UNIVERSITA' DEGLI STUDI DI GENOVA

DOTTORATO DI RICERCA IN NEUROSCIENZE

Curriculum:

Scienze delle Attività Motorie e Sportive

Coordinatore Prof. Piero Ruggeri

XXXVI ciclo

Titolo della tesi di dottorato:

Durability:

importance in competition success across different age-related road cycling categories and training strategies to improve it.

Candidato: Gabriele Gallo

Tutor: Prof.ssa Emanuela Luisa Faelli

SUMMARY

ABSTRACT

Introduction: In addition to maximal oxygen consumption, lactate threshold and efficiency, durability has been recently shown to be an additional parameter determining long duration endurance sports performance. The influence of durability on success in different road cycling age-categories is yet to known. Furthermore, effective training strategies to improve durability have not been explored. Therefore, the aims of this thesis are (i) to understand the impact of durability on success in Junior (JUN), Under 23 (U23) and Professional (PRO) road cycling categories and (ii) to investigate effective training strategies to improve durability.

Study 1: This study aimed to investigate cross sectional differences in race demands between junior, under 23 and professional road cycling categories. Race data collected during the 2019 season of thirty male road cyclists (10 for each category) were retrospectively analysed for race characteristics, external, and internal competition load. JUN races were shorter and included less elevation gain per distance unit compared to U23 and PRO races, but more internally demanding. JUN produced lower record powers output in the moderate-, heavy-, and severe-intensity exercise domains compared with U23 and PRO. U23 and PRO races presented similar work demands per hour and record power outputs, but PRO races were longer than U23.

Study 2: This study investigated the field-derived power performance parameters associate with competition success in road cycling climbing specialists of different age-related categories. Training and racing data of fifty-three male climbers participated in this study (junior [JUN], n = 15; under 23 [U23], n = 21; professional [PRO], n = 17) collected during the 2016-19 competitive seasons were retrospectively analysed for record power outputs (RPOs) and RPOs after prior accumulated work to evaluate durability. For each category, cyclists were classified as high-ranked or low-ranked based on the placement in the final season general ranking of their category. Superior absolute and relative RPOs at rested state characterize high-ranked vs low-ranked JUN climbing specialists. Superior durability

characterized high-ranked U23 and PRO climbers compared with their low-ranked counterpart, as well as PRO versus U23 climbers high-ranked climbers.

Study 3: This investigation examined cross sectional difference in training characteristics between JUN, U23 and PRO male road cyclists. Training data collected during the 2019 competitive season of thirty male cyclists, ten for each age-related categories (JUN; U23; PRO), were retrospectively analysed for training characteristics, external and internal training load. JUN spent more training time at medium and high heart rate intensity zones compared to U23 and PRO. Higher duration per training session were observed in PRO compared to both U23 and JUN. Elevation gain per distance was higher in PRO compared to U23 and JUN, and in U23 compared to JUN.

Study 4: This study described the day-by-day training and racing characteristics in preparation to Giro d'Italia of one world class road cyclist who achieved a place on the podium in the final general classification of the Giro d'Italia. Daily load, daily volume and intensity distribution derived from power meter training and racing data of the 152 days leading up to the podium in the Giro d'Italia final general classification were reported. During training, a pattern alternating 'hard days' versus 'easy days' was observed, as significant amounts of medium or high intensity or load were not performed for more than two consecutive days. This pattern was achieved combining high volume (> 4 hrs) with significant amount of medium and high intensity within the same training sessions.

Study 5: This study investigated if performing high-intensity training (HIT) at the end of long low-intensity training sessions enhances durability. Twenty trained cyclists were randomly allocated to one of two four-week training interventions (CON, n=10 and INT, n=10). INT performed HIT at the end of long low-intensity sessions, while CON performed HIT and long low-intensity sessions on separate days. Weekly training was matched for overall volume and time in zones. An incremental test to determine the first and second ventilatory thresholds, and

a 5-min time trial, was performed in a rested state and after 2.5-h cycling pre- and post-intervention. The data revealed some distinct differences in adaptations to physiological variables depending on the timing of HIT. Specifically, performing HIT in standalone short-duration sessions tended to favor adaptations in the rested state, while performing HIT at the end of long low intensity trainings sessions tended to favor adaptations after 2.5 hours of low-intensity cycling. These results indicate that the timing of HIT has an impact on durability-related adaptations in trained cyclists.

Conclusions: This thesis suggests as durability is a factor determining competition results in U23 and PRO but not JUN road cycling category. Successful PRO road cyclists have superior durability compared to successful U23 and JUN cyclists, therefore young riders stepping up to the professional category should develop durability. Regarding this, this thesis also suggests as performing high-intensity training at the end of long low-intensity training sessions could be an effective training strategy to improve durability.

SECTION ONE

BACKGROUND

1. Physiological model of Endurance Performance

1.1 Historical Context

During the XIX century the Italian physiologist Angelo Mosso (1846-1910) was the first investigating the physiological determinants of fatigue during physical exercise. He was able to characterize muscle fatigue associating its occurrence with central or peripheral influences, and he demonstrated that exercise would increase muscular strength and endurance while prolonging the occurrence of fatigue (Mosso 2001) (Di Giulio et al. 2006). However, given the industrial revolution characterizing his times, it is not surprising that his main drive and interest for studying physiology was the welfare of the working class and not sports performance. It was no coincidence that the publication of his great work ‘La Fatica’ occurred on May 1st, 1891, which was the second anniversary of the Italian Labor Day. After about 30 years in which also the birth of the modern Olympic Games took place (1896), the legendary British physiologist Sir Archibald Vivian Hill was the first pioneer applying physiological concepts to endurance sports performance. ‘Physiology can aid in the development of athletics as a science and an art’ he stated in his work ‘Athletic records’ published in Lancet in 1925, which can be consider the very first sport science’s record in the modern age (A.V. Hill 1925).Among the most important pioneering discoveries made by Sir Hill we can count: a plateau in the relationship between work rate and oxygen consumption (i.e. maximal oxygen consumption, $\dot{V}O_2max$), movement economy, anaerobic energy production, oxygen debt and the curvilinear relationship between speed/power and duration (Bassett 2002). Sir Hill's pioneering approach was the inspiration and starting point that gave way to the countless number of studies on endurance sports performance during the following ~100 years. All together, these studies have led to the popular and widely recognized Joyner and Coyle’s physiological model of endurance performance (Joyner and Coyle 2008).

1.2 Joyner and Coyle's Model

Published in The Journal of Physiology's 2008 Olympic Issue, Joyner and Coyle's model of endurance performance could be considered the review of ~100 years of research in endurance sports performance (Joyner and Coyle 2008). This model suggests three key physiological determinants of endurance performance: performance oxygen consumption ($\dot{V}O_2$), performance oxygen (O_2) deficit and gross mechanical efficiency (Figure 1). Henceforth, the word "determinant" refers to a potential limiting factor.

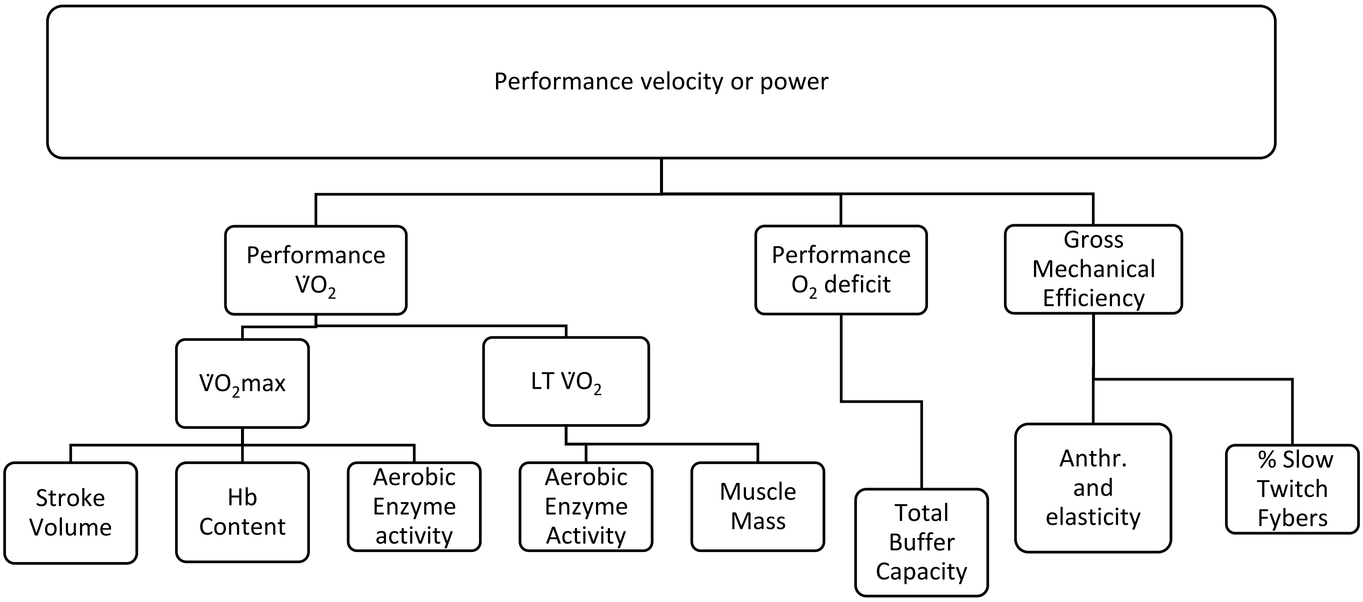
Performance $\dot{V}O_2$ is the level of aerobic metabolism that can be maintained for a given duration. It depends on maximal oxygen consumption ($\dot{V}O_2max$) and lactate threshold (LT). $\dot{V}O_2max$ represents performance $\dot{V}O_2$ upper limit and could vary from ~ 30 to ~ 80 $ml \cdot min^{-1} \cdot kg^{-1}$ from sedentary to elite endurance athlete, with 96.7 $ml \cdot min^{-1} \cdot kg^{-1}$ as the highest value ever reported in a junior road cyclist (Shoenfeld et al. 1977, Gallo et al. 2022, Rønnestad et al. 2019). $\dot{V}O_2max$ is related to stroke volume, total body haemoglobin, capillary density, aerobic enzymes activity and to the ability of the lungs to oxygenate the blood (Bassett and Howley 2000).

