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Analysis of elite road-cycling sprints in relation to maximal power-velocity-endurance profile: a longitudinal one-case study

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Abstract

The aims of the present study were to characterize the mechanical output of final road sprints of an elite sprinter during international competitions in relation to his power-velocity-endurance characteristics and to investigate the relationship between this sprint performance and the power produced during preceding phases of the race. The sprinter performed a set of short and long sprints (5 to 15-s) on a cycle ergometer to determine his maximal power-velocity-endurance profile. Based on eleven races, the distribution of power throughout each race, peak and mean power (P_{peak} and P_{mean}) and associated pedaling rates ($v_{P_{peak}}$ and $v_{P_{mean}}$) during the final sprint were analyzed. The power-velocity-endurance profile of the sprinter indicated that his theoretical mean maximal power and corresponding optimal pedaling rate ranged from 20.0 W.kg⁻¹ (124 rpm) for a 1-s sprint to 15.0 W.kg⁻¹ (109 rpm) for 20 s. Race data showed that final road sprints were mainly performed on the ascending limb of the power-velocity relationship ($v_{P_{peak}}$, 104 ± 8 and $v_{P_{mean}}$, 101 ± 8 rpm). Additionally, P_{peak} and P_{mean} were lower than the theoretical maximal power determined from the power-velocity-endurance profile (9.9 ± 7.0% and 10.6 ± 9.8%, respectively), which highlighted a significant state of fatigue induced by the race. Finally, sprint power exhibited a high variability between races and was strongly related to the level of power produced during the last minute before the sprint. These findings show the importance of considering both the power-velocity-endurance qualities and the power demand of the last lead-up phase before the sprint in order to optimize final sprint performance.

KEYWORDS

fatigue, force-velocity relationship, power-time curve, record power profile in sprint cycling, road race power demand, top-level performance

1 | INTRODUCTION

In road-cycling competitions, the sprint is the last effort of the race and it often determines the final ranking. This effort aims to generate a high acceleration to reach the highest speed possible and cross the finish line first. It mainly depends on a cyclist's maximal power output capacity, and to a lesser extent to their mass and aerodynamic drag.¹⁻³ The power outputs produced during the final sprints of some top-level races were recently reported for a world-class sprinter⁴ (mean power output $\sim 15.8 \pm 1.3$ W.kg⁻¹) and for some other professional sprinters⁵ (mean power output 14.2 ± 1.1 W.kg⁻¹).

From physiological and neuromuscular points of view, the power output produced during this final sprint depends on three main groups of interrelated factors. First, it is well known that maximal power output depends on pedaling rate. Indeed, the maximal power-pedaling rate relationship has a parabolic shape, with a peak maximal value (P_{max}) reached at an optimal pedaling rate (v_{opt}).⁶⁻⁸ Practically, this means that the capacity of a sprinter to reach their actual maximal power output depends closely on the pedaling rate used, which can be adjusted by the gear ratio.⁹ Therefore, a power-velocity test can be used to characterize this power-velocity profile and determine P_{max} and v_{opt} .^{6,7,10-12} Nevertheless, to our knowledge, the maximal power output and pedaling rate attained during sprints performed at the end of actual top-level road-cycling races have never been studied in relation to these power-velocity characteristics.

Second, the duration of elite road-cycling sprints has been reported to range between 9 and 17s,^{1,4,5,13,14} meaning that fatigue inevitably occurs during the sprint and influences the power production over time.¹⁵⁻¹⁷ Thus, it is necessary to consider the maximal power-endurance quality of the sprinter, which characterizes their capacity to resist fatigue and maintain the highest power possible throughout the sprint duration. This quality can be evaluated as the change over time of the peak power output during a long-lasting all-out effort (eg, 15 to 30 s). From such effort, the mean power output can be calculated, as can a fatigue index that reflects the power decline with time.¹⁸ In addition, it is now well established that this decrease in power output during a long sprint also depends on the pedaling rate; lower pedaling rate minimizes the decrease of power output.^{15,19-21} Thus, while the optimal pedaling rate (v_{opt}) maximizes the power output during very short maximal efforts (ie, 1–3 s, fatigue-free conditions), the actual optimal pedaling rate that maximizes the mean power output during a long-lasting sprint necessarily differs from v_{opt} and depends directly on the sprint duration. This optimal pedaling rate represents the best trade-off between the maximal power-generating capacity

produced at the beginning of the sprint and the smallest decrease of this power with time depending on the sprint duration. To the best of our knowledge, the mean power output and corresponding pedaling rate produced during top-level road-racing sprints has never been related to these maximal power-velocity-endurance characteristics.

Third, under racing conditions in the field, sprints are performed after high power has already been produced during the whole race, particularly in the last part preceding this final effort (e.g. 4.4 ± 0.6 W.kg⁻¹, 5.1 ± 0.5 W.kg⁻¹, and 6.8 ± 0.8 W.kg⁻¹ during the 10-min, 5 min, and 1 min before the sprint, respectively)⁵ leading to a potential pre-fatigue state. The effect of this pre-fatigue state on sprint cycling performance remains largely unknown. It was shown that a 6 min pedaling task performed at 90% of maximal oxygen uptake just before a sprint induced a significant decrease in peak and mean power outputs, especially at high pedaling rates.¹⁹ In contrast, a more recent study showed that international cyclists maintained their peak and mean power outputs during a sprint after 10 min of cycling simulating a lead-up phase to the final sprint performed during a race.²² However, this simulation performed in a laboratory setting remained different from a race as it did not include the pre-fatigue caused by the rest of the race. More importantly, the last minute before the sprint was performed at a lower intensity (ie, ~ 5 W.kg⁻¹)²² than during an actual race (6.8 W.kg⁻¹ in Menaspas et al. and $5.3 - 9.9$ W.kg⁻¹ in Van Erp et al.).^{4,5} It, therefore, seems interesting to make a more detailed examination of how the power output produced during the race actually influences sprint performance in the field.

The first aim of this longitudinal study was, therefore, to characterize the power outputs and pedaling rates produced during the final sprint of top-elite road-cycling races and look at how these relate to maximal power-velocity and power-endurance capacities. For this purpose, a professional sprinter was followed over two seasons, and all of his sprints leading to a top 5 final ranking were analyzed with regard to his power-velocity-endurance characteristics evaluated on a cycle ergometer. We hypothesized that i) the peak and mean power outputs produced during the sprint would be lower than the cyclist's maximal power capacities due to the pre-fatigue induced by the race; and ii) these power outputs produced during the final sprint would show non-negligible variability between races. A secondary aim was then to determine whether the efforts during the race, particularly those during the lead-up phase to the sprint would be related to the power and pedaling rate during the final sprint. The present study will provide valuable information about the maximal sprint abilities in road cycling, and the proposed method could be very relevant for monitoring cyclists in elite and sub-elite racing teams.

2 | METHODS

2.1 | Participants

One voluntary professional sprinter participated in this longitudinal study over a two-year period (height, 176 cm; weight, 71 kg; age, 24 years; 5-min cycling mean power output record, $6.6 \text{ W}\cdot\text{kg}^{-1}$). During both years he participated in the study, this cyclist competed on a pro cycling team and took part in the most prestigious races on the *Union Cycliste Internationale* calendar including the *Tour de France*. The experiment was explained to the participant and he gave his written consent. This study was carried out according to the procedures approved by the local ethics committee and in accordance with the Declaration of Helsinki.

