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Examining Durability in Professional Cycling: Reliability, relevance and modifying factors

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TABLE OF CONTENT

LIST OF ABBREVIATIONS

CP: Critical Power

MMP: Maximum Mean Power

PO: Power Output

RPP: Record Power Profile

SEM: Standard Error of Measurement

ICC: Intraclass Correlation Coefficient

VO^{2}max: Maximum Aerobic Capacity

FTP: Functional Threshold Power

W: Watts

kJ·kg^{-1}: Kilojoules per kilogram, unit of accumulated work

ANOVA: Analysis of Variance

SPSS: Statistical Package for the Social Sciences

HRV: Heart Rate Variability

UCI: Union Cycliste Internationale (International Cycling Union)

WKO5: Training analysis software from TrainingPeaks

LIST OF FIGURES AND TABLES

ABSTRACT

Background: Durability, defined as the ability to maintain performance under fatigue, is increasingly recognized as a crucial determinant of elite cycling performance. This thesis integrates findings from several studies exploring different facets of durability, including its repeatability, the impact of exercise intensity, and potential sex differences.

Methods: The first study assessed the repeatability of durability, measured as the decline in power output (PO) values, in 18 male professional cyclists during a full cycling season. Maximum mean power (MMP) values were recorded during training and competition for various effort durations and levels of accumulated work. Repeatability was examined using standard error of measurement (SEM) and intra-class correlation coefficient (ICC).

The second study compared durability across different performance levels in 49 male cyclists categorized as U23, ProTeam, and WorldTour. Critical power (CP) was measured pre-season, and MMP values were determined for efforts of different durations after accumulated work above CP. The third study investigated the effect of work-matched levels of accumulated work at different intensities on performance in 17 male professional cyclists over a competitive season. MMP and CP were measured under 'fresh' conditions and after accumulated work above and below CP. The fourth study examined potential sex differences in durability using power output data from male and female professional cyclists. MMP values for different durations were determined under 'fresh' conditions and after varying levels of accumulated work.

Results: In the first study, MMP values declined progressively with increased accumulated work, showing high repeatability under fatigue conditions (SEM < 5%, ICC > 0.90). The lowest repeatability was observed for the shortest efforts (10-second MMP).

The second study found that U23 cyclists showed significant MMP reductions for efforts ≥1 minute after ≥5 $kJ \cdot kg^{-1}$ above CP, while ProTeam and WorldTour cyclists did not show significant reductions until 7.5 $kJ \cdot kg^{-1}$ above CP. WorldTour cyclists attained higher MMP values for most efforts after 7.5 $kJ \cdot kg^{-1}$ above CP compared to U23 and ProTeam cyclists.

The third study demonstrated that accumulated work above CP significantly impaired MMP values for all effort durations, while no significant changes were observed after work below CP. CP was also impaired after all levels of accumulated work above CP.

In the fourth study, both male and female cyclists showed significant MMP reductions after 20 and 30 $kJ \cdot kg^{-1}$ accumulated work. However, female cyclists exhibited a greater relative decay in MMP values compared to male cyclists for efforts ≥1 minute after 20 kJ·kg-1, with differences increasing after 30 $kJ \cdot kg^{-1}$.

Conclusions: Durability, as measured by MMP decline under fatigue, is a reliable performance indicator in elite cycling. High-intensity durability is more pronounced in higher-level cyclists, supporting its importance for performance. Additionally, female cyclists may exhibit lower durability than male cyclists for longer efforts, indicating potential sex-specific training considerations.

RESUMEN

Antecedentes: La durabilidad, definida como la capacidad de mantener el rendimiento bajo fatiga, se reconoce cada vez más como un determinante crucial del rendimiento en el ciclismo de élite. Esta tesis integra hallazgos de varios estudios que exploran diferentes facetas de la durabilidad, incluyendo su repetibilidad, el impacto de la intensidad del ejercicio y posibles diferencias entre sexos.

Métodos: El primer estudio evaluó la repetibilidad de la durabilidad, medida como la disminución en los valores de potencia (PO), en 18 ciclistas profesionales masculinos durante una temporada completa. Se registraron los valores de potencia máxima media (MMP) durante entrenamientos y competiciones para diversas duraciones de esfuerzo y niveles de trabajo acumulado. La repetibilidad se analizó utilizando el error estándar de medición (SEM) y el coeficiente de correlación intraclase (ICC).

El segundo estudio comparó la durabilidad entre diferentes niveles de rendimiento en 49 ciclistas masculinos categorizados como sub-23, ProTeam y WorldTour. Se midió la potencia crítica (CP) al inicio de la temporada y se determinaron los valores de MMP para esfuerzos de diferentes duraciones tras trabajo acumulado por encima de la CP. El tercer estudio investigó el efecto de niveles de trabajo acumulado iguales, pero a diferentes intensidades, sobre el rendimiento en 17 ciclistas profesionales masculinos durante una temporada competitiva. Se midieron la MMP y la CP en condiciones "frescas" y tras trabajo acumulado por encima y por debajo de la CP. El cuarto estudio examinó posibles diferencias entre sexos en la durabilidad utilizando datos de potencia de ciclistas profesionales masculinos y femeninos. Los valores de MMP para diferentes duraciones se determinaron en condiciones "frescas" y tras diversos niveles de trabajo acumulado.

Resultados: En el primer estudio, los valores de MMP disminuyeron progresivamente con el aumento del trabajo acumulado, mostrando alta repetibilidad en condiciones de fatiga (SEM < 5%, ICC > 0,90). La menor repetibilidad se observó en los esfuerzos más cortos (MMP de 10 segundos).

El segundo estudio encontró que los ciclistas sub-23 mostraron reducciones significativas en la MMP para esfuerzos ≥1 minuto tras ≥5 $kJ\cdot kg^{-1}$ por encima de la CP, mientras que los ciclistas ProTeam y WorldTour no presentaron reducciones significativas hasta ≥7,5 $kJ\cdot kg^{-1}$ por encima de la CP. Los ciclistas WorldTour alcanzaron mayores valores de MMP para la mayoría de los esfuerzos tras ≥7,5 $kJ\cdot kg^{-1}$ por encima de la CP en comparación con los ciclistas sub-23 y ProTeam.

El tercer estudio demostró que el trabajo acumulado por encima de la CP deterioró significativamente los valores de MMP para todas las duraciones de esfuerzo, mientras que no se observaron cambios significativos tras trabajo por debajo de la CP. Además, la CP se deterioró tras todos los niveles de trabajo acumulado por encima de la CP.

En el cuarto estudio, tanto los ciclistas masculinos como femeninos mostraron reducciones significativas en la MMP tras 20 y 30 $kJ\cdot kg^{-1}$ de trabajo acumulado. Sin embargo, las ciclistas femeninas exhibieron una mayor disminución relativa en los valores de MMP en comparación con los ciclistas masculinos para esfuerzos ≥1 minuto tras 20 $kJ\cdot kg^{-1}$, con diferencias más pronunciadas tras 30 $kJ\cdot kg^{-1}$.

Conclusiones: La durabilidad, medida por la disminución de la MMP bajo fatiga, es

un indicador de rendimiento confiable en el ciclismo de élite. La durabilidad en esfuerzos de alta intensidad es más pronunciada en ciclistas de mayor nivel, lo que respalda su importancia para el rendimiento. Además, las ciclistas femeninas podrían presentar menor durabilidad que los ciclistas masculinos en esfuerzos más prolongados, indicando posibles consideraciones específicas de entrenamiento según el sexo.

GENERAL INTRODUCTION

Cycling encompasses a broad spectrum of disciplines, including mountain biking (MTB), track cycling, BMX, cyclo-cross, and road cycling, with the latter enjoying the highest global popularity. The physiological and biomechanical demands differ significantly across these disciplines and even among events within the same discipline. These variations shape the anthropometric and physiological traits, training approaches, and nutritional strategies that support peak performance.
Road cycling is characterized by both single-day and multi-day competitions, the latter often ranging from 5 to 8 stages. At the pinnacle are the three-week Grand Tours—Giro d'Italia, Tour de France, and Vuelta a España—which consist of 21 stages encompassing flat, hilly, mountainous terrain, and individual time trials. These events are renowned for their grueling demands, and even among World Tour professionals, not all riders can withstand the challenges of three consecutive weeks of racing. WT teams typically comprise ~30 cyclists, but only eight are selected for a Grand Tour, each chosen based on their specialization (e.g., sprinters, TT experts, climbers, general classification contenders, or versatile all-rounders) and their specific physiological and physical qualities. Besides these stage races, prestigious single-day events like the Monuments—Milan–San Remo, Tour of Flanders, Paris–Roubaix, Liège–Bastogne–Liège, and Giro di Lombardia—are also key targets for certain riders who shape their preparation around peaking for these competitions.

In addition to racing for their trade teams, road cyclists may also compete for their national teams in prominent events like the World Championships and the Olympic Games, which typically include a mass-start race and a TT. WT riders typically participate in 55–80 races per season, spanning from late January to mid-October. Distinctions between men's and women's professional cycling are notable. Men's events are generally longer in both single-day and stage races. For example, men's single-day races average ~225 km compared to ~145 km for women. Women's stage races are also shorter, with the longest comprising eight stages, while most feature 3–4 stages. These differences result in women's races being, on average, 1.5 to 2 hours shorter than men's.

Moving away from road cycling, track cycling is conducted on a 250-m wooden track and includes both sprint and endurance events. These races range from short sprints (~200 m in ~10 seconds) to longer endurance races, such as the Madison, which can exceed 50 minutes (Craig & Norton, 2001). Meanwhile, MTB offers various subdisciplines like downhill, four-cross, enduro, and e-MTB, with cross-country formats—short circuit (XCC), Olympic (XCO), and marathon (XCM)—gaining prominence, especially after XCO's inclusion in the 1996 Olympics (Impellizzeri & Marcora, 2007). Cyclo-cross, another distinct discipline, is a mix of road and off-road cycling, involving obstacles that require riders to dismount and carry their bikes; it is especially popular in winter months (Ouvrard et al., 2015). BMX, which includes racing on short dirt tracks with jumps and turns (BMX Racing) (Mateo-March et al., 2012) and freestyle events in skatepark-like environments (BMX Freestyle), has grown significantly, with BMX Racing making its Olympic debut in 2008.

As highlighted, numerous factors influence cycling performance, including the discipline, event type, and external conditions such as weather, terrain, and team strategies. Individual factors, including mental resilience, physical attributes, physiological capabilities, and nutritional approaches, also play critical roles (Phillips & Hopkins, 2020). This introduction synthesizes the current knowledge regarding the physical demands of cycling, key performance determinants, the physiological and physical profiles of elite cyclists, their training strategies, and the role of nutrition. While many aspects are discussed, the focus primarily lies on road cycling due to its complexity and the broad range of performance-influencing variables it encompasses.

Physical Demands of Professional Cycling Races

The three-week Grand Tours are often regarded as the pinnacle of endurance sport, serving as an upper limit of sustained daily energy expenditure in humans. These races are associated with a daily energy cost estimated at approximately 4–5 times the basal metabolic rate over the three weeks of competition (Hammond & Diamond, 1997; Peterson et al., 1990; Thurber et al., 2019). In a foundational study from the 1980s, Westerterp et al. applied the doubly labeled water method (using isotopes 2H and 18O) to monitor four cyclists during the Tour de France, which spanned more than 4,000 km and 21 stages. Their results revealed a total daily energy expenditure (TDEE) ranging from 6,931 to 8,604 kcal (Westerterp et al., 1986). Subsequent studies in the same race but using different methodologies reported slightly lower TDEE values (~6,070 kcal) (Saris et al., 1989). More recently, Van Hooren et al. estimated a TDEE of ~7,648 kcal in professional cyclists participating in the Vuelta a España, while single-day races such as the Ardennes classics were found to require a TDEE of ~6,525 kcal (Van Hooren et al., 2023).

Stages in Grand Tours can be categorized as flat, hilly, mountainous, or time trials. However, the designation “flat” is somewhat misleading, as these stages often include significant climbing, with 1,000–2,000 meters of total elevation gain. Mountainous stages, in contrast, typically feature fewer but longer climbs, often concluding with summit finishes at altitude. Among all stage types, mountain stages generally demand the highest energy expenditure, whereas TTs are less taxing due to their shorter duration. Body mass significantly influences TDEE, as shown in data from the 2024 Tour de France, where a ~2,000 kcal variation in TDEE was observed among riders based on differences in body mass.

While comprehensive data for professional female cyclists are limited, emerging research suggests similar relative energy demands. For example, a recent case study reported a TDEE of 7,572 kcal for a 29-year-old female cyclist competing in the eight-day Tour de France Femmes (Areta et al., 2024). These findings highlight the necessity of meeting high daily energy requirements to sustain performance over prolonged efforts. Despite the sustained workload of Grand Tours and the significant length of single-day races, the average power outputs (PO) achieved by professional cyclists are remarkable. Male World Tour (WT) cyclists average a PO of 3.8 $W \cdot kg^{-1}$ across approximately 80 hours of racing in a Grand Tour, with slightly lower values (3.4 $W \cdot kg^{-1}$) observed in ProTeam-level cyclists. These values vary depending on stage type and rider specialization (Sanders & Heijboer, 2019; Sanders & van Erp, 2020; Vogt et al., 2007). For instance, TTs typically demand an average PO of ~5.1 $W \cdot kg^{-1}$, while mountain stages require ~3.5 $W \cdot kg^{-1}$, and semi-mountainous and flat stages involve ~3.0 and 2.7 $W \cdot kg^{-1}$, respectively (Sanders & Heijboer, 2019). Single-day races, particularly Monuments, are associated with higher PO values (~3.3 $W \cdot kg^{-1}$) compared to other single-day events (Sanders & van Erp, 2020).

Similar trends are observed in female professional cycling, albeit with slightly lower PO values. On average, female WT cyclists achieve a PO of ~2.8 $W \cdot kg^{-1}$, with smaller differences between race categories than those observed in male cycling (van Erp & Lamberts, 2023). Women's races, characterized by shorter distances and durations compared to men's events, are associated with higher relative intensities. This is reflected in a greater proportion of time spent in high-intensity heart rate zones and higher training stress indicators (e.g., TSS and TRIMP per km) (Sanders et al., 2019). A case study comparing male and female Grand Tour winners revealed similar relative power distributions (~3.5 and 3.6 W·kg^{-1}, respectively), although the female cyclist sustained higher relative intensities during certain stages, such as the early kilometers of flat stages and the final segments of mountain finishes (Lamberts et al., 2024).

Both male and female cyclists spend most of the race time at low-to-moderate intensities (70–80% below the first ventilatory threshold, VT1), with an average heart rate below 75% HRmax in mass-start events (Padilla et al., 2008; Sanders et al., 2019; Sanders & van Erp, 2020). Notably, micro-pauses in power output (~0 W) account for 10–20% of total race time, often occurring when drafting within the peloton or descending. Despite this, high-intensity efforts above the second ventilatory threshold (VT2) or respiratory compensation point (RCP) are critical for success. These decisive efforts, such as sprints, cobbled segments, or prolonged climbs, often determine race outcomes. For example, flat and semi-mountainous stages frequently hinge on short-duration efforts (<60 seconds), whereas uphill finishes and mountain stages demand longer sustained efforts (≥3 minutes) (van Erp & Lamberts, 2022).

In MTB and track cycling, repeated high-intensity efforts dominate performance. Track events are conducted almost entirely above VT2 or MAP, with short efforts requiring both aerobic and anaerobic contributions. For example, a 1,000-m TT splits energy demands evenly between aerobic and anaerobic pathways (Craig & Norton, 2001). Similarly, MTB races are highly stochastic, with power outputs oscillating from 600–1,000 W on steep uphills to 0 W during descents. Riders spend approximately 30–40% of race time above VT2, emphasizing the importance of carbohydrate fueling (~90–120 g/h) and strategic supplementation to support repeated high-intensity efforts (Jeukendrup, 2014; Podlogar & Wallis, 2022).

In summary, the extreme demands of professional cycling, particularly in Grand Tours, necessitate precise nutritional strategies and specialized training to address the intensity and energy demands of diverse race types.

Physiological Indicators in Professional Cyclists

Achieving success in road cycling demands exceptional performance across a wide range of durations, from explosive sprints lasting seconds to sustained efforts spanning hours. Power output (PO) data from large-scale studies of professional cyclists underscore the importance of both absolute and relative PO values. For male World Tour (WT) cyclists, 90th percentile PO values are reported at 14.2, 7.7, 6.6, and 5.8 W·kg^{-1} for efforts lasting 30 seconds, 5 minutes, 20 minutes, and 1 hour, respectively. Female professional cyclists demonstrate slightly lower values at 11.8, 6.5, 5.5, and 4.9 W·kg^{-1}, aligning with their generally smaller body size and muscle mass (Mateo-March et al., 2022; Valenzuela, Muriel, van Erp, et al., 2022). Specializations such as sprinters, climbers, and time trialists influence these profiles, with distinct performance attributes associated with each.

The physiological basis for cycling performance is traditionally explained through three main determinants: maximal aerobic capacity (VO_2max), fractional utilization of VO_2max, and cycling efficiency. VO_2max represents the upper limit of aerobic performance, closely associated with maximal aerobic power (MAP). Professional cyclists typically exhibit VO_2max values between 70–80 mL·kg^{-1}·min^{-1} and MAP values of 450–550 W, with higher values predictive of success in elite-level racing (Lucía et al., 2001). Longitudinal studies suggest that VO_2max serves as a distinguishing factor for athletes progressing from junior to professional categories (Valenzuela, Alejo, Lucia, et al., 2023).

Cyclists must also sustain a significant proportion of their VO_2max during prolonged efforts. This capacity is reflected in indicators like the ventilatory thresholds (VT1 and VT2) and maximal lactate steady state (MLSS). Elite cyclists typically reach VT1 and VT2 at 65–75% and 90–95% of their VO_2max, respectively (Alejo et al., 2022; Lucia et al., 1998) (Alejo et al., 2022; Lucia et al., 1998). These thresholds are critical for maintaining high intensities without fatigue, allowing athletes to compete effectively during demanding stages.

