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SPORTS PERFORMANCE

Mechanistic influence of the torque cadence relationship on power output during exhaustive all-out field tests in professional cyclists

Peter Leo[a], Borja Martinez-Gonzalez[b], Iñigo Mujika[c,d] and Andrea Giorgi[e]

[a]Department of Sport Science, University Innsbruck, Innsbruck, Austria; [b]Kent and Medway Medical School, University of Kent, Canterbury, UK; [c]Department of Physiology, Faculty of Medicine and Nursing, University of the Basque Country, Leioa, Basque Country; [d]Exercise Science Laboratory, School of Kinesiology, Faculty of Medicine, Universidad Finis Terrae, Santiago, Chile; [e]Department of Internal Medicine, Specialist Medicine and Rehabilitation, Azienda USL Toscana-SouthEast, Siena, Italy

ABSTRACT

Understanding the torque-cadence-power relationship can be important in assessing a cyclist's performance potential. This study explored these relationships in elite male cyclists ($N = 17$; age: 24.1 ± 3.8 years; body mass: 66.0 ± 4.8 kg, critical power (CP): 5.5 ± 0.3 $W.kg^{-1}$) through sprint, torque, and CP tests conducted in fresh and after accumulated work. Testing protocols, performed during a pre-season training camp, included maximal efforts across varied gear ratios and durations (15 s, 3 min, and 12 min), under stable environmental conditions (15–20°C). Results revealed reduced power output, torque, and cadence after accumulated work compared to fresh conditions ($p \leq .001$). Sprint-derived maximum torque (T_{max}) was strongly correlated with torque intercepts for CP fresh ($r = .558$, $p = .020$) and after accumulated work ($r = .556$, $p = .020$). The cadence relationships demonstrated a large negative correlation between maximum cadence (C_{max}) and optimum cadence (C_{opt}) from the sprint test and the 15 s, 3 min and 12 min cadence recorded during CP after accumulated work ($r = -0.541$ to -0.634, $p = 0.006$ to 0.025). These findings highlight that accumulated work-induced reductions in work capacity (W′) and CP values were accompanied by lower cadences across all effort durations.

KEYWORDS
Cycling; testing; high performance; sprinting; training

Highlights

- Influence of Accumulated work.
  This study underscores the critical impact of accumulated work on cyclists' performance by revealing significant reductions in power output, torque, and cadence under accumulated work critical power (CP) conditions compared to fresh conditions.
- Influence of Torque Cadence Dynamics.
  Reductions in power output in a homogenous group are mainly explained by reductions in cadence and not torque.
- Influence on High-Intensity Training.
  These findings highlight the need for incorporating targeted cadence prescriptions to enhance performance under both fresh and accumulated work states.

Introduction

Cycling performance is a multifaceted interplay between physiological, biomechanical, and neuromuscular factors (Faria et al., 2009). Among these, the torque–cadence relationship plays a pivotal role in determining the power output sustainability during high-intensity and prolonged efforts (Leo et al., 2023). Torque and cadence, as key determinants of cycling power output, vary significantly across efforts of differing intensity and duration, and understanding these variations can provide critical insights into fatigue mechanisms and performance optimization (Bertucci et al., 2005; Wackwitz et al., 2024).

While critical power (CP) research has traditionally focused on bioenergetic characteristics (Moritani et al., 1981), the underlying torque-cadence dynamics should not be neglected (Bertron et al., 2024; Leo et al., 2023). Torque, defined as the rotational force applied to the pedals, and cadence, the rotational velocity, together determine power output according to the equation:

Power = Torque × Cadence (Equation 1)

However, the interaction between these variables varies across effort durations and fatigue states. For instance, sprint cycling performance depends on maximizing the mechanistic torque and cadence properties, whereas prolonged efforts require a high bioenergetic capacity to sustain power output production (Douglas et al., 2021; Poole et al., 2016).