2.2 | Experimental design

This longitudinal study was conducted during the 2018 and 2019 road-cycling seasons. The high-level sprinter performed three power-velocity and power-velocity-endurance tests on a stationary cycle ergometer (Excalibur Sport; Lode, The Netherlands) over a period of seven months at the beginning of the 2018 season. Only the best test was conserved in this study to characterize the maximal power-velocity-endurance qualities (see supporting information for more detail). The power output during international competitions over two years was recorded using a power meter (FC-RC9100-P, Shimano, Sakia, Japan) fitted to his road bikes. The consistency between the data measured during sprint sessions in the field through both seasons (ie, with this power meter) and the maximal power output obtained from the power-velocity test on the cycle ergometer was checked in a pilot analysis (see supporting information). Then, an analysis of the road-cycling sprints was done by relating the power and pedaling rate data recorded during official competitions to the power-velocity-endurance profile.

2.3 | Maximal power-velocity test

This test was performed on an electronically braked cycle ergometer (Excalibur Sport; Lode, The Netherlands) equipped with standard cranks (length = 170 mm), and clipless pedals (Look). Positions of the saddle and handlebars were adjusted to ensure the cyclist's position was as usual. The torque exerted on the left and right cranks was measured by strain gauges placed in the crank arms of the cycle ergometer (one mean value every 2° of crank rotation). After a 15 min warm-up consisting of a progressive

increase in power output from 150 to 300 W followed by a first brief maximal sprint, the cyclist performed three maximal cycling sprints of 5-s duration, interspaced by 5 min rest periods. All sprints were carried out in a standing position matching that of racing conditions. Each sprint was performed against a specific resistance or mode allowing different ranges of pedaling rates (70 – 110, 100 – 140, and 120–180 rpm), in a randomized order. The two sprints with the lowest pedaling rates were performed using the isokinetic mode of the ergometer, with an increment of 10 rpm per second. This incremental every second protocol leads to a constant acceleration and the cyclist does not really feel the steps. For the sprint with the highest pedaling rates, the flywheel was already turning at 120 rpm, and the sprint was performed without resistance. This method is an equivalent of the classical isoinertial method that uses 3 sprints with different resistances.^{6,9} The great advantage of using this isokinetic mode compared to the isoinertial mode is the possibility to easily and robustly impose an effort in a target range of pedaling rate. The cyclist was encouraged throughout the 5-s to produce the highest power output possible. For data processing, power output was averaged for each crank revolution and four to eight crank revolutions were considered for each sprint (depending on the pedaling rate) to draw the power-velocity relationship. The power-velocity relationship was fitted with a second-order polynomial model⁶ (Figure 1, equation (1)), which made it possible to determine the maximal power output relative to the body mass (P_{max} , in $\text{W}\cdot\text{kg}^{-1}$) and the corresponding optimal pedaling rate (v_{opt}). Then, theoretical maximal power output produced for each pedaling rate measured in the field ($P_{max}(v)$) was calculated using the second-order polynomial function (equation 1) fitted to the experimental data:

$$P_{max}(v) = av^2 + bv + c \quad (1)$$

where v is the measured pedaling rate (in rpm) and a , b , and c are the constants determined during the fitting of experimental data.

2.4 | Maximal power-endurance test and determination of the maximal power-velocity-endurance profile

After a 10 min rest period, the cyclist performed two 15-s isokinetic sprints at 100 and 130 rpm (in a randomized order) with a 15-min rest in between. He was asked to perform an all-out effort, which consisted of immediately attaining his maximal power output and maintaining it until the end of the 15-s countdown without any pacing strategy. In order to estimate the sprinter's maximal

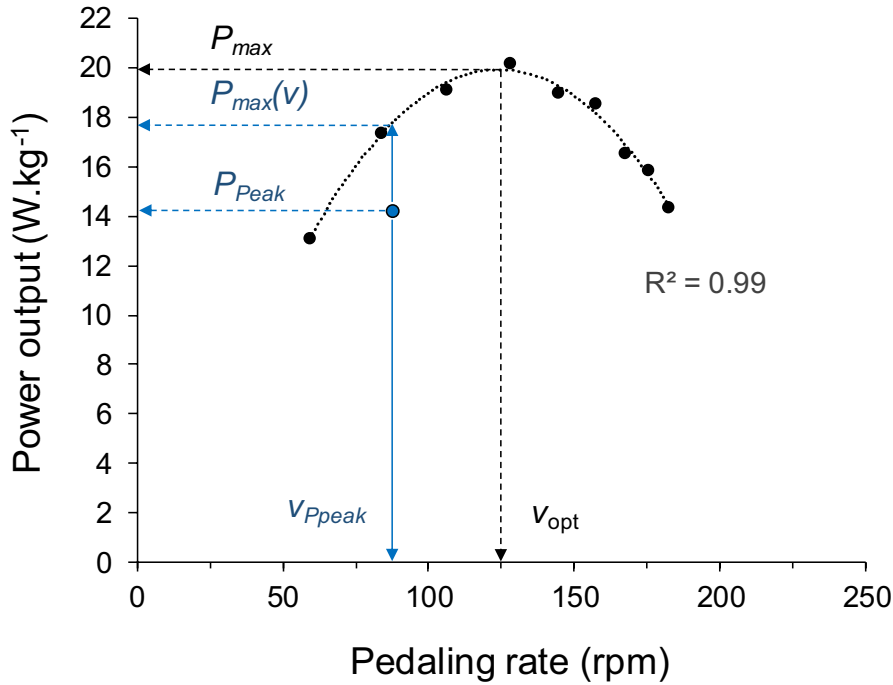


FIGURE 1 Power-velocity relationship of the sprinter fitted with a second-order polynomial model to determine the maximal power (P_{max}) and the corresponding optimal pedaling rate (v_{opt}). The blue point represents an example of peak power reached during a road-sprint (P_{peak}) with the corresponding pedaling rate (v_{Ppeak}) and the theoretical maximal power at this pedaling rate ($P_{max}(v)$). Note that for data processing, v_{Ppeak} (in rpm) was also expressed in percentage of v_{opt} , and P_{peak} (in $W.kg^{-1}$) was also expressed in percentage of P_{max} and $P_{max}(v)$

power output capacity for each sprint duration and for any pedaling rate ($P_{max}(v, duration)$), a model taking into account both the power-velocity test and these two power-endurance tests was used (Figure 2). First, for each of the two pedaling rates tested, the mean maximal power produced over the first 5-s, the first 10-s, and the entire 15-s of sprinting during the 15-s isokinetic sprints were calculated (Figure 2A). Second, using an additional point corresponding to the theoretical maximal power output during 1-s at the equivalent pedaling rate (ie, $P_{max}(v)$), the relationship between maximal mean power (in $W.kg^{-1}$) and sprint duration were drawn and fitted by linear regression (Figure 2B) for both 100 ($R^2 = 0.99$) and 130 rpm ($R^2 = 0.95$) conditions. The index of power decrease (S_p) was calculated for each pedaling rate ($S_p(100)$ and $S_p(130)$, in $W.kg^{-1}.s^{-1}$), it corresponded to the slope of these linear relationships. Since sprint duration could reach 20-s during road races, the model was extrapolated up to 20 s. Third, considering the difference in the index of power decrease between 100 and 130 rpm conditions, the index of power decrease at each intermediate pedaling rate ($S_p(v)$, in $W.kg^{-1}.s^{-1}$) was interpolated assuming a linear decrease of this index with the pedaling rate (ie, higher negative values at higher pedaling rates, Figure 2C) using the following equation 2:

$$S_p(v) = \alpha v + \beta \quad (2)$$

where v is the pedaling rate (in rpm) and α and β are constants.

