In-situ MMP - cadence relationship for 2-, 5- and 20-min duration: a proof of concept in U19 cyclists.

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Abstract

Background. Power profiling has been very well studied with Mean Maximal Power (MMP) but the cadence at which power has been produced has never been taken into account. However, the power-cadence relationship defines that the power production is limited according to the rate. A maximal power ($P_{\max}$) can only be produced in optimal torque (T_{opt}) and cadence (C_{opt}) conditions. This study aimed to propose and evaluate a method to determine the MMP – cadence relationship for different typical exercise duration based from *in-situ* data. *Methods.* Fourteen under 19 national level cyclists participated in this study. A complete U19 season was analyzed and MMP was calculated for each cadence between 50 to 120 rpm for 2-, 5- and 20- minutes duration. the MMP-cadence relationship was fit with a second order polynomial function. Goodness of the fit (r^2) and odd-even days absolute and relative reliability have been measured respectively for ($P_{\max}$), (T_{opt}) and (C_{opt}). *Results.* The goodness of the fit was very high for every duration (median r^2 were 0.90, 0.89 and 0.72 for 2-, 5- and 20- minutes respectively). The relative reliability (ICC) and magnitude of the random error (SEM) was good to excellent for all parameters and durations ($0.73 < \text{ICC} < 0.92$; $2.5 < \text{SEM} < 8.2\%$). *Discussion.* The evaluation of a MMP – cadence relationship is feasible and reliable for 2, 5 and 20-min durations from in situ data. This profiling approach would allow to better detect the strengths and weaknesses of cyclists and to design more-effective training interventions.

Keywords: power profiling, force-velocity, endurance, training, racing

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INTRODUCTION

Over the years, power profiling in cycling has been very well studied [1–9]. With the advent of power-meter two decades ago, cyclists and coaches can measure cycling power output in-situ to guide training prescription, to analyze race performance or to track longitudinal change over seasons. To do so, a widely used method is the Mean Maximal Power output (MMP). It consists in calculating the highest average power output recorded for a given duration during an event (training or racing). By identifying the best MMP over large period (e.g., one season) for a range of duration from the second to hours, Pinot & Grappe [7] proposed to determine the Record Power Profile (RPP) . This best mean power output that can be produced by a cyclist for a given duration is useful to characterize its physical capacities and to determine training intensities [2, 7]. For instance, the power produced during efforts of 2-, 5- and 20- minutes have been related to different power capacities in cycling. These durations are all part of the severe exercise intensity domain [5], which is accepted to be linked with race performance [9, 10]. 2-min MMP have been associated with glycolytic capacities [2] because $\dot{V}O_{2max}$ may not be attainable [11], 5-min MMP represents maximal aerobic effort [12] and 20-min MMP is commonly used to estimate the functional threshold power (FTP) [2].

Cycling power is mechanically the product of both crank torque and angular velocity. For understanding purpose, crank angular velocity will be further express in cadence (i.e., revolution per minute). During maximal intensity cycling, the relationship between maximal torque and cadence is linear [13–18] and defined as follows:

$$T(C) = T_0 \cdot (1 - \frac{C}{C_0}) \tag{1}$$

with T being the crank torque (in N.m), C the cadence (in rpm), T_0 the theoretical maximal torque at null cadence and C_0 the theoretical maximal cadence until which torque can be produced. Thus, the power-cadence relationship can be mathematically described by a second order polynomial function:

$$P(C) = T_0 \cdot (1 - \frac{C}{C_0}) \cdot C \tag{2}$$

with P being the power (in W). The apex of the power-cadence relationship characterized the maximal power output capacity (P_{max}) which can be produced at an optimal cadence (C_{opt}) being the half of C_0. This means that any other pedaling rate will automatically lead to a non-maximal power production despite maximal voluntary effort.