Cycling efficiency, defined as the ratio of mechanical work to metabolic energy expended, further influences performance. Gross efficiency values of 22–24% are common among professional cyclists, and incremental improvements in efficiency can partially compensate for lower VO_2max values (Bell et al., 2017; Santalla et al., 2009). However, some studies suggest no significant efficiency differences between elite and recreational cyclists, calling into question its standalone value as a predictor of success (Moseley et al., 2004).

Training Characteristics in Cyclists

The physical demands of professional cycling necessitate rigorous training regimens designed to develop and sustain the exceptional physiological traits required for elite performance. However, evidence regarding the optimal training methods for professional cyclists is limited, with most insights derived from observational studies and case reports rather than randomized controlled trials (Galán-Rioja et al., 2023).

Professional cyclists predominantly employ a pyramidal or polarized intensity distribution, with the majority of training time spent at low intensity. Typically, ~65% of training time is performed in Zone 1 (below the ventilatory threshold), ~29% in Zone 2 (between the ventilatory threshold and the respiratory compensation point), and ~6% in Zone 3 (above the respiratory compensation point) (Gallo et al., 2023; Gallo, Mateo-March, et al., 2022; Sperlich et al., 2023). The intensity distribution becomes more polarized during competitive phases, with a greater emphasis on high-intensity efforts.

Recent case series have detailed the training routines of elite male cyclists preparing for Grand Tours. Weekly training volumes ranged between 15 and 22 hours, with intensity distributions favoring low intensity (81–91%), moderate intensity (6–14%), and high intensity (2–6%) (Gallo et al., 2023; Gallo, Mateo-March, et al., 2022). Periodization patterns vary based on the season’s phase. For example, during high-intensity stage races, athletes adopt a block periodization strategy, incorporating moderate and high-intensity training to simulate race demands. Conversely, during periods without competition, a more polarized intensity distribution with a higher proportion of low-intensity training is observed.
Individual variability in training approaches is also evident. Some cyclists incorporate strength training during preparatory phases, typically performing resistance exercises 1–2 times per week. Others focus exclusively on cycling. Similarly, altitude training is used selectively, with some athletes completing multiple training camps at altitudes exceeding 1,800 meters to maximize physiological adaptations before key events (Rønnestad & Hansen, 2018).

Day-to-day training strategies also reflect a balance between stress and recovery. For instance, a case study of a Grand Tour podium finisher revealed alternating “hard” and “easy” days. Hard days included sessions exceeding 4 hours or 3,000 kJ, often with at

least 30 minutes of high-intensity efforts. Easy days, by contrast, focused on recovery, with less than 2 hours of riding and minimal intensity (Gallo et al., 2024). This alternation ensures adequate recovery while maintaining high training loads.
Nutritional strategies are closely integrated with training demands. Energy and macronutrient intake are periodized across macrocycles and microcycles to align with the intensity and duration of training sessions. For example, carbohydrate intake is prioritized before and during high-intensity sessions to optimize glycogen availability and performance (Jeukendrup, 2014).

Differences in training practices between male and female cyclists have also been documented. Female cyclists generally train at lower volumes, particularly in low- and moderate-intensity zones, but their relative training loads, such as Training Stress Score (TSS), are similar to those of male cyclists (Van Erp et al., 2019). As women's professional cycling continues to evolve, with greater support and access to full-time training opportunities, these differences are expected to diminish.

In summary, professional cycling training involves a dynamic interplay of intensity distribution, periodization, and individualized approaches. These strategies are underpinned by precise nutritional planning to sustain performance and optimize recovery, reflecting the complex demands of elite-level competition.

Fatigue, Performance, and Durability in Professional Cycling

Endurance sports, particularly professional cycling, demand a delicate balance between sustained effort, strategic execution, and the management of fatigue. Cyclists face unique physiological and psychological challenges, ranging from maintaining power output over extended durations to responding effectively to high-intensity demands such as sprints and climbs. These demands make fatigue, performance, and the emerging concept of durability central to understanding success in this sport.
Fatigue, broadly defined, represents the reversible decline in an athlete's capacity to sustain power output or performance. It encompasses central mechanisms originating in the nervous system and peripheral mechanisms localized in the muscles. Durability, on the other hand, shifts the focus beyond traditional performance metrics such as maximal oxygen uptake (VO_2max) to emphasize sustained functionality under cumulative fatigue. This framework explores the interplay between these elements, highlighting their significance in optimizing performance (Hawley et al., 1997).

Fatigue: A Complex and Multidimensional Phenomenon

Fatigue is a dynamic and multifaceted construct influenced by physiological, biochemical, and psychological factors. It can be broadly categorized into central and peripheral components, each contributing to performance limitations during prolonged efforts.

Central Fatigue

Central fatigue stems from the central nervous system (CNS) and is characterized by reduced motor drive to the muscles. Factors such as decreased cortical excitability, altered neurotransmitter levels (e.g., serotonin and dopamine), and heightened perception of exertion impair an athlete's ability to sustain voluntary contractions (Gandevia, 2001). In professional cycling, central fatigue becomes increasingly relevant during multi-stage events, where sleep deprivation, cognitive demands, and psychological stress accumulate.

Psychological factors, including motivation and perceived exertion, interact with central fatigue. Athletes with higher mental resilience demonstrate delayed onset of fatigue, underscoring the importance of psychological endurance (Marcora et al., 2009). This is particularly evident in high-pressure race scenarios, such as breakaways or sprint finishes, where decision-making and focus are critical.

Peripheral Fatigue

Peripheral fatigue arises from within the musculature, driven by metabolic disturbances and mechanical impairments. Key contributors include metabolite accumulation, where the buildup of byproducts such as lactate, hydrogen ions (H^+), and inorganic phosphate (Pi) disrupts excitation-contraction coupling, reducing muscle force production (Allen et al., 2008). Substrate depletion also plays a role, as glycogen depletion diminishes ATP production, forcing reliance on less efficient energy pathways such as fat oxidation (Hawley et al., 1997). Additionally, electrolyte imbalances caused by altered ionic balances in sodium, potassium, and calcium affect muscle excitability and contractility, further limiting performance. In professional cycling, these mechanisms manifest as reduced power output during prolonged efforts, particularly in the latter stages of races or during mountain climbs where energy demands are highest.

Tactical Execution and Pacing Strategies

Strategic pacing is essential for managing fatigue and optimizing performance. Cyclists who distribute their efforts evenly across a race experience less physiological strain and perform better in the final stages (van Erp et al., 2021). Conversely, erratic pacing or early surges in intensity exacerbate fatigue, compromising performance during critical moments.

Durability: Sustaining Output Under Cumulative Fatigue

Durability represents a paradigm shift in endurance performance research. Unlike traditional metrics, durability emphasizes the ability to maintain performance under conditions of cumulative fatigue (Maunder et al., 2021). This concept is particularly relevant in multi-stage events like the Tour de France, where cumulative workloads significantly impact performance (Muriel et al., 2022). Durable athletes exhibit smaller declines in power output, maintaining higher power outputs across varying intensities, even under fatigue (Muriel et al., 2022; van Erp et al., 2021). They demonstrate sustained efficiency, with stable gross efficiency during prolonged efforts that reduce the metabolic cost of sustained workloads (Hawley & Noakes, 1992). Additionally, durable cyclists display superior fatigue resistance, excelling in decisive efforts such as climbs or sprints during the latter stages of races (Mateo-March et al., 2024; Muriel et al., 2022). The mechanisms supporting durability include enhanced mitochondrial function, where increased mitochondrial density supports sustained energy production and delays metabolic fatigue (Hawley & Noakes, 1992). Capillary density further aids durability by improving oxygen delivery and facilitating metabolic waste removal, enabling higher workloads (Coetzer et al., 1993). Finally, neuromuscular coordination plays a crucial role, as optimized motor unit recruitment patterns sustain force production under fatigue (Weston et al., 1996).

Durability represents a paradigm shift in endurance performance research. Unlike traditional metrics, durability emphasizes the ability to maintain performance under conditions of cumulative fatigue (Maunder et al., 2021). This concept is particularly relevant in multi-stage events like the Tour de France, where cumulative workloads significantly impact performance (Muriel et al., 2022; van Erp et al., 2021).

Durability in Professional Cycling: Specific Scenarios and Applications

The concept of durability has gained prominence in endurance sports research as a critical determinant of sustained performance under conditions of cumulative fatigue (Maunder et al., 2021). In professional cycling, durability refers to the capacity to maintain high power outputs and physiological efficiency despite prolonged exertion and escalating workload (van Erp et al., 2021). Unlike traditional metrics such as VO_2max or peak power, durability encapsulates an athlete's ability to delay performance deterioration over extended durations, particularly in scenarios where cumulative fatigue and energy expenditure are unavoidable (Maunder et al., 2021; van Erp et al., 2021). This section delves into the practical manifestations of durability in cycling, exploring specific race scenarios, physiological implications, and strategies for optimization.

Durability in cycling is heavily influenced by race characteristics, such as stage profiles, terrain, and race strategies. Each scenario poses unique challenges, requiring cyclists to sustain performance while managing fatigue accumulation.

Flat Stages and Durability in Sustained Workloads

Flat stages, often characterized by long distances with minimal elevation gain, might appear less demanding than mountainous or time trial stages. However, these stages impose unique durability requirements due to high average speeds, constant pedaling, and the need to stay within the peloton to conserve energy (van Erp et al., 2021). Cyclists in flat stages typically accumulate substantial mechanical work (measured in kJ) over hours, which taxes the metabolic system and necessitates careful energy management. In flat stages, durability becomes critical during breakaways, where riders must sustain high power outputs for extended periods while maintaining enough energy reserves for potential sprints or tactical surges (van Erp et al., 2021). It is also essential during sprints, as sprinters rely on durability to deliver peak power outputs at the race's conclusion, often after enduring hours of steady-state efforts in the peloton. Durable sprinters demonstrate smaller declines in their ability to generate explosive power following prolonged workloads. For instance, successful sprinters maintain higher maximal mean power (MMP) values in the final kilometers compared to their less durable counterparts, even after energy expenditures exceeding 3,500 kJ (van Erp et al., 2021).

Mountain Stages: The Intersection of Fatigue and High-Intensity Efforts

Mountain stages place significant demands on durability due to the repeated requirement for sustained high-intensity efforts during long climbs. Unlike flat stages, where drafting reduces energy expenditure, climbing necessitates prolonged work against gravity, amplifying the role of body mass and relative power output (W/kg). Key aspects of durability in mountain stages include climbing durability, where cyclists must maintain high power-to-weight ratios while minimizing performance decrements during successive climbs. Durable climbers exhibit smaller reductions in power output across multiple ascents, a critical factor in stages with several categorized climbs. Additionally, final climbs and summit finishes are often decisive, as durable riders maintain their ability to produce near-threshold or supra-threshold power outputs (e.g., 5.5–6.5 W/kg) despite cumulative fatigue from earlier climbs and high total energy expenditure. Data from Grand Tours shows that successful climbers maintain relative power outputs (e.g., 3–4 W/kg) even after workloads exceeding 50 kJ/kg, highlighting the importance of durability in distinguishing elite performers (Van Erp et al., 2021). In contrast, less durable riders experience significant performance drops, often losing critical time in the general classification.

Time Trials (TT): Sustained High-Intensity Efforts Under Fatigue

Individual time trials require cyclists to sustain their highest possible power output for a given distance or duration without external drafting. While TTs are often shorter than flat or mountain stages, they impose immense physiological strain due to the high intensity of effort. Durability in TTs is particularly relevant when these events are scheduled after consecutive days of racing, such as in the middle or final stages of a Grand Tour. Cyclists with greater durability can maintain near-threshold power outputs (e.g., 90–95% of their functional threshold power) despite the fatigue accumulated from prior stages. Research shows that durable time trialists exhibit smaller declines in their ability to sustain steady-state power compared to their competitors, even after total workloads of 60–70 kJ/kg (van Erp et al., 2021).

Single-Day Classics: High Variability and Stochastic Demands

Classics like Paris-Roubaix and the Tour of Flanders present unique durability challenges due to their highly variable nature. These races feature frequent changes in intensity, cobbled sectors, and short, steep climbs, requiring cyclists to repeatedly produce high-intensity efforts interspersed with recovery. Durability in single-day classics is exemplified by stochastic power demands, as cyclists must handle abrupt surges in power (e.g., >8–10 W/kg) on cobbled sections or during attacks, while recovering quickly to sustain efforts over 200–250 km. Additionally, durable riders maintain their capacity to perform decisive attacks or sprints in the final kilometers, often after spending significant time in high-intensity zones (>90% VO_2max). Successful riders in classics demonstrate resilience in both short-duration efforts (e.g., 10–30 seconds) and sustained work, enabling them to adapt to the race's stochastic nature (van Erp et al., 2021).

Durability and High Workloads: Insights From Power Data

Durability is often assessed using power-duration curves, which analyze an athlete's maximal mean power (MMP) output across different timeframes. These curves provide insights into how cyclists maintain performance under fatigue. Key findings include:
Energy Expenditure and Performance Decline: Riders with higher durability exhibit smaller reductions in MMP values after accumulating substantial workloads (e.g., >3,000–5,000 kJ). For instance, durable climbers sustain higher MMP for 20-minute efforts following prolonged stages compared to less durable peers.

Critical Fatigue Thresholds: Research identifies critical energy expenditure thresholds (e.g., 30–50 kJ/kg) beyond which performance begins to deteriorate significantly. Durable cyclists demonstrate delayed performance declines even at these thresholds (van Erp et al., 2021).

Factors Influencing Durability in Cycling

Durability is shaped by a combination of physiological, biomechanical, and psychological factors, as well as environmental and nutritional influences. Physiological adaptations play a key role, with enhanced mitochondrial density improving oxidative capacity, delaying fatigue, and supporting sustained power output (Hawley et al., 1997; Maunder et al., 2021). Neuromuscular efficiency, through optimized motor unit recruitment patterns, allows for consistent force generation under fatigue (Muriel et al., 2022), while increased buffering capacity and lactate shuttling reduce the metabolic cost of high-intensity efforts (Barranco-Gil et al., 2024). Psychological resilience also contributes, as cyclists with greater mental endurance exhibit lower perceived exertion during high workloads, enabling them to maintain effort during critical moments (Morris et al., 2008).

Nutritional support is crucial, with adequate carbohydrate intake during races (e.g., 90–

120 g/h) sustaining glycogen stores and delaying metabolic fatigue, while supplements like caffeine and bicarbonate enhance durability by improving alertness and buffering acidosis (Hawley et al., 1997; Mateo-March et al., 2024). Training strategies to optimize durability include high-intensity interval training (HIT), which develops fatigue resistance and improves the ability to sustain power under metabolic stress; endurance rides, which enhance mitochondrial efficiency and fat oxidation; and race simulations, where back-to-back high-intensity sessions replicate the demands of multi-stage races, fostering both physiological and psychological adaptations (Muriel et al., 2022).

The first study highlights the importance of maximum mean power (MMP) values and their decline under fatigue conditions as a crucial performance indicator. In cycling, MMP, also known as "maximum mean power," refers to the highest power output a cyclist can sustain for different effort durations. Research has shown that differences in MMP between successful and less successful professional cyclists become more pronounced under fatigue. This suggests that the ability to maintain high MMP levels when fatigued is a critical factor for performance. For example, Van Erp and colleagues reported that professional cyclists who perform better under fatigue conditions show less decline in MMP compared to their peers (van Erp et al., 2021). Similarly, Muriel et al. found that World Tour cyclists exhibit a lower decline in MMP than ProTeam cyclists after equivalent amounts of accumulated work (Muriel et al., 2022).

Research on the durability paradigm is growing, focusing on various factors that contribute to interindividual variability in power output (PO) decline after accumulated work. These include the volume and intensity of exercise, and the effectiveness of nutritional or training interventions aimed at enhancing durability (Mateo-March et al., 2024; Maunder et al., 2021). However, for durability to be a reliable performance indicator, it must be consistent and repeatable under similar conditions. Without this reliability, it is challenging to distinguish between biological and methodological variability or a real improvement in durability. This feature is especially relevant in elite sports, where small performance variations can determine the difference between winning and losing (Muriel et al., 2022).

One of the less explored aspects in the current literature is the ability to consistently measure durability in elite cycling, particularly under conditions of fatigue. Durability, defined as the decline in performance (measured as maximal mean power, MMP) after a given amount of accumulated work, is widely recognized as a critical determinant of success in professional cycling (Muriel et al., 2022). However, there is limited evidence regarding the reliability of this measure across different contexts. Understanding the repeatability of MMP decline could provide valuable insights into performance assessment and contribute to more effective training strategies in elite cycling (Maunder et al., 2021).

The Role of Exercise Intensity and Accumulated Work

The influence of the nature of accumulated work on fatigue and subsequent performance remains an underexplored area in cycling research. While most studies have evaluated accumulated work without accounting for its specific characteristics (Mateo-March, Valenzuela, et al., 2022; Muriel et al., 2022; Sanders & van Erp, 2020), recent evidence highlights the critical role of exercise intensity in shaping fatigue responses. For example, high-intensity efforts have been shown to cause a more pronounced decline in subsequent power output compared to moderate-intensity tasks (Leo, Giorgi, et al., 2022). Additionally, cycling performance appears to deteriorate more rapidly at intensities above the gas exchange threshold than at lower intensities (Brownstein et al., 2022) underscoring the need for a more nuanced understanding of how the characteristics of accumulated work influence performance outcomes.