Note that the values of 100 and 130 rpm were initially chosen to match the maximal and minimal pedaling rates reached during road-cycling sprints (personal data from a pilot analysis). As the actual lowest pedaling rate observed during a racing sprint was 85 rpm, S_p was finally slightly extrapolated for pedaling rates below the 100-rpm measured pedaling rate. Finally, the theoretical maximal mean power output for each pedaling rate and each sprint duration ($P_{max}(v, duration)$) was calculated with the following equations 3:

$$P_{max}(v, duration) = P_{max}(v) + [S_p(v) \cdot (duration - 1)] \quad (3)$$

Substituting (1) and (2) into (3) gives:

$$P_{max}(v, duration) = [av^2 + bv + c] + [(\alpha v + \beta) \cdot duration - 1] \quad (4)$$

where v is the pedaling rate (in rpm) and $duration$ is the duration of the sprint (in s).

Ultimately, this equation was used to calculate the theoretical maximal mean power output for each sprint duration (from 1 to 20-s with an increment of 1-s) and for each pedaling rate (from 85 to 130 rpm with an increment of 1 rpm). Then, for each sprint duration, we detected the

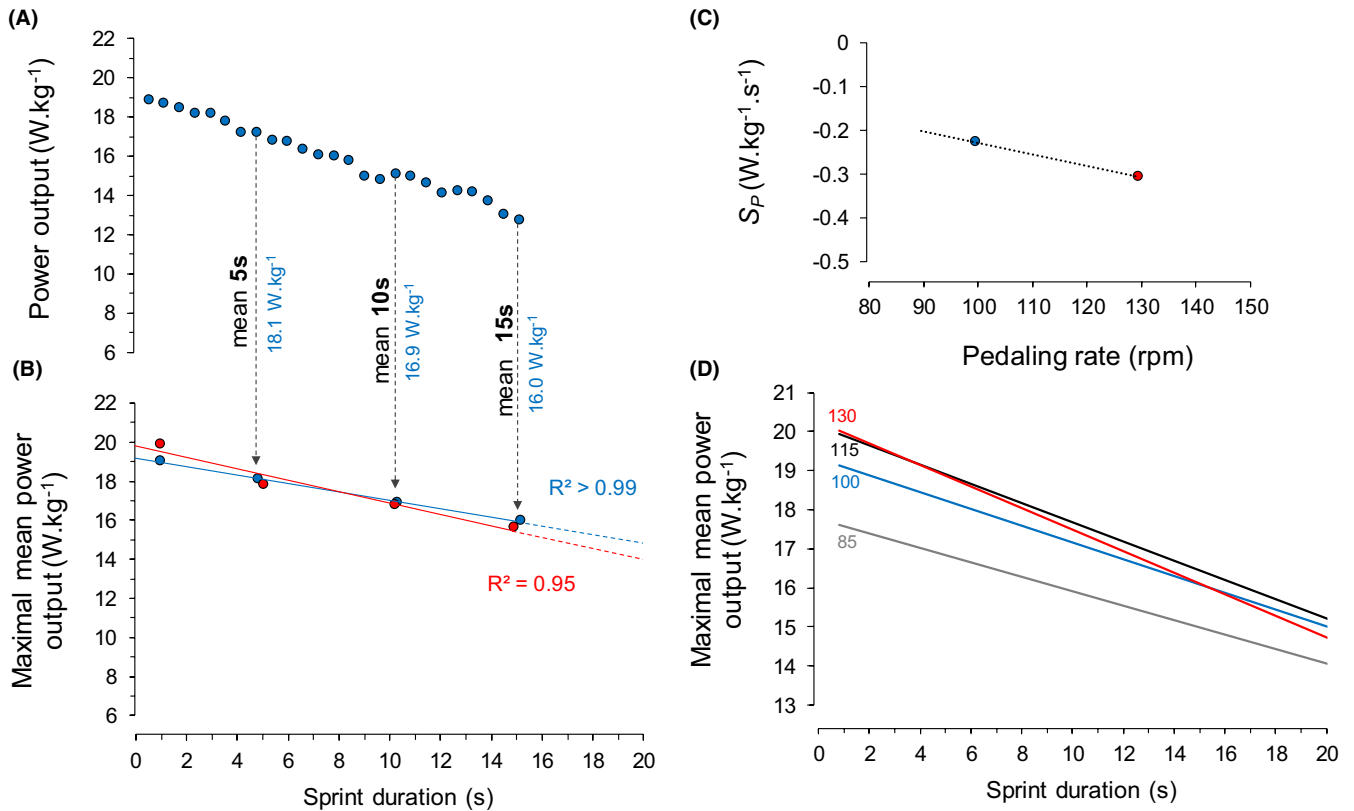


FIGURE 2 Maximal power-velocity-endurance model method. Example of power output (in W.kg⁻¹) produced during the 15-s isokinetic test at 100-rpm is shown in panel A. These data are used to determine the maximal mean power produced during 5-, 10-, and 15-s. Adding the maximal 1-s power produced at this pedaling rate (ie, $P_{max}(100)$, determined from the power-velocity relationship), the relationship between maximal mean power and sprint duration was fitted by linear regression (panel B, $R^2 = 0.99$) allowing to determine a power decrease index (ie, the slope of this relationship ($S_P(100)$ in W.kg⁻¹.s⁻¹). The same methodology was used for the second pedaling rate condition (130 rpm, with $P_{max}(130)$, $R^2 = 0.95$, and $S_P(130)$, in red). Then, considering the values of this index at 100 and 130 rpm, the power decrease index at each adjacent pedaling rates from 85 to 130 rpm was estimated using a linear extrapolation (ie, the linear decrease of this index with pedaling rate, panel C). Finally, the maximal power produced in 1-s ($P_{max}(v)$) and the decrease index ($S_P(v)$) allowed us to estimate the theoretical maximal mean power produced for each sprint duration from 1 to 20-s and for each pedaling rate ($P_{max}(v, duration)$). Only four models are depicted as examples in panel D: 85 (in gray), 100 (in blue), 115 (in black), and 130 (in red) rpm. For each sprint duration, we detected the highest value of mean power output ($P_{max}(duration)$) and the corresponding optimal pedaling rate ($v_{opt}(duration)$). The final model is presented in Figure 4B

highest value of mean power output ($P_{max}(duration)$) and the corresponding optimal pedaling rate ($v_{opt}(duration)$, Figure 2D).

