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Conference Abstract

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The impact of fatigue accumulation on performance during stage races in professional road cyclists

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Abstract

Cumulative fatigue influences performance in professional road cyclists during stage races. This study examined the interaction between internal and external factors on performance parameters using race data from seven male professional cyclists collected over three seasons. Maximal rolling means for power output (PO) and heart rate (HR) were calculated across durations from 1 to 3600 s, and PO– and HR–duration curves were generated for grouped race days (Days 1–3 to 19–21). Mean PO and HR for 5-, 10-, and 20-min efforts were also analysed. For each effort duration, average PO, relative performance (% best), mean HR, PO/HR ratio, cumulative energy expenditure, and consecutive race days were computed. Data was analysed with mixed-effects linear models (REML). Both HR ($p<0.0001$) and PO ($p<0.01$) were altered between the first and later race days group, confirming performance declines across stages. Maintaining a higher PO/HR ratio was associated with superior 5-min (Z-score=0.5915), 10-min (Z-score=0.6524), and 20-min (Z-score=0.7299) efforts (all $p<0.0001$). Accordingly, cyclists with higher PO/HR ratios maintained better 10- and 20-min performance considering prior mechanical work and successive race days accumulated. Despite overall reductions in PO and HR across stages, riders able to preserve a higher PO/HR ratio under accumulated fatigue produced superior short- to mid-duration efforts, highlighting cardiovascular efficiency as a key determinant of performance during multi-stage competitions.

Keywords

cycling, durability, power output, heart rate

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1 Introduction

Performance in professional road cycling competitions emerges from the complex interaction between physiological capacity, race demands, tactical decisions, and the cumulative load imposed across multi-day events (Barranco et al, 2025). In particular, stage races require athletes to repeatedly produce high-intensity efforts under conditions of progressive fatigue, which may negatively affect the primary determinants of cycling performance (Leo et al 2021).

Previous research has examined isolated determinants of cycling performance under fatigued conditions, such as the power–duration relationship and heart rate (HR) dynamics. However, fewer studies have investigated how these factors interact within the ecological context of stage races, where internal and external loads accumulate over consecutive days of competition (Sanders et al, 2018).

The present investigation aims to address this gap by conducting a quantitative analysis of key performance parameters, specifically 5-, 10-, and 20-min power output (PO), and examining how they are influenced by internal factors, represented by HR responses, and external factors, represented by energy expenditure. This approach seeks to provide a more integrated understanding of performance modulation in cumulative fatigue conditions in professional cyclists participating in stage races.

2 Material and Methods

2.1 Participants

Seven male professional cyclists (age: 28 ± 3 yr; body mass: 67.9 ± 4.1 kg; stature: 1.78 ± 0.05 m) classified at Tier 4 (McKay et al., 2022) took part in the observational study over 3 seasons from January to May. During this period, the riders participated in multi - day stage races and the Giro d'Italia.

2.2 Methodology

Racing data from multi -day stage races and Giro d'Italia (including Giro d'Italia rest days) were collected across 3 seasons, from January to May. HR (Bryton heart rate monitor, Bryton Inc, Taipei City, Taiwan) and PO (Favero Assioma Duo, Favero Electronics srl., Arcade, TV, Italy) were recorded using the same cycle computer (Bryton S800, Bryton Inc, Taipei City, Taiwan) and were resampled at 1Hz.

Rolling means for maximal PO and HR were computed across durations ranging from 1 s to 3600 s to plot PO and HR as function of time across grouped race days (Days 1–3, 4–6, …, 19–21). All individual stage races were analysed and grouped together with shorter races typically contributing to 1-3, 4-6 and/or 7-9 portions and Giro d'Italia contributing to later groups. Additionally, mean PO and HR were calculated for 5-, 10-, and 20-min durations. For each effort duration, the following were computed: a) average power (W); b) relative percentage compared to the best performance recorded during the season; c) mean HR (bpm), d) PO to HR ratio ($W \cdot bpm^{-1}$); e) cumulative energy expenditure at the start of the effort (kJ); f) number of consecutive race days before the start of the effort.

During the stage races, the riders adhered to a team recovery protocol updated according to the most recent scientific evidence. Nutritional strategies and recovery interventions (including massage and sleep management) were tailored to the riders' energy expenditure across the different stages.

2.3 Statistical Analysis

Repeated measures mixed-effects linear models (REML) were used to compare grouped race days using duration (s) and energy expenditure (kJ) as fixed effects and subject as a random intercept. 5-, 10-, and 20-min predictors (a to f) were standardized (z-scored) within each

duration subset prior to model fitting and results presented as coefficient of SD (Z-score), meaning that, for an increase of 1 SD, Z-score represent the corresponding increase in the effort's relative percentage compared to the best performance recorded during the season.