This relationship has been extensively studied during maximal intensity bouts (i.e. sprints of few seconds) using mainly anaerobic alactic metabolism [19, 20]. Furthermore, it has been recently showed that the torque-cadence relationship can be determined from in situ data [16, 17]. This allow to assess cyclists physical profile and capacity directly from real practice data without requiring specific testing. Some evidence suggests that the power-cadence relationship continue to follow a parabolic shape for other submaximal intensities/longer durations [21, 22]. For instance, Zoladz et al. [22] showed that the power-cadence relationship during submaximal intensities such as maximal aerobic power or 2 and 4 mmol lactate thresholds, highlights a condition of optimal cadence where the power is maximized while any other cadence enters a decrease of the produced power. Furthermore, this optimal cadence seems to vary according to the intensity required. Despite a similar parabolic shape between maximal and submaximal intensity power-cadence relationship, the latter has never been evaluated. The actual RPP or MMP method determination take the best average power for a given duration, but they are blind to the cadence rate condition. To consider the power-cadence relationship for a given duration may allow to significantly enhance the comprehension of power production during training and racing. Numerous applications could be extracted from this new approach such as to test the ability of a cyclist to voluntary select optimal cadence rate, to prioritize torque vs. cadence training based on the individual profile or to assist for gear choice.

The aims of this study were to i) test the feasibility and reliability to determine the MMP – cadence relationship for different typical exercise duration based from *in-situ* data and ii) to explore the inter-individual variability in MMP – cadence relationship. We hypothesized that by recording the 2-, 5- and 20- minutes MMP for each cadence rate, it would be possible to fit the power-torque–cadence relationship, with a high goodness of fitting and a high odd–even days' reliability.

METHODS

Participants and study design

Fourteen under-19 national level cyclists (17 ± 1 years, 66.9 ± 4.4 kilograms, 11h ± 1h30 training $\cdot$ week^{-1}) were included in this study. They all competed at national and international level races for the 2019-2020 or 2020-2021 U19 seasons. Independently from this study, they all use a power meter (Quarq Dzero, West Fulton Market, Chicago, USA) to record their activity for training purpose. The mechanical data (power, cadence, time) were monitored for each training session and race over one season (total per participant = 258 ± 48 sessions) accordingly to the manufacturer recommendation (e.g., calibration once a year, zero offset before each session). This study aimed at retrospectively analyzing those data. The cyclists have given their informed consent to have their data included in the database. The latter have been declared and constituted accordingly to the European General Data Protection Regulation (GDPR).

Data processing and MMPs determination

All the subsequent data processing was performed with custom matlab scripts (Matlab 2022a, Mathworks). For each file (i.e., training or competition session), data were resampled at 1 Hz, power and cadence data outliers were removed when out the mean ± 3 SD interval for the durations selected: the 2-, 5- and 20-minutes MMPs. For a given duration, the MMPs for every mean cadence between 50 and 120 rpm were screened (resolution of 1 rpm). This has been done as previously described [2, 7] with adding the cadence condition. Furthermore, to be further considered and to exclude portions with high cadence variability, the MMP should have presented homogenous cadence distribution defined as 70% of the MMP's cadences included between the considered cadence ± 15 rpm. The parameters (70% and ± 15 rpm) have been arbitrary set during an exploratory phase as it was an acceptable trade-off allowing to conserve enough data while eliminating the very variable cadence portions. At this point, for each session, a MMP have been calculated for each duration and cadence. At a season' scale, there is no reason to believe that the number of the day may influence in a way or another the power nor the cadence.

In-situ power-cadence fitting procedure

The following procedure aimed to fit the power-cadence relationship for a given duration. First, the highest MMP of all the considered sessions were conserved for each cadence. Then, according to the torque-cadence relationship definition, a MMP was conserved if it presents both the highest torque (calculated from Eq. 3) of all higher cadence MMPs and the highest cadence of all higher torque MMPs. Those conserved MMPs are denoted below ”top values”.

$$T = \frac{30 \cdot P}{\pi \cdot C} \tag{3}$$

For each duration, the torque – cadence relationship (Eq. 1) was firstly fitted with top values via least squares procedures using an iterative process in order to minimize the sum of squared error between the fitted function and the observed values. Then, in order to consider only the highest MMPs, the values which presented positive residuals with the first fitting were conserved to fit the power-cadence relationship (Eq. 2) to estimate $\mathrm{T_{opt}}$ and $\mathrm{C_{opt}}$, $\mathrm{P_{max}}$ being:

$$P_{max} = C_{opt} \cdot T_{opt} = \frac{C_0 \cdot T_0}{4} \tag{4}$$

All procedure's steps and MMPs selection are presented in figure 1.