Power output production after accumulated workloads introduces additional complexities, altering neuromuscular recruitment patterns, reducing maximal torque production, and shifting optimal cadence ranges (Foss & Hallén, 2005; Lucia et al., 2001; Vercruyssen & Brisswalter, 2010; Vogt et al., 2008). Studies have observed that fatigue disproportionately

CONTACT Peter Leo peter.leo@uibk.ac.at Department of Sport Science, University Innsbruck, Fuerstenweg 108, Innsbruck, 6020 Austria

This article has been corrected with minor changes. These changes do not impact the academic content of the article.

affects torque generation during high-intensity efforts, while cadence reductions often accompany prolonged submaximal work (Leo et al., 2023; Sanchez-Jimenez et al., 2023).

Prior studies have explored the torque-cadence-power dynamics in diverse cycling populations, highlighting their implications for sprint performance, prolonged efforts, and fatigue resistance (Abbiss & Laursen, 2005; Leo et al., 2023; Poole et al., 2016; Sanchez-Jimenez et al., 2023; Wackwitz et al., 2024). For example, Leo et al. (2023) demonstrated that torque generation primarily drives power output differences across heterogeneous groups. However, in homogenous elite populations, differences in power output after accumulated work are mainly explained by cadence rather torque (Sanchez-Jimenez et al., 2023). Sanchez-Jimenez et al. (2023) emphasized that reductions in cadence, rather than torque, after accumulated work significantly affect power output sustainability.

Building on this foundation, the current study aims to characterize the torque-cadence properties of elite male cyclists and assess the impact of fatigue on their power output across different testing protocols. By incorporating sprint, torque, and CP tests (Leo et al., 2021; Taylor et al., 2022), both in a fresh state and after accumulated work (Spragg et al., 2022), this study attempts to provide a comprehensive evaluation of the torque–cadence relationship under varied conditions. Such insights could have direct applications in training and competition preparation strategies.

For this reason, the authors hypothesized that changes in sustained power output are mainly explained by reductions in cadence rather than torque.

Materials & methods

Participants

A total of 19 male elite cyclists participated in this study ($N = 19$, age 23.9 ± 3.5 years, body mass 66.4 ± 4.6 kg). All participants were active members of a UCI Pro Team at the time of data collection, and recruitment was based on voluntary participation. Two cyclists who experienced illness during the assessment period were excluded from the analysis which resulted in a final N of 17 (age 24.1 ± 3.8 years, body mass 66.0 ± 4.8 kg).

Informed written consent was obtained from each participant after they received both verbal and written explanations of the experimental protocol and demonstrated full understanding of the potential risks. Ethical approval for the study was granted by the local ethics committee (code: AGBMG23). Conducted within the framework of the team's service provision, the study adhered to the ethical principles outlined in the Declaration of Helsinki.

Design

The study design involved evaluating the torque-cadence-power relationship using the field-testing protocol outlined by Taylor et al. (2022). Additionally, participants completed three exhaustive exercise bouts with a fixed gear ratio (53/14 or 8.06 m of development). CP tests were conducted in both fresh and fatigued states, following the methodology of Spragg et al. (2024). All data collection took place during a pre-season training camp. The data were subsequently analysed to compare torque, cadence, and power output across different testing conditions. Since all participants were experienced elite cyclists familiar with varying cadences, no familiarization trial was deemed necessary.

Testing protocols

All testing was conducted in the same pre-season training camp within 1 week and took place in ambient temperatures between 15°C and 20°C on flat, traffic-safe roads with gradients less than 2% for the sprint and torque tests, and an average gradient of 5.5% for the CP tests. To prevent any sampling issues at low cadences, all sprints were performed at cadences exceeding 40 rpm. Field power output was measured using a commercially available power meter (Assioma Duo, Favero Electronics Srl, Arcade, Italy) with a sampling rate of 1 hz, which has been validated in previous research (Rodríguez-Rielves et al., 2021). The power meter was calibrated according to the manufacturer's specifications, and participants were instructed to perform a zero-offset calibration before the sprint profiling session.