Competitive cycling is inherently stochastic, with races often including numerous intermittent high-intensity efforts (Etxebarria et al., 2014; Sanders & van Erp, 2020). Success in these events is associated with the ability to perform repeated high-intensity efforts and maintain performance despite fatigue. This concept has led to the introduction of terms such as 'high-intensity repeatability' and 'high-intensity durability,' which describe the ability to perform and sustain numerous high-intensity efforts, respectively (Muriel et al., 2022). Research indicates that more successful cyclists spend more racing time at high relative intensities, suggesting that the ability to tolerate such high loads is a major performance determinant (Muriel et al., 2022).

In this regard, recent investigations suggest that high-intensity work may have a differential impact on cyclists of varying performance levels, with more experienced athletes potentially demonstrating better tolerance to such demands. Furthermore, evidence indicates that work performed above critical power has a greater effect on performance decline compared to equivalent workloads carried out at lower intensities, specifically below critical power. These findings highlight the importance of understanding the interplay between work intensity and fatigue to optimize performance and tailor training strategies for elite cyclists.

Sex Differences in Durability

Despite the increasing popularity of female cycling, most scientific studies have focused on male athletes. Emerging evidence suggests that women may exhibit higher durability than men, particularly in ultra-endurance events. For instance, studies have reported that women experience less performance decline than men during prolonged endurance exercises and ultra-endurance competitions (Hunter, 2014). Deaner et al., (2015) observed that women had a lower reduction in running pace compared to men in marathons, while Baumgartner et al., (2020) found no sex differences in performance for ultra-cycling races of 400-500 miles.

Potential sex differences in durability among professional cyclists remain an underexplored area, particularly when analyzed using real-world, field-based data. Preliminary findings suggest that professional male cyclists exhibit a noticeable reduction in power output capacity even after relatively low levels of accumulated work. However, it is not yet clear whether female cyclists are better able to mitigate the effects of fatigue compared to their male counterparts. Exploring these differences could provide valuable insights into sex-specific performance determinants, contributing to a more nuanced understanding of how fatigue impacts male and female cyclists at the elite level.

GENERAL OBJECTIVE

To investigate and analyze durability as a key determinant of elite cycling performance, focusing on its repeatability, the impact of exercise intensity, and potential sex differences, with the aim of optimizing training and performance strategies.

SPECIFIC OBJECTIVES

Study 1: "Reliability of the durability concept in professional cyclists: a field-based study"

- To evaluate the repeatability of durability, measured as the decline in maximal mean power (MMP) after various levels of accumulated work in professional cyclists during training and competition conditions across a full cycling season.
- To determine the standard error of measurement (SEM) and intra-class correlation coefficient (ICC) of MMP values under fatigue, providing a reliable framework for monitoring durability as a performance indicator.
- To analyze the influence of different effort durations and fatigue levels on the variability of MMP, identifying the thresholds above which changes in durability reflect meaningful performance variations.

Study 2: "The influence of high-intensity work on the record power profile of U23, ProTeam, and World Tour cyclists"

- To compare the durability of elite cyclists across three competitive levels (U23, ProTeam, and World Tour) based on their ability to sustain MMP after high-intensity accumulated work above critical power (CP).
- To examine how performance differences between competitive categories manifest under varying levels of accumulated work, focusing on the high-intensity durability required for elite cycling success.
- To identify the thresholds of accumulated work at which significant declines in MMP occur, highlighting the role of high-intensity durability as a differentiating factor in elite cycling performance.

Study 3: "Is all work the same? Performance after accumulated work of differing intensities in male professional cyclists"

- To investigate the effects of accumulated work intensity (above and below CP) on MMP declines across various effort durations in professional cyclists.
- To analyze the interaction between accumulated work intensity and fatigue, identifying the differential impacts of high- versus low-intensity work on cycling performance.
- To assess the thresholds of work intensity and accumulated load that critically impair performance, providing insights for optimizing training strategies focused on improving high-intensity durability.

Study 4: "Sex-specific differences in durability among professional cyclists: insights from real-world power output data"

- To explore gender-specific differences in durability by comparing MMP declines in male and female professional cyclists after varying levels of accumulated work.
- To determine the relative impact of fatigue on performance for different effort durations in both genders, identifying the conditions under which female cyclists may exhibit greater performance impairments.
- To provide insights into sex-specific physiological and tactical considerations for designing training programs that address the distinct durability needs of male and female elite cyclists.

Hypotheses for Each Study

Study 1: "Reliability of the durability concept in professional cyclists: a field-based study"

- Durability, measured as the decline in maximal mean power (MMP) under fatigue, is a reliable and repeatable indicator of performance in professional cyclists, with high consistency across training and competition conditions during a full cycling season (Van Erp & Lamberts, 2021).

Study 2: "The influence of high-intensity work on the record power profile of U23, ProTeam, and World Tour cyclists"

- World Tour cyclists demonstrate superior durability compared to U23 and ProTeam cyclists, tolerating higher levels of high-intensity accumulated work above critical power (CP) before experiencing significant declines in MMP (Sanders & Heijboer, 2019).

Study 3: "Is all work the same? Performance after accumulated work of differing intensities in male professional cyclists"

- Accumulated work performed above critical power (CP) results in greater declines in MMP compared to equivalent work performed below CP, highlighting the critical role of intensity in fatigue-induced performance impairments (Brownstein et al., 2022).

Study 4: "Sex-specific differences in durability among professional cyclists: insights from real-world power output data"

- Female professional cyclists exhibit greater relative declines in MMP under fatigue compared to male cyclists, particularly during longer-duration efforts, indicating gender-specific differences in durability (Hunter, 2014).

Together, these general and specific objectives aim to provide a holistic view of durability in cycling, emphasizing its significance as a key performance determinant. By examining the repeatability of performance measures, the influence of exercise intensity, and potential sex differences, this thesis aims to contribute valuable insights into optimizing training and performance strategies for elite cyclists.

The concept of durability encompasses the ability to maintain performance under fatigue, which is crucial for success in endurance sports like cycling. To achieve these objectives: (1) the first study will evaluate the reliability and repeatability of durability measures, specifically the decline in maximal mean power (MMP) under fatigue. Establishing consistent metrics is critical for accurately assessing performance and the effectiveness of targeted interventions. (2) The second and (3) third studies will investigate the nature of accumulated work, focusing on how exercise intensity influences fatigue and subsequent performance. These studies aim to provide a deeper understanding of the role of intensity in designing training programs to enhance high-intensity durability. Finally, (4) the fourth study will explore potential sex differences in durability by analyzing field-based data from male and female professional cyclists. This approach seeks to address the lack of inclusive research in this area and provide insights to tailor training strategies to the specific needs of both male and female athletes.
Understanding and enhancing durability could have important potential applications in elite cycling. Coaches and sports scientists might use reliable measures of durability to monitor athletes' performance and adjust training loads to optimize outcomes. By considering the nature of accumulated work, training programs could be tailored to improve high-intensity durability, a critical factor for success in competitive cycling. Furthermore, recognizing potential sex differences in durability could pave the way for more personalized training strategies that address the specific needs of male and female cyclists.

Durability is increasingly recognized as a key performance determinant in elite cycling, encompassing the ability to sustain high power output levels under fatigue. This thesis seeks to explore various facets of durability through four studies, including its repeatability, the influence of exercise intensity, and potential sex differences. By advancing the understanding of durability, this research aims to provide insights that could inform training and performance strategies to enhance success in elite cycling. As the field of sports science evolves, the findings of this thesis have the potential to contribute to the development of more effective and individualized training approaches, ultimately improving performance outcomes in competitive cycling.

SUMMARY OF METHODS

Participants and Study Design

The research encompassed four independent studies involving professional male and female cyclists from various teams, representing diverse levels of expertise and competition categories. Participants engaged in different phases of their training and competition schedules to ensure the ecological validity of the data. Each study adhered strictly to ethical standards, with participants providing written informed consent. The research protocols were approved by local ethics committees, ensuring compliance with the Declaration of Helsinki guidelines.

Study 1: Repeatability of Durability

This study investigated the reliability of durability as a performance indicator in 18 male professional cyclists from a World Tour team (age 27 ± 4 years; body mass 65.5 ± 4.3 kg). Data collection spanned a full cycling season (November 2021 to October 2022), covering training sessions and competitive events. Using factory-calibrated power meters, the highest maximum mean power (MMP) values for different effort durations (10 seconds, 1, 5, 10, and 20 minutes) were recorded after various levels of accumulated work (0–40 $kJ \cdot kg^{-1}$). Repeatability was assessed using the standard error of measurement (SEM) and intraclass correlation coefficient (ICC) for MMP values across conditions, ensuring robust statistical evaluation.

Study 2: High-Intensity Durability

The second study explored the effects of accumulated work above critical power (CP) on MMP across different performance levels. A total of 49 male cyclists participated, categorized as U23 (n=11), ProTeam (n=13), and World Tour (n=24). CP was evaluated during the pre-season using field-based tests involving multiple maximal efforts of varying durations (2–20 minutes). MMP values for efforts ranging from 5 seconds to 30 minutes were recorded after accumulated work at increasing intensities above CP (0–7.5 $kJ \cdot kg^{-1}$). Data collection was conducted from November 2021 to October 2022. The influence of accumulated work on MMP was analyzed using one-way ANOVA, with post-hoc tests applied to identify significant differences between conditions and performance categories.

Study 3: Intensity of Accumulated Work

This observational study examined the effects of exercise intensity on performance under conditions of accumulated work. Seventeen male WorldTour cyclists participated, with data collected during a competitive season (January to October). MMP values for effort durations (5 seconds, 5 minutes, 10 minutes, and 20 minutes) were measured under ‘fresh’ conditions and after accumulated work at varying intensities (2.5, 5.0, and 7.5 $kJ \cdot kg^{-1}$) performed either above or below CP. CP was reassessed every four weeks to account for physiological adaptations during the season. Data were analyzed using repeated-measures ANOVA to determine the interaction between work intensity and MMP decline.

Study 4: Sex Differences in Durability

The fourth study focused on gender-specific differences in durability. Data were collected over multiple seasons (2013–2021) from male and female professional cyclists (specific numbers and ages not reported). MMP values for effort durations (10 seconds, 1 minute, 5 minutes, and 20 minutes) were recorded under ‘fresh’ conditions and after accumulated work at three levels (10, 20, and 30 $kJ \cdot kg^{-1}$). The interaction between accumulated work and MMP decline was analyzed using a mixed-design repeated-measures ANOVA, allowing comparisons between male and female cyclists.

General Procedures

Power output data were collected using various factory-calibrated power meters (Power2Max, SRAM Red Quarq, Shimano Dura-Ace, and Pioneer). All devices were zero-offset before each session to ensure measurement accuracy. Data were scrutinized for abnormalities, such as "spikes," and were either corrected or excluded based on rigorous quality-control protocols. This ensured that only valid and reliable data were included in the analyses.

Statistical Analysis

Data were presented as mean ± standard deviation (SD). Normality was tested using the Shapiro-Wilk test, and differences between conditions were analyzed using various statistical methods, including one-way and repeated-measures ANOVA. Post-hoc Bonferroni corrections were applied where appropriate to account for multiple comparisons. SEM and ICC values were calculated to assess the reliability of MMP measurements. A significance level of $p \leq 0.05$ was set for all analyses, ensuring robust statistical inference.

Tables and Figures

Comprehensive tables and figures were prepared to visualize the results, including descriptive statistics of participants, MMP values across conditions, and the effects of accumulated work and exercise intensity on performance. Graphical representations provided clear insights into the relationships between CP, MMP, and accumulated work, facilitating the interpretation of complex datasets.

Ethical Considerations

All studies adhered to ethical research principles, with protocols approved by local ethics committees. Participants provided informed consent after being fully briefed on the procedures and potential risks. The studies followed the ethical standards set by the Declaration of Helsinki.

Conclusion

This methodological framework allowed for a detailed examination of durability as a multifaceted determinant of cycling performance. By addressing repeatability, the impact of high-intensity work, and sex-specific differences, the studies provide valuable insights for advancing the understanding of durability in elite cycling. The robust data collection and analytical approaches underscore the validity of durability as a key performance metric and its potential applications in training and competition.

GENERAL DISCUSSION

The studies integrated in this thesis collectively underscore the significance of durability as a critical determinant of elite cycling performance. Durability, defined as the ability to maintain high power output (PO) under fatigue (Maunder et al., 2021), has been examined through various lenses including repeatability, the impact of high-intensity accumulated work, and potential sex differences. This discussion synthesizes key findings from each study, addresses their implications, acknowledges limitations, and suggests avenues for future research.

Repeatability of Durability

The first study demonstrated that the decline in PO after a given accumulated work is a highly repeatable measure of field-based performance. This high repeatability, indicated by low standard error of measurement (SEM) and high intra-class correlation coefficient (ICC), suggests that even small improvements in durability (<5%) can reflect significant performance changes. The study highlights the importance of using both training and competition data to capture the full spectrum of maximal efforts exerted by cyclists. However, the slightly lower repeatability observed for the shortest efforts (10-second MMP) suggests the need for specific sprint tests to assess this parameter accurately.

Despite the robustness of the findings, some limitations must be acknowledged. The study could not determine whether the observed inter-individual variability in MMP values was due to biological differences or technical factors such as power meter discrepancies. Additionally, while MMP values are indicative of a cyclist's capabilities, they do not necessarily represent their maximum potential (Jesús G. Pallares Pedro L. Valenzuela Xabier Muriel Manuel Mateo-March David Barranco-Gil and Alejandro Lucia, 2022). External factors like environmental conditions and changes in body mass were not accounted for, which could influence MMP values (Manuel Mateo-March Pedro L. Valenzuela Alexis Gandia-Soriano Mikel Zabala David Barranco-Gil Jesús G. Pallares Alejandro Lucia, 2022; Valenzuela, Mateo-March, et al., 2022). Nonetheless, the high-performance level of the participants and the ecological validity of the data strengthen the study's conclusions.

Impact of High-Intensity Accumulated Work

The second study revealed that the record power profile (RPP) of professional cyclists declines after high-intensity exercise (~5 kJ·kg-1 above CP), equivalent to ~330 kJ of total work. Notably, higher-level cyclists (World Tour) could tolerate greater levels of accumulated work before performance impairment, highlighting the importance of high-intensity durability. This finding aligns with previous research indicating that more successful cyclists can sustain higher intensities for longer durations (Valenzuela, Muriel, et al., 2022).

Most studies to date have assessed accumulated work without considering its nature per se (in terms of intensity), even if recent preliminary evidence suggests that high-intensity exercise can induce a larger decline in subsequent power output levels compared to moderate-intensity tasks (Leo et al., 2022). The study's novel contribution lies in its focus on the impact of high-intensity accumulated work on durability, showing that even low doses of high-intensity exercise can reduce MMP values. However, limitations include the single assessment of CP during the pre-season and potential inaccuracies in RPP due to the inability to confirm if MMP values represented true maximal efforts. Future research should explore the differential effects of high versus moderate intensity accumulated work on performance.

Intensity of Accumulated Work

The third study provided evidence that even small amounts of high-intensity accumulated work (above CP) can impair performance in male professional cyclists, whereas similar or higher amounts of low-intensity work do not have the same effect. This finding emphasizes the significant role of exercise intensity in inducing fatigue, supporting the use of CP as a critical threshold for performance monitoring.

Previous studies have suggested that low levels of accumulated work can induce fatigue in highly trained cyclists, but the role of intensity was not clear (Mateo-March et al., 2022; van Erp et al., 2021). This study fills that gap, demonstrating that high-intensity work above CP leads to greater performance declines. However, the observational nature of the study and the relatively small sample size limit the generalizability of the findings. Additionally, the potential influence of environmental factors on CP calculations suggests a need for more comprehensive methodologies that account for these variables (Manuel Mateo-March Pedro L. Valenzuela Alexis Gandia-Soriano Mikel Zabala David Barranco-Gil Jesús G. Pallares Alejandro Lucia, 2022; Valenzuela, Mateo-March, et al., 2022).

Sex Differences in Durability

The fourth study addressed potential sex differences in durability, showing that both male and female professional cyclists experience significant MMP declines after >10 kJ·kg-1 accumulated work. However, female cyclists exhibited greater relative performance decay, particularly for efforts lasting ≥1 minute, suggesting lower durability compared to their male counterparts.

Contrary to some previous studies suggesting higher fatigue resistance in women (Glace et al., 1998; Temesi et al., 2015). this study indicates that female cyclists might be more affected by accumulated work. The observed sex differences could be due to physiological factors such as differences in muscle fiber composition, hormonal influences, or varying tactical demands between male and female races. Limitations include the use of field-derived power output data, which may not fully capture maximal capabilities, and potential confounding factors like environmental conditions and race strategies (Manuel Mateo-March Pedro L. Valenzuela Alexis Gandia-Soriano Mikel Zabala David Barranco-Gil Jesús G. Pallares Alejandro Lucia, 2022; Mateo-March et al., 2024; Valenzuela, Mateo-March, et al., 2022). Further experimental research is needed to confirm these findings and explore underlying mechanisms.

Practical Implications

The insights gained from these studies have significant practical implications for training and performance optimization in elite cycling. Coaches and sports scientists can use reliable measures of durability to monitor athletes' performance and adjust training loads accordingly. Emphasizing high-intensity durability in training programs can enhance cyclists' ability to sustain high intensities during competitions. Additionally, recognizing sex differences in durability can inform personalized training strategies that address the specific needs of male and female cyclists.

Limitations identified in each study

The studies presented in this thesis exhibit limitations that should be acknowledged. Firstly, the inability to differentiate between biological variability and technical discrepancies, such as differences in power meter models, may have influenced the observed variability in performance metrics. Additionally, not all recorded maximum mean power (MMP) values necessarily represent true maximal efforts, limiting the conclusions about absolute capacity. Environmental factors, such as weather conditions and body mass changes, were not standardized across studies and could have affected performance outcomes. For shorter effort durations (e.g., 10-second MMP), lower repeatability was observed, highlighting the need for specific sprint assessments.