Lactate Threshold is the exercise intensity associated with the first abrupt increase in arterial lactate concentration. This is the lowest intensity at which the rate of glycolysis-produced pyruvate delivery to the mitochondria exceeds the ability of the mitochondria to oxidize pyruvate and this leads to accelerated generation of lactic acid (Holloszy and Coyle 1984). This, in turn, leads to an increase in hydrogen ions which is likely a pivotal factor in muscle fatigue and also evokes important hormonal activations and autonomic reflexes (Schneider et al. 2000, Allen et al. 2008). LT usually occurs at a percentage of $\dot{V}O_2max$ ranging from ~ 50% in sedentary to ~ 90% in elite athletes. The main determinant factor of LT seems to be the oxidative capacity of the skeletal muscle and the quantity of muscle mass that the athlete can recruit to sustain power production, as a higher muscle mass recruited reduces the stress per mitochondria and muscle fibre (Holloszy and Coyle 1984) (Vikmoen and Ronnestad 2021).

Performance O_2 deficit represents the contribute of anaerobic metabolism to energy production to sustain a given power or speed. Shorter the duration higher the importance of anaerobic metabolism contributing to performance. Furthermore, performance O_2 deficit might be very important also in longer duration endurance competitions characterised by a stochastic nature with several high-intensity bursts above the critical power (i.e. heavy to severe intensity transition), such as road cycling. The main factor determining performance O_2 deficit seems to be total buffer capacity, which is the ability of the body to remove or recycle muscle fatiguing metabolites (e.g. H^+, Na^+/K^+) (Bishop et al. 2004).

Gross Efficiency (GE) is the ratio of work generated to the total metabolic energy cost. It represents movement economy. When considering running at a certain speed, it could vary 30–40% among individuals (Joyner MJ 1991), while when cycling at a given power output the variability seems lower, about 20-30% (Coyle EF 1995). GE limiting factors seems to be the percentage of type I (slow twitch) muscle fibres of the active muscles (Coyle et al. 1992), mitochondrial efficiency (Iaia et al. 2009), muscle morphology, elastic elements and joint mechanics. (Joyner and Coyle 2008).

Figure 1: *Joyner and Coyle physiological model of endurance performance. Redrawn from Joyner and Coyle 2008.*



Abbreviations: anthr, anthropometric Hb, haemoglobin; LT, lactate threshold; $\dot{V}O_2$, oxygen consumption; $\dot{V}O_2max$, maximal oxygen consumption.

Joyner and Coyle's model has repeatedly been shown to predict endurance performance lasting from ~10 min to ~2 hours with good accuracy. For example, $\dot{V}O_2max$ and $\dot{V}O_2$ at LT showed very strong correlations with performance time in running distances from 3000m to marathon (r = –0.83 to –0.98) (Farrell et al. 1979; Peronnet et al. 1987). Lucia and colleagues showed as power at LT was related to performance time trials during Tour de France in professional cyclists (r = –0.77 to –0.92) (Lucia et al. 2000).

However, when considering longer duration performance Joyner and Coyle model predictive power sometimes decreases. For example, O'Toole and Colleagues determined that the relationship between bike exercise test variables were not highly related to bike finish times ($r = -0.26$ to -0.58) in the 1985 Hawaiian Ironman Triathlon (O'Toole et al. 1989). Regarding this, even if also psychological and tactical factors could also play an important role, it could be that other physiological variables outside Joyner and Coyle's model also influence performance with longer duration.

1.3 Durability

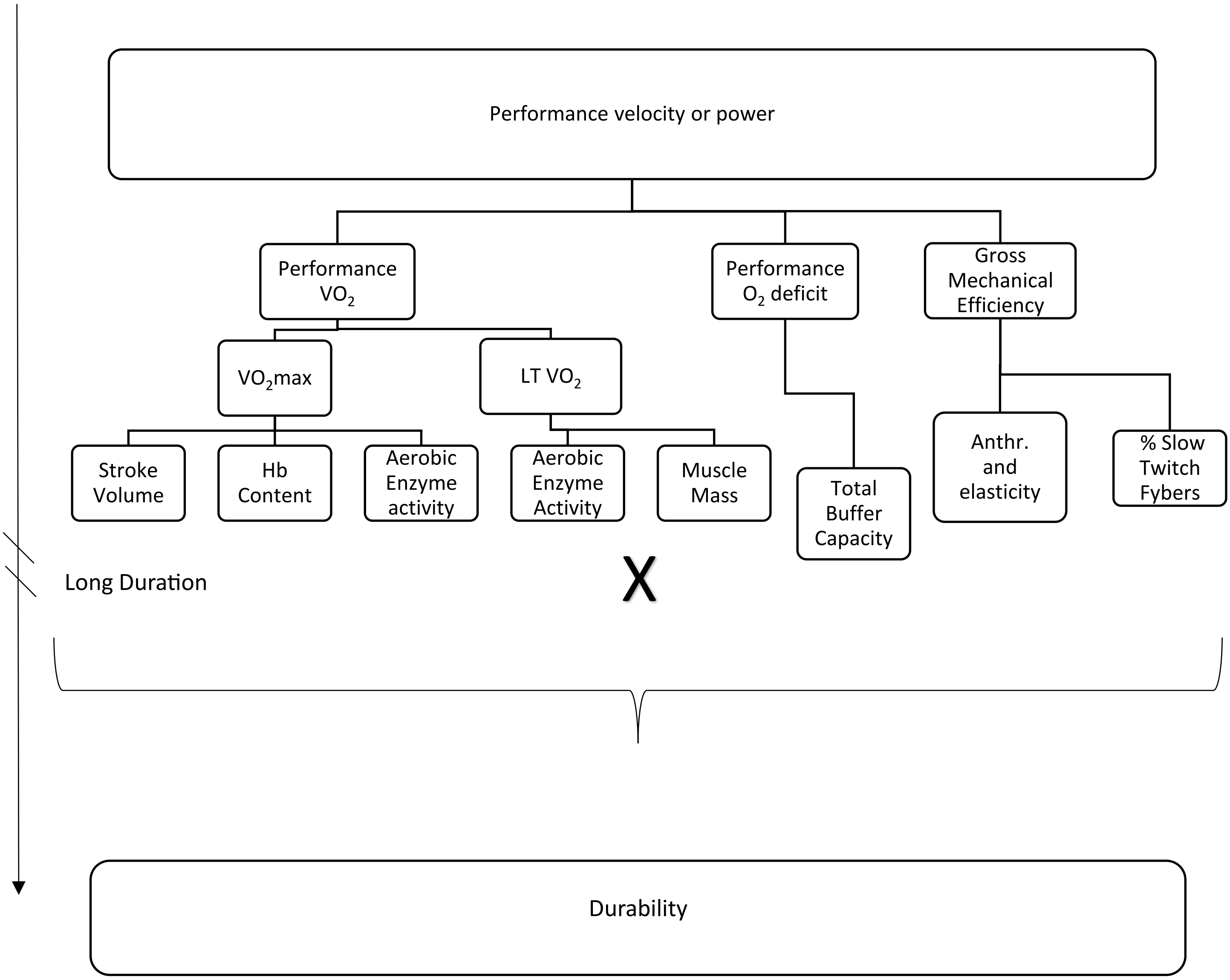
A series of very interesting studies shown as Joyner and Coyle's physiological parameters determining endurance performance and endurance performance itself are not stable but degrade over time during prolonged exercise. Passfield and Colleagues showed as 60 minutes' moderate-intensity endurance cycling at 60% $\dot{V}O_2$peak induced a significant decrease in gross efficiency, 5-min time trial and sprint power output in trained endurance subjects. Interestingly, the reduction in 5-min performance after exercise was associated with the decline in gross efficiency but not with $\dot{V}O_2$peak. (Passfield et al. 2000). Clark and Colleagues showed as critical power (CP) and anaerobic reserve (W') calculated through a 3-minute all-out test (3MT) decreased by 8% and 20% respectively after 2 hrs of exercise in the heavy intensity domain in trained subjects. (Clark et al. 2018). The same authors reported a similar decrease in CP (10%) and W' (20%) calculated trough three severe intensity trials instead of the 3MT after the same prolonged exercise (2 hrs of exercise in the heavy intensity domain) with a similar cohort (Clark et al. 2019). In a third study, Clark and Colleagues investigated CP and W' decrease after different heavy exercise duration (40, 80 and 120 min) while consuming a placebo beverage or a carbohydrates (CHO) supplement (60 g/h). CP and W' declines significantly after 80 and 120 min, with CHO ingestion negating the reduction in CP but not W' (Clark et al. 2019). When pooling together the data of the last two mentioned

studies, a significant relationship between percentage changes in W' but not CP and % change in muscle [glycogen] was found after two hrs of heavy intensity exercise (r= 0.44). Noordhoff and Colleagues reported that peak speed during an incremental step test was largely lower after 90 min of exercise at 65% $\dot{V}O_2$peak compared to rested state in 26 cross country male skiers. The decrease in performance was correlated to decrease in gross efficiency at submaximal intensities and shorter cycle length. (Noordhof et al. 2020)
Stevenson and Colleagues showed as external work output at the moderate-to-heavy intensity transition (first ventilatory threshold, VT_1 and lactate threshold, LT) decreases after 2 hours of cycling at 90% of VT_1 power. The decrease in VT_1/LT was attributable to decreased gross efficiency and rates of metabolic energy expenditure but not to Peak Fat Oxidation (PFO), $\dot{V}O_2$max, prolonged exercise-induced sweat loss, or prolonged exercise-induced dehydration. (Stevenson et al. 2022).
Valenzuela and Colleagues showed as average power output during a 20 min lab time trial was decreased after ~4 hours of exercise at power below the Functional Threshold Power (FTP) in professional cyclists consuming 60 g/h CHO. The performance decrease was not related to traditional laboratory endurance parameters: $\dot{V}O_2$max, LT, respiratory compensation point and peak power output during incremental test. (Valenzuela et al. 2022)
Spragg and Colleagues reported that 5 x 8-min efforts at 105%–110% of CP interspersed with 8 min recovery decrease CP in professional road cyclists. The decrease in CP resulted significantly positive correlated with $\dot{V}O_2$max, VT_1, GE and RCP, and negative correlated with CHO oxidation at 200 W. (Spragg et al. 2023). The fact that differently from the above-mentioned studies the decrease in performance was related to traditional endurance marker, it could be due to the severe intensity of the 'fatiguing' exercise compared to the moderate/heavy intensity adopted in the others above cited studies. Interestingly, all these studies highlighted a degree of interindividual variability (~0 to ~20%) in the percentage

decrease in performance and physiological parameters after prolonged exercise. Except with Spragg's study, this variability was not related to Joyner and Coyle traditional physiological parameter of endurance performance ($\dot{V}O_2max$, LT, GE). This seems to suggest as durability, that is the time of onset and magnitude of deterioration in performance and physiological parameters during prolonged exercise (Maunder et al. 2020), can be considered an additional and independent parameter determining endurance performance (Figure 2).