Sprint test

The sprint test followed Taylor et al. (2022) protocol. After a 15-min individual warm up all participants completed 2 × 6 s activation sprints (1× seated and 1× standing with 53/16 and 39/28 gearing, respectively) with a rating of perceived exertion (RPE) 8 out of 10 interspersed by 5 min active recovery at an RPE of 1–2 out of 10. The main set consisted of 6 × 6 s maximum sprints in the order outlined below at an RPE of 10/10 with 5 min active recovery in between, at an RPE of 1–2 out of 10.

To cover the whole cadence and torque spectrum gearing was varied as follows:

- 1 seated sprint with 39/28 gearing from 40 rpm rolling start
- 2 standing sprints with 53-54/15 and 53-54/16 gearing from 80rpm rolling start
- 2 standing sprints with 53-54/11 gearing from 40 rpm rolling start
- 1 seated sprint with 39/23 gearing from 40 rpm rolling start

Critical power test fresh and after accumulated work

The CP protocols followed established methodologies from previous research (Spragg et al., 2024), incorporating 15 s, 3 min and 12 min efforts for both fresh and after accumulated work conditions with 10 min active recovery at an RPE of 2 out of 10 between the 15 s and 3 min efforts and 30 min active recovery between the 3 and 12 min efforts. The CP test after accumulated work conditions involved 2500 kJ of total work including 5 × 8 min in power zones 3 and 4 corresponding to 90% to 100% of CP fresh before completing the 15 s, 3 min, and 12 min efforts. The participants followed their race day nutritional targets of ~90 $g.h^{-1}$ of carbohydrate intake, which has been informed by the team's nutritionist (Peeters et al., 2025). All tests were conducted within the first three days of the training camp to ensure participants had adequate recovery and maintained high motivation levels.

Torque test

Based on the parameter estimates from the sprint test – maximum torque (T_{max}) and maximum cadence (C_{max}) – the participants completed three exercise bouts to time to task failure for 30, 60 and 90 s using a fixed gear ratio of 53/14 which corresponds to 8.06 m of development per pedal revolution interspersed by 30 min of active recovery. To ensure no gear shifting during the trials, the batteries for both the front and rear electronic derailleurs were removed.

Data analysis

All data were collected and uploaded to a commercially available training software (TrainingPeaks LLC, Boulder, USA). Data files of type.fit were exported and uploaded to a free accessible online training analysis software (EnDuRa, Bluecattechnical, West Sussex, UK). For sprint test data analysis, the power and cadence data were processed using the following equation 2:

$$\text{Torque (N.m)} = \frac{Power(W)}{\left(\frac{(Cadence \times \pi)}{30}\right)}$$

Equation 2, π (Pi) – ratio of a circle's circumference to its diameter

A linear regression analysis between torque and cadence derived T_{max} as the y-intercept, C_{max} as the x-intercept and C_{opt} as half of the x-intercept (C_{max}). The parabolic power cadence relationship was fitted with a second order polynomial model to derive modelled peak power (P_{max}) as followed in equation 3:

$$P_{max} = a\left(C_{opt}\right)^2 + b\left(C_{opt}\right) + c$$

Equation 3, P_{max} – peak power (W), C_{opt} – optimum cadence

For the CP tests, the inverse of time model, using a least sum of squares linear regression analysis, was used to derive the power-duration parameter estimates. The intercept of the regression line represented CP and the slope the work capacity (W´) according to the following equation 4:

$$\mathrm{P(t)} = \mathrm{W}' \times \frac{1}{\mathrm{t}} + \mathrm{CP}$$

Equation 4, P – power output (W), t – duration of effort (s), CP – critical power, W' – work above CP

The same linear regression analysis was used as in previous research (Pethick et al., 2020), to derive the parameter estimates of the torque test as well as CP fresh and CP after accumulated work according to the following equation:

$$\mathrm{P(t)} = \mathrm{W}' \times \frac{1}{\mathrm{t}} + \mathrm{T}$$

Equation 4, T = torque (Nm), t = duration of effort (s)