Cadence distribution

The cadence distribution of near-maximal efforts over the season was computed to analyze the voluntary cadence selection according to the individual MMP – cadence profile. To do so, for the three durations considered (2-, 5- and 20- minutes), the efforts performed at least at 90% of the MMP-cadence relationship were conserved (i.e., the MMPs > 90% of the maximal power production theoretically possible when cycling at the cadence observed). A probability density function was then computed by a kernel estimator normalized to peak density (with a smoothing bandwidth = 0.07%) and expressed relatively to the optimal cadence. The median density was also computed.

Statistical analysis

The Shapiro-Wilk's test and Levene's test were applied to verify the normality and homoscedasticity of

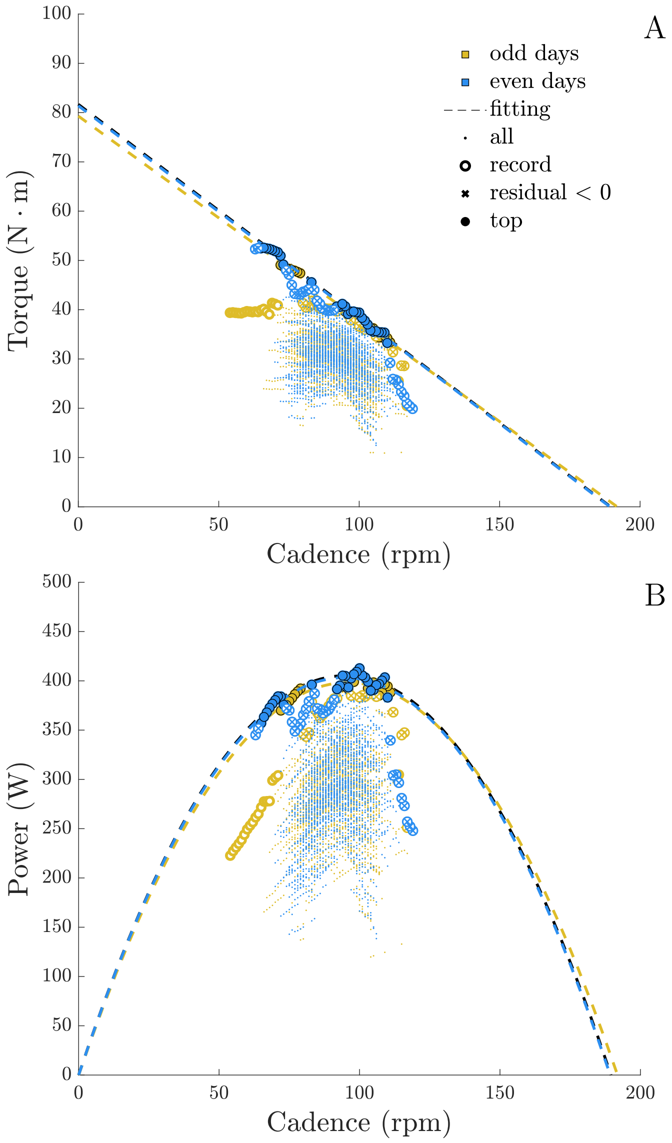

Figure 1: Typical example of a 5-min torque – cadence (A) and power – cadence (B) relationships obtain from training and racing data. Yellow and blue represent the odd and even days, respectively . The following steps were performed: i) for each cadence, the session MMP is computed (dots); ii) record MMP over the season for each cadence are conserved (circles); iii) non top-values are removed (empty circles); iv) torque - cadence function is fitted with the remaining data; v) negative residual data are removed (circles with a cross inside); vi) power-cadence function is fitted with the remaining data (filled circles).