The assessment of critical power (CP) was limited to a single pre-season measurement, potentially overlooking seasonal variations. Furthermore, while focusing on the impact of high-intensity work, other characteristics of accumulated work, such as intermittent versus continuous efforts, were not fully explored. Observational designs and relatively small sample sizes in some studies limit the generalizability of findings, particularly in exploring sex differences and real-world cycling scenarios. Finally, the use of field-based data, though ecologically valid, may not always capture true maximal efforts or account for tactical and physiological differences, such as hormonal influences or muscle fiber composition, between male and female cyclists. These limitations highlight the need for controlled experimental designs, broader participant samples, and standardized testing protocols in future research.

Future research perspectives

Future research on durability in professional cycling should focus on optimizing training programs tailored to individual athletes, utilizing critical power (CP) and maximum mean power (MMP) data to improve performance across different competitive levels. This includes evaluating the impact of nutritional interventions and recovery strategies in enhancing durability under fatigue. Additionally, understanding the physiological and biomechanical underpinnings of durability is essential, such as analyzing muscle fiber composition, metabolic profiles, and pedaling biomechanics to optimize efficiency under accumulated work. Longitudinal studies are needed to track how durability evolves throughout a competitive season and a cyclist’s career, while exploring the long-term effects of different periodization strategies.

Expanding research to other cycling disciplines, such as mountain biking, cyclocross, and track cycling, and assessing the influence of environmental factors like terrain, weather, and altitude on durability is also critical. From a gender perspective, future investigations should explore physiological, hormonal, and tactical differences between male and female cyclists to develop tailored training strategies, considering factors such as the menstrual cycle, menopause, or contraceptive use in female athletes. Technological advancements, including artificial intelligence and wearable devices, could facilitate real-time analysis of durability-related parameters and improve training decision-making. Lastly, research into the psychological and tactical aspects of durability, including motivation, perceived exertion, and race strategies, could provide valuable insights into optimizing performance in competitive scenarios. These directions will collectively enhance our understanding and application of durability in cycling.

GENERAL CONCLUSIONS

The findings presented in this thesis collectively highlight the importance of durability as a critical determinant of performance in professional cycling. Durability, defined as the ability to maintain high power output under fatigue, was shown to be a highly repeatable and reliable metric across a competitive season, reinforcing its validity as a performance indicator. The results demonstrate that higher-level cyclists, such as those in World Tour teams, exhibit greater durability compared to their ProTeam and U23 counterparts, tolerating higher levels of accumulated work before experiencing significant declines in MMP. This suggests that durability is not only a function of absolute performance capacity but also reflects the ability to sustain performance under conditions of fatigue, which is essential in the stochastic nature of competitive cycling. The studies also revealed that the intensity of accumulated work significantly impacts performance declines, with high-intensity efforts above critical power (CP) causing greater impairments than equivalent work performed at lower intensities. This emphasizes the importance of considering exercise intensity in the design of training and competition strategies.

Sex-specific differences in durability were observed, with female cyclists displaying greater relative declines in MMP under fatigue compared to male cyclists, particularly during longer efforts. These findings underscore the necessity for gender-specific approaches in training and performance monitoring. Despite these insights, the ecological nature of the studies points to the need for controlled experimental designs to further investigate underlying physiological and biomechanical factors contributing to durability, such as muscle fiber composition, metabolic efficiency, and pedaling mechanics.

The practical implications of these findings are significant, as they provide a robust foundation for optimizing training programs to enhance high-intensity durability and tailoring strategies to the individual needs of athletes. By integrating measures of durability into regular performance monitoring and leveraging advanced technologies for real-time data collection, coaches and sports scientists can better predict performance outcomes and refine training prescriptions. Overall, this thesis contributes to a more comprehensive understanding of the multifaceted nature of durability, establishing it as a cornerstone of competitive cycling performance and a vital focus for future research and practical application.

CONCLUSIONES GENERALES

Los hallazgos presentados en esta tesis destacan colectivamente la importancia de la durabilidad como un determinante crítico del rendimiento en el ciclismo profesional. La durabilidad, definida como la capacidad de mantener una alta producción de potencia bajo fatiga, ha demostrado ser una métrica altamente repetible y confiable a lo largo de una temporada competitiva, lo que refuerza su validez como indicador de rendimiento. Los resultados muestran que los ciclistas de mayor nivel, como aquellos que compiten en equipos del World Tour, presentan una mayor durabilidad en comparación con sus homólogos de equipos ProTeam y de la categoría sub-23, ya que toleran mayores niveles de trabajo acumulado antes de experimentar descensos significativos en su Potencia Media Máxima (MMP). Esto sugiere que la durabilidad no solo es una función de la capacidad de rendimiento absoluto, sino que también refleja la habilidad de sostener el rendimiento en condiciones de fatiga, aspecto esencial en la naturaleza estocástica del ciclismo competitivo.

Los estudios también revelaron que la intensidad del trabajo acumulado impacta significativamente en la disminución del rendimiento, siendo los esfuerzos de alta intensidad por encima de la Potencia Crítica (CP) los que causan mayores deterioros en comparación con un trabajo equivalente realizado a intensidades más bajas. Esto enfatiza la importancia de considerar la intensidad del ejercicio en el diseño de estrategias de entrenamiento y competición.

Se observaron diferencias específicas por sexo en la durabilidad, con las ciclistas femeninas mostrando mayores descensos relativos en la MMP bajo fatiga en comparación con los ciclistas masculinos, especialmente durante esfuerzos más prolongados. Estos hallazgos subrayan la necesidad de enfoques diferenciados por género en la planificación del entrenamiento y en la monitorización del rendimiento. A pesar de estas aportaciones, la naturaleza ecológica de los estudios señala la necesidad de diseños experimentales controlados para investigar en mayor profundidad los factores fisiológicos y biomecánicos subyacentes que contribuyen a la durabilidad, como la composición de fibras musculares, la eficiencia metabólica y la mecánica del pedaleo.

Las implicaciones prácticas de estos hallazgos son significativas, ya que proporcionan una base sólida para optimizar los programas de entrenamiento con el objetivo de mejorar la durabilidad en esfuerzos de alta intensidad y adaptar las estrategias a las necesidades individuales de los deportistas. Integrar medidas de durabilidad en la monitorización habitual del rendimiento y aprovechar tecnologías avanzadas para la recopilación de datos en tiempo real permitirá a entrenadores y científicos del deporte predecir mejor los resultados del rendimiento y refinar la prescripción del entrenamiento. En general, esta tesis contribuye a una comprensión más completa de la naturaleza multifacética de la durabilidad, estableciéndola como un pilar fundamental del rendimiento en el ciclismo competitivo y un foco clave para futuras investigaciones y aplicaciones prácticas.

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APPENDIX 1

Reliability of the durability concept in professional cyclists: a field-based study

The study was previously submitted as:

Mateo-March, M., Hernández-Belmonte, A., Javaloyes, A., Muriel, X., Barranco-Gil, D., Pallarés, J. G., Lucia, A., & Valenzuela, P. L. (2024). Reliability of the durability concept in professional cyclists: a field-based study. Journal of sports sciences. In review

This journal is indexed in the Journal Citation Reports with an impact factor of 2.300 (2023) and is ranked 42 out of 127 in the category of sports sciences, and additionally, the journal remains in the Q2 category.

ABSTRACT

Background: Durability is increasingly recognized as a determinant of cycling performance. However, the interpretation of changes in durability requires this indicator to be reliable, which would enable discerning real performance changes from inherent biological variability. We assessed the repeatability of durability (determined as the ability to attenuate the decline in power output [PO] values after accumulated work).

Methods: We registered the highest PO values (i.e., maximum mean power values [MMP]) attained by 18 professional cyclists (27±4yrs) during training and competition for different effort durations (10 seconds, and 1, 5, 10, and 20 minutes) after different levels of accumulated work (0-40 kJ·kg-1) during a cycling season. Repeatability was examined through the standard error of measurement (SEM) and the intra-class correlation coefficient (ICC) calculated from the two highest MMP values obtained by each cyclist for each duration and level of accumulated work.

Results: A progressive decline of MMP values compared to the non-fatigued state was observed after previously accumulated works of 20 kJ/kg (20-minute MMP, $p<0.05$ to $p<0.001$), 30 kJ/kg (5 and 20-minute MMP, $p<0.05$ to $p<0.001$), and 40 kJ/kg (all MMP, $p<0.001$). All MMP values showed a high repeatability under fatigue states (all SEM<5%, ICC>0.90), with the lowest repeatability observed for the shortest efforts (10-second MMP). These findings were confirmed separately for training sessions and competitions, albeit with a lower repeatability (SEM<8% and ICC>0.80).

Conclusions: The measure of durability (as MMP decline) appears reliable even under fatigue conditions, which might support its validity for monitoring field-based performance in professional cyclists.

KEYWORDS: cycling, power output, endurance, performance, assessment

INTRODUCTION

The ability to attain high power output (PO) values per se (also known as 'maximum mean power' [MMP]) for different effort durations is a major determinant of elite cycling performance.[1] Yet growing evidence shows that the ability to maintain MMP levels under fatigue—the so-called 'durability'—might be a more important determinant factor of performance.[2–7] For instance, Van Erp et al. reported that differences in MMP between successful and less succesful professional cyclists enlarged under fatigue conditions.[2] Similarly, Mateo-March et al. recently showed that, after an equivalent amount of accumulated work, World-Tour cyclists showed a lower decline in MMP than their ProTeam referents.[5]

Research on the durability paradigm is growing—notably, with respect to the factors associated with interindividual variability in the magnitude of PO decline after a given accumulated work,[8] the role of different exercise-related factors (e.g., volume or intensity) on subsequent performance decline,[8] or the effectiveness of nutritional[9] or training interventions[10] aimed at improving durability. Of note, however, the interpretation of durability (or any other performance-related) requires this indicator to be reliable,[11 12] wherein a cyclist experiences a similar MMP decline when exposed to the same accumulated work under the same conditions. Otherwise, coaches and scientists would be unable to determine whether a modification in the MMP decline after a given work reflects the biological and methodological variability inherent to this measure or a real change in durability.[13] This question is especially relevant when considering that, in elite sports, small variations in performance make the difference between the winner of a race and his/her contenders with a very similar competition level.

Although the MMP under fresh conditions is emerging as an important, reliable performance indicator in professional cyclists,[14] to the best of our knowledge no evidence exists on the repeatability of this measure under fatigue conditions. This study therefore aimed to examine the repeatability of durability (i.e., here determined as the decline in performance [MMP] after a given accumulated work) in male professional cyclists.

METHODS

Participants

Eighteen male professional road cyclists from the same World-Tour team (age 27 ± 4 years; body mass, 65.5 ± 4.3 kg; experience in the professional category, 5 ± 3 years) volunteered to participate in this study. Cyclists were free of any type of musculoskeletal injury that would have hindered their participation in the study. All participants were informed of all the procedures and signed an informed consent form. The study protocol was approved by the local university ethics committee, and all procedures were conducted following the standards set by the Declaration of Helsinki.

Study design

The study was conducted during a whole cycling season (November 2021 to October 2022). Data were registered during all training sessions and competitions in that period, and the highest PO values (i.e., MMP) attained for different effort durations (i.e., 10 seconds, 1, 5, 10 and 20 minutes) after different levels of accumulated work (between 0 and 40 kJ/kg) were determined. Repeatability was assessed through the analysis of the two highest MMP values attained during the season.

Procedures

PO was registered with two different types of power meters (Power2Max Type SNieder

Seifersdorf; Waldhufen, Germany; or SRM Red, Quarq, Spearfish, SD), but always the same for each participant. All devices were factory-calibrated at the beginning of the season, and a zero offset was performed before each training session or competition attending to manufacturers' instructions. Each PO file was checked for non-physiological or outlying data points ('spikes') using a specific software (WKO5 Build 576; TrainingPeaks LLC, Boulder, CO), with these points manually corrected with the Data Spike ID and FIX chart when a nonprogressive increase or decrease in PO appeared near the maximum values for each effort duration—that is, an upward or downward variation >10% from a previous series of data (e.g., a spike of 455 W following a series of 345, 346, 345, 348, and 350 W). When more than 50 records for a single session file were found to be erroneous, the file was excluded from further analysis. The two highest MMP values attained through the season were determined for different effort durations (i.e., 10 seconds, and 1, 5, 10 and 20 minutes) and after different levels of accumulated work (between 0 and 40 kJ/kg) as explained elsewhere.[5,14] The duration of MMP and the levels of accumulated work were restricted to the aforementioned ranges to ensure that they corresponded to true maximal efforts.

Statistical analyses

The effect of different levels of accumulated work on a given MMP compared to the 'fresh' state (0 kJ/kg) was determined through one-way repeated measures analysis of variance (ANOVA), with the Bonferroni test applied post hoc. We assessed the repeatability of the decline in MMP after a given accumulated work for each effort duration. The standard error of measurement (SEM) was calculated from the square root of the mean square error term using repeated-measures ANOVA,[15] and expressed in W and $W \cdot kg^{-1}$. The SEM was also expressed in relative terms (%, i.e. [100*SEM]/mean) in order to enable the comparison between the different MMP. To address potential variations between the different periods of the cycling season, sensitivity analyses were performed categorizing the data into two distinct periods: the preparation (which solely included training sessions) and the competition period (wherein only competition data were included in the analyses). Statistical analyses were performed using the SPSS software version 26.0 (IBM Corp., Armonk, NY).

RESULTS

A total of 6570 $\pm$ 43 PO files (293 $\pm$ 27 for training sessions and 73 $\pm$ 11 for competitions per cyclist) were analyzed.

Participants' MMP averaged 992, 596, 456, and 429 W for 10-second, 1-minute, 5-minute, and 20-minute effort-duration, respectively, under fresh conditions (corresponding to 14.8, 8.9, 6.8 and 6.4 $W \cdot kg^{-1}$). Although no significant decline was observed for any MMP value after 10 kJ/kg compared to the fresh state, a significant decline was observed for the longest efforts after 20 kJ/kg (i.e., $p<0.05$ and $p<0.01$ for 20-minute MMP) (Figure 1). A significant decline in all MMP values was also observed after 40 kJ/kg ($p<0.001$ for all) (**Figure 1**).

When analyzing training sessions and competitions together, all MMP showed a high repeatability regardless of effort duration and level of accumulated work (all SEM<5%, intra-class correlation coefficient [ICC]>0.90) (**Table 1**). Notwithstanding, a trend towards lower repeatability was found with greater levels of fatigue and shorter effort durations, particularly for 10-second MMP (**Table 1**). These findings were overall confirmed when separately analyzing training sessions and competitions, albeit with a slightly higher variability than when analyzing the two conditions together (SEM ≤8% and ICC>0.80) (**Supplementary Table 1**).

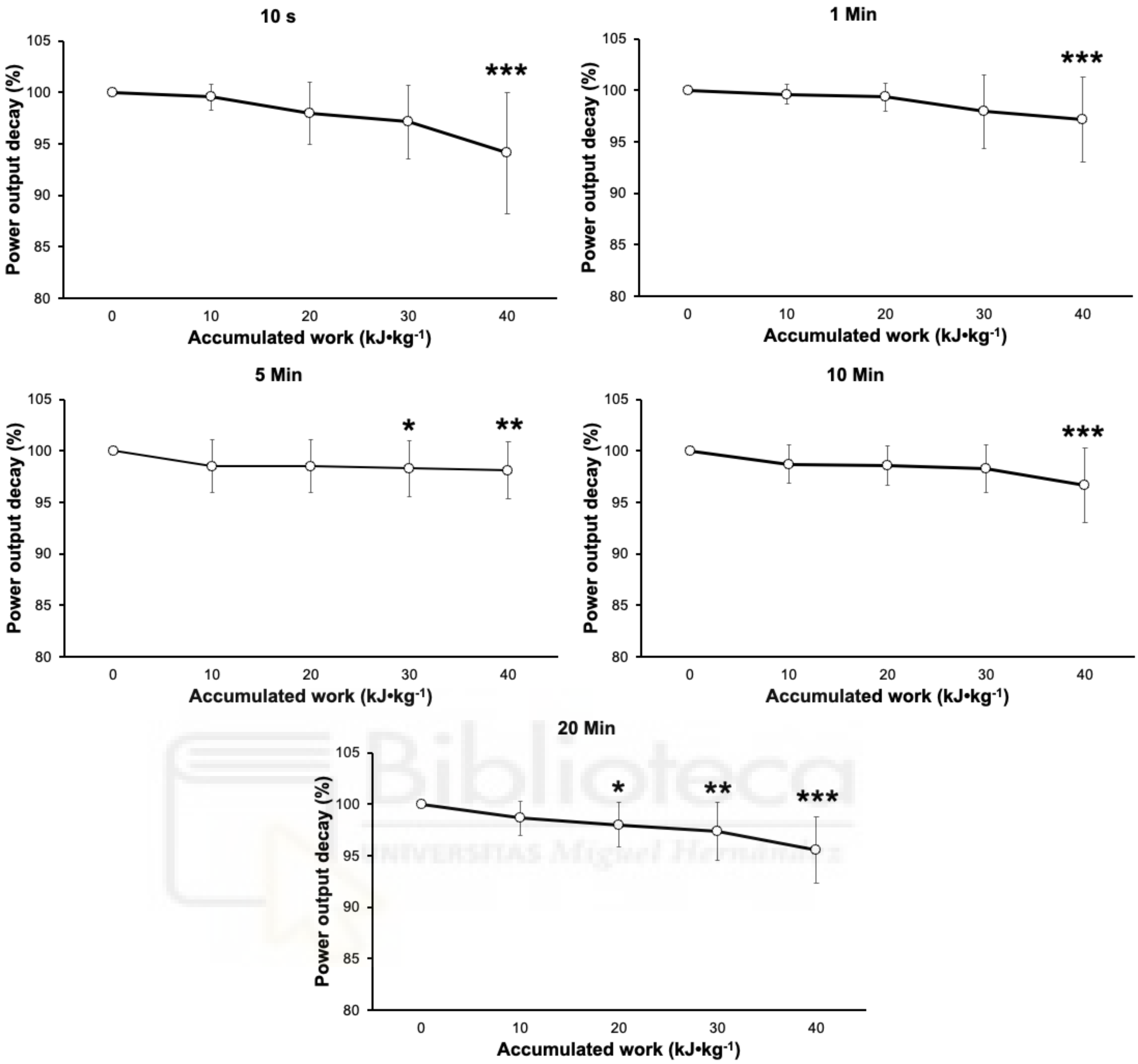

Figure 1. Maximum mean power values attained for different effort durations after different levels of accumulated work. Differences compared to the fresh state (0 kJ/kg): *p<0.05, **p<0.01, ***p<0.001.