Intuitively, longer the performance duration, more important could be the relative contribution of durability. Therefore, durability could be considered particularly relevant in longer duration endurance sports, such as road cycling.

***Figure 2**: Durability perspective within Joyner and Coyle's model of endurance performance.*



Abbreviations: anthr, anthropometric; Hb, haemoglobin; LT, lactate threshold; $\dot{V}O_2$, oxygen consumption; $\dot{V}O_2max$, maximal oxygen consumption.

Table 1: *List of studies investigating the effect of prolonged endurance exercise on durability.*

References	Subjects	Prior exercise	Performance test	Average Impact of Prolonged Exercise	Interindividual variability in Durability	Physiological correlates of Durability	No Physiological correlates of Durability
Passfield et al. 2000	10 trained cyclists	60 min @60% VO_2peak No CHO	5' Time Trial 30s Sprint Test	↓ 5' TT (-4%) ↓ 30s TT (-6%)	5' TT: - 1.8 to -7.8%	5' TT with ΔGE	VO_2peak LT
Clark et al. 2018	9 trained cyclists	120 min @heavy intensity No CHO	3 min all-out test	↓ CP (-8%) ↓ W' (-20%)	N.R.	N.I.	N.I.
Clark et al. 2019	14 endurance trained participants	120 min @heavy intensity No CHO	3 severe intensity trials	↓ CP (-10%) ↓ W' (-20%)	N.R.	N.I.	N.I.
Clarke et al. 2019	16 endurance trained participants	40, 80 and 120' @heavy intensity With 0 and 60 g/h CHO	3 minutes all-out test	80': ↓ W' 120': ↓ CP, W' CHO negates decrease in CP	N.R.	ΔW' with ΔMuscle [Glycogen]*	ΔCP with ΔMuscle [Glycogen]*

Nordhoff et al. 2020	26 subelite cross country skiers	90' @65% VO_2peak No CHO	Maximal incremental step test	↓ Peak speed (-7%)	-31 to +5.3%	ΔGE ΔCycle Length ΔVO_2peak	/
Stevenson et al. 2022	14 trained cyclists and triathletes	120 min @90% power VT_1 No CHO	VT_1 LT	↓ VT_1 (-10%) ↓ LT (-10%)	-4 to - 20%	ΔGE ΔEE	Dehydration Sweat Loss VO_2peak PFO ΔFO
Valenzuela et al. 2022	12 professional cyclists	240 min @below FTP 60 g/h CHO	20' Time Trial	↓ 20' TT power (-2.8%)	-8.5 to +1.1%	/	VO_2peak VT_1 RCP PPO
Spragg et al. 2022	10 professional cyclists	5 x 8-min efforts @ 105%–110% CP 60 g/h CHO	CP through two severe intensity trials	↓CP (~ -3%)	~ - 6.0 to - 0.5%	VO_2peak $VT_{1,}$ RCP PPO GE CHO/Fat Ox.	/

*Abbreviations: *, Data are pooled with Clark e al. 2019; Δ, difference; CHO, Carbohydrates; CP, Critical Power; EE, Energy Expenditure; FO, Fat Oxidation; FTP, Functional Threshold Power; GE, Gross Efficiency; LT, Lactate Threshold; NI, Not Investigated; NR, Not Reported; Ox,* *Oxidation; PFO, Peak Fat Oxidation; PPO, Peak Power Output; RCP, Respiratory Compensation Point; TT, Time Trial;* VT_1*, First Ventilatory Threshold; W', Anaerobic Reserve.*

2. Peculiarities of Road cycling

2.1 Road cycling race demands

Professional male road cycling is one of the most extreme endurance sports having the highest exercise volume per year (~30 000–35 000 km, ~1000 h) and some of the most demanding competitions such as 3-week Grand Tours (Giro d'Italia, Tour de France, Vuelta a España), in which athletes compete for 21 days (~100 h) with only two rest days in between (Lucia et al. 2001). In the last 20 years, there has been a rapid increase in the capacity to capture real-time data through portable mechanical power meters. This has led to a deeper understanding of professional road cycling race demands. There are two cycling races' categories: time trials and mass-start races. Time trials represent a minor percentage of races calendar. They are relative short duration effort (i.e. less than ~60 km and ~60 min) performed at a relative constant high intensity (average: ~85-89% HR_{max}) (Sanders and Van Erp 2021). The main factor determining success in these competitions is a high record power output (RPO) relative to aerodynamic for duration ranging from ~10 to ~60 min. (Sanders and Van Erp 2021). Mass-start races represent most of the cycling races. They are characterized by longer duration (~100 to 300 km and ~3 to 6 hrs) and a lower average intensity (~66-76% HR_{max}). During these competitions, intensity is not constant but stochastic due to tactical factors (e.g. drafting) and different terrains (e.g. flat, uphill, downhill). (Sanders and Van Erp 2020). Given this, "race-winning efforts" are usually high intensity efforts after previous prolonged exercise performed prevalently in the moderate and heavy domain, with some bursts in the severe intensity domain. (Menaspà et al. 2015).

2.2 Physiological Laboratory Parameters and Road Cycling Performance

Descriptive research has been previously conducted on the physiology of professional male road cyclists. These studies investigated the Joyner and Coyle's model laboratory parameters. VO_2max usually ranges from ~70 to 85 ml·min^{-1}·kg^{-1} with flat terrain specialists having lower values compared to time trial and uphill specialists. (Mujika and Padilla 2000) Power outputs at lactate threshold values were reported to be between 200 and 420 W (4.5-5.5 W·kg^{-1}) and occurs between 74 and 83% of VO_2max. (Mujika and Padilla 2000). Gross Efficiency depends on the exercise intensity, with higher the relative intensity higher GE until a plateau is reached near an intensity corresponding ~LT (de Koning et al. 2012). Gross Efficiency values between 20.9 and 28.1% were reported during cycling at 80% of VO_{2max}. (Lucia et al. 2002). While it has been shown as long (~1 hour) time trial performance is correlated to LT but not VO_{2max} or RCP (Lucia et al. 2000), no study has yet investigated whether physiological laboratory parameters are positively correlated or not with performance in professional mass-start road cycling races. It could be that given the stochastic nature and longer duration of mass-start races compared to time trials, the determining performance factors could differ between these two race types. As regularly performing lab tests with high-level competitive cyclists is very difficult, due to the high number of travel and races (especially during the competitive period, from January to October), alternative physical performance parameter obtained by power meter data has been introduced.

2.3 Power Road-Derived Physical Performance Parameters

In the last ~20 years, there has been a rapid increase in the capacity to capture training and races real-time data through portable mechanical power meters. These data could be then elaborated through online platforms (e.g. Training Peaks) to obtain power-derived physical performance parameters. These represent an important tool to assess physical performance given the easier logistics compared to laboratory test. One of the most widely used power meters-derived physical performance parameter is the Record Power Profile. It represents the highest mean recorded power outputs (RPOs) over different durations (Pinot and Grappe 2011). The most used durations are: 1, 5, 30 and 60 s, and 5, 10, 20. 30, 45, 60, 120, 180, and 240 min. Differently from lab-based parameters, RPOs are usually derived by training sessions and races data and not by standardized testing protocols. However, Quod and Colleagues reported no differences between mean maximal power output over different time durations (60–600 s) recorded during road races and standardized laboratory tests (Quod et al 2010). This could suggest as RPOs could be used as a valid and more feasible approach to evaluate physical attributes of road cyclists compared to laboratory testing.

Given the growing interest about the durability's impact on road cycling performance, a novel power-derived physical performance parameter has been introduced: the RPOs after certain amounts of work done. (Van Erp et al. 2021) These amounts of work done can be measured as absolute kilojoules (e.g. 1000, 2000, 3000 kJ) or, with the aim compare more accurately cyclists with different anthropometric characteristics, as kilojoules relative to body mass (e.g. 10, 20, 30, 40, 50 $kJ \cdot kg^{-1}$).

Very interestingly, a series of recent studies shown as RPOs after high amount of works done are more important than RPOs at rested state to achieve success in professional male road cycling races. Van Erp and Colleagues showed as more successful climbers and sprinters have a smaller percentage decline in RPOs after high amounts of work done (40-50 $kJ \cdot kg^{-1}$) compared to their less successful counterparts (Van Erp et al. 2021). Leo and Colleagues showed as using also RPOs after amounts of work done (1000-3000 kJ) allows for greater power when predicting the final general classification of the stage race Tour of the Alps, when compared to consider only RPOs at rested state (Leo et al. 2021). Muriel and

Colleagues investigated the differences in RPOs at rest and after amounts of work done in 8 World Tour (WT, the highest road cycling team’s level) and 7 Professional Tour (PT. lower team’s level) road male cyclists during a three-weeks stage races (La Vuelta 2020). They reported that, while no consistent significative differences were found for RPOs at rest, WT cyclists recorded higher power outputs after amounts of work done (i.e. 15-35 kJ·kg^{-1}) compared to PT cyclists. This was observed in correspondence of a better ranking in the final general classification in WT (average 31^{st}/142) compared to PT cyclists (71^{st}/142) (Muriel et al. 2022).