3 Results

Progressive fatigue accumulation in successive race day groups (1-3, 4-6, …, 19-21) impacted both HR ($p<0.0001$) and PO ($p<0.01$), with an average of 4.5% and 1.1% decrease, respectively, across all durations between days 1-3 and 19-21 (see Table 1).

Across athletes, higher PO/HR values were associated with better 5min (coef=0.5915), 10min (coef=0.6524) and 20min (coef=0.7299) performance (all $p< 0.0001$). Athletes maintaining higher PO/HR throughout 10- and 20min efforts produced higher power as mechanical work prior to effort (coef=0.3325; $p<0.05$; coef=0.5625; $p<0.05$; respectively) or successive race days (coef=0.1956; $p<0.05$; coef=0.3543; $p<0.01$; respectively) increase. 5-, 10-, and 20-min efforts' parameters are presented in Table 2.

Table 1. PO- and HR-duration curves. *: different from group 1-3; †: different from group 4-6; °: different from group 10-12. 1 symbol $p<0.05$; 2 symbols $p<0.01$; 3 symbols $p<0.001$.

Duration (s)	1	5	15	30	60	120	300	600	1200	1800	3600
Day 1-3	182 ± 11 (216)	181 ± 11 (216)	180 ± 10 (216)	180 ± 10 (216)	179 ± 10 (216)	177 ± 10 (216)	174 ± 11 (216)	170 ± 11 (215)	165 ± 12 (202)	162 ± 11 (194)	155 ± 12 (192)
	1024 ± 160 (234)	919 ± 150 (234)	717 ± 130 (234)	592 ± 100 (234)	504 ± 72 (234)	445 ± 55 (234)	391 ± 46 (234)	358 ± 44 (233)	324 ± 42 (220)	307 ± 39 (211)	276 ± 38 (209)
Day 4-6	176 ± 11 (137)***	176 ± 11 (137)***	175 ± 11 (137)***	175 ± 11 (137)***	174 ± 11 (137)***	172 ± 11 (137)***	169 ± 12 (137)**	166 ± 11 (136)*	162 ± 11 (136)	158 ± 12 (135)	151 ± 13 (134)
	1021 ± 148 (151)	920 ± 144 (151)	731 ± 136 (151)	592 ± 101 (151)	495 ± 68 (151)	441 ± 53 (151)	393 ± 49 (151)	365 ± 45 (150)	331 ± 46 (150)	311 ± 47 (149)	277 ± 45 (148)
Day 7-9	171 ± 15 (53)*	171 ± 15 (53)**	170 ± 15 (53)**	169 ± 15 (53)**	168 ± 16 (53)*	166 ± 17 (53)*	163 ± 18 (53)	160 ± 18 (53)	156 ± 19 (53)	154 ± 19 (53)	147 ± 19 (45)
	943 ± 203 (60)	856 ± 186 (60)	647 ± 142 (60)	537 ± 111 (60)*	463 ± 87 (60)*	417 ± 74 (60)**	375 ± 66 (60)	346 ± 67 (60)	318 ± 65 (60)	304 ± 64 (60)	272 ± 63 (51)
Day 10-12	168 ± 21 (30)	168 ± 21 (30)	167 ± 21 (30)	166 ± 21 (30)	165 ± 21 (30)	163 ± 22 (30)	160 ± 22 (30)	156 ± 21 (30)	151 ± 22 (30)	147 ± 22 (30)	141 ± 22 (29)
	1008 ± 200 (39)	888 ± 172 (39)	670 ± 185 (39)	548 ± 151 (39)	461 ± 108 (39)*	411 ± 84 (39)**†	365 ± 72 (39)***†	332 ± 62 (39)**†††	300 ± 58 (39)*††	281 ± 57 (39)	252 ± 56 (37)
Day 13-15	173 ± 13 (37)	173 ± 13 (37)	172 ± 13 (37)	171 ± 13 (37)	170 ± 12 (37)*	169 ± 12 (37)*	165 ± 12 (36)	161 ± 12 (36)	158 ± 13 (36)	156 ± 14 (36)	150 ± 15 (32)
	953 ± 213 (40)	863 ± 199 (40)	704 ± 157 (40)	571 ± 115 (40)	476 ± 71 (40)**	422 ± 58 (40)***	386 ± 42 (39)**	351 ± 43 (39)*†	328 ± 47 (39)	315 ± 49 (39)	279 ± 51 (35)
Day 16-18	170 ± 17 (34)	169 ± 17 (34)	169 ± 16 (34)*	167 ± 16 (34)*	166 ± 16 (34)*	164 ± 16 (34)*	160 ± 18 (34)*	156 ± 19 (34)	152 ± 19 (34)	148 ± 20 (34)	142 ± 21 (34)
	971 ± 204 (39)	867 ± 175 (39)	670 ± 141 (39)	542 ± 117 (39)**	459 ± 94 (39)***	405 ± 73 (39)***†	362 ± 67 (39)***	329 ± 66 (39)**††	305 ± 67 (39)†	287 ± 67 (39)††	259 ± 70 (39)
Day 19-21	173 ± 10 (30)	173 ± 10 (30)	172 ± 10 (30)	171 ± 10 (30)	170 ± 10 (30)	168 ± 9 (30)	165 ± 9 (30)	162 ± 9 (30)	158 ± 9 (30)	155 ± 9 (30)	149 ± 9 (30)
	1023 ± 139 (33)	921 ± 153 (33)	714 ± 142 (33)	575 ± 81 (33)	485 ± 55 (33)	429 ± 42 (33)**	382 ± 35 (33)***	351 ± 35 (33)	326 ± 34 (33)	308 ± 36 (33)°	283 ± 36 (31)