the variables. All data are presented as mean ± standard deviation (SD). Determination coefficients (r^2) were computed to estimate the goodness of the fit. In order to test the reliability of the proposed procedure, we separated the database into two sub datasets constituted of the odd and even days' sessions, respectively. Relative reliability was analyzed with Intra Class Correlation (ICC) and absolute reliability with Standard Error Measurement (SEM). ICC values less than 0.5, between 0.5 and 0.75, between 0.75 and 0.9, and greater than 0.90 are indicative of poor, moderate, good, and excellent reliability, respectively [23]. One-way Analysis of Variance (ANOVA) was performed to test the effect of duration (2, 5 and 20-min) on the C_{opt}, T_{opt} and P_{max} parameters with JASP (version 0.14.1, University of Amsterdam, Netherlands). A Tukey post-hoc test was performed to determine where the differences occurred when appropriate. The alpha threshold of significance was arbitrary set at 5%.

RESULTS

The goodness of the fit was very high for every duration (median r^2 were 0.90, 0.89 and 0.72 for 2-, 5- and 20-min respectively; a typical example in presented in Fig. 1). The MMP–cadence parameters' reliability is presented in Table 1. T_{opt} and P_{max} were significantly higher for shorter durations ($p < 0.001$) but C_{opt} was not statistically different between the durations (Table 1).

Table 1: T_{opt}, C_{opt} and P_{max} odd-even days reliability for 2-, 5- and 20-min. ICC: Intraclass Correlation Coefficient; SEM: Standard Error Measurement (raw units). a, b and c: significant difference between 2 & 5, 2 & 20 and 5 & 20 min duration, respectively.

		2 min	5 min	20 min
$T_{opt} (N \cdot m^{-1})$	Mean	48.0±8.5 ^{a,b}	42.6± 7.0 ^{a,c}	34.8±6.4 ^{b,c}
	ICC	0.90	0.90	0.73
	SEM	2.8	2.2	2.8
C_{opt}(rpm)	Mean	95±11	91±8	96±11
	ICC	0.78	0.76	0.78
	SEM	4.2	4.3	5.0
P_{max}(W)	Mean	470±43 ^{a,b}	402±40 ^{a,c}	342±37 ^{b,c}
	ICC	0.91	0.92	0.92
	SEM	12.9	11.0	9.9

Despite similar P_{max}, C_{opt} can be very different between cyclists (typical data for 5-min duration are presented in Fig. 2. However, there was a strong correlation between T_{opt} and P_{max} for the three durations (Fig. 3): $r^2 = 0.62$, 0.68 and 0.64 for 2-, 5- and 20- minutes ($p<0.001$) while there is no correlation between

C_{opt} for the three durations ($r^2 = 0.20$, 0.20 and 0.16; $p = 0.104$, 0.073 and 0.162 respectively).

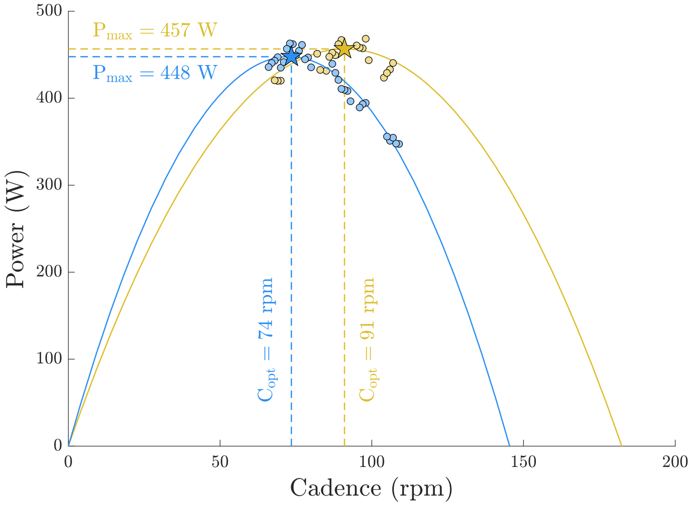

Figure 2: Typical 5-min MMP – cadence relationship for two cyclists with distinct profiles. Dots represent the top MMPs. Stars are the maximal power (P_{max}) for the optimal cadence (C_{opt}).