Table 1. Repeatability of maximum mean power (MMP) values for different effort durations and after different levels of accumulated work.

Effort duration		**No fatigue**	**10 kJ/kg**	**20 kJ/kg**	**30 kJ/kg**	**40 kJ/kg**
10 seconds	*SEM ($W \cdot kg^{-1}$)*	0.43	0.47	0.52	0.73	0.64
	SEM (%)	2.8	3.1	3.4	4.9	4.4
	ICC	0.935	0.926	0.907	0.833	0.912
1 minute	*SEM ($W \cdot kg^{-1}$)*	0.16	0.20	0.24	0.23	0.22
	SEM (%)	1.8	2.2	2.6	2.5	2.5
	ICC	0.962	0.953	0.933	0.953	0.961
5 minutes	*SEM ($W \cdot kg^{-1}$)*	0.13	0.14	0.14	0.14	0.19
	SEM (%)	1.8	2.0	2.0	2.1	2.8
	ICC	0.954	0.950	0.950	0.949	0.906
10 minutes	*SEM ($W \cdot kg^{-1}$)*	0.13	0.11	0.16	0.16	0.10
	SEM (%)	1.9	1.7	2.5	2.6	1.5
	ICC	0.955	0.967	0.935	0.934	0.980
20 minutes	*SEM ($W \cdot kg^{-1}$)*	0.08	0.11	0.14	0.13	0.13
	SEM (%)	1.3	1.9	2.3	2.2	2.2
	ICC	0.979	0.959	0.944	0.953	0.953

Power output data were obtained across a whole cycling season from both training sessions and competitions. Abbreviations: SEM; standard error of measurement; ICC, intraclass correlation coefficient. Relative SEM (in $W \cdot kg^{-1}$) was computed with the average body mass of each cyclist through the season.

Supplementary Table 1. Repeatability of maximum mean power (MMP) values for different effort durations and after different levels of accumulated work during training sessions or competitions. Abbreviations: SEM; standard error of measurement; ICC, intraclass correlation coefficient.

		No fatigue		**10 kJ/kg**		**20 kJ/kg**		**30 kJ/kg**		**40 kJ/kg**	
		Training	*Competition*	*Training*	*Competition*	*Training*	*Competition*	*Training*	*Competition*	*Training*	*Competition*
10 sec	*SEM (W·kg⁻¹)*	0.55	0.54	0.59	0.55	0.26	0.63	1.06	0.75	0.85	0.74
	SEM (%)	3.7	3.6	4.1	3.8	1.9	4.4	7.8	5.2	6.6	5.2
	ICC	0.949	0.910	0.944	0.902	0.99	0.869	0.858	0.811	0.939	0.840
1 min	*SEM (W·kg⁻¹)*	0.35	0.22	0.34	0.29	0.29	0.30	0.25	0.27	0.34	0.31
	SEM (%)	4.0	2.4	3.9	3.3	3.3	3.3	3.0	3.1	4.3	3.5
	ICC	0.895	0.925	0.91	0.897	0.933	0.896	0.948	0.928	0.923	0.915
5 min	*SEM (W·kg⁻¹)*	0.14	0.14	0.16	0.13	0.23	0.13	0.27	0.14	0.34	0.19
	SEM (%)	2.1	2.1	2.4	1.9	3.6	1.9	4.1	2.1	5.4	2.7
	ICC	0.952	0.949	0.929	0.959	0.864	0.959	0.833	0.955	0.718	0.918
10 min	*SEM (W·kg⁻¹)*	0.13	0.13	0.14	0.09	0.23	0.11	0.22	0.12	0.31	0.10
	SEM (%)	2.1	2.0	2.2	1.5	3.7	1.7	3.7	1.9	5.4	1.6
	ICC	0.947	0.953	0.943	0.979	0.843	0.971	0.858	0.967	0.768	0.979
20 min	*SEM (W·kg⁻¹)*	0.08	0.09	0.10	0.13	0.17	0.16	0.20	0.14	0.16	0.14
	SEM (%)	1.4	1.5	1.7	2.2	3.1	2.7	3.7	2.5	3.1	2.4
	ICC	0.98	0.971	0.964	0.949	0.886	0.928	0.825	0.942	0.938	0.954

Abbreviations: SEM; standard error of measurement; ICC, intraclass correlation coefficient.

DISCUSSION

The findings of this study suggest that the decline in PO after a given accumulated work (usually considered an indicator of durability) is a repeatable measure of field-based performance.

The observed SEM values support indeed the high repeatability of durability, and might allow cyclists and coaches to establish for each individual cyclist—or group of cyclists with the same performance level—the minimum threshold above which a change in durability would to reflect a real change in actual performance.[12] In this regard, the present study suggests that even improvements of small magnitude (<5%) might be considered relevant, that is, above the normal variation observed for this parameter. It must be noted, nonetheless, that in line with our previous report analyzing the repeatability of the 'fresh' MMP,[14] a slightly lower repeatability was observed in the present study when separately analyzing training sessions or competitions alone, which support the importance of gathering both types of data, particularly given the higher number of maximal efforts that the cyclists must perform during official races and in-season training compared to the preparation period.[16] Moreover, in line with our previous study,[14] a lower repeatability was observed for the shortest efforts (i.e., 10-second MMP), which might reinforce the need for including *ad hoc* sprint tests for assessing this indicator.

Several limitations and potential confounders should be considered in this study. First, we cannot discern whether the inter-individual variability observed for MMP values was attributable to actual biological differences or technical factors (e.g., differences between power meters). In addition, we cannot ensure that all efforts were maximal, as MMP values solely represent what the cyclists did, but not necessarily what they are capable of. Notwithstanding, evidence suggests that MMP values might be a valid indicator of cyclists' maximal capabilities.[17] It is also worth noting that several factors can influence MMP values that were not accounted for (e.g., environmental conditions, changes in body mass),[18,19] and that a given accumulated work might induce a different fatigue level depending on factors such as intensity.[20] In turn, strengths of the present study are the high performance level of the participants as well as the ecological validity of the recorded data.

CONCLUSIONS

The decline in PO after a given accumulated work (commonly assessed as an indicator of durability) appears highly repeatable through a cycling season, which might support the validity of this measure for monitoring field-based performance. In order to increase the validity and repeatability of this indicator, it might be recommendable not only to include both training and competition data, but also *ad hoc* sprint tests. The SEM values reported here might be of assistance for scientists and coaches to establish the minimum threshold above which a change in durability would reflect a change in actual performance.

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APPENDIX 2

The influence of high-intensity work on the record power profile of U23, Pro and World Team cyclists

The study was previously published as:

Leo, P., Mateo-March, M., Giorgi, A., Muriel, X., Javaloyes, A., Barranco-Gil, D., Pallarés, J. G., Lucia, A., Mujika, I., & Valenzuela, P. L. (2024). The Influence of High-Intensity Work on the Record Power Profile of Under-23, Pro Team, and World Tour Cyclists. International journal of sports physiology and performance, 19(6), 545–549. https://doi.org/10.1123/ijspp.2023-0451

This journal is indexed in the Journal Citation Reports with an impact factor of 3.500 (2023) and is ranked 11 out of 127 in the category of sports sciences, and additionally, the journal remains in the Q1 category.

ABSTRACT

BACKGROUND:
Durability (i.e., the ability to attenuate the decline in performance after accumulated work) has been identified as a performance determinant in elite cyclists. The aim of the present study was to compare durability in elite cyclists of various performance levels, particularly after high-intensity work, referred to as 'high-intensity durability'.

METHODS:
Forty-nine (N=49) male road cyclists were categorized as either U23 (N=11), ProTeam (N=13) or World Tour (N=24). The participants' critical power (CP) was assessed during the pre-season. Thereafter, the participants' maximum mean power (MMP) values were determined for efforts of different durations (from 5 seconds to 30 minutes) after different levels of accumulated work above CP (from 0 to 7.5 $kJ \cdot kg^{-1}$).

RESULTS:
U23 cyclists showed a significant reduction of all relative MMP values for durations ≥1 minute after ≥5 $kJ \cdot kg^{-1}$ above CP compared to the 'fresh' state (0 $kJ \cdot kg^{-1}$), whereas in ProTeam and World Tour cyclists a significant reduction was not observed until 7.5 $kJ \cdot kg^{-1}$ above CP. In the 'fresh' state, both ProTeam and particularly World Tour cyclists attained higher MMP values for efforts ≥ 10 minutes than U23 riders. However, more differences emerged with greater previous work levels, and indeed after 7.5 $kJ \cdot kg^{-1}$ above CP World Tour cyclists attained higher MMP values than both U23 and ProTeam cyclists for most efforts (≥30 seconds).

CONCLUSION:
ProTeam and particularly World Tour cyclists tolerate greater levels of accumulated work at high intensity, which might support the importance of high-intensity durability for performance.

KEYWORDS: cycling, racing, volume, intensity, periodization, performance

INTRODUCTION

The record power profile (RPP, i.e., the highest power output that a cyclist can attain for different effort durations under field-based conditions) is a major determinant of elite cycling performance [1,2]. The ability to attenuate the deterioration in the physiological responses to exercise under fatigue and/or to maintain high power output values under fatigue, often referred to as 'durability', is also a critical factor [3]. Indeed, recent evidence suggests that the ability to sustain power output after accumulated work, rather than in 'fresh' conditions, is a key performance determinant [4–6]. Notably, Mateo-March et al. [5] recently reported that, after an equivalent amount of accumulated work, World Tour cyclists show a lower decline in RPP than ProTeam peers.

Preliminary evidence suggests that not only the quantity, but also the nature of the previously accumulated work might influence the level of fatigue experienced and thus its effects on performance. Although most studies to date have assessed accumulated work without considering its nature per se (e.g., whether intensity is high or low, or whether the effort is continuous or intermittent), Leo et al. recently reported that previous high-intensity intermittent exercise induces a larger decline in subsequent power output levels than moderate-intensity tasks [7,8]. Furthermore, subsequent cycling performance declines at intensities above the gas exchange threshold more rapidly than at intensities below this threshold [8].

The aforementioned findings might be of relevance, particularly given the essentially stochastic nature of competitive cycling[9], with most races typically including numerous intermittent, high-intensity efforts—which is also the case in other events such as mountain biking or triathlon races [10,11]. It has been indeed reported that the more successful cyclists spend more racing time at high relative intensities (e.g., above the so-called functional threshold power or above the critical power [CP]) than less successful riders [2], thereby suggesting that the ability to tolerate such high loads is a major performance determinant. This has led to the concepts of 'high-intensity repeatability' (the ability to perform numerous high-intensity efforts, e.g., above CP) and 'high-intensity durability' (the ability to attenuate the subsequent performance decrement induced by this type of efforts) [3].

The aim of the present study was to compare high-intensity durability in cyclists of different performance levels. We hypothesized that Pro Team and World Tour cyclists better tolerate high-intensity work than U23 cyclists.

MATERIALS & METHODS

Participants and study design
Forty-nine male cyclists volunteered to participate in this study. They were categorized attending to their performance level as U23 (N=11; age [mean ± SD], 19.9 ± 1.4 years; body mass, 67.2 ± 4.6 kg; CP, 5.3 ± 0.4 $W \cdot kg^{-1}$), Pro Team (N=13 (final N for analyses=12) 25.3 ± 4 years; body mass, 66.7 ± 4.2 kg; CP, 5.5 ± 0.3 $W \cdot kg^{-1}$), or World Tour (N=24; age, 33.3 ± 4.1 years; body mass, 67.6 ± 6.3 kg; CP, 6.1 ± 0.4 $W \cdot kg^{-1}$). In cases of prolonged illness, injury, or termination of cycling career, participants were excluded from all analyses. Informed written consent was obtained after each participant was given a verbal and written explanation of the experimental protocol and fully understood the possible risks involved in taking part in the study. The study protocol was approved by the local ethical review board and followed the principles as set out in the declaration of Helsinki.

Study design
The study was conducted from November 1st, 2021 to October 31st, 2022, and was divided into a pre-season (until end of January) and a race season (from the start of February to the

end of October) period. Thus, the study involved two main phases: 1) analysis of CP during the pre-season, 2) analysis of the RPP during the race season after different levels of work accumulated above CP (i.e., through power output data registered during training sessions and competitions in this phase).

Measures

Critical power

CP was assessed at baseline in 2 testing sessions on a standardized uphill climb (average gradient, 5.5%; ambient temperature, 15-20 °C). These procedures are in line with previously validated methods [5,12,13]. CP assessment involved 2 to 3 maximum efforts lasting between 2 to 20 minutes, with a difference between the shortest and longest effort of at least 10 minutes. The efforts were executed in a randomized order. When multiple tests were performed in the same session, these were interspersed by a 30-minute active recovery phase (i.e., pedalling at a very low intensity, eliciting a rating of perceived exertion <2 out of 10). During each test, participants were encouraged to produce the highest possible average power output with a cadence of 80 to 100 rpm. The power output was continuously recorded (sampling rate, 1 Hz) using three different power meter models: U3 category, SRAM Red (Quarq; Spearfish, SD); ProTeam, Shimano Dura-Ace FCRC9100-P (Shimano; Sakia, Japan); and World Tour, Power2Max (SChneider; Seifersdorf, Germany). A static calibration of all power meters was undertaken in the pre-season according to Wooles et al. (2005). Participants were instructed to perform a 'zero-offset' before each testing session.

The inverse of time model, using a least sum of squares linear regression analysis was used to derive the `power-duration parameter estimates. CP was defined as the intercept of the regression line, and the slope was considered as the work above CP (W´). For better comparisons between cyclists, 2, 5 and 12-minute power output values were calculated based on the following equation:

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

Equation 1, PO = power output (W), t=duration of effort (s)

Record power profile

Each cyclist used the same power meter during the whole season (i.e., during both the pre-season and the racing season). Mean maximal power output (MMP) values relative to body mass ($W \cdot kg^{-1}$) attained during both training sessions and competitions for efforts lasting either 5 and 30 seconds, and 1, 5, 10, 20 and 30 minutes, respectively, were identified during the racing season using a cycling software platform (WKO5 Build 562, TrainingPeaks LLC; Boulder, CO). All the MMP data were manually checked for data spikes. Additionally, the influence of different levels of accumulated work above CP (0, 2.5, 5.0, or 7.5 $kJ \cdot kg^{-1}$) on MMP was analyzed using an online cycling software platform (WKO5 Build 562, TrainingPeaks LLC; Boulder, CO).

Statistical analyses

All values were expressed as mean ± standard deviation. Normal distribution was tested using Shapiro-Wilk test. For descriptive purposes, a mixed design analysis of variance (ANOVA) was used to compare MPP and CP values between groups in the pre-season. MPP values after different levels of accumulated work (0.0, 2.5, 5.0, or 7.5 $kJ \cdot kg^{-1}$) above the CP were analyzed using a 3-factor (group, levels of previously accumulated work, MPP) mixed design ANOVA. In case of significance, a post-hoc Bonferroni procedure was applied for between and within-group comparisons. All statistical analyses were completed using JASP statistics software (version 0.13.1 for Mac OS, JASP Team; Amsterdam, the Netherlands). Statistical significance was established at $p \leq 0.05$ (two tailed).

RESULTS

During the assessments performed in the pre-season, World Tour cyclists attained a higher MPP (W·kg^{-1}) in the 5- and 12-minute field tests than U23 and Pro team peers, as well as a higher CP (**Figure 1**).

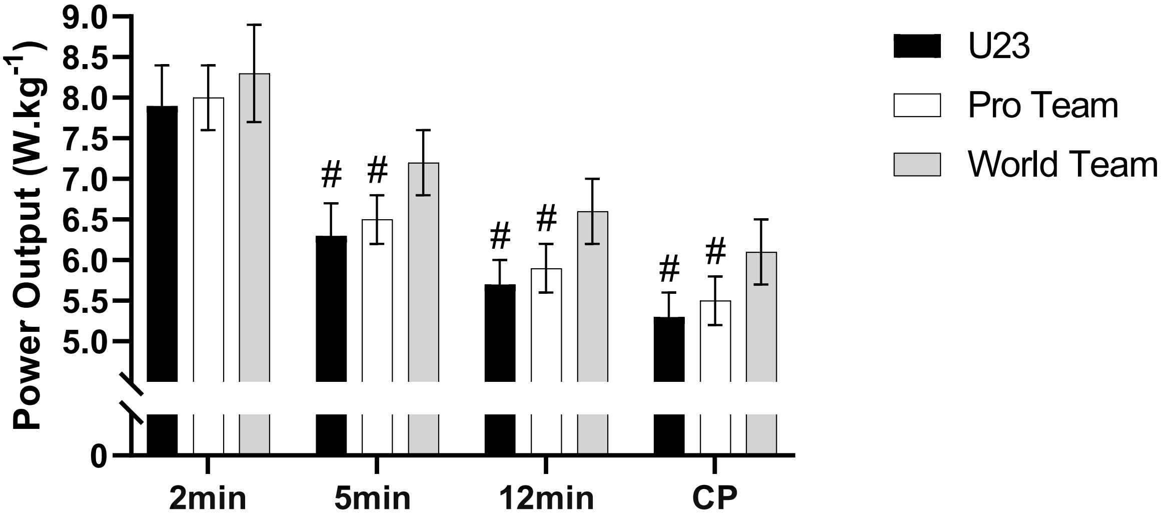

Figure 1. Differences between U23, Pro Team and World Tour participants in the three field tests performed during the pre-season for the maximum mean power output (usually known as 'MPP') attained during 2, 5 and 12-minute efforts or for the power output at the estimated Critical Power (CP). Symbol: # $p<0.01$ vs World Team.