2.5 | Analysis of sprints during road-cycling races

Power and pedaling rate data recorded during official competitions were collected over two entire cycling seasons. Only bunch sprints leading to a top 5 final ranking were included in this study. If the sprinter was hampered, trapped by other cyclists and/or unable to perform a maximal effort, the race was excluded from the analysis. Thus, eleven races met these selection criteria: three first places, two second, one third, three fourth, and two fifth in *Hors Catégorie* (N = 1) or *Catégorie 1*

(N = 10) races. Each race has been given a specific color in all Figures and Table 1. The power meter recorded data at 1 Hz and its offset was checked before each training or competition. Race files were uploaded using the TrainingPeaks web service and WKO+4.0 software (Peakware LLC, Lafayette, CO, USA), and processed using custom MATLAB scripts (The MathWorks, Natick, MA). The beginning of the final sprint was determined as the time when the cyclist decided to initiate his maximal all-out final effort (ie, when the power output suddenly increased, Figure 3). For each sprint, the duration, peak power output (P_{peak}), mean power output (P_{mean}), and corresponding pedaling rates ($v_{P_{peak}}$ and $v_{P_{mean}}$, respectively) were determined (Table 1). For peak data, P_{peak} (in W.kg⁻¹) was also expressed relative to P_{max} , determined by the power-velocity test (in % P_{max}) and relative to the theoretical maximal power at the

TABLE 1 Characteristics of the sprints performed by a professional sprinter during different races

Sprint duration s	Peak data during the sprint				Mean data during the sprint							
	P_{peak}		$v_{P_{peak}}$		P_{mean}				$v_{P_{mean}}$			
	$W \cdot kg^{-1}$	% P_{max}	% $P_{max}(v)$	rpm	% v_{opt}	$W \cdot kg^{-1}$	% P_{max}	% $P_{max}(v, duration)$	rpm	% $v_{opt}(duration)$		
13	17.3	86.3%	86.9%	116	93.2%	16.1	80.5%	97.5%	105	91.3%		
20	14.2	70.8%	79.3%	88	70.7%	10.4	52.2%	74.9%	85	78.4%		
16	17.3	86.3%	89.4%	104	83.6%	14.6	73.1%	93.0%	102	91.3%		
7	17.0	84.9%	85.7%	114	91.6%	15.1	75.5%	82.8%	114	95.3%		
15	19.0	94.9%	99.7%	100	80.4%	16.6	83.2%	104.9%	100	88.6%		
4	17.4	86.8%	91.7%	99	79.6%	15.8	78.8%	87.0%	97	79.4%		
19	18.5	92.4%	94.0%	110	88.4%	15.4	77.2%	102.4%	105	95.5%		
15	14.9	74.5%	80.6%	94	75.6%	11.2	55.9%	74.0%	88	77.8%		
9	20.3	101.5%	103.8%	108	86.8%	16.8	84.1%	95.2%	111	94.6%		
10	17.2	85.9%	88.7%	105	84.4%	14.5	72.3%	84.6%	102	86.8%		
15	17.7	88.4%	91.2%	105	84.4%	13.9	69.4%	86.6%	105	93.3%		
13.0 (4.7)	17.3 (1.6)	86.6 (8.1)	90.1 (7.0)	104 (8)	83.5 (6.4)	14.6 (2.0)	72.9 (9.9)	89.4 (9.8)	101 (8)	88.4 (6.4)		

Note: Peak power output produced during the sprint (P_{peak}) was expressed in power relative to the body mass ($W \cdot kg^{-1}$), in percentage of maximal power output ($\%P_{max}$) and in percentage of maximal power output at the pedaling rate used ($\%P_{max}(v)$). The pedaling rate associated to peak power output ($v_{P_{peak}}$) was expressed in revolution per minute (rpm) and in percentage of the optimal pedaling rate ($\%v_{opt}$). Mean power output during the sprint (P_{mean}) was expressed in power relative to the body mass ($W \cdot kg^{-1}$), in percentage of maximal power output ($\%P_{max}$), and in percentage of maximal power output on the duration and at the pedaling rate used ($\%P_{max}(v, duration)$). Mean pedaling rate during the sprint ($v_{P_{mean}}$) was expressed in revolution per minute (rpm) and in percentage of the optimal pedaling rate on the duration of the sprint ($\%v_{opt}(duration)$). Means (standard deviation) are given for each parameter.

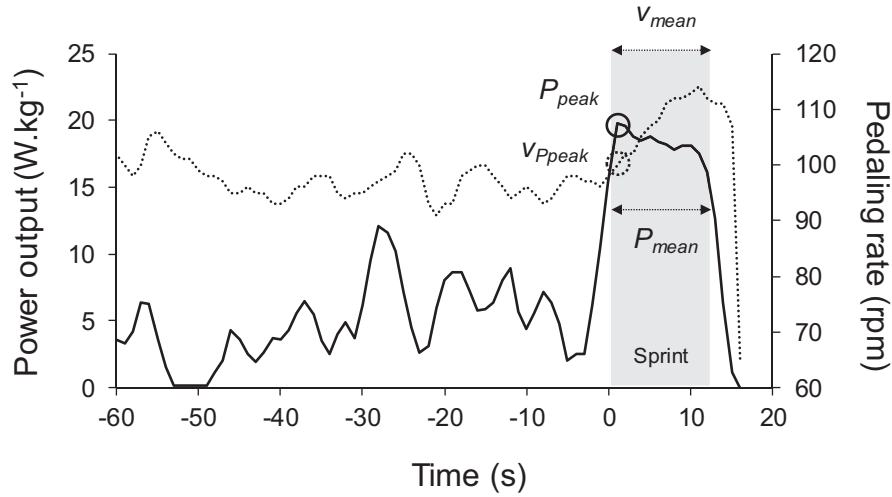


FIGURE 3 Typical example of power output (black line) and pedaling rate (dotted line) data recorded at 1 Hz at the end of a road race (including the final sprint and the preceding minute). The gray area represents the sprint, with the peak power output (P_{peak}) and the corresponding pedaling rate (v_{Ppeak}), and the mean power output (P_{mean}) produced during the whole sprint and the corresponding mean pedaling rate (v_{Pmean})

pedaling rate used (in $\%P_{max}(v)$). v_{Ppeak} (in rpm) was also expressed relative to the optimal pedaling rate (in $\%v_{opt}$). For mean data, P_{mean} (in $W.kg^{-1}$) was also expressed relative to P_{max} (in $\%P_{max}$) and relative to the theoretical maximal mean power at the pedaling rate used and over the corresponding duration (in $\%P_{max}(v,duration)$). v_{Pmean} (in rpm) was also expressed relative to the optimal pedaling rate for the corresponding duration (in $\%v_{opt}(duration)$). Finally, power output and pedaling rate data recorded during the entire race (ie, all data except those included in the final sprint) were analyzed to characterize the overall effort preceding this final sprint. Data were averaged over different time windows (ie, whole race, 60-, 10-, 5-, 4-, 3-, 2-, and 1-min before the sprint, Figure 5) in order to investigate whether the mean power produced over these different periods was related to the capacity to produce high power during the final sprint.

2.6 | Statistical analysis

Statistics were done using ORIGIN 2018 (Origin 8; OriginLab Corporation). Since the data consistently passed the normality test (Shapiro-Wilk's test), results were expressed as mean \pm SD. The regression models used for the power-velocity relationship and the power-velocity-endurance profile were described above in specific parts. Pearson's product-moment correlations (r) were used to determine whether, on all the races considered ($N = 11$), the cyclist's capacity to reach his maximal power output during the sprint was related to the

duration of the sprint and to the mean power output produced during the different phases of the race preceding this final effort (ie, whole race, 60-, 10-, 5-, 4-, 3-, 2-, and 1-min before the sprint). The threshold of significance was set at $p < 0.05$.