Statistical analysis

All descriptive data are reported as mean ± standard deviation (SD) and mean difference (Δ). Data normality was assessed using the Shapiro–Wilk test. When the assumption of normal distribution was violated, non-parametric tests were employed: the Friedman test replaced the two-way analysis of variance (ANOVA), and the Spearman rank correlation coefficient substituted the Pearson's product-moment correlation coefficient, with these substitutions explicitly noted. A two-way ANOVA (effort duration × test condition) was performed to evaluate differences in cadence, torque, and power output across the different test modalities (torque test, CP fresh, and CP after accumulated work). Sphericity was controlled using Mauchly's test with a Greenhouse Geisser correction. Holm's test was used for pairwise comparisons to determine significance. Relationships between torque and cadence across test modalities were analyzed using Pearson's product-moment correlation coefficient (r). Furthermore, Pearson's product-moment correlation coefficient (r) was classified as small (0.1–0.3), moderate (0.3–0.5), or large (> 0.5) effect, following guidelines of Hopkins (2002).

The level of statistical significance (alpha) was set to $p < .05$ two tailed. Statistical analyses were conducted using the open-source software JASP (version 0.15.1 for Windows, JASP Team, Amsterdam, the Netherlands). Graphs and figures were created using GraphPad Prism (version 8.0.0 for macOS, GraphPad Software, San Diego, USA).

Results

Sprint test

Descriptive data of the power, torque and cadence characteristics of the sprint test are presented in Table 1.

Torque test

Descriptive data of the power, torque and cadence characteristics as well as parameter estimates of the torque test are presented in Table 2.

Effort 1 in the torque test revealed significantly higher power output and torque compared to effort 2 (Δ = 50 ± 12 W, 93 ± 7 N.m; $p \leq .001$) and effort 3 (Δ = 111 ± 14 W, 128 ± 8 N.m; $p \leq .001$) and effort 2 showed significantly higher power output and torque than effort 3 (Δ = 61 ± 8 W, 35 ± 2 N.m; $p \leq .001$). Cadence, however, was not significantly different between efforts 1–3 ($p > .05$).

Critical power fresh and after accumulated work

Descriptive data of the power, torque and cadence characteristics as well as parameter estimates of the fresh CP test are presented in Table 3.

In the CP test, after accumulated work, participants completed a 2500 kJ ride including 5 × 8 min at power zones 3 and

Table 1. P_{max} –5 s maximum power, T_{max} – maximum torque, C_{max} – maximum cadence, C_{opt} – optimum cadence.

Measure	
P_{max} [W]	1154 ± 10
T_{max} [N.m]	211 ± 24
C_{max} [rpm]	209 ± 10
C_{opt} [rpm]	104 ± 5

Table 2. Avg – average, CP – critical power, W′ – work capacity, *significantly different to effort 1, #significantly different to effort 2, level of statistical significance $p < 0.05$.

Measure	Effort 1	Effort 2	Effort 3
Time [s]	31.4 ± 1.9	59.8 ± 3.4*	90.9 ± 3.3$^{*,\#}$
Avg Power [W]	576 ± 92	526 ± 53*	465 ± 48$^{*,\#}$
Avg Cadence [rpm]	53 ± 8	56 ± 5	54 ± 4
Avg Torque [N.m]	177 ± 35	84 ± 11*	49 ± 5$^{*,\#}$
Parameter Estimates			
W′ [J]	1056 ± 642		
Torque intercept [N.m, N.m.kg^{-1}]	71 ± 13	1.07 ± 0.2	

Table 3. Avg – average, CP – critical power, W′ – work capacity, *significantly different to 15 s effort, #significantly different to 3 min effort, level of statistical significance $p < 0.05$.