Within-group differences

'Fatigued' MMP values that elicited a significant within-group reduction after levels of accumulated work above CP (i.e., 5.0 kJ·kg^{-1}) are shown in **Table 1**. All cyclists had to perform at least 2.5 kJ·kg^{-1} above CP to show a significant decline in MMP values. Nonetheless, while U23 cyclists experienced a noteworthy decline in all MMP values for efforts lasting ≥1 minute following prior exertion surpassing ≥2.5 to 5.0 kJ·kg^{-1} above CP, ProTeam and World Tour cyclists only exhibited a significant reduction after reaching ≥5.0 to 7.5 kJ·kg^{-1} above CP.

Table 1. Significant within-group effects of accumulated work above Critical Power (CP) on the record power profile (RPP) normalized to body mass.

RPP (W·kg^{-1})	***U23***	***Pro Team***	***World Team***
5s	16.9 ± 1.4^{++}	16.5 ±1.7^{++}	17.1 ± 1.2^{++}
30s	11.4 ± 0.7^{++}	11.2 ± 0.9^{+}	11.8 ± 1.1^{++}
1 min	8.7 ± 0.6^{++}	8.0 ± 0.9^{+++}	8.9 ± 0.6^{+++}
5 min	6.1 ± 0.4^{++}	6.4 ± 1.1^{+++}	6.7 ± 0.5^{+++}
10 min	5.6 ± 0.4^{++}	5.7 ± 1.3^{+++}	6.1 ± 0.4^{+++}
20 min	4.7 ± 0.4^{+++}	5.1 ± 1.5^{+++}	5.6 ± 0.4^{+++}
30 min	4.4 ± 0.4^{+++}	4.9 ± 1.6^{+++}	5.2 ± 0.5^{+++}

RPP – record power profile, +2.5 kJ·kg^{-1},++ 5.0 kJ·kg^{-1}, +++7.5 kJ·kg^{-1}

Between group differences
A significant interaction effect between Group by MMP by levels of accumulated work) was found ($p<0.001$)

'Fresh' state (**Figure 2A**). World Tour cyclists attained higher 10 ($p=0.010$), 20 ($p\leq0.001$) and 30-minute ($p\leq0.001$) MPP values than U23 peers whereas Pro Team cyclists attained higher 20 ($p=0.003$) and 30-minute ($p\leq0.001$) MMP than U23 riders. On the other hand, World Tour cyclists attained higher 20 ($p=0.035$) and 30-minute ($p=0.021$) MMP levels than Pro Team riders.

2.5 kJ·kg^{-1} above the Critical Power (**Figure 2B**). The U23 group showed higher 5-second MMP values than Pro ($p\leq0.001$) and World Tour ($p=0.020$) cyclists. By contrast, the U23 group presented lower 10-minute MMP than World Tour riders ($p=0.018$). On the other hand, the U23 ($p\leq0.001$) and World Tour ($p=0.004$) groups showed higher 30-second MMP values than Pro Team riders. The U23 group exhibited lower 20 ($p=0.027$ and 0.005, respectively) and 30-minute ($p=0.020$, $p\leq0.001$) MMP levels than Pro Team and World Tour cyclists.

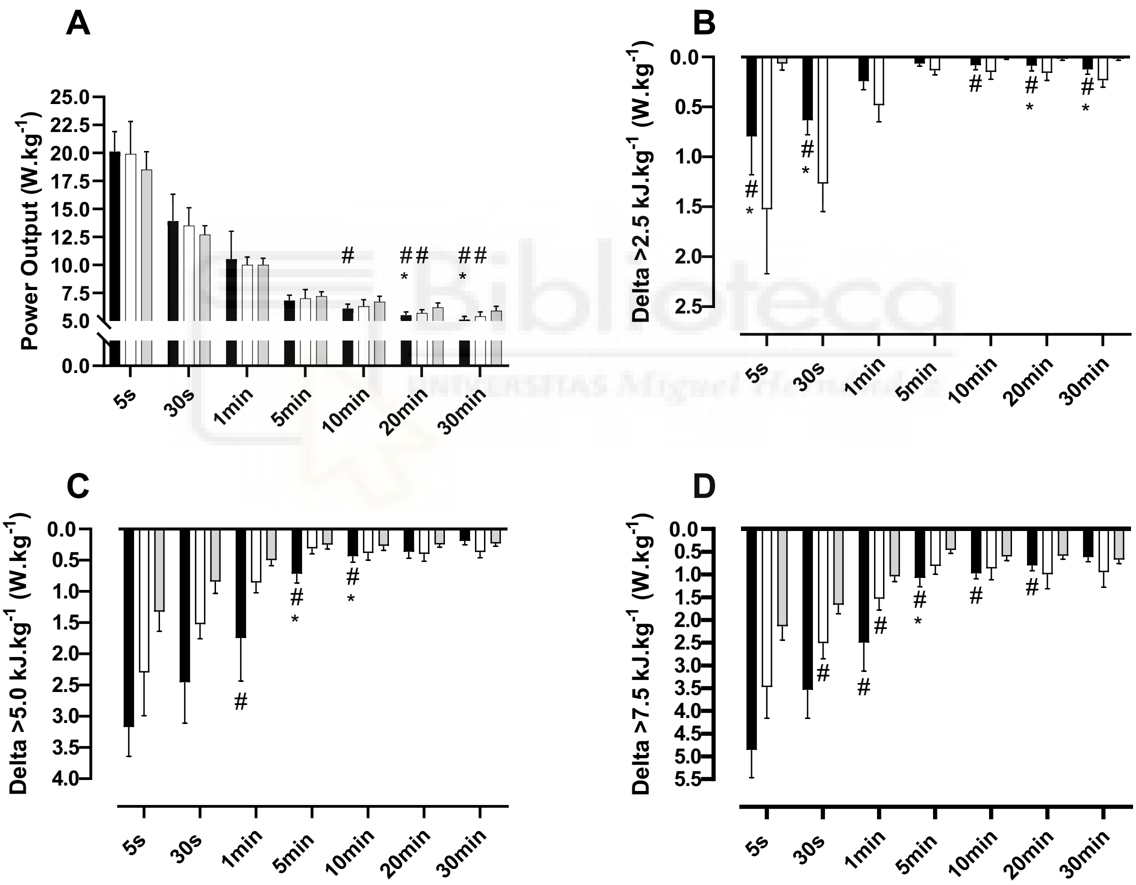

Figure 2. Differences in maximal mean power output (MPP) at different exercise durations in 'fresh' conditions (i.e., after 0 kJ·kg^{-1} above the Critical Power (CP), **panel A**) as well as relative changes to fresh RPP (record power profile) after 2.5 (**B**), 5.0 (**C**) and 7.5 kJ·kg^{-1} (**D**) above CP. Symbols: # $p<0.05$ vs World Team; * $p<0.05$ vs Pro Team.

5.0 kJ·kg^{-1} above the Critical Power (**Figure 2C**). The U23 group showed lower 5-minute MMP values than World Tour ($p\leq0.001$) and Pro Team ($p=0.003$) cyclists. The World Tour group demonstrated higher relative 1-minute MMP levels after 5.0 kJ·kg^{-1} above CP than the U23 (p=0.015) and Pro Team (p=0.020) group.

7.5 kJ·kg^{-1} above the Critical Power (**Figure 2D**). The World Tour (p=0.002) and Pro Team (p=0.006) groups showed a higher 1-minute MMP than the U23 group. The 10-minute MMP was higher in Pro Team (p=0.034) and World Tour (p=0.003) cyclists than in the U23 group. The World Tour group showed a higher 30-second MMP (p=0.008) than Pro Team group. The 10-minute MMP was higher in World Tour than in U23 cyclists (p=0.006). Finally, the World Tour group recorded higher 20-minute MMP values than the U23 group (p=0.023).

DISCUSSION

The present study shows that the RPP of professional cyclists decreases after high-intensity—i.e., ~5 kJ·kg^{-1} above CP—exercise, which corresponds to ~330 kJ of total work. Notwithstanding, our findings also suggest that cyclists with a higher performance level (World Tour category) may tolerate greater levels of previously accumulated work above CP before showing a subsequent impairment in the RPP. Moreover, differences between categories increased with the amount of accumulated work above CP.

Although not directly related to the main aim of our study, the finding of higher MMP values under 'fresh' conditions (i.e., with essentially no fatigue) in cyclists of higher categories compared to peers of a lower competition level (e.g., World Team versus U23, respectively) is overall in line with previous studies [1] and would support the importance of the MPP as a performance determinant. Notwithstanding, the main novelty of the present study was the assessment of high-intensity durability, that is, the changes in the RPP induced by the fatigue associated with different levels of previous high-intensity exercise [3]. In this regard, our findings show that even low doses of accumulated high-intensity exercise (5 kJ·kg^{-1}), corresponding to ~330 kJ of total work, can subsequently reduce some MMP values (particularly those corresponding to short exercise bouts) regardless of the cyclists' category. However, the main finding was that cyclists with a greater performance level could sustain greater levels of high-intensity exercise before showing a deterioration in MMP values for longer efforts (≥1 minute), which might suggest that they are able to better tolerate fatigue. Indeed, after the greatest level of high-intensity work assessed in this study (7.5 kJ·kg^{-1} above CP, corresponding to ~500 kJ of total work,, World Tour cyclists attained overall higher MMP values than both U23 and ProTeam cyclists. This accumulation of total work is reflective of exercising ~50 to 60min above CP, which is 20-30% of total race time in a 4.5 to 5h race.
Growing evidence supports a link between durability and competition performance [13], with recent research showing that MMP values for both short and prolonged efforts obtained under fatigue allow to differentiate cyclists of different competition levels [2,5,6,12,14]. It has been proposed that the ability to tolerate the fatigue induced by high-intensity exercise might also be a determinant of performance in cycling [3], and indeed Muriel et al. recently reported that, during a Grand Tour, the more successful cyclists spend longer time periods at high intensities [2]. However, most studies to date have assessed accumulated work without considering its nature per se (in terms of intensity), even if recent preliminary evidence suggests that high-intensity exercise can induce a larger decline in subsequent power output levels compared to moderate-intensity tasks [7]. Therefore, the present findings can be considered novel.

Some limitations of the present study should, however, be acknowledged. Of note, CP was assessed only once during the pre-season and was not continuously assessed during the competition season, which can be considered a potential confounding factor. There were also limitations inherent to the RPP, such as the inability to discern whether the assessed MMP values correspond to participants' actual maximal capabilities. Further research is needed to confirm if the decreasing effect that the fatigue associated with previous high-intensity exercise exerts on MPP differs from that elicited by the same total amount of work performed at lower intensities.

Practical applications
The present findings might support the importance of considering accumulated fatigue (in this case, due to previous exercise at intensities above CP) in the RPP of endurance athletes, since even relatively low levels of high-intensity work can result in a significant reduction of MMP values. Moreover, our results highlight the role of high-intensity durability as a performance determinant in elite cyclists, and might support the implementation of strategies (e.g., training, nutrition) aimed at improving this indicator.

CONCLUSIONS

Cyclists with a higher performance level (Pro Team and World Tour) are able to tolerate greater levels of accumulated high-intensity work compared to U23 before they show subsequent decrements in RPP, particularly for efforts lasting above 1 min. Moreover, differences between World Team cyclists and U23 or ProTeam cyclists seem to enlarge with the amount of high-intensity work. These findings might support the importance of high-intensity durability as a performance determinant in elite cycling.

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AUTHOR CONTRIBUTIONS
All authors equally contributed to the production of the manuscript.

CONFLICT OF INTEREST
The authors report no conflict of interest.

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APPENDIX 3

Is all work the same? Performance after accumulated work of differing intensities in male professional cyclists.

The study was previously published as:

Mateo-March, M., Leo, P., Muriel, X., Javaloyes, A., Mujika, I., Barranco-Gil, D., Pallarés, J. G., Lucia, A., & Valenzuela, P. L. (2024). Is all work the same? Performance after accumulated work of differing intensities in male professional cyclists. Journal of science and medicine in sport, 27(6), 430–434. https://doi.org/10.1016/j.jsams.2024.03.005

This journal is indexed in the Journal Citation Reports with an impact factor of 3.000 (2023) and is ranked 22 out of 127 in the category of sports sciences, and additionally, the journal remains in the Q1 category.

ABSTRACT

Objectives: Although the ability to attenuate power output (PO) declines after accumulated work (i.e., 'durability') is increasingly recognized as a major determinant of cycling performance, the potential role of the intensity of the previous work is unclear. We assessed the effect of work-matched levels of accumulated work at different intensities on performance in male professional cyclists.

Design: Observational field-based study.

Methods: PO data was registered in 17 cyclists during a competition season, and the critical power (CP) was repeatedly determined every 4wks from training sessions and competitions. Participants' maximum mean power (MMP) for different durations (5s, 5min, 10min, and 20 min) and the CP were determined under 'fresh' conditions (0 $kJ \cdot kg^{-1}$) and after varying levels of accumulated work (2.5, 5.0 and 7.5$kJ \cdot kg^{-1}$) at intensities below and above the CP.

Results: A significant decline was found for all MMP values following all levels of accumulated work above the CP (-4.0%, -1.7%, -1.8%, and -3.2% for 30s, 5min, 10min and 20 min-MMP, respectively; all $p<0.001$), versus no change after any level of accumulated work below the CP (all $p>0.05$). Similar results were observed for the CP, which decreased after all levels of accumulated work above (-2.2%, -6.1%, and -16.2%, after 2.5, 5.0 and 7.5$kJ \cdot kg^{-1}$, $p<0.001$) but not below this indicator ($p>0.05$).

Conclusions: In male professional cyclists, accumulated work above the CP impairs performance compared with work-matched, albeit less intense efforts. This raises concerns on the use of mechanical work per se as a single fatigue/stress indicator in these athletes.

Key words: cycling; fatigue; durability; endurance.

INTRODUCTION

The ability to attenuate the decline in performance that inevitably occurs under fatigue conditions compared with a 'fresh' state—recently known as 'durability' or 'fatigue resistance'—is increasingly recognized as a major determinant of cycling performance.[1] Although elite cyclists show a decrease in their ability to sustain high power output (PO) values even after little accumulated work (15 $kJ \cdot kg^{-1}$),[2] those with a greater performance level (i.e., professional category versus under 23 category, or WorldTour versus ProTeam riders) seem less affected.[2,3]

Most studies have assessed the influence of total levels of previous accumulated work—conventionally determined through the analysis of mechanical energy expenditure estimated from PO data—on subsequent cycling performance without considering the inherent characteristics of the previous exercise, especially intensity.[2–7] Yet, exercise intensity might play a major role on subsequent fatigue, even for a similar amount of total accumulated work. For instance, cycling above the gas exchange threshold results in greater fatigue compared with a less intense effort matched for total work.[8] In this respect, it must be also considered that most elite cycling competitions include numerous bouts of high or very high intensities.[9,10]

However, to the best of our knowledge, no evidence exists on how the intensity of previous accumulated work affects subsequent performance in professional cyclists under actual field-based conditions. Here, assessing the so-called critical power (CP) could be of interest, as this marker has been reported to represent the highest constant work rate that can be sustained via a steady state of substrate utilization and resynthesis while preserving physiological homeostasis (i.e., without depletion of muscle high-energy phosphates or rapid accumulation of hydrogen ions and inorganic phosphate in muscle tissue or in the bloodstream).[11,12] Thus, the CP is usually considered to delianete the boundary between steady state and non-steady state exercise conditions, or between heavy and severe exercise domains.[12]

The aim of this study was to assess the effect of different levels of the same amount of previous total mechanical work performed above or below the CP, respectively, on subsequent PO-producing capacity in male professional cyclists.

METHODS

The study followed an observational design. PO data from a male professional cycling team categorized as 'WorldTour' (i.e., the highest level of professional road cycling, as sanctioned by the '*Union Cycliste Internationale*') were collected during training sessions and competitions throughout a competition cycling season (January to October). If a cyclist experienced a long-term illness or injury, his data were not included in the analyses. All the participants provided informed written consent after receiving both verbal and written explanations of the experimental protocol. The study was approved by the local ethical review board and adhered to the principles outlined in the declaration of Helsinki.

PO data during all training sessions and competitions was continuously recorded (sampling rate, 1 Hz) using a power meter (Power2Max, Schneider; Seifersdorf, Germany).[13] Every cyclist used the same device throughout the entire season. A static calibration of all power meters was undertaken in the pre-season,[14] and participants were instructed to perform a 'zero-offset' before each ride. Each individual PO data point was inspected for abnormal or extreme values known as "spikes" using TrainingPeaks software (WKO5 Build 576; TrainingPeaks LLC, Boulder, CO). Any anomalous data was manually adjusted utilizing the software's Data Spike ID and FIX chart, particularly when there was a sudden non-linear increase or decrease in the PO data at the highest values recorded for each effort duration.

This was identified by a change ≥0.10% compared to the preceding consistent data points (e.g., an abrupt increase up to 455 watts following consistent readings of 345, 346, 345, 348, and 350 watts). If over 50 entries in a file from a single session were determined to be flawed, this file was removed from any additional analysis. The cyclists always used their own bicycles (as provided by the team and previously configured personally).