Mateo-March and Colleagues further investigated the differences in RPOs at rested state and after amounts of work done between World Tour cyclists (n=66) and Professional Tour cyclists (n=46) across a longer timespan (from season 2013 to 2021). Again, while no consistent differences were found between WT and PT cyclists in RPOs values assessed at rested state (0 kJ·kg^{-1}), PT cyclists showed a significant greater decay of RPOs values after amounts of work done compared to WT. These differences increased with accumulating levels of work completed: -1.8 to -2.9% WT vs -1.1% to -4.4% PT after 15 kJ·kg-^{1}: -4.7% to -8.8% WT vs -7.6% to -11.6% PT after 45 kJ·kg^{-1}) (Mateo-March et al. 2022).

Altogether, these applied studies seem to suggest as durability is a pivotal factor in determining success in professional male road cycling races.

Table 2: *List of studies highlighting the importance of durability in professional male road cycling.*

	Subjects	Outcome
Van Erp et al. 2021	26 Male Pro	↓ % decrease in RPOs after 40-50 kJ·kg^{-1} in successful vs less successful cyclists
Leo et al. 2021	17 Pro Cyclists	↑ Predictive power for Tour of the Alps GC when adding RPOs after 1000-3000 kJ to RPOs at rested state
Muriel et al. 2022	15 Pro Cyclists 8 WT, 7 PT	↓ % decrease in RPOs after 40-50 kJ·kg^{-1} ↑ final GC in WT vs. PT cyclists during Vuelta 2020
Mateo-March et al. 2022	112 Pro Cyclists 66 WT, 46 PT	↓ % decrease in RPOs after 15-45 kJ·kg^{-1} in WT compared to PT over one season

Abbreviations: GC, General Classification, PT, Professional Tour; RPOs, Record Power Outputs; WT, World Tour.

3. Durability and road cycling: what's next?

While its importance for professional cyclists seems important, no studies have yet investigated the impact of durability on youth cycling categories success. Interestingly, Schumacher and Colleagues reported that the cyclists who achieved a top 10 in the professional road world championships was similar between cyclists who previously reached or not a top 10 in the junior (i.e. 17-18 age category) road world championship. (Schumacher et al. 2006). Therefore, it seems as in road cycling there is a mismatch between junior and professional success. While different non-physical factors (e.g. experience, tactical issues, environment, opportunities, psychology) could contribute to the observed mismatch, the difference in success could be also related to different physical race demands and physiological factors determining performance between junior and pro races. Specifically, durability could be more relevant in pro compared to youth categories, given the distance limit imposed by the Union Cycliste Internationale (UCI) for youth races. Understanding these differences in physiological demands determining success between youth and professional cyclist could be particularly important for talent identification and longitudinal training strategies for long term athlete development.

While high volume training, high intensity training, heat training and strength training, have all been shown to be effective strategies to improve Joyner and Coyle's performance parameters and endurance performance at rested state (Foster et al. 2022, Rønnestad and Mujika 2015, Rønnestad et al. 2022), no studies have yet investigated which is the best training strategy to improve durability. This could be very relevant for road cycling as well as other long duration sport events: marathon, ultramarathon, ultra cycling, ironman.

THESIS AIM:

Therefore, the first aim of this thesis was to assess difference in physiological factor determining competition success between different age-based (junior, under 23 and professional) male road cycling categories with a special focus on durability. This could give useful insights for talent identification and long-term athlete development (Study 1 and 2). Hypothesizing durability as a more relevant factor for professional compared to youth road cycling success, the second aim of this thesis was to investigate effective training strategies to improve durability. To address this, first, cross sectional differences in training characteristics between more durable (professional) compared to less durable (under 23 and junior) cyclists were investigated (Study 3). Then, day-by-day training data of a successful world-class road cyclists were analysed to identify possible effective training strategies which could contribute to reach an exceptional durability (Study 4). In study 5, it was tested whether a specific training strategy (high intensity training within long low-intensity sessions) identified in study 4 is effective or not to improve durability. This could be relevant for optimize performance in professional male road cycling and other long duration sports, such as marathon, ultra cycling and ironman.

LIST OF STUDIES:

- STUDY 1: Cross sectional differences in race demands between junior, under 23, and professional road cyclists.
- STUDY 2: Power Road-Derived Physical Performance Parameters in Junior, Under-23, and Professional Road Cycling Climbers
- STUDY 3: Differences in Training Characteristics Between Junior, Under 23
- and Professional Cyclists.
- STUDY 4: The Day-by-Day Periodization Strategies of a Giro d'Italia Podium Finisher.
- STUDY 5: Performing high-intensity training following prolonged exercise impacts durability-related adaptations.

SECTION TWO

STUDY 1

Cross-Sectional Differences in Race Demands Between Junior, Under 23, and Professional Road Cyclists

Gallo G, Leo P, Mateo-March M, Giorgi A, Faelli E, Ruggeri P, Mujika I, Filipas L. Cross-Sectional Differences in Race Demands Between Junior, Under 23, and Professional Road Cyclists. Int J Sports Physiol Perform. 2022 Mar 1;17(3):450-457.

Abstract:

Purpose: To compare the race demands of junior (JUN), under 23 (U23), and professional (PRO) road cyclists. **Methods:** Thirty male cyclists, divided into 3 age-related categories (JUN, n = 10; U23, n = 10; and PRO, n = 10), participated in this study. Race data collected during the 2019 competitive season were retrospectively analyzed for race characteristics, external, and internal competition load. **Results:** Higher annual and per race duration, distance, elevation gain, Edward's training impulse, total work, and work per hour were observed in PRO versus U23 and JUN, and U23 versus JUN ($P < .01$). PRO and U23 recorded higher mean maximal power (RPOs) between 5 and 180 minutes compared with JUN ($P < .01$). Edward's training impulse per hour was higher in JUN than PRO and U23 ($P < .01$). Accordingly, JUN spent a higher percentage of racing time in high internal intensity zones compared with U23 and PRO, while these 2 categories spent more time at low internal intensity zones ($P < .01$). **Conclusions:** JUN races were shorter and included less elevation gain per distance unit compared to U23 and PRO races, but more internally demanding. JUN produced less power output in the moderate-, heavy-, and severe-intensity exercise domains compared with U23 and PRO (RPOs: 5-180 min). U23 and PRO races presented similar work demands per hour and RPOs, but PRO races were longer than U23.

Introduction

International road cycling racing, ruled by the Union Cycliste Internationale (UCI), includes 3 age-related categories which follow a race calendar culminating with world championships: junior (JUN; 17–18 y), under 23 (U23; 19–23 y), and professional (PRO; >23 y).

Previous studies have already reported anthropometrical and laboratory-based physiological characteristics of these 3 categories, but the widespread use of mobile heart rate (HR) monitors and portable mechanical power meters permits nowadays to capture field data for a deeper understanding of the requirements of road cycling competition. (Menaspà et al. 2015, Sallet et al. 2006, Padilla et al. 1999, Passfield et al. 2017). Indeed, power output (PO) and HR-derived parameters provide insights about the external (the objective measure of the work that an athlete completes) and internal (the individual psychophysiological response to cope with the external load) demands of exercise.(Impellizzeri et al. 2019) A number of studies have analysed the external and internal demands of professional road races, comparing men and women events, professional men races with different competitive levels, and altimetric profiles. (Sanders and Van Erp 2021, Sanders et al. 2019, Van Erp and Sanders 2020, Sanders and Hejboer 2019). On the other hand, only one study described the racing demands of youth cycling categories. In that study, however, Rodríguez-Marroyo et al. reported only internal demands of JUN and in under 17 cyclists. (Rodriguez-Marroyo et al.2011)

To the best of our knowledge, a cross-sectional analysis of external and internal race demands in JUN, U23, and PRO has not yet been carried out. Possible differences between the competition demands in the different categories could underline different physical attributes required to compete and succeed in different age categories, which in turn could negatively influence talent selection based only on race performance (eg, not selecting JUN unsuccessful cyclists who have the physical attributes to be successful in the PRO category). Regarding this point, Menaspà et al. reported that JUN selected for the national team mainly included flat specialists. The authors suggested this could be due to the lower elevation gain typical of JUN compared with PRO races, which penalizes climbers. (Menaspà et al. 2012) In addition, even if coaches traditionally attempt to modulate both volume and intensity of training considering the maturation level of the cyclists during development stages, comparing different age categories, actual race demands could give further responses on how to adjust training strategies for competing in different road cycling categories.

Therefore, the aim of this study was to compare the external and internal race demands of the 3 UCI age-limited road cycling categories: JUN, U23, and PRO. Our hypothesis is that the progressive increase in distance per race through categories leads to substantial differences in external and internal demands between categories and that JUN races includes less elevation gain per distance unit compared with both U23 and PRO races. These might valorise less highly durable and/or climber cyclists in JUN and U23 compared to PRO category.

Methods

Participants

Thirty male cyclists, divided into the 3 age-related categories ruled by the UCI (JUN, n = 10; U23, n = 10; and PRO, n = 10) participated in this study. Anthropometric characteristics of the participants are reported in Table 1. Each category cohort was composed of cyclists riding for the same team. The competitive level of all 3 groups was high within their category: the JUN group won the Italian national team seasonal ranking and included a rider who won the silver medal at UCI Road World Championships; 5 out of 10 U23 cyclists became professional within 2 seasons after the one considered in the present study (ie, within 2021); and the PRO group ranked in the top 10 in the World Tour team seasonal ranking.