Measure	15 s	3 min	12 min
Avg Power [W]	952 ± 103	478 ± 32*	402 ± 25$^{*,\#}$
Avg Cadence [rpm]	113 ± 7	96 ± 4*	92 ± 4$^{*,\#}$
Avg Torque [N.m]	81 ± 10	48 ± 4*	42 ± 3$^{*,\#}$
Parameter Estimates			
W′ [kJ]	18.3 ± 5.1		
CP [W, W.kg^{-1}]	376 ± 27	5.6 ± 0.4	
Torque intercept [N.m, N.m.kg^{-1}]	40 ± 3	0.6 ± 0.05	

Table 4. Avg – average, CP – critical power, W′ – work capacity, *significantly different to 15 s effort, #significantly different to 3 min effort.

Measure	15 s	3 min	12 min
Avg Power [W]	763 ± 122	462 ± 29*	390 ± 30$^{*,\#}$
Avg Cadence [rpm]	109 ± 5	94 ±4*	89 ± 4$^{*,\#}$
Avg Torque [N.m]	67 ± 12	48 ± 4*	42 ± 4$^{*,\#}$
Parameter Estimates			
W′ [kJ]	17.2 ± 4.7		
CP [W, W.kg^{-1}]	366 ± 33	5.5 ± 0.5	
Torque intercept [N.m, N.m.kg^{-1}]	40 ± 5	0.6 ± 0.07	

4 resulting in an average power output of 360 ± 25 W, 5.4 ± 0.3 W.kg^{-1} and 95.3 ± 0.6% of CP fresh. In addition, participants averaged a cadence of 84 ± 6 rpm and a torque of 41 ± 5 N.m (0.6 ± 0.07 N.m.kg^{-1}). Descriptive data from the CP test after accumulated work are presented in Table 4.

Power output between during 15 s, 3 min and 12 min efforts was significantly lower in CP after accumulated work compared to CP fresh ($p \le .001$, see Tables 3 and 4). The power duration parameter estimates, CP and W′, were significantly lower during CP after accumulated work compared to CP fresh ($p \le .001$, see

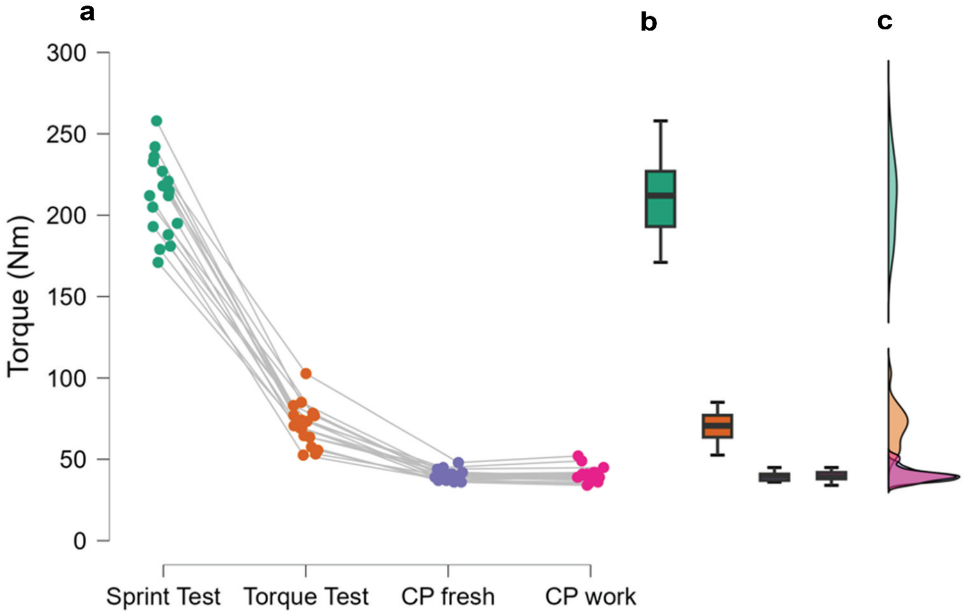

Figure 1. Torque comparisons between the sprint test, torque test as well as CP fresh and after accumulated work. CP – critical power. Panel (a) represents individual torque profile between different test modalities, panel (b) demonstrates torque box plots and panel (c) violin distribution plots of each test modality.