3 | RESULTS

3.1 | Maximal power-velocity relationship and power-velocity-endurance profile

The P_{max} and v_{opt} of the cyclist were $20.0 W.kg^{-1}$ and 124 rpm (Figure 1). During the 15-s isokinetic sprints, the mean maximal power outputs produced were $16.0 W.kg^{-1}$ (79.8% of P_{max}) and $15.6 W.kg^{-1}$ (78.2% of P_{max}) at 100 and 130 rpm, respectively. The index of the power decrease (S_p) was $-0.217 W.kg^{-1}.s^{-1}$ and $-0.297 W.kg^{-1}.s^{-1}$ at 100 and 130 rpm, respectively (Figure 2). Theoretical maximal mean power produced for each sprint duration ($P_{max}(duration)$, from 1 to 20 s) are shown in Figure 4B (with the corresponding optimal pedaling rate, $v_{opt}(duration)$, for 1, 5, 10, 15, and 20-s sprint duration). This provides an overview of the maximal power-velocity-endurance profile of the sprinter, characterizing his capacity to produce power in long-lasting sprints up to 20-s duration. For instance, for a 20-s sprint duration, his theoretical maximal mean power output ($P_{max}(20-s)$) amounted to $15.0 W.kg^{-1}$ with an optimal pedaling rate ($v_{opt}(20-s)$) of 109 rpm, representing 75.1% of P_{max} and 87.5% of v_{opt} , respectively.

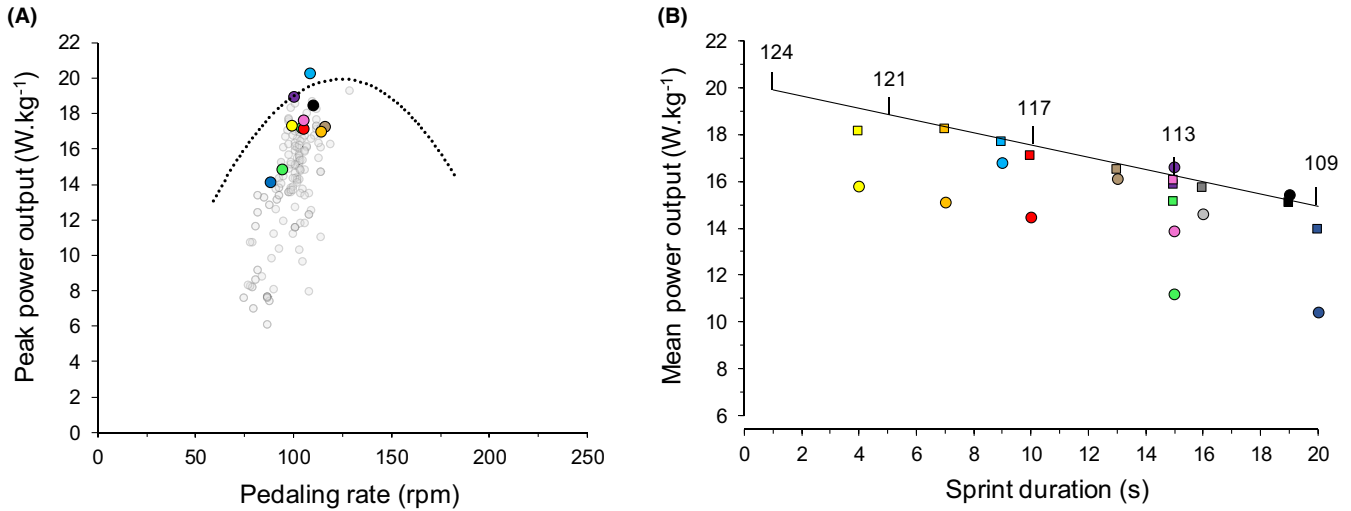


FIGURE 4 Power output and pedaling rate data recorded at 1 Hz during 11 road race sprints (in gray) and power-velocity relationship (dotted line) are represented in panel A. Colored circles represent the peak power output (P_{peak}) for each sprint (each represented by a different color, $N = 11$). Mean power output produced during the 11 sprints and maximal power-endurance profile measured on a cycle ergometer is shown in panel B. Theoretical relationship between maximal mean power output and sprint duration (black line) is represented with the corresponding optimal pedaling rates for 1-s, 5-s, 10-s, 15-s, and 20-s sprint durations. Colored circles represent the mean power outputs produced during road sprints, and colored squares represent the theoretical maximal mean power of the sprinter for the corresponding pedaling rate and sprint duration ($P_{max}(v,duration)$). As an example, for the orange sprint that lasted 7 s, P_{mean} was 15.1 W.kg^{-1} whereas $P_{max}(v,duration)$ was 18.2 W.kg^{-1} . Thus, the vertical difference in power output between the square and the circle of a same color represents the level of fatigue

3.2 | Road-racing sprints in relation to power-velocity relationship and power-velocity-endurance profile

Power output and pedaling rate recorded each second during all considered racing sprints are presented in Figure 4A together with the maximal power-velocity relationship. The peak and mean values obtained on each road-racing sprint are shown in Table 1. Sprints were mainly performed on the ascending limb of the power-velocity relationship. Considering all the sprints, mean $v_{P_{peak}}$ and $v_{P_{mean}}$ were $104 \pm 8 \text{ rpm}$ ($83.5 \pm 6.4\%$ of v_{opt}) and $101 \pm 8 \text{ rpm}$ ($88.4 \pm 6.4\%$ of $v_{opt}(duration)$), respectively. The mean P_{peak} and P_{mean} were $17.3 \pm 1.6 \text{ W.kg}^{-1}$ (representing $86.6 \pm 8.1\%$ of P_{max} and $90.1 \pm 7.0\%$ of $P_{max}(v)$) and $14.6 \pm 2.0 \text{ W.kg}^{-1}$ (representing $72.9 \pm 9.9\%$ of P_{max} and $89.4 \pm 9.8\%$ of $P_{max}(v,duration)$), respectively.

3.3 | Between-race sprint performance variability and relationship with power demand during races

We noticed a large between-race variability in sprint duration (from 4 to 20 s), for both P_{peak} (from 14.2 to 20.3 W.kg^{-1}), and P_{mean} (from 10.4 to 16.8 W.kg^{-1}). This between-race

variability was also observed for P_{peak} expressed relative to $P_{max}(v)$ (from 79.3 to 103.8%) and for P_{mean} expressed relative to $P_{max}(v,duration)$ (from 79.9 to 104.9%). P_{peak} (in W.kg^{-1} or in $\%P_{max}(v)$) and P_{mean} (in W.kg^{-1} and in $\%P_{max}(v,duration)$) were not significantly correlated with the sprint duration ($p = 0.357$, $p = 0.459$ and $p = 0.130$, $p = 0.862$, respectively). In addition, we observed a large variability in mean power output produced during the different phases of the races, especially during the last minute before the sprint (Figure 5). This mean power output produced during the last minute was significantly related to P_{peak} (in $\%P_{max}(v)$, $r = -0.75$, $p < 0.01$) and P_{mean} (in $\%P_{max}(v,duration)$, $r = -0.79$, $p < 0.01$, Figure 6). No significant correlations were found between P_{peak} or P_{mean} and the mean power produced during the other phases of the races (ie, whole race, 60-, 10-, 5-, 4-, 3-, and 2-min before the sprint).