Table 1: *Anthropometric Characteristics of the Participants, Divided by Age Category*

	JUN	**U23**	**PRO**	***P***	**ES**
Age (years)	17.2 ± 0.5	19.7 ± 0.3*	27.7 ± 1.4*#	< 0.001	0.776
Height (cm)	179 ± 2	181 ± 2	182 ± 2	0.860	0.011
Weight (kg)	65.8 ± 6.4	65.1 ± 5.2	66.7 ± 7.0	0.519	0.049
BMI (kg/m^2)	20.5 ± 0.8	19.9 ± 1.2	20.0 ± 1.4	0.527	0.048

Abbreviations: BMI, body mass index; ES, effect size; JUN, junior; PRO, professional; U23, under 23. Note: Data are presented as mean (SD).

**Significantly different from JUN. #Significantly different from U23.*

Considering their cycling status, all participants can be classified as “performance level 5” (training frequency per week > 5, cycling experience > 5 y, and training hours per week > 10) according to the guidelines of De Pauw et al. (De Pauw et al. 2013).

The study design and procedures were approved by the research ethics committee of the Università degli Studi di Milano and followed the ethical principles for medical research involving human participants set by the World Medical Association Declaration of Helsinki. Participants were provided with written instructions outlining the procedures and risks associated with the study and gave informed written consent.

Experimental Design

For each category, the 2019 season was taken into consideration for data analysis. Race characteristics, HR, and PO data were collected during races using a cycling performance software analyzer (WKO5; TrainingPeaks LLC, Boulder, CO). All data were visually checked for erroneous data, and incomplete data files due to technological issues (eg, flat battery of a power meter) were removed when necessary. If one of the 2 main variables (ie, PO, HR) was missing for a given race but no erroneous data were present within the given session, the data set was still analyzed using the available variables. For each category, we took into consideration all races, not distinguishing between race typologies (ie, stage races, 1-d races, etc), because JUN ride almost all 1-day races.

Race Characteristics

Duration, distance, and elevation gain were recorded using 2 different power meter head units: JUN and U23 used Garmin Edge 520, while PRO used Garmin Edge 810 (Garmin, Schaffhausen, Switzerland). It has been previously shown that the analyzed variables were relatively consistent within devices of this brand if, as in our case, the same setting was used (ie, elevation correction) (Menaspà et al. 2014). In addition, the total annual number of races was also recorded (race days). The percentage of the annual exercise duration spent in races (race percentage) and the elevation gain per distance ratio were also calculated.

Race External Demands

Race external demands were calculated based on power data collected with portable power meters: JUN, Garmin Vector 3 (Garmin); U23, SRAM RED eTap (SRAM RED, Spearfish, South Dakota); and PRO, Power2max (Saxonar GmbH, Waldhufen, Germany). The accuracy of these instruments in power calculation was previously verified and validated. (Maier et al. 2017) All riders were informed about the importance of the zero calibration of power meters and were instructed to do the zero calibration before every ride.

Annual total work was derived summing the total work accumulated during each race, calculated with the following formula:

$$\text{Total work(kJ)} = \text{Power output(W)} \times \text{duration(s)}/1000.$$

Race external intensity was calculated using the total work per duration ratio. To distinguish the different contribution of race days and durations on annual total work, the total work per race days ratio was calculated. Record power profiles were also calculated following Pinot and Grappe's method, as the highest absolute (in watts) and relative (in watts) mean recorded POs (RPO) over the corresponding time durations, considering thirteen time frames (1, 5, 30, 60 s and 5, 10, 20, 30, 45, 60, 120, 180, 240 min) (Pinot and Grappe 2011). In addition, the percentage of total race time spent at different PO bands was calculated using steps of 0.75 $W \cdot kg^{-1}$ ranging from <0.75 to >7.50 $W \cdot kg^{-1}$, as already done in previous studies. (Menaspà et al. 2017)

Race Internal Demands

Race internal demands were assessed based on HR data collected with portable HR monitors connected with a chest strap (Garmin).

Race internal load was calculated using Edwards' training impulse (eTRIMP) (Edwards S. 1994). eTRIMP was calculated based on time spent in the 5 predefined HR zones multiplied by a zone-specific arbitrary weighting factor: zone 1, 50% to 59% HR_{peak} (multiplication factor 1); zone 2, 60% to 69% HR_{peak} (factor 2); zone 3, 70% to 79% HR_{peak} (factor 3); zone 4, 80% to 89% HR_{peak} (factor 4); and zone 5, 90% to 100% HR_{peak} (factor 5). HR_{peak} was defined as the highest HR recorded during the season. Race internal intensity was calculated using the eTRIMP per duration ratio. To distinguish the different contribution of race days and durations on annual eTRIMP, eTRIMP per race days ratio was also calculated. The same 5 HR zones used in the eTRIMP calculation were used to report the race internal intensity distribution expressed as percentage of time spent in each intensity zone.

Statistical Analysis

All data are presented as mean (SD). For each variable, outliers which were more than 3 SDs from the mean of the respective group were excluded from further analysis. For all the variables analyzed per race, the total annual of each variable was obtained from WKO for each cyclist and then, divided by the number of races the cyclist completed. Assumptions of statistical tests such as normal distribution and sphericity of data were checked with Shapiro–Wilk and Mauchly tests, respectively. Greenhouse–Geisser correction to the degrees of freedom was applied when violation of sphericity was present. To compare the mean of all variables between the 3 groups, 1-way analysis of variance was performed when normality assumption was met, otherwise a Kruskal–Wallis H test was performed. Depending on whether assumption of homogeneity of variance was met or not (Levene test), Bonferroni or Games–Howell post hoc test was performed, respectively. Significance was set at .05 (2-tailed) for all analyses. Effect sizes (ESs) for 1-way analysis of variance are reported as partial eta squared and for Kruskal–Wallis H test as epsilon squared, using the small (<0.13), medium (0.13–0.25), and large (>0.25) interpretation for ES (Bakeman D. 2005). Data analysis was conducted using the statistical package for the social sciences (version 26; SPSS Inc, Chicago, IL).

Results

Race Characteristics

Race characteristics for the 3 age categories are reported in Table 2. There were significant differences with large effects among the 3 groups for all the parameters considered. Post hoc tests showed that annual duration, duration per race, annual distance, distance per race, annual elevation gain, and elevation gain per race were higher in PRO compared with U23 and JUN and in U23 compared with JUN ($P < .01$). Race days and race percentage were higher in PRO compared with U23 and JUN ($P < .001$) but did not differ between U23 and JUN. Elevation gain per distance was higher in PRO and U23 compared with JUN ($P < .001$) but did not differ between PRO and U23.

Table 2: *Race Characteristics of the 3 Age Categories*

	JUN	U23	PRO	*P*	ES
Race days (n)	36 ± 7	42 ± 11	77 ± 6*#	< 0.001	0.831
Annual duration (hours)	86 ± 20	129 ± 33*	303 ± 27*#	< 0.001	0.926
Race percentage (%)	16.9 ± 0.8	18.2 ± 3.3	33.5 ± 2.6*#	< 0.001	0.903
Duration per race (hours)	2.4 ± 0.2	3.1 ± 0.3*	3.9 ± 0.2*#	< 0.001	0.882
Annual distance (km)	3300 ± 815	4920 ± 1345*	11569 ± 981*#	< 0.001	0.919
Distance per race (km)	94 ± 3	124 ± 10	150 ± 7*#	< 0.001	0.761
Annual elevation gain (km)	18 ± 5	57 ± 16*	145 ± 19*#	< 0.001	0.937
Elevation gain per race (m)	520 ± 57	1387 ± 100*	1870 ± 63*#	< 0.001	0.876
Elevation gain per distance ($m \cdot km^{-1}$)	5.9 ± 0.3	11.6 ± 0.4*	12.5 ± 0.3*	< 0.001	0.923

Abbreviations: ES, effect size; JUN, junior; PRO, professional; U23, under 23.

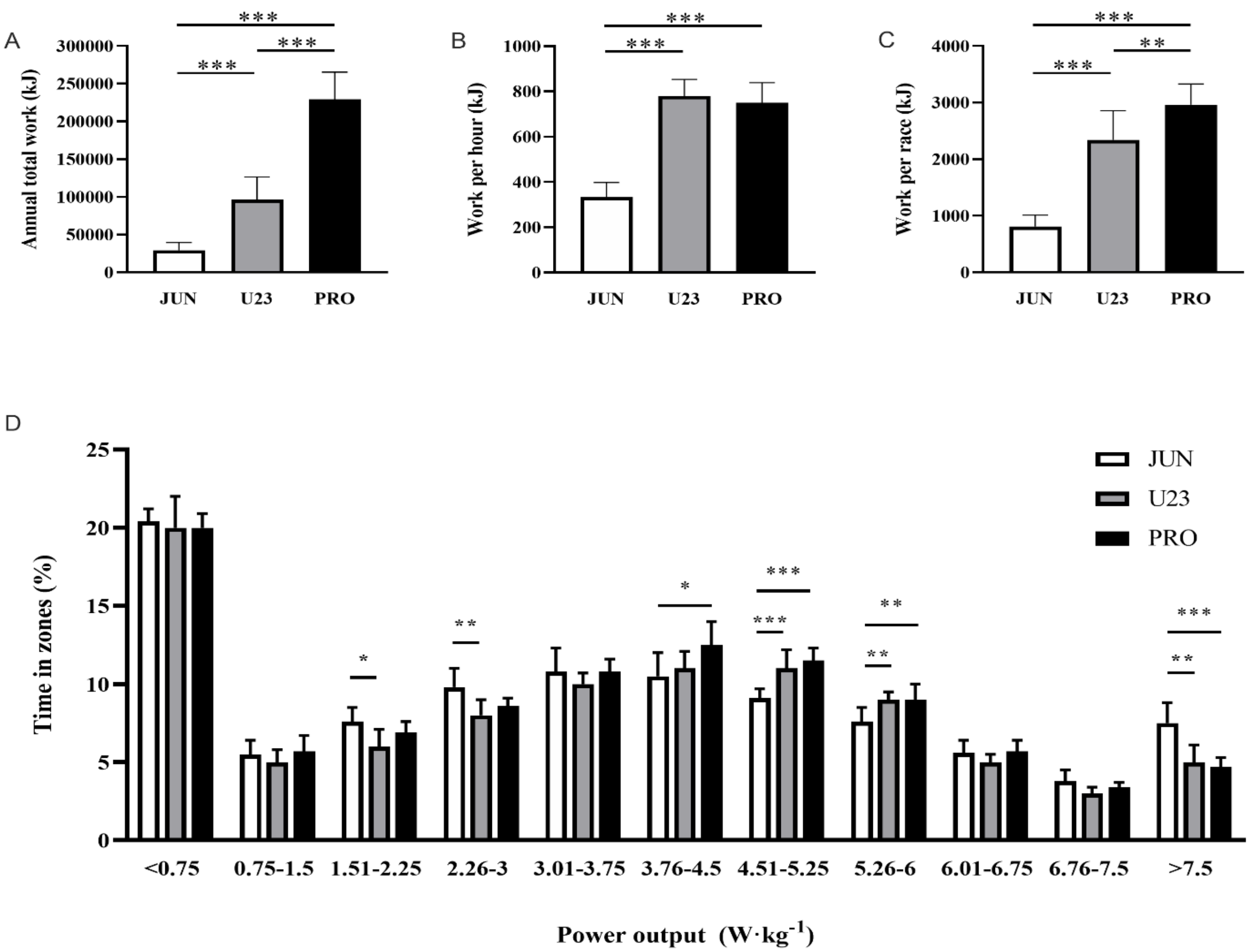
Note: Data are presented as mean (SD).

