The limits of endurance exercise. *Basic Res Cardiol*. 2006;101(5):408–17.
33. Padilla S, Mujika I, Angulo F, Goiriena JJ. Scientific approach to the 1-h cycling world record: a case study. *J Appl Physiol (1985)*. 2000;89(4):1522–7.
34. Padilla S, Mujika I, Cuesta G, Goiriena JJ. Level ground and uphill cycling ability in professional road cycling. *Med Sci Sports Exerc*. 1999;31(6):878–85.
35. Padilla S, Mujika I, Orbananos J, Santisteban J, Angulo F, Jose Goiriena J. Exercise intensity and load during mass-start stage races in professional road cycling. *Med Sci Sports Exerc*. 2001;33(5):796–802.

36. Passfield L, Doust JH. Changes in cycling efficiency and performance after endurance exercise. *Med Sci Sports Exerc*. 2000;32(11):1935–41.

37. Pinot J, Grappe F. A six-year monitoring case study of a top-10 cycling Grand Tour finisher. *J Sports Sci*. 2015;33(9):907–14.

38. Reilly T, Drust B, Gregson W. Thermoregulation in elite athletes. *Curr Opin Clin Nutr Metab Care*. 2006;9(6):666–71.

39. Santalla A, Earnest CP, Marroyo JA, Lucia A. The Tour de France: an updated physiological review. *Int J Sports Physiol Perform*. 2012;7(3):200–9.

40. Swart J, Lamberts RP, Lambert MI, et al. Exercising with reserve: evidence that the central nervous system regulates prolonged exercise performance. *Br J Sports Med*. 2009;43(10):782–8.

41. Teo W, Newton MJ, McGuigan MR. Circadian rhythms in exercise performance: implications for hormonal and muscular adaptation. *J Sports Sci Med*. 2011;10(4):600–6.

42. Tilkens MJ, Wall-Scheffler C, Weaver TD, Steudel-Numbers K. The effects of body proportions on thermoregulation: an experimental assessment of Allen's rule. *J Hum Evol*. 2007;53(3):286–91.

43. Vogt S, Heinrich L, Schumacher YO, et al. Energy intake and energy expenditure of elite cyclists during preseason training. *Int J Sports Med*. 2005;26(8):701–6.

44. Wilber RL, Zawadzki KM, Kearney JT, Shannon MP, Disalvo D. Physiological profiles of elite off-road and road cyclists. *Med Sci Sports Exerc*. 1997;29(8):1090–4.

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