4 | DISCUSSION

In accordance with our first hypothesis, the present study showed that the peak and mean powers produced and corresponding pedaling rates used by the sprinter during road-racing sprints were lower than his maximal power output capacities and his optimal pedaling rates determined by the power-velocity-endurance test. Thus, peak and mean power outputs expressed in percentages

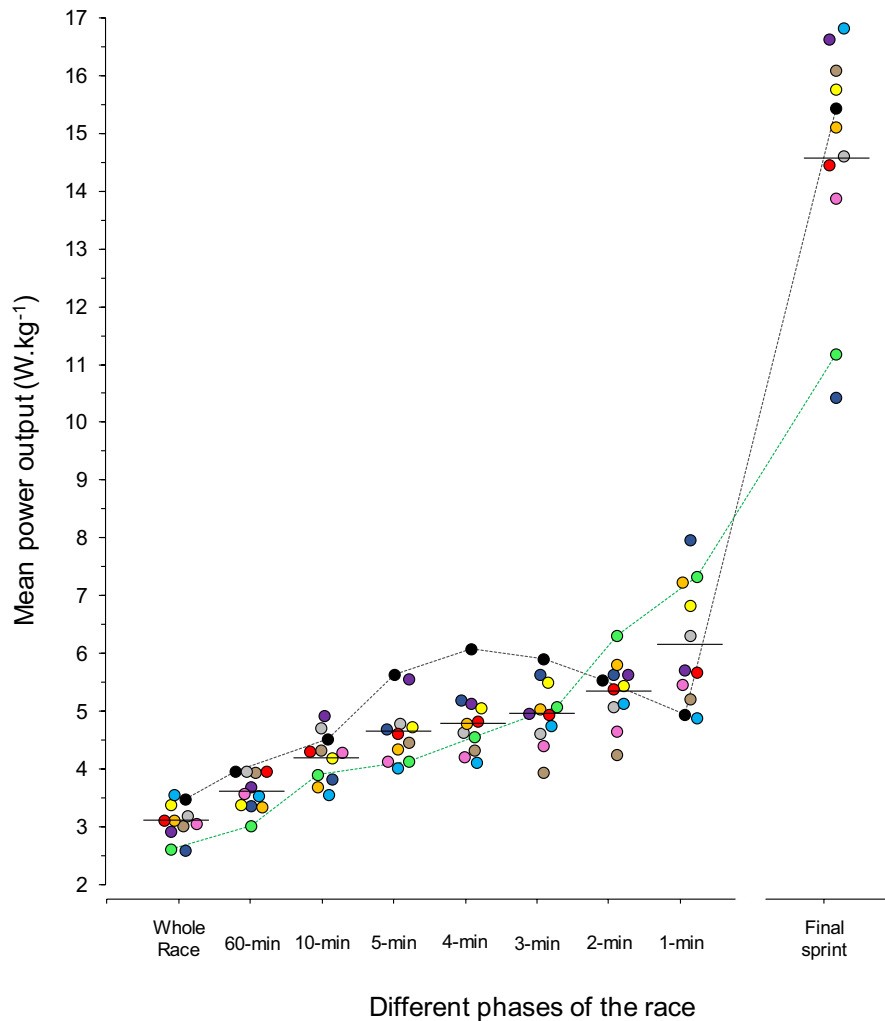


FIGURE 5 Mean power output data recorded during different phases of the race: the whole race, last 60-min, 10-min, 5-min, 4-min, 3-min, 2-min, and 1-min before the sprint and during the final sprint. Each colored circle represents a different race, and the horizontal black line represents the average value across all races for each phase. Green and black races are highlighted in the graph to illustrate the important effect of the power output produced during the last minute before the sprint on the sprint performance. The green race was one of the races with the lowest power output until two minutes before the sprint and one of the highest power output during the last minute before the sprint and was characterized by one of the lowest peak and mean power output during the sprint. Conversely, the black race was one of the most intense races (considering all the races), but associated with a low power output during the last minute before the sprint and then was characterized by one of the highest power output during the sprint

of theoretical maximal power outputs that accounted for both the pedaling rate and the duration of sprints, highlighted fatigue caused by the race. In accordance with our second hypothesis, a large between-race variability was found in power output during this final sprint, as well as during the different phases of the race. A strong negative correlation was observed between the mean power produced during the last minute before the sprint and the peak and mean power outputs during the final sprint. This result demonstrates that the pre-fatigue state, when the cyclist started his final sprint effort is more directly related to the power demand during the lead-up phase immediately preceding the sprint than to the race as a whole.

4.1 | Characteristics of road-racing sprints

Sprint durations observed in the present study (13.0 ± 4.7 -s) were in accordance with those reported in two recent studies (13.2 ± 2.3 s by Menaspa et al. and 13.1 ± 2.5 s by Van Erp et al.),^{4,5} despite having a slightly higher variability. Peak power output produced by our top-elite sprinter during final sprint (17.3 ± 1.6 W.kg⁻¹, $N = 11$) was in accordance with data previously reported for professional sprinters of a UCI World Tour team (17.4 ± 1.7 W.kg⁻¹, $N = 15$).⁵ Logically, the power output produced by the sprinter in our study was lower than that recently reported by Van Erp et al.⁴ from one of the

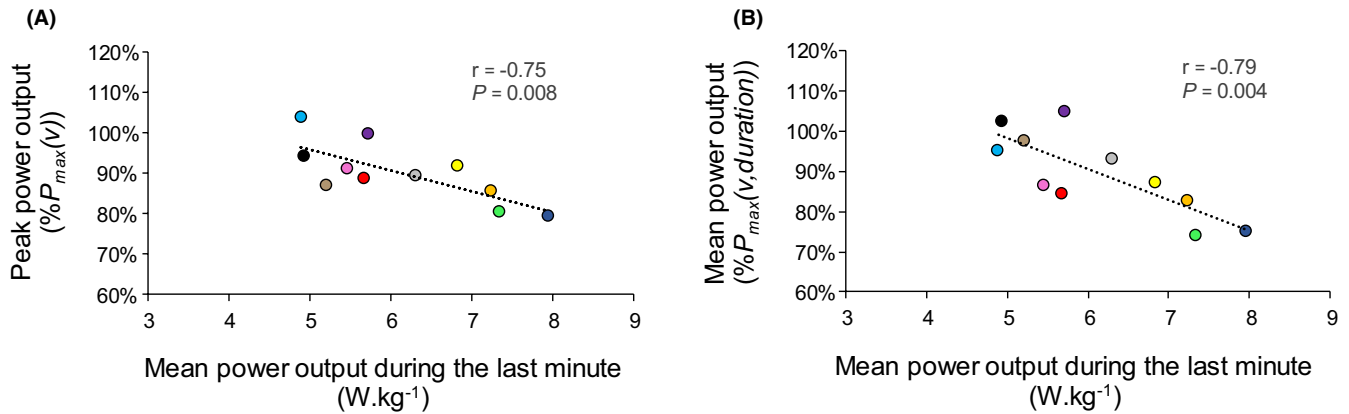


FIGURE 6 Relationships between power outputs produced during road sprints and the mean power output sustained during the last minute before the sprint. Peak power (P_{peak}) is expressed as the percentage of the theoretical maximal power at the pedaling rate (panel A). Mean power output (P_{mean}) is expressed as a percentage of the theoretical maximal mean power for the pedaling rate and duration (panel B)

best sprinters in the world ($\sim 19.5 \pm 1.1 W.kg^{-1}$) during winning sprints of the *Tour de France* stages ($N = 14$). The same trend was observed regarding the mean power produced over the whole sprint ($14.6 \pm 2.0 W.kg^{-1}$ in the present study versus $14.2 \pm 1.1 W.kg^{-1}$ in Menaspas et al.),⁵ but the difference from the data reported by Van Erp et al. was smaller ($\sim 15.8 \pm 1.3 W.kg^{-1}$).⁴ The originality of the current study is to relate the power outputs and pedaling rates produced during road-racing sprints to the sprinter's own power-velocity-endurance characteristics, and thus improve our interpretation of the efforts underlying performance.