**Significantly different from JUN (P < .05). #Significantly different from U23 (P < .05).*

Race External Demands

Race external demands are presented in Figure 1. There were significant differences with large effects among the 3 groups for annual total work, work per hour, and work per race ($P < .001$, ES = 0.86–0.89). Percentage time spent at low PO intensity (1.51–3.00 $W \cdot kg^{-1}$) was higher in JUN compared with U23 ($P < .05$, ES = 0.29–0.37), but did not differ between U23 and PRO or JUN and PRO. Percentage time spent within the 3.76 to 4.50 $W \cdot kg^{-1}$ band was lower in JUN compared with PRO ($P < .05$, ES = 0.29), but did not differ between JUN and U23 or U23 and PRO. Percentage time spent between 4.51 and 6.00 W·kg^{-1} was lower in JUN compared both to PRO and U23 ($P < .01$, ES = 0.40–0.60), but did not differ between U23 and PRO. Percentage time spent at the higher end of the power bands (>7.50 W·kg^{-1}) was higher in JUN ($P < .01$, ES = 0.57) compared with U23 and PRO, but did not differ between U23 and PRO.

Figure 1: *Race external demands of JUN, U23, and PRO cyclists.*

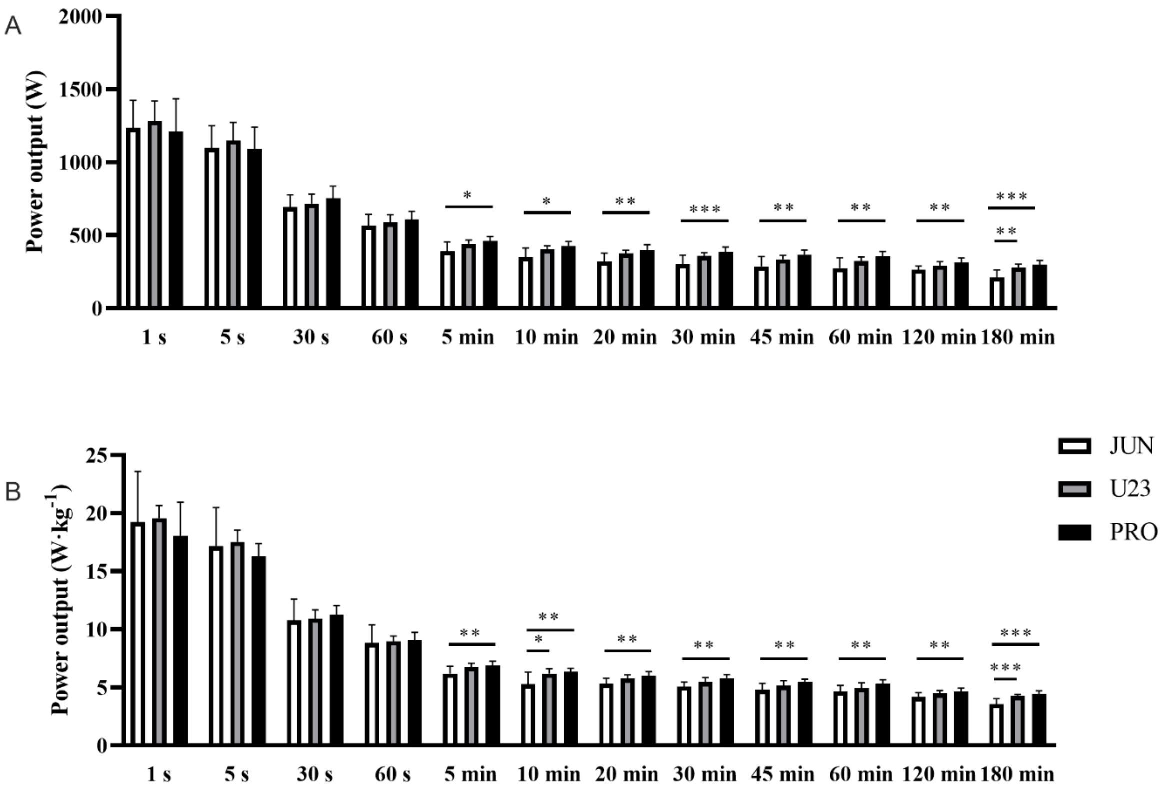


Abbreviations: (A) Annual total work, (B) total work per hour, (C) total work per race, and (D) power output distribution as percentage of racing time spent in different power bands. JUN indicates junior; PRO, professional; U23, under 23.

Significant difference between the groups ($P < .05$, **$P < .01$, and ***$P < .001$).*

Record PO profiles showed significant differences with large effects among the 3 groups for both absolute and relative RPO-5 minutes, RPO-10 minutes, RPO-20 minutes, RPO-30 minutes, RPO-45 minutes, RPO-60 minutes, RPO-120 minutes, and RPO-180 minutes ($P < .01$; ES =0.29–0.61; Figure 2).

***Figure 2**: Absolute (A) and relative (B) mean recorded power outputs over the corresponding time durations considering 13 time frames (1, 5, 30, 60 s and 5, 10, 20, 30, 45, 60, 120, 180, 240 min).*

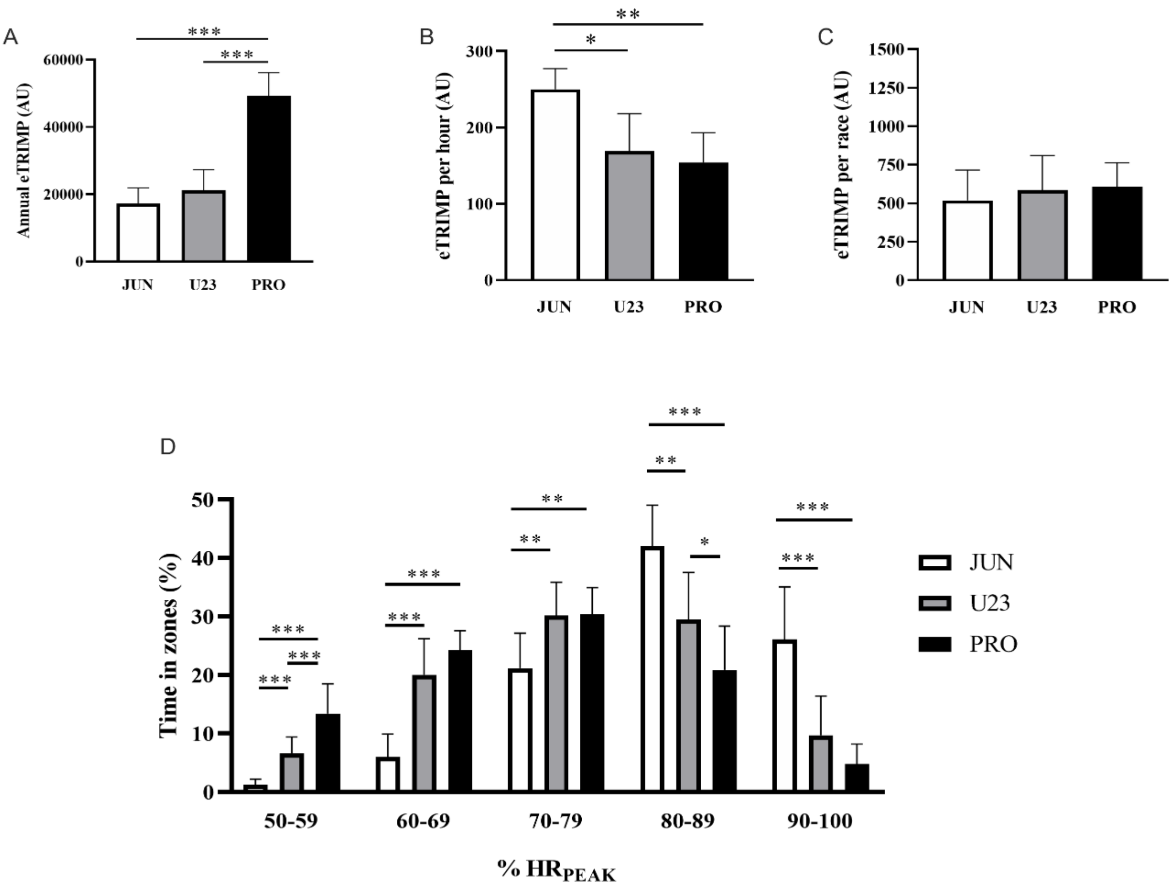


*Abbreviations: JUN indicates junior; PRO, professional; U23, under 23. Significant difference between the groups (*P < .05, **P < .01, and ***P < .001).*

Race Internal Demands

Race internal demands are presented in Figure 3. There were significant differences among the 3 groups for annual eTRIMP and eTRIMP per hour ($P < .01$, ES = 0.39–0.85), while eTRIMP per race did not differ between groups. Race internal intensity distribution showed significant differences among the 3 groups for the percentage of time spent in all the intensity zones ($P < .01$, ES = 0.40–0.74).