Tables 3 and 4). The torque recorded during the 15 s sprint was significantly higher in the CP fresh condition than in CP after accumulated work ($\Delta = 170 \pm 4$ N.m, $p \le .001$). However, no significant differences in torque were observed for the 3 min and 12 min efforts ($p > .05$). Cadence was significantly lower during the fatigued CP test across all three effort durations (15 s, $p \le .001$; 3 min, $p = .001$ and 12 min, $p = .004$ – see Tables 3 and 4).

The torque – cadence relationship between tests

Comparing the intensity and time-dependent relationship of the torque recordings (see Figure 1), T_{max} from the sprint test demonstrated large effects to the torque intercepts of CP fresh ($r = .558$, $p = .020$) and CP after accumulated work ($r = .556$, $p = .020$). Similarly, the torque intercept from the torque test demonstrated a large effect between the torque intercepts of CP fresh ($r = .609$, $p = .010$) and CP after accumulated work ($r = .591$, $p = .013$). Furthermore, a large effect was also found in the torque intercepts between CP fresh and CP after accumulated work ($r = .874$, $p \le .001$).

The cadence relationships demonstrated a large negative correlation between C_{max} and C_{opt} from the sprint test and the cadence recorded during the CP after accumulated work. Specifically, significant large negative correlations were observed for the 15 s effort (C_{max} r =-.541, p = .025; C_{opt} r =-.551, p = .095), 3 min effort (C_{max} r =-.619, p = .008; C_{opt} r =-.620, p = .008), and 12 min effort (C_{max} r =-.636, p = .006; C_{opt} r =-.634, p = .006) see Figure 2.

Discussion

This study found that reductions in power output between fresh and after accumulated work are mainly explained by reductions in cadence rather than torque. These findings highlight the significant influence of the torque–cadence relationship on power output sustainability during prolonged cycling. These results not only align with previous research but also provide a deeper understanding of how the accumulation of work at different intensities affects power output production, particularly through the torque and cadence relationship.

Earlier studies have examined the impact of torque and cadence on the power profiles of male junior, U23, and elite cyclists (Bertron et al., 2024; Hovorka et al., 2022; Leo et al., 2023). However, this study characterized elite cyclists based on their torque-cadence properties using a series of standardized testing protocols to examine the mechanistic and energetic limitations of sprint and prolonged maximum work bouts.

Leo et al. (2023) concluded that differences in power output across heterogenous groups are primarily affected by the ability of cyclists to generate higher torque. As hypothesized, this study found that declines in power output are primarily explained by reductions in cadence rather than torque within a homogeneous group. These findings are consistent with Sanchez-Jimenez et al. (2023), who also reported that, under fatigued conditions, power output reductions are more closely associated with a drop in cadence than in torque.

Influence of cadence on power output

Research on sprint cycling has shown that cyclists experience fatigue with each pedal stroke (Douglas et al., 2021; Gardner et al., 2007; Kordi et al., 2020; Wackwitz et al., 2024). This is evident from the negative correlations between C_{max} and C_{opt} from sprint tests observed in the present investigation, as well as the cadence reduction observed during CP after accumulated work. In addition, cyclists with higher C_{max} and C_{opt} tend to experience a more rapid decline in cadence during prolonged efforts. This fatigue pattern can be linked to muscle fiber composition, as cyclists exhibiting higher C_{max} and C_{opt} also show a greater proportion of type IIa muscle fibers (Kordi et al., 2020; Wackwitz et al., 2024). It is well known that cycling at a frequency of 1 hz (i.e. 60rpm) induces less neuromuscular fatigue than cycling at 1.5 hz (90 rpm) or 2 hz (120 rpm) or higher (Vercruyssen et al., 2005; Wackwitz et al., 2024). One of the potential mechanistic limitations could be the muscle's ability to 'deactivate' on the muscle tendon unit (Bieuzen et al., 2007; Klich et al., 2024). This becomes even more relevant in gear-restricted events such as track cycling events, where