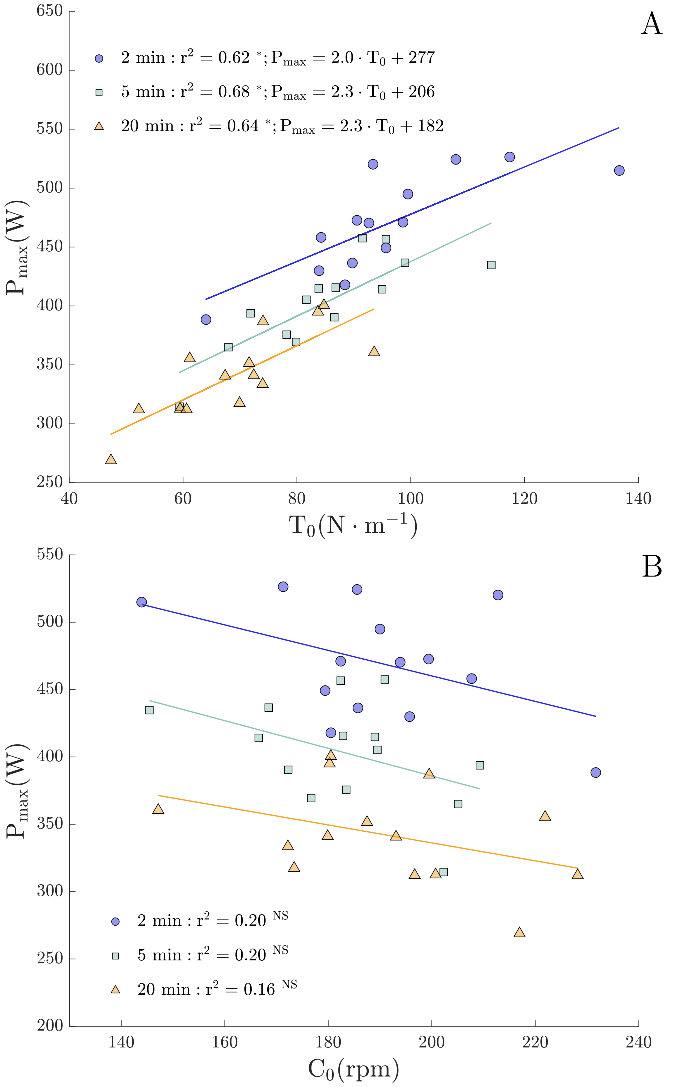

Figure 3: $P_{max} - T_0$ (A) and $P_{max} - C_0$ (B) relationships for 2, 5 and 20 min. *: significant correlation; NS: not significant correlation.

The distribution of the selected cadence over the season during near-maximal efforts are presented in Fig. 4 for all cyclists and durations and Fig. 5 for illustrative typical profiles.

DISCUSSION

The first aim of this study was to test the feasibility and reliability to determine the MMP – cadence relationship for different typical exercise duration (2, 5 and 20 min) based on *in-situ* data and the second aim of this study was to explore the inter-individual variability in MMP – cadence relationship. The main results are i) the second order polynomial MMP–cadence relationship present a very good fit with MMPs extracted from power meters for all tested durations; the MMP–cadence relationships' parameters (T_{opt}, C_{opt} and P_{max}) present good odd-even days absolute and relative reliability; ii) cyclists presented a high inter-individual variability in MMP – cadence relationship's parameters with the optimal torque being strongly associated with a high-power production.