Table 2. Mean ± SD for 5-, 10- and 20 min efforts.

	5 min Mean ± SD	N	10 min Mean ± SD	N	20 min Mean ± SD	N
PO/HR	2.47 ± 0.32	537	2.33 ± 0.28	476	2.18 ± 0.23	415
Mean PO (W)	411 ± 24	596	385 ± 24	525	354 ± 23	443
Mean HR (bpm)	168 ± 12	537	166 ± 13	476	163 ± 11	415
Percentage of best effort	92.1 ± 2.4	596	92.2 ± 2.6	525	92.16 ± 2.68	443
Total work prior (kJ)	1647 ± 1249	596	1485 ± 1144	525	1420 ± 1062	443
Work above FTP prior (kJ)	148 ± 119	594	139 ± 114	522	124 ± 98	443
Successive race days	4.95 ± 4.09	596	5.87 ± 5.04	525	6.55 ± 5.45	443

4 Discussion

The present findings suggest that the combined assessment of internal and external performance metrics provides additional insight into performance capacity under conditions of cumulative fatigue in cyclists competing in stage races.

It is well established that athletes with greater cardiovascular efficiency are able to sustain higher PO at a given submaximal HR, thereby preserving cardiac reserve for decisive race moments and attenuating the accumulation of cardiovascular strain across successive stages (Van Erp et al, 2020).

In this context, the PO/HR ratio emerges as a robust predictor of best-effort performance, indicating that cyclists with higher PO/HR ratios can generate greater PO during efforts lasting 5 to 20 minutes. This trend aligns with the progressively greater reliance on aerobic metabolism during longer efforts.

Under fatigue conditions, cyclists with higher PO/HR ratios maintained superior 10- and 20-min PO, likely reflecting a better aerobic efficacy that support sustained aerobic power (Jeukendrup et al., 2000). In contrast, the absence of significant interaction effects for 5-min PO under fatigue suggests that shorter efforts rely more heavily on anaerobic pathways and neuromuscular power and are therefore less dependent on cardiovascular efficiency (Jeukendrup et al., 2000). In this context, prior mechanical work performed at low intensities was positively associated with subsequent 5-min PO, likely reflecting a priming or warm-up phenomenon. Low - intensity prior activity is known to increase muscle temperature, accelerate oxygen uptake kinetics, enhance glycolytic enzyme activity, and improve neuromuscular recruitment, all of which can augment short-duration maximal performance (Spragg et al, 2024). Conversely, sustained high-intensity prior work impaired both anaerobic and aerobic cycling performance (Spragg et al, 2024). Specifically, 10- and 20-min PO were negatively influenced by accumulated prior mechanical work, and high-intensity efforts performed earlier in the race were particularly detrimental to subsequent 5-min PO.

Finally, the negative effects of successive race days on HR and PO confirm the progressive accumulation of fatigue during multi-day competitions. This pattern is consistent with reduced cardiovascular efficiency, potentially linked to diminished catecholamine sensitivity and glycogen depletion (Lucia et al., 2001). Periodic fluctuations further suggest that fatigue develops non-linearly, influenced by race tactics and course profile, modulating PO and HR responses throughout stage races (Sanders et al., 2017).

As potential limitations, the alteration of the PO/HR ratio may be influenced by race dynamics and environmental factors. However, this influence was minimized by analysing the PO/HR ratio only during selected segments of the race rather than across the entire event.

HR was monitored using a commercially available device that was not specifically validated while technically replicating a widely accepted and robust telemetry protocol for such HR belts.

Stage patterns and route may finally also have influenced riders' performance parameters. However, our investigation included only riders who completed the same multi - day stage races and the Giro d'Italia across three consecutive seasons, thereby reducing the impact of route-profile variability on the performance parameters analysed.

5 Practical Applications

This study identifies the PO/HR ratio as a key determinant of performance in professional cyclists during stage races. Higher values were associated with superior 5-, 10-, and 20-min PO, with stronger protective effects under accumulated fatigue, particularly for longer efforts. Monitoring the PO/HR ratio may offer coaches a practical tool to assess cardiovascular efficiency, track fatigue, and optimize pacing and recovery strategies in multi-stage competitions.

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