Figure 3: *Race internal demands of JUN, U23, and PRO cyclists. (A) Annual eTRIMP, (B) eTRIMP per hour, (C) eTRIMP per race, and (D) HR distribution as percentage of racing time spent in different heart rate zones.*



*Abbreviations: HR indicates heart rate; JUN, junior; PRO, professional; eTRIMP, Edwards training impulse; U23, under 23. Significant difference between the groups (*P < .05, **P < .01, ***P < .001).*

Discussion

To the best of our knowledge, this is the first study that reported cross-sectional differences in race characteristics and external and internal race demands of the 3 UCI age-limited road cycling categories: JUN, U23, and PRO. In line with our hypothesis, the results highlighted large differences among categories for general race characteristics, external, and internal race demands.

Race Characteristics

The annual race distance, duration, and elevation gain increased progressively across the 3 age categories. This could be due to the increase in difficulty of races from JUN to PRO, together with a higher number of race days in PRO compared with JUN and U23. The progressive increase of the duration per race, distance per race, and elevation gain per race is a natural consequence of length restrictions established by national and international rules for each category. Concerning race days, PRO competed in approximately twice as many races (77 [6]) than U23 (2 [11]) and JUN (36 [7]) cyclists. Furthermore, PRO spent a higher percentage of the annual cycling volume in races compared to youth categories. Hence, when planning the annual periodization, practitioners should be aware that an appropriate programming of a racing schedule is far more important in professional than in youth categories, to appropriately find the right balance between training and/or competition load and recovery. This approach could be helpful to achieve performance peaks in the high-priority races.

In line with our initial hypothesis, elevation gain per distance was lower in JUN compared with both U23 and PRO. This finding could suggest that climbers (i.e, riders with higher relative PO on medium and long-duration uphill efforts) might have less opportunity to emerge than flat terrain specialists (ie, cyclists with higher absolute PO on short and medium-duration efforts) in JUN compared with U23 and PRO races. Accordingly, Menaspà et al. found that JUN cyclists selected by their national team for international races possess superior level-ground abilities (ie, body mass, absolute peak oxygen uptake, oxygen uptake at the respiratory compensation point, and ventilatory threshold) than riders who were not selected, suggesting that successful JUN riders are those more competitive in flat races (Menaspà et al. 2010). As JUN race characteristics are not tailored for their performance capacities, these riders might show their true potential only in mountainous races of U23 and PRO categories. Therefore, talent scouts and practitioners should evaluate JUN cyclists with also physiological testing and not only by race performance, in order to include this type of riders in the athletes' selections in the superior age categories (ie, from JUN to U23 and from U23 to PRO) even if the race results are not as promising as other riders.

Race External Demands

The results of the present study showed that annual total work and work per race increase progressively across the 3 age categories. Total work per hour did not differ between U23 and PRO, but was lower in JUN. Such lower external intensity despite a lower duration per race indicates that JUN riders are not able to produce the same PO as U23 and PRO cyclists. Although JUN showed similar short-duration RPOs (1–60 s) compared with U23 and PRO, they recorded lower long-duration RPOs (5–180 min). Hence, according to the PO spent at different exercise intensity domains, (Pinot and Grappe 2011) the lower external intensity expressed in JUN races might be due to the JUN cyclists' lower ability to produce power in the moderate, heavy, and severe exercise intensity zones compared with their U23 and PRO counterparts.

When looking at PO intensity distribution, a rightward shift between 1.51 and 6.00 $W \cdot kg^{-1}$ for U23 and PRO compared to JUN was observed. As the range 1.51 to

6.00 W·kg^{-1} approximately represent the moderate-, heavy-, and severe-intensity exercise domains, the power intensity distribution seems to confirm a higher capacity to produce PO in these exercise intensity domains in PRO and U23 compared with JUN. On the other hand, the higher percentage racing time spent at PO > 7.50 W·kg^{-1} in JUN compared to both U23 and PRO could be a consequence of a similar capacity to produce PO in the force–velocity exercise intensity domain across the 3 categories (confirmed by similar short durations RPOs [1 s to 1–60 s]), combined with JUN's lower duration per race respect to U23 and PRO. Very interestingly, PRO completed more total work per race than U23, but these 2 categories did not differ for the external intensity (ie, total work per hour), and for both absolute and relative RPOs. Thus, PRO and U23 races differ only in duration and not external intensity: PRO cyclists do not produce higher POs than U23, but they produce the same PO for longer durations than U23 cyclists. Accordingly, Leo et al. showed that during a 5-day cycling multistage race including both PRO and U23 teams, absolute and relative RPOs were not different between professional and U23 cyclists but, interestingly, professional cyclists showed higher relative RPOs after a certain amount of work (1000–3000 kJ) than U23 cyclists. (Leo et al. 2021) From this perspective, our findings could suggest that durability (ie, the ability to decrease the PO as little as possible after a prior amount of exercise) could be a peculiar feature that differentiates PRO from U23 cyclists.

Race Internal Demands

eTRIMP per race was similar between the 3 categories, but volume and internal intensity were combined in different ways across the 3 categories. Specifically, in contributing to the total eTRIMP per race, intensity (i.e, eTRIMP per hour) played a major role in JUN (i.e, higher eTRIMP per hour in JUN compared to both U23 and PRO); conversely, volume (i.e, duration per race) played a more important role in the latter 2 categories respect to JUN.

Accordingly, the HR intensity distribution showed that JUN spent much more time at high-intensity zones (ie, 80%–89% and 90%–100% HR_{peak}), while U23 and PRO accumulated a higher percentage of racing time in lower intensity zones (ie, 50%–59%, 60%–69%, and 70%–79% HR_{peak}).

Hence, it seems clear that JUN compensate for the shorter duration of their races with a higher internal intensity, similarly to what Sanders et al. observed for professional women compared with their men counterparts (Sanders et al. 2019).

The PRO races were longer, and a similar or higher percentage of time was accumulated in low-intensity HR zones compared with U23 and JUN. This could suggest that "low-intensity durability" (i.e, preserving the capacity to produce PO after prior long-duration moderate-intensity exercise) as a specific facet of durability could be a peculiar feature required to become a PRO cyclist. In addition to the lower duration per race, another factor which might contribute to the higher intensity observed in JUN races could be that, in this category, teamwork dynamics are less present in comparison with U23 and PRO races. This means that traditionally no teams control the race by pulling the peloton, allowing other riders to follow a constant pace taking advantages from the draft (Ouvrard et al. 2018). At the opposite, in JUN races, there are more individual attacks, which might contribute to the higher mean intensity observed.

Limitations

The main limitation of this study is the low sample size and that all athletes for each category are part of only one team. Including more than one team for each category could eliminate the influence of team racing tactics on external and internal demands. However, such an approach is not easily feasible since it is difficult to aggregate data from high-level teams competing against each other within the same age category due to possible conflicts of interest and data liability rules. In addition, the calculation of HR to derive eTRIMP and HR intensity distribution has been performed only on an annual basis using seasonal $HR_{peak.}$ This approach could have led to suboptimal accuracy, as HR_{peak} could change day-to-day due to fatigue state (Sanders et al. 2018). Ideally, HR should have been updated more frequently across the season using standardized tests. However, during the time of the analysis, not all the 3 cohorts (JUN, U23, and PRO) performed controlled exercise testing using the same protocol, making such approach not feasible.

Another possible limitation of this study was that PO data were collected with different power meter brands. Even if the accuracy of these instruments in power calculation was previously verified and validated (Maier et al. 2017), there could be a difference between all the power meter brands used.

Practical Applications

The differences we found in race characteristics and physical external and internal demands between JUN, U23, and PRO could lead to useful practical implications for coaches and practitioners. First, concerning talent identification, our results demonstrated that climbers are less likely to show their full potential in JUN races, due to the lower elevation gain per distance observed in JUN compared with U23 and PRO. Practitioners should be careful when selecting riders from the youth categories, considering that climbers are disadvantaged by race characteristics at JUN level.

Secondly, when selecting U23 cyclists to become PRO cyclists, durability should be taken into consideration, as PRO and U23 PO did not differ during races, but in PRO races the same PO is maintained for longer durations.

Regarding training strategies, JUN could potentially benefit from more high-intensity training, whereas U23 and PRO could benefit from more volume accumulated at moderate intensities. On the other hand, the results of this study could also be seen as an indication for coaches on how to set their training programs in a talent development perspective. In this sense, at the JUN level, it could be important from a long-term perspective not to chase the physical demands of the current age category (ie, fostering high-intensity training), but to focus more on athlete long-term development by targeting the requirements of the U23 and PRO categories (ie, fostering high-volume training). However, even if training at race-specific intensities is a concept which has been widely used by coaches during the last decades, it is still debated if training intensity specificity is a fundamental requirement in endurance sports context (Laursen PB 2010).

Conclusions

The JUN cycling races were shorter, more intense, and included less elevation gain for distance unit compared to U23 and PRO races, suggesting that JUN climbers are likely to show their true potential only in mountainous races of U23 and PRO categories. During races, JUN produced less PO in the moderate-, heavy-, and severe-intensity exercise domains compared with U23 and PRO (RPOs: 5–180 min). Work per hour and RPOs were similar in U23 and PRO races, but PRO races had longer durations than U23. These results could suggest as durability is a feature required of road cyclists moving up from the JUN/U23 to PRO category.