We proposed in the present study i) to compute MMPs for each meaningful cadence (50 to 120 rpm) in order to take into account the cadence condition in the power production; ii) a procedure to identify the top MMPs for each cadence. The goodness of the fit of the MMP–cadence polynomial function (Eq. 2) with those selected MMPs was very high for 2 and 5 min (median $r^2 = 0.90$ and 0.89) and still high, yet lower, for 20 min ($r^2 = 0.72$). Although the MMP–cadence relationship has been extensively studied for very short burst of exercise, this is the first time that this relationship is applied to describe the effect of cadence on power production capacities for longer duration involving different metabolisms [22].

To test the reliability of the proposed procedure, the full dataset was split into sessions that took place on even days or odd days. The relative reliability was ex-

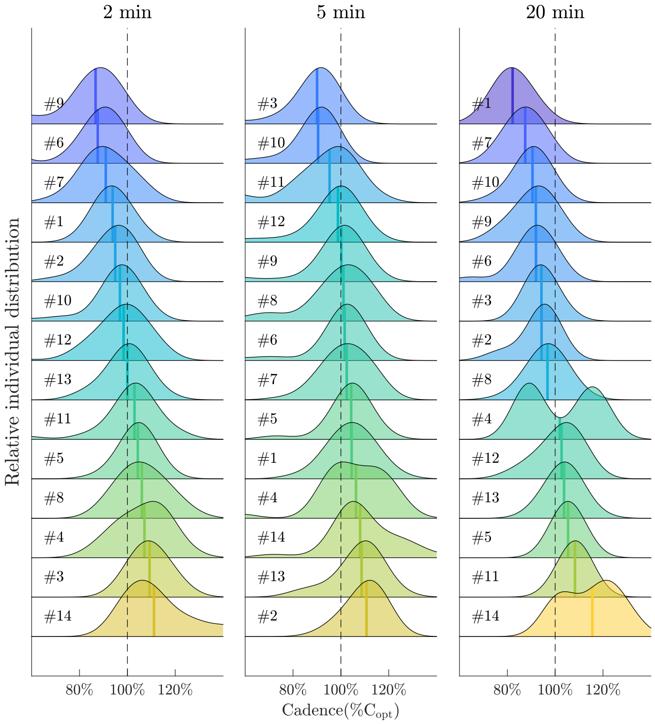

Figure 4: Relative cadence distribution (% C_{opt}) for all cyclists (identifiable by their #) and durations. Color scale represent the median probability density of the kernel function. Cyclists pedaling more often with too low or two high cadences are represented respectively in blue and yellow.

cellent to good for all parameters (T_{opt}, C_{opt}, P_{max}) and durations (2, 5 and 20 min; all ICC $>$ 0.75; Table 1). The magnitude of the random error (SEM all $<$ 10%, Table 1) are the one typically reported for MMP–cadence evaluation with cycling sprints in laboratory conditions [24] or as recently proposed, for acceleration-speed profile evaluated from *in-situ* data in team sports [25]. Nevertheless, one should notice that both reliability and goodness of the fit tends to be less good for the longest duration (20 min). It is likely that 20 min duration maximal efforts are less frequent, especially for low ($<$ 70 rpm) or high ($>$ 100 rpm) cadences. This is probably even more the case for U19 cyclists which usually perform less long duration maximal effort [26]. This requires further investigations, especially if the present approach would be extend to even longer durations as initially proposed in the PPR model [7]. Furthermore, it has been shown that the reliability on long duration (longer than a few minutes) decreased, because of the variables that could impact the steady effort pacing (nutrition, pacing and race strategy, motivation and more) [23].