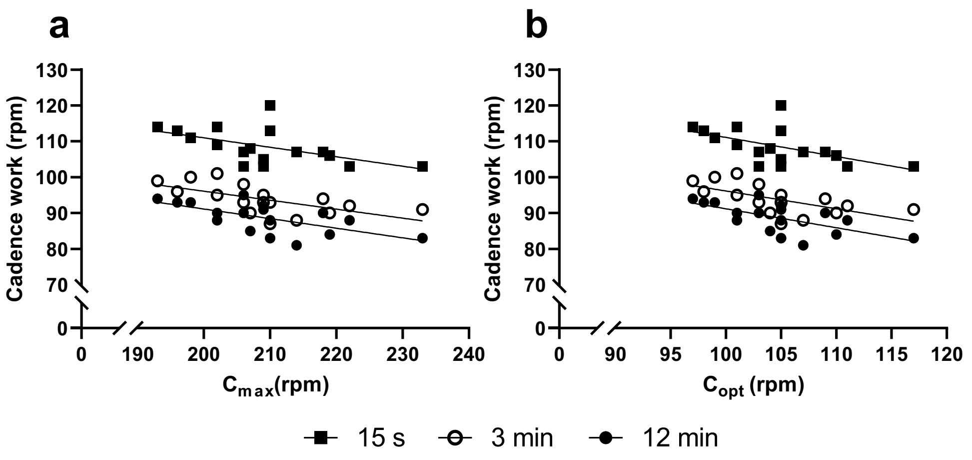

Figure 2. Linear relationships between the C_{max} (panel a) and C_{opt} (panel b) to the 15 s, 3 min and 12 min cadence in the CP after accumulated work. C_{max} – maximum cadence, C_{opt} – optimum cadence, CP – critical power.

cyclists need to optimize the gear ratio to fully utilize the energetic contribution for power production while optimizing the energetic cost of pedalling (Babault et al., 2018; Boillet et al., 2024; Mognoni & diPrampero, 2003; Pugh et al., 2022; Wackwitz et al., 2024). While the freely chosen cadence also known as preferred cadence, is mainly influenced by training status, the optimum cadence reflects more the strength capabilities of a cyclist (Bertucci et al., 2005; Bieuzen et al., 2007; Foss & Hallén, 2005; Lucia et al., 2001; Reed et al., 2016; Vercruyssen & Brisswalter, 2010).

Influence of torque on power output

Previous research on the mechanistic properties of torque production during severe intensity exercise reported a 'critical torque' for peripheral limitation (Pethick et al., 2020). The same concept was applied in this study where cyclists performed a torque test with three gear-restricted efforts (e.g. gear ratio 53/14, 102.2 gear inches and 7.93 m of development) over 30, 60 and 90 s in the extreme domain (Alexander et al., 2019). The rational for choosing efforts shorter than 90s was to reach peripheral failure, before systemic failure e.g. attaining maximum oxygen uptake (Morton & Billat, 2000; Poole & Jones, 2012). The torque intercept of those three efforts revealed an average of 71 ± 13 N.m or 1.08 ± 0.20 N.m.kg^{-1}. The goal of this test was to examine the sustained torque delivery, while participants were not able to use optimal or freely chosen cadence (Vercruyssen & Brisswalter, 2010; Vercruyssen et al., 2005). Contrary to the CP testing, where participants could ride at optimum or freely chosen cadence (Reed et al., 2016). Interestingly, the sustained torque during both the fresh (40 ± 3 N.m; 0.60 ± 0.04 N.m.kg^{-1}) and CP after accumulated work (40 ± 5 N.m; 0.60 ± 0.07 N.m.kg^{-1}) was significantly lower than in the torque test indicating that the participants only use 57% of their sustained torque ability. One possible explanation could be that participants try to avoid peripheral failure and reach a 'critical torque' level (Pethick et al., 2020); therefore, they optimize cadence through gear selection and shifting (Bertron et al., 2024; Sanchez-Jimenez et al., 2023; Vercruyssen & Brisswalter, 2010). This neuromuscular pattern is associated with the excitation-contraction coupling of myocytes and reflects an imbalance in intramuscular homeostasis, marked by the accumulation of inorganic phosphate and hydrogen ions. These factors disrupt the calcium release complex, ultimately leading to muscle impairment (Allen et al., 2008).