Participants' average maximum mean power (MMP, in W) for different effort durations (i.e., 30 s, and 5, 10 and 20 min) was determined from the analysis of PO data resulting from all training and competition sessions throughout the season using a specific software (WKO5 Build 576). These durations were chosen as they involve either anaerobic (30 s) or aerobic metabolism (≥5 min) and the longer bouts (20 min) were not long enough to preclude the cyclists can reach actual maximal intensities. Data from both training sessions and competitions were used as this procedure provides more valid estimates of cyclists' maximal performance compared to using only training or competition data.[15] In addition, participants' MMP values and CP were determined after different levels of accumulated work (i.e., 0, 2.5, 5.0, and 7.5 $kJ \cdot kg^{-1}$) performed below and above the CP. For this purpose, the CP was regularly updated with the highest values identified every 4 weeks, starting after the first competition of the season. Specifically, the CP was determined as recommended elsewhere from 2, 5 and 12-min MMP values[16] with the inverse of time model (1/t); that is, plotting the MPP for each duration against the inverse of the time (t), and considering CP as the intercept of the equation.[17] The estimation of CP from MMP values has been previously shown to be valid.[15]

Data are presented as mean ± standard deviation. The normal distribution of the data was assessed using the Shapiro-Wilk test. Data were analyzed through a 3-way repeated measures ANOVA considering the total levels (from 0 to 7.5 $kJ \cdot kg^{-1}$) and intensity (above or below CP) of previously accumulated work, as well as the different effort durations for MMP determination (from 5 s to 20 min) as within-subject factors. In the event of statistical significance for the interaction between these factors, post-hoc analyses (Bonferroni) were performed. All statistical analyses were conducted using SPSS software version 26.0 (IBM Corp., Armonk, NY). Statistical significance was determined at $p \leq 0.05$ (two-tailed).

RESULTS

Seventeen cyclists were studied (age, 32 ± 5 years; body mass, 66.0 ± 5.2 kg; body mass index, 21.0 ± 1.3 $kg \cdot m^{-2}$), with a total of 283 ± 27 files analyzed per participant (less than 2% of the files were excluded from the analyses). The participants' MMP and CP values after each level of accumulated work are shown in **Table 1**.

Table 1. Mean maximum power (MMP) and estimated critical power (CP) after different levels of accumulated work performed below and above CP.

	0 $kJ \cdot kg^{-1}$	2.5 $kJ \cdot kg^{-1}$		5 $kJ \cdot kg^{-1}$		7.5 $kJ \cdot kg^{-1}$	
		above CP	below CP	above CP	below CP	above CP	below CP
CP (W)	408±25	399±21*	406±22	383±24*	404±23	342±32*	403±23
30 s MMP (W)	825±80	791±28*	811±85	739±97*	811±85	647±103*	810±83
5 min MMP (W)	475±27	467±23*	474±28	453±29*	471±29	408±33*	470±27
10 min MMP (W)	437±26	428±18*	434±22	409±22*	432±21	364±31*	432±21
20 min MMP (W)	409±26	396±25*	404±23	373±25*	403±23	331±32*	403±24

* Significant differences compared with the 'fresh' state (i.e., 0 $kJ \cdot kg^{-1}$) and with the same level of work below CP: $p<0.001$.

A significant main effect was observed for the three within-subject factors (total levels and intensity of previously accumulated work, and effort duration for MMP determination), as well as a significant interaction between the three of them (all p<0.001). In post hoc analyses, significant differences (p<0.001) were observed between the intensities of previous exercise for all MMP values at all levels of accumulated work. Thus, a significant MMP decline was observed compared to 'fresh' conditions (previously accumulated work = 0 $kJ \cdot kg^{-1}$) for all effort durations with previously accumulated work above the CP, even with the lowest values above this marker (i.e., -4.0%, -1.7%, -1.8%, and -3.2 for 30 s, 5 min, 10 min and 20 min after 'only' 2.5 $kJ \cdot kg^{-1}$ above the CP, respectively, compared to 'fresh' conditions) (all p<0.001) (**Figure 1**). In contrast, no significant MMP decline was found after previous work accumulated below the CP compared to the 'fresh' state, even with the highest possible work levels below this boundary (i.e., after 7.5 $kJ \cdot kg^{-1}$ below the CP).

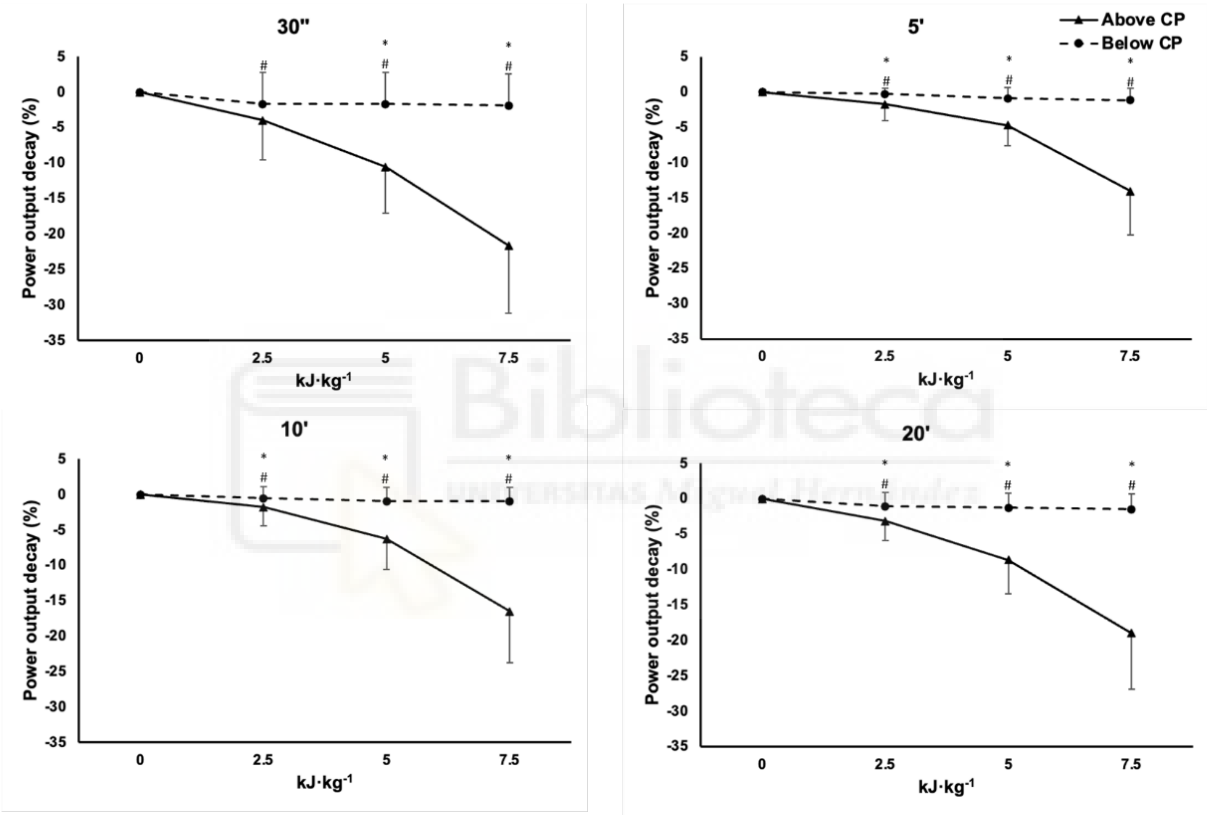

Figure 1. Effect of different levels of accumulated work performed above and below the critical power (CP) on maximum mean power values for different effort durations. Significant differences between intensities: *p<0.001 versus the 'fresh' condition (i.e., 0 $kJ \cdot kg^{-1}$): # p<0.001.

A significant decline in subsequent CP was observed after all levels of previously accumulated work above the CP (i.e., -2.2%, -6.1%, and -16.1% after 2.5, 5.0 and 7.5 $kJ \cdot kg^{-1}$, respectively) compared to the 'fresh' state (**Figure 2**). Conversely, these levels of accumulated work resulted in no significant CP decline compared to the 'fresh' condition when performed below the CP.

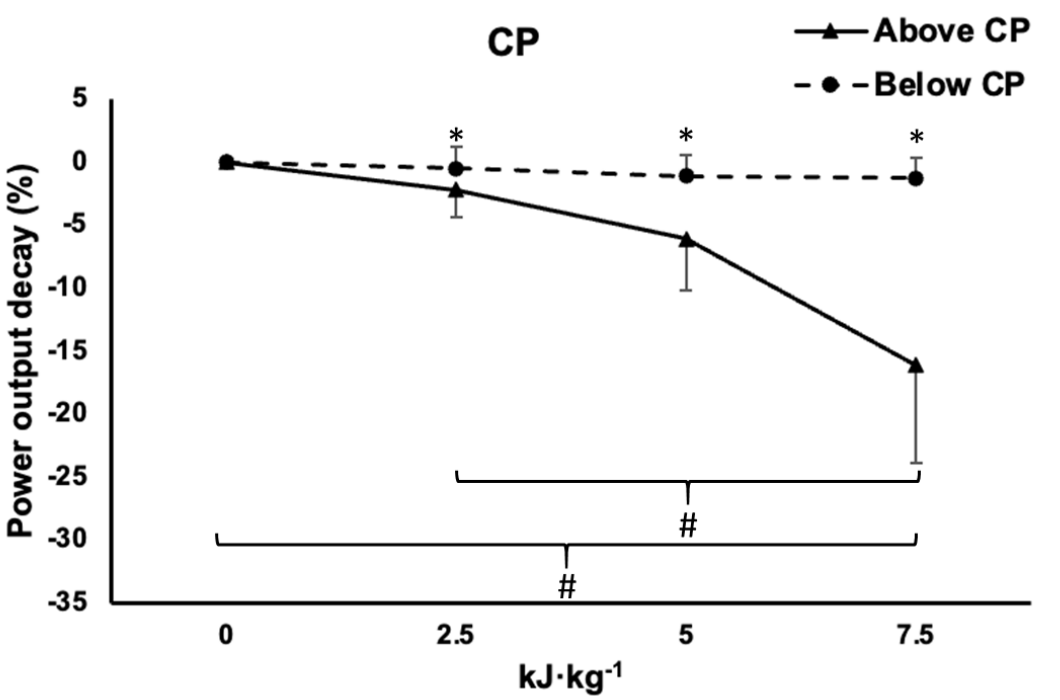

Figure 2. Estimated critical power (CP) after different levels of accumulated work performed above and below CP. Significant differences between intensities: Symbols: * p<0.001 versus the ‘fresh’ condition (i.e., 0 kJ·kg^{-1}): # p<0.001.

DISCUSSION

The present study indicates that even small amounts of exercise performed at high (above physiological homeostasis) intensities (i.e., total mechanical work above the CP = 2.5 kJ·kg^{-1}) can impair subsequent performance in male professional cyclists, with performance declines increasing with the amount of intense accumulated work. In turn, the same or even higher amounts of previously accumulated work performed at lower intensities, below physiological homeostasis (i.e., total work below the CP ≤ 7.5 kJ·kg^{-1}) do not seem to affect subsequent wattage during short (30 s) to relatively long-duration (up to 20 min) efforts.

Previous evidence suggests that even low amounts of previous accumulated work can induce fatigue in highly trained cyclists, although the influence of intensity was not taken into account. In professional cyclists, previous accumulated work amounting 15 kJ·kg^{-1} sufficed to induce a significant decline (-1.6% to -3.0%) in MMP values for efforts ranging from 10 s to 120 min[2] but it was not discerned whether intensity played a role. Similarly, Van Erp et al. found a progressive deterioration of MMP values even after low levels of total accumulated work (10 kJ·kg^{-1}) of undescribed intensity, especially in those professional cyclists with a lower performance level.[3] Our study therefore provided novel evidence and puts recent evidence in context, by showing that even very low amounts of accumulated work can impair performance in male professional cyclists, but only when performed at high intensities (i.e. above CP).

The present findings are in line with previous studies reporting greater fatigue levels following high-intensity exercise compared to less intense tasks. For instance, in a recent study, a high-intensity interval training session induced a larger impairment in a 12-min time trial compared to a moderate-intensity continous training session.[18] However, the sessions were not matched for total mechanical work, which can be considered a confounding factor.[18] Overcoming this limitation, a recent study indicated that steady cycling above the gas exchange threshold resulted in greater subsequent fatigue than a work-matched effort below this threshold.[8] In the present study, we show that cycling above the CP results in a greater deterioration of subsequent performance compared to cycling below this threshold, which is also in line with previous evidence.[19] Thus, our results might support the role of CP as an important threshold above which fatigue exponentially occurs due to a loss of homeostasis (i.e., depletion of high-energy phosphates and accumulation of hydrogen ions and inorganic phosphate in muscle tissue and/or in the bloodstream).[11,12,16]

The present findings also raise concerns on the validity of total mechanical work per se as a single indicator for fatigue monitoring, as the same amount of work can impair performance differently in the same subject due to variations on exercise intensity. In the same line, Kesisoglou et al. observed that efforts associated with different amounts of total mechanical work (i.e., a 5-min versus a 20-min time trial) can elicit similar fatigue levels for a given individual.[20] Thus, prescribing a given amount of mechanical work cannot only result in different levels of fatigue between subjects, as confirmed by different studies,[2,3,5] but also within a given individual, supporting the notion that using mechanical work to equalize the stress imposed by training sessions might be flawed.[21] Future research should determine whether using other training load indicators that also take account for other important variables such as intensity (e.g., the so-called 'training stress score', commonly abbreviated as known as 'TSS') results in more homogeneous responses.

Some limitations of the present study should be acknowledged, notably its observational nature and the relatively small sample size—an understandable limitation given the high-performance level of the participants. Moreover, given that the analyses were conducted with field-derived PO data, it cannot be discerned whether the obtained MMP values were genuinely maximal, even though strict procedures were applied to avoid this limitation (e.g., analyzing both training and competition data, restricting MMP values to efforts with a duration no longer than 20 min, which corresponds to ~7.5 $kJ \cdot kg^{-1}$).[15] In this regard, it is worth noting that using field-based MMP values has proven to be a reliable and valid method for assessing cyclists' maximal capabilities, also including CP estimation.[15,22] Notwithstanding, the potential confounding role of several factors such as altitude and temperature should not be disregarded,[23,24] and therefore future experimental studies (e.g., employing *ad hoc* tests for performance assessment) integrating these environmental variables should confirm our findings.

CONCLUSION

The present field-based study shows that work-matched efforts affect subsequent performance differently in male professional cyclists depending on the intensity of these efforts. Thus, whereas even small levels of accumulated work performed at high intensities (i.e., 2.5 $kJ \cdot kg^{-1}$ above CP) result in an impaired performance, the same (or even higher) amounts of accumulated work performed at lower intensities (i.e., at least up to 7.5 $kJ \cdot kg^{-1}$ below CP) do not significantly affect performance capacity.

Practical applications

- Efforts performed at high intensities (above the CP) result in a greater fatigue compared with total work-matched but less intense (below the CP) efforts.
- Even small levels of accumulated work performed at high intensities (above the CP) seem to affect performance in male professional cyclists. These findings might highlight the importance of 'high-intensity durability' for performance.
- These findings might raise concerns on the use of total mechanical work (i.e., kJ spent) as an indicator to homogenize the stress imposed by training sessions, at least when not considering exercise intensity. Future research should confirm whether other

indicators considering exercise intensity might be used as more accurate indicators of actual training loads.

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CONFLICT OF INTEREST

The authors report no conflict of interest.

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APPENDIX 4

Sex-specific differences in durability among professional cyclists: insights from real-world power output data

The study was previously submitted as:

Mateo-March, M., Barranco-Gil, D., Leo, P., van Erp, T., Muriel, X., Javaloyes, A., Pallarés, J. G., Lucia, A & Valenzuela, P. L. (2024). Sex-specific differences in durability among professional cyclists: insights from real-world power output data. Journal of science and medicine in sport. In review

This journal is indexed in the Journal Citation Reports with an impact factor of 3.000 (2023) and is ranked 22 out of 127 in the category of sports sciences, and additionally, the journal remains in the Q1 category.

ABSTRACT

Background: Durability is emerging as a key performance determinant in cycling, but scarce evidence exists on the durability of female cyclists, and particularly on whether sex-specific differences exist for this indicator. We aimed to determine potential sex differences in durability.

Design: Observational field-based study.

Methods: Power output data from training sessions and competitions were registered in female and male professional cyclists (n=42 each) during 1-10 seasons. Participants' maximum mean power (MMP) values for different effort durations (10 s, 1 min, 5 min, and 20 min) were determined under 'fresh' conditions (0 kJ/kg) and after varying levels of accumulated work (10, 20 and 30 kJ/kg).

Results: A significant reduction in all MMP values compared with the fresh condition was observed after >10 kJ/kg in both female and male cyclists ($p<0.001$), with no significant impairment observed below this level of accumulated work ($p>0.05$ for all). A similar relative decay (as a % compared with the fresh condition) was observed between sexes for 10-s MMP ($p>0.05$). However, a significantly higher relative decay was observed in female compared to male cyclists after 20 kJ/kg for 1-min, 5-min, and 20-min MMP (+4%, 4% and 2%, respectively; $p<0.05$), with these differences enlarging after 30 kJ/kg (+8%, 6% and 7%, respectively; $p<0.001$).

Conclusions: Despite the limitations associated with the record power profile, professional female cyclists present a greater relative decline in their field-based MMP values after a given accumulated work compared to male cyclists (particularly for durations ≥ 1 min), which might be reflective of a lower durability.

Key words: cycling; power profile; endurance; resilience; performance.