4.2 | Power-velocity relationship and peak power output during road-racing sprints

Surprisingly, data on power-velocity characteristics of professional road sprinters are scarce in the literature. P_{max} of the current sprinter performed in a standing position ($20.0 W.kg^{-1}$) was close to the highest values previously reported in cyclists of different disciplines in either seated or standing positions ($12.5 W.kg^{-1}$ to $22 W.kg^{-1}$) while v_{opt} (124 rpm) was close to the average value (115 rpm up to 141 rpm).^{2,23,24} However, these values understandably remained lower than the highest values recorded on world-class BMX and track sprint cyclists ($25\text{--}26 W.kg^{-1}$ with an optimal pedaling rate of 135–140 rpm).⁹

On all the road-racing sprints, results showed that the average peak power output (P_{peak}) was $13.4 \pm 8.1\%$ lower than P_{max} (Table 1). The fact that the pedaling rate at P_{peak} ($v_{P_{peak}}$) was on average 20 rpm lower than the optimal pedaling rate ($83.5 \pm 6.4\%$ of v_{opt}) should theoretically limit the maximal power output of the sprinter and may partly explain why P_{peak} was lower than P_{max} . However,

by relating this to the power-velocity relationship, it appears that the sprinter produced much less power than the theoretical maximal power he is able to produce at this pedaling rate ($90.1 \pm 7.0\%$ of $P_{max}(v)$). This discrepancy of $9.9 \pm 7.0\%$ demonstrated that the sprinter was not able to reach his theoretical maximal power, irrespective of the pedaling rate used. As the goal for the sprinter is to maximize power during the sprint, this finding strongly suggests a non-negligible state of fatigue induced by the efforts of the race before this final sprint. Although we cannot totally exclude a slight holding back of power (even unconscious) at the beginning of the effort during the long-lasting sprints (>15 s), it appears unlikely as the all-out strategy remains the best for maximizing sprint power output. Interestingly, the further analysis of the mean power output produced over the entire sprint made it possible to overcome this phenomenon.

4.3 | Power-velocity-endurance profile and mean power output during road-racing sprints

To the best of our knowledge, this study is the first to characterize a maximal power-velocity-endurance profile, moreover in a high-level road sprinter, which allowed us to determine the subject's capacity to produce maximal power output taking into consideration both the pedaling rate and duration of the sprint (from 1 to 20 s), (Figure 4B). In the absence of values from the literature, we compared our results with personal unpublished data obtained with the same method. The maximal mean power output during the 15-s sprint at 100-rpm was $16.3 W.kg^{-1}$ (81.5% of P_{max}) for the sprinter who participated in the present study compared with $14.8 \pm 1.5 W.kg^{-1}$ ($76.9 \pm 1.5\%$ of P_{max}) for a group of seven road-cycling elite sprinters. It

can be argued that the sprinter in the present study has good power-endurance qualities for long-duration sprints compared with other road sprinters. This highlights the relevance of such measurements for both sprinter evaluation and personalized training.

The mean power obtained in the two 15-s tests performed at 130 and 100-rpm confirmed the decrease in power is specific to pedaling rate.²¹ Modeling the maximal power-velocity-endurance profile, by assuming a linear evolution of the index of power decrease with pedaling rate, made it possible to determine the theoretical maximal mean power output for each sprint duration (from 1 to 20-s) and for each pedaling rate (from 85 to 130 rpm). This profile provided experimental evidence that the optimal pedaling rate maximizing the mean power output decreases with sprint duration. Indeed, the model predicted that the maximal mean power output during a sprint of 15-s was $16.3 \text{ W}\cdot\text{kg}^{-1}$, which corresponds to a decrease of 18.5% compared to P_{max} . In this example, this difference in mean power produced during 1-s (ie, P_{max}) and 15-s ($P_{max}(15\text{-s})$) is associated with (i) a decrease of the optimal pedaling rate from 124 rpm (v_{opt}) to 113 rpm ($v_{opt}(15\text{-s})$), which corresponds to a decrease of 9.2%, and (ii) a decrease of the optimal force from $9.0 \text{ N}\cdot\text{kg}^{-1}$ (F_{opt}) to $8.1 \text{ N}\cdot\text{kg}^{-1}$ ($F_{opt}(15\text{-s})$), which corresponds to a decrease of 10.2%. These findings are in agreement with the shift to the left and to the down of the power-velocity relationship with fatigue reported by MacIntosh et al. (2004) at the end of a 30-s Wingate test,²⁵ and highlighted a decrease in both force and velocity capacities after a fatigue exercise, while maintaining a linear force-velocity relationship.²⁶ Since the road-racing sprints had different durations and the pedaling rates used differed between races, this profile was used as a reference to interpret the mean power data produced during the different sprints. Considering the average results of the eleven road-racing sprints, we noticed that the mean power output during sprinting represented $89.4 \pm 9.8\%$ of the theoretical maximal mean power output for the corresponding pedaling rate and duration (Table 1). This is visually illustrated by the vertical distance between circles and squares for each sprint in figure 4B. Thus, in addition to peak power, discussed previously, this result provides evidence that the final sprint in professional races is performed in a significant pre-fatigue state.

4.4 | Between-race variability in sprint performance and relationship with power demand during a race

Beyond the analysis considering the eleven races together, we observed a high variability in peak and mean power

outputs during sprints among these races. Interestingly, although the variability in sprint duration should strongly influence the mean power output, no significant correlation was found between P_{mean} and the duration of the sprint. Thus, higher mean power was sometimes produced during longer sprints (eg, brown and purple sprints compared with the shorter yellow and orange sprints, Table 1 and Figure 4B). In addition, P_{mean} expressed relative to the theoretical maximal mean power output at the pedaling rate and duration was still highly variable, confirming that P_{mean} , and hence, sprint performance is strongly influenced by the level of pre-fatigue induced by previous effort throughout the race.

The mean power output during an entire race ($3.2 \pm 0.3 \text{ W}\cdot\text{kg}^{-1}$) in the current study was slightly higher than previous data reported by Menaspa et al.⁵ ($2.8 \pm 0.4 \text{ W}\cdot\text{kg}^{-1}$) and Van Erp et al.²⁷ during flat stage of the *Tour de France* ($2.4 \pm 0.3 \text{ W}\cdot\text{kg}^{-1}$). The end of the race was associated with an increase in mean power output (Figure 5) that reached 4.2 ± 0.4 , 4.6 ± 0.5 , and $6.1 \pm 1.0 \text{ W}\cdot\text{kg}^{-1}$ during the 10-min, 5-min, and 1-min preceding the final sprint, respectively. In addition, this increase in power output in the phases preceding the sprint was very variable depending on the race, particularly during the last minute (coefficient of variation of 16.4% in mean power output, range: 4.9 to $8.0 \text{ W}\cdot\text{kg}^{-1}$). Interestingly, in accordance with our second hypothesis, the mean power produced during the last minute before the sprint was significantly correlated with the sprinter's capacity to achieve his maximal power output during the final sprint. The case of the green race clearly illustrates this result. It was one of the races with the lowest power output until two minutes before the sprint and had one of the highest during the last minute before the sprint (Figure 5). It was characterized by one of the lowest peak and mean power output during the sprint (Figures 4, 5, and 6), whether power was expressed in absolute terms or relative to the theoretical maximal value determined from the power-velocity-endurance profile. Conversely, the black race was one of the most intense races, especially during the last 4 min, when the sprinter had a mean power of $6 \text{ W}\cdot\text{kg}^{-1}$, but a decrease in power output below the critical power of the sprinter during the last minute before the sprint allowed him to perform one of the highest power outputs throughout the sprint, despite its very long duration (19 s, Figure 6). This is in accordance with the W prime concept (which represents the work doable above the critical power),^{28,29} meaning that the power output level during the last minute before the sprint directly influences the amount of W' consumed. This last minute should therefore subsequently induce an alteration of the sprinter's maximal power output capacity during the final sprint.