The Torque - cadence relationship after accumulated work

Fatigue-induced reductions in torque and cadence, particularly during the 15 s sprint, align with the physiological effects of neuromuscular fatigue described above and are linked to peripheral limitations (Ducrocq & Blain, 2022). The observed declines in 3 and 12 min power outputs during the CP test after accumulated work corroborate prior findings that highlight systemic limitations by altering the CP and W′ relationship (Leo et al., 2020, 2022, 2023; Spragg et al., 2022).

Interestingly, cadence reductions after accumulated work were consistent across all effort durations, suggesting a combined effect of peripheral and systemic fatigue on pedaling dynamics. This observation is consistent with the findings of Dunst et al. (2024), which demonstrated that optimal cadence decreases in an intensity-dependent manner. These reductions in cadence likely reflect a shift towards greater reliance on torque to sustain power during prolonged efforts (Leo et al., 2023). Systemic failure to sustain a given power output may be characterized by an inability to maintain cadence at the athlete's preferred torque relative to their energy expenditure rate (Dunst et al., 2024). Consequently, an intensity-dependent torque–cadence relationship emerges, where athletes seek an optimal pedaling dynamic to achieve the required power output (Ducrocq et al., 2021; Dunst et al., 2024; Reed et al., 2016)

Limitations

This study has several limitations that should be considered when interpreting the findings. First, the small sample size ($N = 17$) and population were elite male cyclists from a homogeneous group, which limits the generalizability of the results to other populations, such as female cyclists, amateur athletes, or different age groups (juniors, U23, senior). Additionally, the field-based testing environment, while ecologically valid, introduces potential variability in environmental conditions (e.g. road surface, and pacing) that could have influenced performance outcomes. RPE information was assessed where possible; however, due to the lack of a continuous record, this variable was excluded from further data analysis. The sampling rate of 1 hz used for power output data collection may also pose a limitation, as higher-frequency sampling rate (e.g. 20 hz) could provide a more detailed insight into instantaneous fluctuations in torque and cadence readings at power outputs above 650 W (Rodríguez-Rielves et al., 2021). Furthermore, the reliability and validity of the power meters used in this study must be acknowledged, as any inaccuracies in these devices could introduce measurement errors that affect the interpretation of torque and power output data (Maier et al., 2017; Salas-Montoro et al., 2025).

Conclusion

The findings of this study have important implications for both training and competition strategies in elite cycling. The observed reductions in power output after accumulated work, driven primarily by declines in cadence rather than torque, suggest that optimizing cadence is critical for sustaining performance during prolonged efforts. Coaches and athletes should consider incorporating cadence-specific high-intensity training to enhance the ability to maintain higher cadences after accumulated work (Whitty et al., 2016). Additionally, the significant relationships between torque-cadence properties and critical power parameters indicate that tailored training protocols targeting both maximum torque and optimal cadence could improve overall cycling performance in the field.

Future directions

Building on the findings of this study, future research should aim to explore the torque–cadence relationship across more diverse populations, including different competitive levels, age groups, and genders. Longitudinal studies could investigate how these relationships evolve over time with targeted training interventions. Furthermore, incorporating biomechanical and physiological assessments, such as muscle fiber composition, could provide a more comprehensive understanding of the mechanisms underlying cadence and torque adaptations. Finally, advancements in wearable technology and real-time data analysis could enable more precise monitoring and optimization of cadence-torque dynamics during training and competition, offering new avenues for performance improvements.

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ORCID

Peter Leo http://orcid.org/0000-0002-4501-7688

Author contributions

All authors equally contributed to the production of the manuscript. PL, AB and IM provided the theoretical framework. PL and AB developed the methodological approach. AG and BGM completed the data assessment. PL analyzed the results and completed the writing of the manuscript. AB, JH and IM revised the manuscript and provided feedback.

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