The maximal power (P_{max}) obtained for the different durations are in line with MMPs previously reported in similar population. For instance, Pinot & Grappe [1] reported a RPP of 6.4 and 5.7 $W \cdot Kg^{-1}$ (5- and 20-min efforts, respectively) for a future top10 contender of Grand Tours during his under-19 level years. The best cyclist from the present study has a relative MMP of 7.03 and 6.08 $W \cdot Kg^{-1}$ for the same duration (cyclist #5). In the same way, a study on U23 elite cyclist reported MMP of 7.2 and 6.1 $W \cdot Kg^{-1}$ for 2 and 5-min durations [3] only slightly higher than the MMP reported in the present study (6.7 and 5.7 $W \cdot Kg^{-1}$, respectively). These little differences could be explained by the difference in physical development of the U19 in comparison with U23 category. The maximal theoretical power that can be produced for different durations estimated through the proposed procedure thus seems to be plausible from an order of magnitude point of view.

The maximal power that can be produced decrease with the increased durations (Table 1). Interestingly, the significant difference obtained on maximal power over the three different durations seems to be associated with the capacity to maintain a high level of torque over the time (Table 1). However, the optimal cadence seems not to be altered by the duration of the effort. Furthermore, for all durations, when considering inter-individual variability, T_0 was highly correlated with P_{max} (Fig. 3A) while C_0 was not (Fig. 3B). This result is very interesting as it suggests that the conservation of maximal power production capacities over time would be more related to the torque than the cadence component.

The novel *in-situ* MMP – cadence relationship approach proposed in the present study provides an interesting tool to understand the power production of cyclists during training and racing. The present results evidenced that the cadence chosen by the cyclists can deviate from the optimal mechanical condition for power production (C_{opt}; Fig. 4 and 5). For instance, the cadence distribution was centered around the optimal cadence for 5, 6 and 3 cyclists for the 2-, 5- and 20- min durations, respectively. A large proportion of the population studied seems thus to select non-optimal cadence frequently during training and racing (e.g., Fig. 5C and 5D). Differences in the cadence adopted may result either in suboptimal power production (decreased performance) or unnecessary increase