INTRODUCTION

Durability (*i.e.*, the ability to attenuate the decline in performance that occurs under fatigue conditions, also known as fatigability or resilience) is emerging as a key performance determinant in endurance sports and particularly in cycling.[1,2] Growing evidence shows indeed that cyclists with a greater performance level (*i.e.,* professional *versus* under 23 category, or WorldTour *versus* ProTeam riders) have a preserved ability to sustain high power output values after a given accumulated work, even if presenting similar power output levels under 'fresh' conditions (*i.e.,* with no previous accumulated work).[3,4]

Female cycling is growing in popularity in the last decade. However, the vast majority of scientific studies are still conducted on men.[5] In this regard, although men present a higher absolute physical performance compared to women, controversy exists regarding potential sex-specific differences in durability.[6] For instance, it has been reported that women present an overall higher durability (*i.e.,* lower fatigability) during isometric muscle contractions — particularly when performed at low relative intensities.[7] Different studies have also reported greater reductions in maximal strength in men compared to women after prolonged endurance exercise.[8,9] Moreover, using data from 14 US marathons, Deaner et al. observed that women had a lower reduction of running pace compared to men.[10] Confirming the potentially higher durability in women compared to men, it is worth noting that whereas the male-to-female performance gap in traditional endurance sports such as the marathon remains at ~ 10%, in ultra-endurance competitions this gap has been reported to be much lower, despite the markedly lower number of female participants.[11–13]

Evidence on the durability of female cyclists is however scarce. Analysis of popular ultracycling events (*e.g.,* 5000-km Race Across America) revealed that male winners were 18-28% faster than female winners.[14] However, using 12,716 race results from ultra-cycling races of different distances, Baumgartner et al. reported that whereas men were faster than women in 100- and 200-mile races, there were no sex differences for the 400- and 500-mile races, which might be reflective of a greater fatigue resistance among women.[12] Scarce evidence exists therefore on whether female cyclists could have a higher durability compared to men. For instance, a recent study by our research group revealed that professional male cyclists experience a reduction of their power output producing capacity (as assessed through the record power profile) even after low levels of accumulated work (15 kJ/kg).[3] However, whether female cyclists could attenuate the effects of fatigue remains unknown.

The present study aimed to determine potential sex differences in durability between professional male and female cyclists using real-world field-based data.

METHODS

Study design and participants

We had access to power output data from a convenience sample of professional female (n=42) and male cyclists (n=42), respectively, from three different WorldTour teams (descriptive characteristics shown in **Table 1**). Power output data were registered during training sessions and competitions over 1-10 years for each participant. The protocol complied with the

Declaration of Helsinki, participants provided written informed consent, and the local Ethics Committee approved the protocol (ID: 3482/2021, Universidad de Murcia).

Power profile

Power output was registered with four different power meters (Power2Max Type SNieder Seifersdorf, Waldhufen, Germany; SRAM Red, Quarq, Spearfish, South Dakota, USA; Shimano Dura-Ace FCRC9100-P, Shimano, Sakia, Japan; and Pioneer SGY-PM910H2, Pioneer, Kawasaki, Japan) that have been previously used in the scientific literature.[15–20] Every cyclist used the same device throughout the entire season. All power meters were factory-calibrated at least once per season, and a zero-offset was performed by the cyclist before each training or competition session attending to manufacturers' instructions. Each individual power output data point was inspected for abnormal or extreme values known as "spikes" using a specific TrainingPeaks software (WKO5 Build 576; TrainingPeaks LLC, Boulder, CO). Any anomalous data was manually adjusted utilizing the software's Data Spike ID and FIX chart, particularly when there was a sudden non-linear increase or decrease in the power output data at the highest values recorded for each effort duration. This was identified by a change ≥0.10% compared to the preceding consistent data points (*e.g.*, an abrupt increase up to 455 watts following consistent readings of 345, 346, 345, 348, and 350 watts). If over 50 entries in a file from a single session were determined to be flawed, this file was removed from any additional analysis. The cyclists always used their own bicycles (as provided by the team and previously configured personally).

Participants' average maximum mean power (MMP, in W/kg) for different effort durations (*i.e.,* 10 s, and 1, 5 and 20 min) was determined from the analysis of power output data resulting from all training and competition sessions throughout the season using a specific software (WKO5 Build 576). These durations were chosen as they involve either anaerobic (10 s) or aerobic metabolism (≥5 min), and the longer duration (20 min) was not long enough to ensure that it could correspond to a maximal effort. Data from both training sessions and competitions were used as this procedure provides more valid estimates of cyclists' maximal performance compared to using only training or competition data.[21] In addition, participants' MMP values after different levels of accumulated work (i.e., 0, 10, 20, and 30 kJ/kg) were also assessed. We did not assess MMP values after greater levels of accumulated work as this would reduce the likelihood of a maximal effort especially in the case of female cyclists, due to the duration and characteristics of their training and races.

Statistical analysis

Data are shown as mean ± SD. Differences between female and male cyclists in descriptive variables were assessed through unpaired Student's t-tests or chi-squared tests for continuous and categorial variables, respectively. A mixed-design repeated measures ANOVA with sex as the between-subject factor and level of accumulated work (i.e., fatigue) as the within-subject factor was performed for each MMP value. To minimize the risk of statistical type I error, post hoc comparisons (Bonferroni test) were only performed when a significant interaction effect was found. Statistical analyses were conducted using a statistical software package (SPSS 23.0; IBM Corp, Armonk, NY) setting the significance level at $p<0.05$.

RESULTS

Participants' main descriptive characteristics are shown in **Table 1**. Male riders were older, heavier, taller and had a greater experience in the professional category. Although a greater number of seasons was available for male riders, the number of analyzed files did not differ between sexes (**Table 1**). Both groups had a similar relative performance level, with no significant differences in the proportion of "top" cyclists (i.e., cyclists who had achieved a top5 position in major races) (**Table 1**).

Table 1. Descriptive characteristics of study participants.

	Men (n=42)	Women (n=42)	p-value
Age (years)	29.91 ± 4.26	26.91 ± 4.15	0.002
Body mass (kg)	66.1 ± 5.8	56.7 ± 6.8	<0.001
Height (cm)	1.78 ± 0.05	1.65 ± 0.06	<0.001
Body mass index (kg/m^2)	20.81 ± 0.2	20.61 ± 1.66	0.538
Experience as professional (years)	11.1 ± 4.7	5.9 ± 2.9	<0.001
Seasons registered (n per cyclist)	3.3 ± 2.0	2.1 ± 1.1	<0.001
Files analyzed (n per cyclist)	832 ± 772	704 ± 335	0.329
Top-5 in main races (n, %)	11 (26%)	15 (36%)	0.345
Top-5 in Grand Tours (n, %)	7 (17%)	7 (17%)	1.000
Top-5 in Classics races (n, %)	3 (7%)	9 (21%)	0.061
Top-5 in Worlds Championships (n, %)	5 (12%)	5 (12%)	1.000

Data are mean ± SD or Median (IQR). Top 5 in main races refers to the proportion of cyclists who have achieved a top-5 position in a top-level race such as a Grand Tour, a Classic or a World Championship.

Average and normative MMP values under fresh conditions (i.e., after 0 kJ/kg) and after increasing levels of accumulated work are shown in **Table 2**. A significant sex (p<0.001), fatigue (p<0.001) and sex by fatigue interaction effect (p<0.001) was observed for all MMP values. Significantly higher MMP values (in W/kg) were observed in male compared to female cyclists for all effort durations and after all levels of accumulated work (p<0.001).

A significant reduction in all MMP values compared with the fresh condition was observed after 20 and 30 kJ/kg in both female and male cyclists (p<0.001), with no significant impairment observed after 10 kJ/kg in either female or male cyclists (p>0.05 for all), albeit with a non-significant trend (p=0.064) towards a reduced 20-min MMP after 10 kJ/kg in the former (**Table 2**).

Table 2. Normative values of power output for different effort durations after increasing levels of accumulated work in professional male and female cyclists.

MMP	Mean ± SD		Percentiles									
			10th		25th		50th		75th		90th	
	Men*#	Women#	Men	Women	Men	Women	Men	Women	Men	Women	Men	Women
10 s												
0 kJ/kg	16.38 ± 1.22	14.32 ± 1.47	14.74	12.15	15.51	13.48	16.56	14.41	17.17	14.97	17.61	15.80
10 kJ/kg	16.18 ± 1.36	14.18 ± 1.43	14.46	12.03	15.09	13.35	16.29	14.37	17.13	14.97	17.61	15.55
20 kJ/kg	15.92 ± 1.25	13.87 ± 1.49	14.24	11.63	14.99	12.84	16.24	14.13	16.75	14.76	17.59	15.47
30 kJ/kg	15.76 ± 1.32	13.53 ± 1.53	14.01	11.49	14.91	12.57	15.82	13.56	16.70	14.64	17.59	15.13
1 min												
0 kJ/kg	10.11 ± 1.06	8.61 ± 0.93	9.12	7.53	9.50	8.06	9.79	8.45	10.54	9.15	11.29	9.46
10 kJ/kg	9.94 ± 1.02	8.46 ± 0.96	9.05	7.45	9.48	7.84	9.70	8.36	10.24	9.09	11.06	9.46
20 kJ/kg	9.78 ± 0.68	7.96 ± 0.92	9.05	6.98	9.23	7.34	9.70	7.83	10.21	8.49	11.03	9.26
30 kJ/kg	9.67 ± 0.61	7.53 ± 0.98	9.05	6.25	9.17	6.91	9.70	7.39	10.10	8.10	10.29	8.76
5 min												
0 kJ/kg	7.27 ± 0.47	5.86 ± 0.6	6.81	5.19	6.89	5.50	7.23	5.73	7.46	6.14	7.77	6.53
10 kJ/kg	7.18 ± 0.43	5.72 ± 0.57	6.73	5.12	6.87	5.40	7.15	5.67	7.37	5.87	7.57	6.28
20 kJ/kg	7.13 ± 0.36	5.53 ± 0.58	6.67	4.83	6.86	5.16	7.14	5.49	7.36	5.83	7.52	6.15
30 kJ/kg	7.10 ± 0.37	5.35 ± 0.64	6.63	4.68	6.82	4.90	7.14	5.34	7.32	5.65	7.47	6.08
20 min												
0 kJ/kg	6.18 ± 0.4	4.92 ± 0.49	5.55	4.38	5.97	4.55	6.18	5.03	6.48	5.13	6.66	5.29
10 kJ/kg	6.12 ± 0.42	4.83 ± 0.51	5.54	4.34	5.87	4.46	6.13	4.80	6.44	5.11	6.63	5.29
20 kJ/kg	6.07 ± 0.41	4.72 ± 0.55	5.49	4.15	5.77	4.36	6.10	4.73	6.34	5.02	6.60	5.29
30 kJ/kg	6.02 ± 0.42	4.45 ± 0.56	5.49	3.78	5.77	4.07	6.08	4.44	6.29	4.76	6.51	4.88

*Significantly higher maximum mean power (MMP) values were observed for male compared to female cyclists for all effort durations and after all levels of accumulated work ($p<0.001$). # A significant reduction of all MMP values ($p<0.001$) was observed in both male and female cyclists after 20 and 30 kJ/kg, but not after 10 kJ/kg.

Analysis of the relative decline (as a %) of MMP values compared with the fresh condition revealed no significant differences between sexes after any level of accumulated work for 10-s MMP (**Figure 1**). However, a significantly higher relative decline was observed in female compared to male cyclists after 20 kJ/kg for 1-min, 5-min, and 20-min MMP (+4.4%, 3.5% and 2.4%, respectively; $p<0.05$), with these differences increasing after 30 kJ/kg (8.5%, 6.2% and 7.0%, respectively; $p<0.001$) (**Figure 1**).

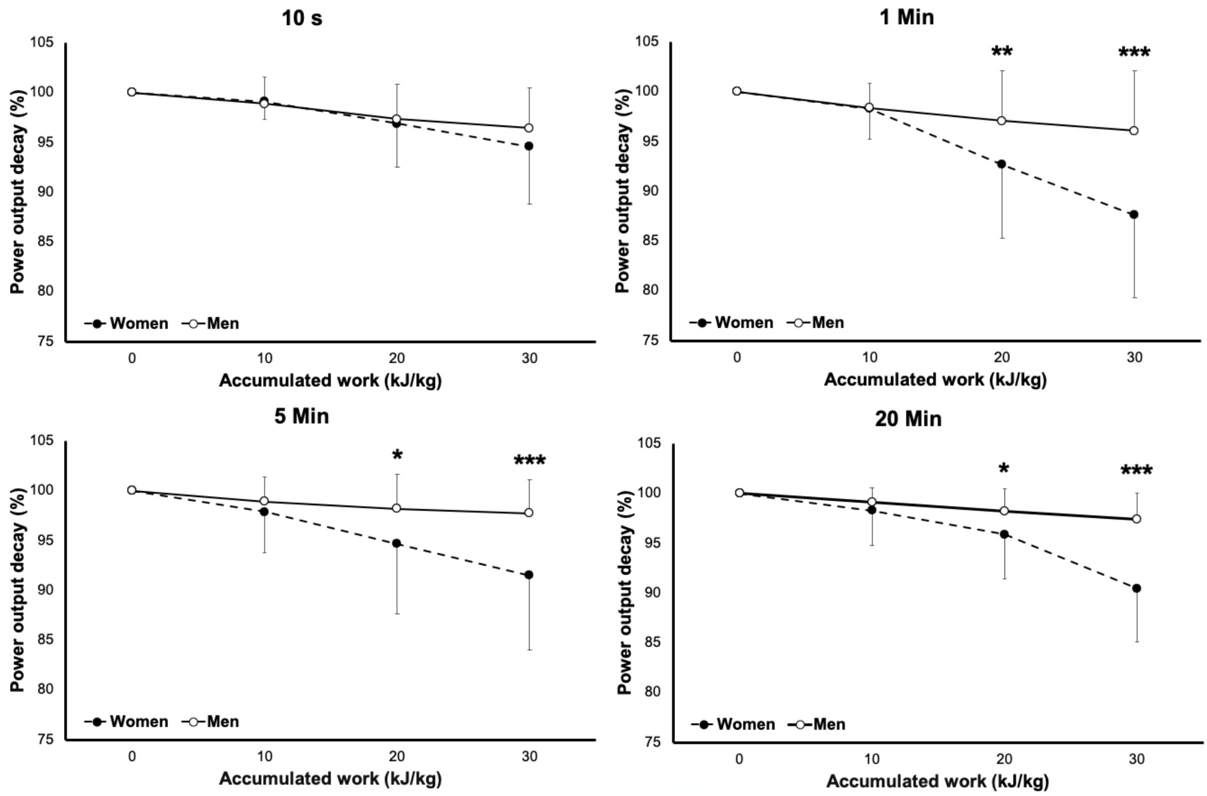

Figure 1: Power output decay (expressed as a %) after increasing levels of accumulated work in professional male and female cyclists. Significant differences between sexes: *p<0.05, **p<0.01, ***p<0.001

DISCUSSION

The present study shows that both male and female professional cyclists present a significant decline of their MMP values after >10 kJ/kg, although this performance impairment seems to be of greater magnitude among the later (particularly for efforts lasting ≥ 1 minute).

Controversy exists on the potential sex-specific differences in fatigue resistance (also known as durability), although growing evidence suggests that women might have an increased fatigue resistance compared to men. For instance, Temesi et al. observed a lower decrease in maximal force after a 110-km ultra-trail-running race in women compared to men.[9] Moreover, Glace et al. reported that, after 2 hours of running at the same relative intensity (the intensity associated with the ventilatory threshold), only men showed a reduction in running economy and in knee flexion and extension strength.[8] In addition to these experimental studies, observational evidence also shows that the research gap between male and female athletes is reduced in ultra-endurance sports, including ultra-cycling events. [12,13]

Several factors have been proposed to explain these findings, including a greater resistance at the peripheral level in women.[9,22] For instance, in the abovementioned study by Temesi et al., similar levels of central fatigue were observed between male and female runners after the 110-km ultra-trail running race, but the later presented lower levels of peripheral fatigue.[9] Studies in rodents and humans also suggest that females might have a higher endurance exercise capacity, which might be partly due to their greater ability to mobilize and utilize fatty acids.[7,23,24] Moreover, female mice have also been reported to present a greater proportion of type I muscle fibers, with the greater endurance performance partly attributable to higher estrogen levels and subsequent increases in nitric oxide synthase activity –which were not present in ovariectomized female rodents.[25]

However, contrary to the abovementioned findings, the present study suggests that after a given amount of accumulated mechanical work, female professional cyclists present a greater decline of their MMP values, thus reflecting a lower durability. Other studies also support a greater fatigue resistance in men. For instance, Monteiro et al. reported that men had lower fatigue levels after resistance exercise compared to women.[26] Moreover, Avin et al. reported that sex differences in fatigue resistance might be muscle-specific, with women showing a greater resistance at the elbow but not at other muscle groups,[27] and other studies have failed to find sex-specific differences in fatigability after performing other types of exercise.[28]

The potential physiological mechanisms underlying the present findings should be further explored. However, given the limitations associated with the record power profile, the role of potential confounding factors (*e.g.,* intensity of the accumulated work, ambient temperature, altitude)[29–31] should not be disregarded. Indeed, although the record power profile has been reported as a valid indicator of the cyclists' maximal capabilities,[21] it should be noted that it is only reflective of what the cyclists did, and not necessarily of what the cyclists were able to do. Thus, the observed findings could also be attributed to factors such as tactical differences between male and female races. Moreover, although we analyzed a similar number of files for both male and female cyclists, and cyclists of both sexes could be considered of the highest competitive level (*i.e.,* WorldTour), it is possible that the demands of male cyclists are currently higher than those of female cyclists (e.g., longer races and training sessions in the former), although this sex gap is being reduced. Confirming this trend, Zingg et al. reported that the difference between top three men and women in the 720-km 'Swiss Cycling Marathon' decreased from 35% in 2001 to 20% in 2012.[32] Therefore, although the fact of having analyzed a relatively large sample of male and female professional cyclists using field-derived power output data can be considered a major strength, these findings and the potential underlying mechanisms should be confirmed in experimental studies.

CONCLUSIONS

Professional female cyclists present a greater relative decline in of their MMP values after a given accumulated work compared to male cyclists (particularly for durations ≥ 1 min), which might be reflective of a lower durability.

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Conflicts of interest
None

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