4.5 | Practical application

The road-racing sprint analysis proposed in the current study could be very useful for coaches and elite sprinters wanting to maximize power output and hence sprint performance. First, this study provides the first published data on a maximal power-velocity-endurance profile of a professional sprinter and could serve as a reference for future and comparative studies as well as for coaches of elite cyclists. Second, the methodology used in this study can be applied to sprinters who would like to determine their power-velocity-endurance profile in order to better analyze their road-cycling sprints. Indeed, although most of the sprints in this study were performed in a pre-fatigue state, some of them exhibited peak and mean power output close to 100% of $P_{max}(v)$ and $P_{max}(v,duration)$ (Table 1). Thus, we can reasonably assume that they were performed with very low pre-fatigue and hence can be related to the power-velocity-endurance characteristics to determine whether the pedaling rates used were close to the optimal. This is the case for the purple race, where P_{peak} amounted to $19.0 \text{ W}\cdot\text{kg}^{-1}$, 99.7% of $P_{max}(v)$, and 94.9% of P_{max} . Interestingly, the pedaling rate associated with P_{peak} (v_{Ppeak}) was 19.6% lower than the v_{opt} , which may limit power output and, therefore, explain the 5.1% loss of peak power output compared with P_{max} at the beginning of the sprint. From a performance point of view, it suggests that, in this specific final sprint, the sprinter could improve his peak power output at the start of the sprint by slightly decreasing his gear ratio in order to increase his pedaling rate and hence maximize power. Considering the difficulty of gaining a few percent of maximal power output in elite cyclists' training, this kind of optimization process is very important. Road bike theoretically allows the sprinter to change gear ratio in order to adjust the pedaling rate throughout the sprint and thus limit the power decrease and maximize the mean power output. However, in order to avoid to derail during the changing gear ratio, the cyclist must release chain tension by decreasing the crank torque and hence power. Therefore, in practice, sprinter is recommended to choose the appropriate gear ratio before the sprint and keep this gear ratio throughout the sprint. Nevertheless, in the particular case where the sprint is very long and the pedaling rate used becomes too far from the optimal, the sprinter can change gear ratio. Interestingly, our sprinter used this strategy of increasing the gear ratio for two long-lasting sprints (ie, the "brown" and the "black" of 13 and 19-s duration, respectively) which seems to be useful to bring the pedaling rate closer to the optimal value predicted by his power-velocity-endurance profile (Figure 4B).

When the level of pre-fatigue was greater, particularly related to the intensity of the effort in the last minute before

the sprint, the sprinter necessarily endured a decrease in both force and velocity capacities, and consequently in optimal pedaling rate.²⁵ Therefore, in such cases, it remains more complicated to provide precise recommendations about the pedaling rates to use. However, the lower pedaling rate used by the sprinter during road-racing sprints performed in a pre-fatigue state, compared with the fatigue-free optimal pedaling rates (for both maximal power, v_{opt} , and maximal mean power on the duration, $v_{opt}(duration)$) could be considered as a natural suitable adaptation to maintain a high power level. This is particularly the case for the two sprints with the lowest P_{peak} and P_{mean} compared with $P_{max}(v)$ and $P_{max}(v,duration)$, respectively (green and dark blue sprints, Figure 4), which were also the two sprints with the lowest v_{Ppeak} and v_{Pmean} .

From strategic point of view, the detrimental effect of producing very high power during the last minute on the final sprint performance highlights that the sprinter and his teammates should pay particular attention to this preparation phase. Indeed, in the current study, the sprinter lost ~20% of sprint mean power output when the mean power during this last minute was higher than his 5-min cycling mean power output record (ie, $6.6 \text{ W}\cdot\text{kg}^{-1}$). Consequently, this finding provides experimental confirmation that the sprinter must be well placed early in the front of the peloton during the phase preceding the sprint to avoid any supplementary effort.⁴ In addition, this tactic reduces the risks of crash and maximizes the possibility of a successful outcome.^{4,14}

Finally, these findings underline the interest for a sprinter to have good aerobic qualities to reduce the state of fatigue before the sprint and thus save the amount of 'W'. It also highlights the importance of performing sprints with a state a pre-fatigue during training to be close to competitive sprint conditions.

4.5.1 | Methodological considerations

Findings of the present work should be interpreted in view of the inherent limitations of a study design based on a single case. The elite sprinter participated in a good number of sprints but they were mainly performed during Category 1 races. Nevertheless, focusing on the power produced during different phases of the race, we observed only a few differences concerning the lead-up phase before the sprint, especially during the last minute, between the races considered here ($6.1 \pm 1.0 \text{ W}\cdot\text{kg}^{-1}$) and the World Tour level races previously analyzed ($6.8 \pm 0.8 \text{ W}\cdot\text{kg}^{-1}$ in Menaspa et al.).⁵ Thus, our conclusion about the effect of pre-fatigue on sprint performance would certainly be emphasized during World Tour level races. Although only one power-velocity-endurance profile was presented in this study, it actually corresponds to the best of three tests performed over a period of seven

months (including the competition season), in order to represent the maximal power-velocity-endurance capacity of the sprinter. The between-test variability in power-velocity-endurance characteristics on this mature sprinter was slight and much smaller than the between-race variability in power outputs during the final sprint (see supporting information for more detail). Therefore, whereas we would advocate repeating this evaluation throughout the year so as to monitor performance in different races more precisely, we are confident that this variability does not interfere with the conclusions of the present study. Finally, it is important to note that our way of calculating the theoretical maximal mean power output and the corresponding optimal pedaling rate is clearly limited to efforts up to almost 20-s duration. Indeed, we do not claim it to be consistent beyond this duration, due to the non-linear shape of the relationship between record power and duration.³⁰

5 | CONCLUSION AND PERSPECTIVES

This study showed that road-racing sprints are mainly performed on the high portion of the ascending limb of the power-velocity relationship, and that both peak and mean power output reached during sprints are very variable. Even if this power is sometimes close to the sprinter's maximal power capacities evaluated in fatigue-free conditions by the power-velocity-endurance profile obtained on a cycle ergometer, the power produced during sprint is usually much lower than this maximal capacity. High between-race variability is observed in peak and mean power outputs during the final sprint, which are strongly related to the power output produced during the minute preceding this sprint. Overall, the methods proposed in the present study, consisting of characterizing the power and pedaling rate during the final sprints of road races, based on the individual power-velocity-endurance profile, would be very valuable for following top-elite sprint road cyclists. Further studies are needed to investigate how different one-minute pre-fatigue scenarios would influence the capacity of sprinters to express their maximal power-velocity-endurance capacities, and thus better determine the highest power output level over one minute that would allow a quasi-maximal potential to be kept for the final sprint.

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CONFLICT OF INTEREST

The authors report no conflict of interest.

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SUPPORTING INFORMATION

Additional supporting information may be found in the online version of the article at the publisher's website.

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