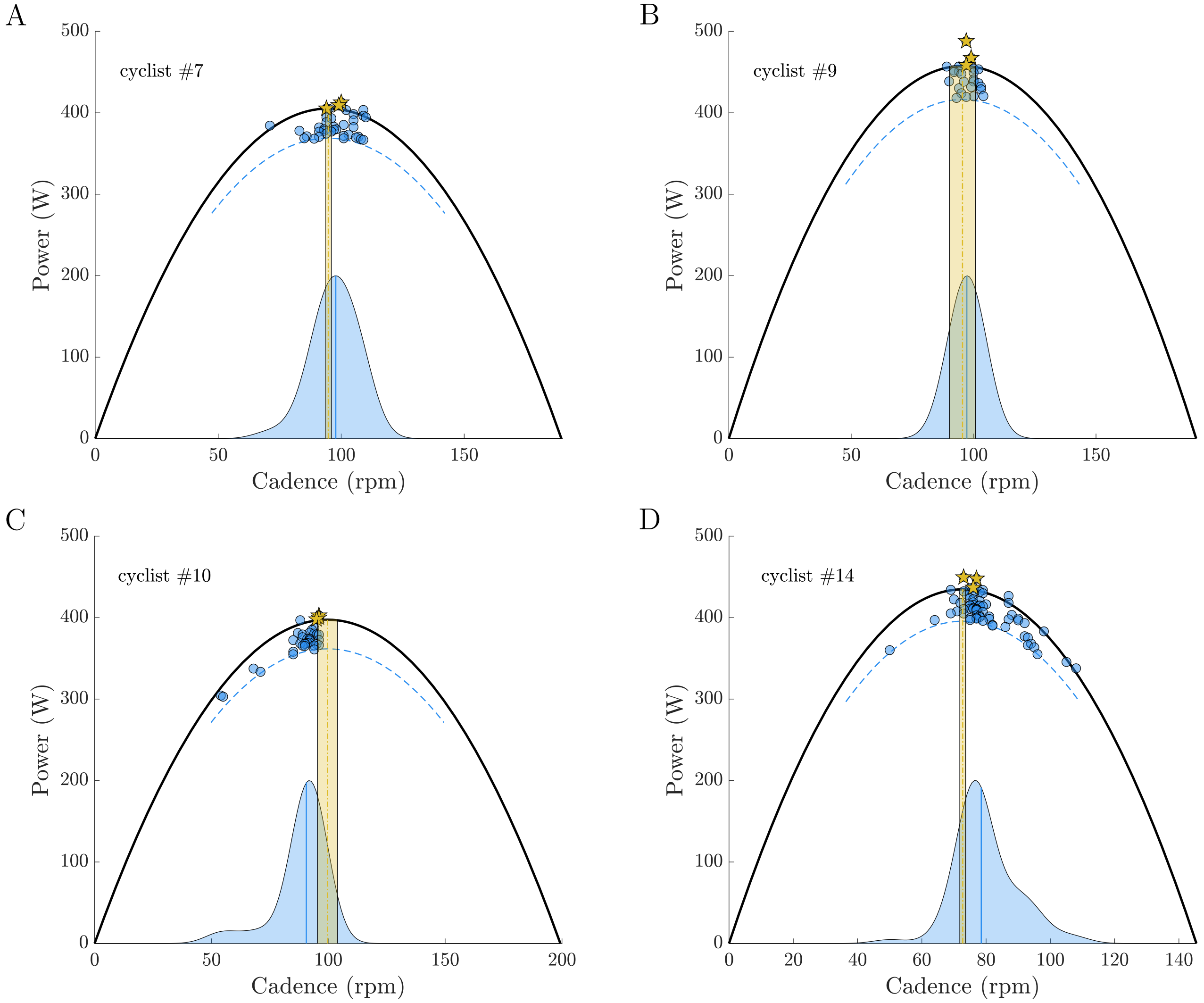

Figure 5: Typical 5-min Power–Cadence relationships (black line) and the associated distribution of near maximal efforts (dots). Dashed blue line represent 90% of the MMP – cadence relationship. Blue dots represent all the near maximal efforts (> 90%) recorded during the season while yellow stars represent the three-best performances. Light blue area is the kernel density estimation of the cadence for near maximal efforts. The yellow strip is the C_{opt} 95% confidence interval. Typically, cyclist #7 and #9 present a centered distribution of the cadence but more (#7) or less (#9) wide. Conversely, #10 and #14 presented a cadence distribution shifted to the left (too low cadence) and right (too high), respectively.

of the relative intensity for a given power production (premature fatigue) [21, 27], which will ultimately reduce the performance. We should acknowledge that the data used for this analysis included both training and racing data. Some of the near-maximal intensity efforts at non-optimal cadence might have been a training choice in order to induce specific adaptation which cannot be identified in the present study (e.g., intermittent torque training at very low cadence). Furthermore, the optimal cadence is certainly impacted by the period of the season or by competition such as a 3-week Grand Tour. Some of the effort in conditions here qualified as non-optimal might have been the best choice at a specific moment. Nevertheless, it seems that, at least a part of the U19 who participated in this study, may not optimize their performance due to a cadence not optimal for power production.

Conclusion

The present study shows that the estimation of a second order polynomial power–cadence relationship for

2, 5 and 20 min *in-situ* is feasible and reliable. Such an evaluation from *in-situ* data provides useful information to individualize the performance analysis and the cyclists profiling. Especially, it allows to distinguish the torque and the cadence component of the power production in road cycling. The ability to produce the maximal power for a given duration and/or to maintain a power is affected by the torque and cadence adopted. Furthermore, the ability to generate and maintain power over time is positively correlated to the torque capacity while the cadence might be a tuning parameter to optimize the power production.

Contributions

Contributed to conception and design: YB, MB, PS, FH & BM; Contributed to acquisition of data: AP; Contributed to analysis and interpretation of data: YB, MB, PL & BM; Drafted and/or revised the article: YB, PS, PL, FH & BM; Approved the submitted version for publication: YB, MB, PS, PL, FH & BM

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Data and Supplementary Material

Because of the confidentiality and the sensitivity of the athlete's personal data, no database has been published or given for a full access.

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