STUDY 2

Power Road-Derived Physical Performance Parameters in Junior, Under-23, and Professional Road Cycling Climbers

Gallo G, Mateo-March M, Leo P, Campos-Donaire A, Gandia-Soriano A, Giorgi A, Faelli E, Ruggeri P, Codella R, Mujika I, Filipas L. Power Road-Derived Physical Performance Parameters in Junior, Under-23, and Professional Road Cycling Climbers. Int J Sports Physiol Perform. 2022 Apr 28;17(7):1094-1102.

Abstract

Purpose: To investigate the relationship of field-derived power and physical performance parameters with competition success in road cycling climbing specialists of different age-related categories and to explore cross-sectional differences between high-ranked (HIGHR) climbing specialists of each category. **Methods:** Fifty-three male climbers participated in this study (junior [JUN], n = 15; under 23 [U23], n = 21; professional [PRO], n = 17). Training and racing data collected during the 2016-19 competitive seasons were retrospectively analyzed for record power outputs (RPOs) and RPOs after prior accumulated work. **Results:** In JUN, body mass, absolute RPOs, and relative RPOs were higher in HIGHR compared with low ranked (d = 0.97-2.20, large; P = .097-.001); in U23 and PRO, the percentage decrease in RPOs after 20, 30, 40, and 50 $kJ \cdot kg^{-1}$ was less in HIGHR compared with low ranked (d = 0.77-1.74, moderate-large; P = .096-.004). JUN HIGHR presented lower absolute and relative RPO-20 min ($\eta^2 p$=.34-.38, large; P = .099-.001) and higher percentage decrease in RPOs after prior accumulated work compared with U23 and PRO HIGHR ($\eta^2 p$=.28-.68, large; P = .060-.001); percentage decrease in RPOs after prior accumulated work was the only parameter differentiating U23 and PRO HIGHR, with PRO declining less in relative RPO-1 min, RPO-5 min, and RPO-20 min after 20 to 50 $kJ \cdot kg^{-1}$

(η^2p=.28-.68, large; P = .090-.001). **Conclusions:** Superior absolute and relative RPOs characterize HIGHR JUN climbing specialists. Superior durability differentiates HIGHR U23 and PRO climbers compared with low ranked, as well as PRO versus U23 climbers.

Introduction

Despite complex race strategies and team dynamics, practitioners identify cyclists' individual physical attributes as the pivotal factor for competition success in road cycling (Leo et al. 2021). Traditionally, laboratory-based physiological parameters such as maximal oxygen uptake (VO_2max) and lactate thresholds have been used to identify physical attributes associated with road cycling performance (Lucia et al. 2004). However, especially during the competitive period, regular laboratory-based testing with high-level competitive cyclists could be complicated due to busy racing schedules, logistics, and expensive equipment. A relatively recent alternative is using performance parameters derived from mechanical power output expressed during training and racing. Some performance parameters widely used by cycling coaches are record power outputs (RPOs)6 and RPOs after a certain amount of accumulated work (Pinot and Grappe 2011, Leo et al. 2021). All these parameters are calculated using mean maximal power output over different time durations. Even if these parameters are not derived by standardized testing protocols like laboratory-based parameters, Quod et al reported no differences between mean maximal power output over different time durations (60–600 s) recorded during road races or standardized laboratory tests. This suggests that field mean maximal power outputs could be used as a valid and more feasible approach to evaluate physical attributes of road cyclists compared to laboratory testing (Quod et al. 2010).

International road cycling racing, ruled by the Union Cycliste Internationale (UCI), includes 3 age-related categories which follow a race calendar culminating with world championships: junior (JUN; 17–18 y), under 23 (U23; 19–23 y), and professional (PRO; >23 y). Although some descriptive studies already reported power-derived physical performance parameters among U23 (Leo et al. 2020, Leo et al. 2021) and PRO (Pinot and Grappe 2011, Van Erp et al. 2021) road cyclists, to the best of our knowledge, no studies have explored the association between these parameters and competition success in each of these 3 categories. Even if success in youth categories increases the chances to become a PRO cyclist, (Svendsen et al. 2018, Mostaert et al. 2021) no significant differences in best professional world championship ranking was reported between cyclists who were placed in the top 10 at Junior World Championships and those who were not (Schumacher et al. 2006). As road cycling race demands differ across different age-related categories, (Gallo et al. 2022) it is plausible that different physical attributes are required to excel in the different age-categories, contributing to the mismatch between youth and professional road cycling competition success.

Therefore, the first aim of this study was to investigate whether field-derived physical performance parameters are associated with competition success in each age-related road cycling category in climbing specialists. Identifying possible between-age-categories differences in physical attributes associated with competition success could lead to improve talent selection (i.e, selecting young cyclists transitioning from JUN to U23 or PRO, and U23 to PRO). Our hypothesis was that, while the ability to sustain power output after prior accumulated work (i.e, durability) distinguishes between high-ranked (HIGHR) versus low-ranked (LOWR) PRO and U23 climbing specialists, it would not play a pivotal role in competition success in JUN races, given their lower duration compared with the U23 and PRO races.

The secondary aim of this study was to explore cross-sectional differences in field-derived physical performance parameters between HIGHR climbers of each category. This could give an interesting insight into talent development (i.e., adopting the best possible training strategies with cyclists transitioning to the successive age category).

Methods

Participants

Fifty-three male road cyclists divided into the 3 age-related categories ruled by the UCI (JUN, n = 15; U23, n = 21; PRO, n = 17) participated in this study. Only “climbers” were included in the sample. The cyclists were classified as “climbers” based on their assigned role within the team, as they were more likely to outperform their competitors uphill than on the flat according to their team’s coaching staff. JUN cyclists were part of 2 different Italian teams affiliated with the Italian National Cycling Federation. U23 cyclists were part of 5 different U23 Continental teams affiliated with the UCI. PRO cyclists were part of 3 different World Tour teams affiliated with the UCI. The study design and procedures were approved by the research ethics committee of the Università degli Studi di Milano and followed the ethical principles for medical research involving human participants set by the World Medical Association Declaration of Helsinki. Participants gave informed written consent.

Experimental Design

For each cyclist, one season between 2016 and 2019 was taken into consideration for data analysis. To evaluate competition success in the selected season, each cyclist’s end-season position in their age-category ranking was retrieved from online databases. Field-derived physical performance parameters were obtained from power output data collected during training and racing using a cycling performance software (WKO5, TrainingPeaks LLC). All data were visually checked for erroneous data, and corrupted data files due to technological issues (eg, flat battery of a power meter) were removed.

Competition Success

For each category, the position at the end of the season (31^{st} December) in the age-category ranking was taken into consideration: the Italian National Cycling Federation ranking for

JUN, the U23 Continental ProCyclingStats (www.procyclingstats.com) ranking for U23, and the PRO ProCyclingStats (www.procyclingstats.com) ranking for PRO. Cyclists were allocated into a HIGHR or a LOWR group, depending on their classification within their age-category ranking. For U23 and PRO, HIGHR cyclists were defined as cyclists classified within the top 15% positions (Van Erp et al. 2021). Based on the total number of cyclists for each category, classifying within the top 15% meant to be ranked in the top 250 and in the top 150 for U23 and PRO, respectively. For JUN, HIGHR cyclists were defined as cyclists classified within the top 5% (~top 50) in the JUN Italian National Cycling Federation ranking. We adopted this tighter cut-off for JUN as we considered a national ranking for this age category, while international rankings were used for both U23 and PRO. We deemed it appropriate to compare the best 15% U23 and PRO worldwide with the best 5% Italian JUN, as Italy classified in the top 3 of UCI Nations' Cup JUN in the seasons analyzed.

Field-Derived Physical Performance Parameters

Field-derived physical performance parameters were calculated based on power data of training sessions and races collected with portable power meters: JUN, Garmin Vector 3 (Garmin); U23, SRAM Red eTap (SRAM, Red) and Rotor INpower (Rotor Inc); and PRO, Power2max (Saxonar GmbH). The accuracy of these instruments in power calculation was previously verified and validated (Maier et al. 2017). All riders were informed about the importance of the zero calibration of power meters and were instructed to do the zero calibration before every ride. The field-derived physical performance parameters considered were RPOs over different time durations (10 s, 1 min, 5 min, and 20 min) and RPOs after certain amounts of work done (10, 20, 30, 40, and 50 $kJ \cdot kg^{-1}$). For each of these parameters, the highest value of the season was considered. RPO-10 s, RPO-1 min, RPO-5 min, and RPO-20 min were defined as the highest mean maximal power over 10 seconds, 1 minutes, 5 minutes, and 20 minutes, respectively (Pinot and Grappe 2011). For each parameter, both absolute (in watts) and relative (in watts per kilogram) power outputs were considered. Fatigue resistance was evaluated through the percentage of decline of RPOs after 5 levels of work done corrected for body mass (ie, 10, 20, 30, 40, and 50 $kJ \cdot kg^{-1}$). Only 2 JUN participants recorded RPOs after 50 $kJ \cdot kg^{-1}$, thus the percentage decline up to 40 $kJ \cdot kg^{-1}$ was reported and analyzed for this group.

Anthropometric Measurements

Age was reported referring to the 31st December of the season considered. Cyclists' body mass was updated during the season at least once a month. The most recent mass was used for the calculation of relative (in watts per kilogram) power. In the "Results" section, body mass is reported as the average of the mass recorded during the season. Body surface area (BSA) was calculated using the Du Bois and Du Bois's formula (Du Bois and Du Bois 1989).

Statistical Analysis

All data are presented as mean (SD). The assumption of normality was checked using the Shapiro–Wilk test. For each age category, independent samples t tests or Mann–Whitney U tests were conducted for comparisons between HIGHR and LOWR for age, height, weight, BSA, RPOs, and percentage decline in RPOs after 10, 20, 30, 40, and 50 $kJ \cdot kg^{-1}$. To compare the mean of all variables between the HIGHR JUN, U23, and PRO, 1-way analysis of variance was performed when normality assumption was met, otherwise Kruskal–Wallis H test was performed. Depending on whether assumption of homogeneity of variance was met or not (Levene test), Bonferroni or Games-Howell post hoc test was performed, respectively. The effect sizes for independent samples t tests or Mann–Whitney U tests are reported as Cohen d using the small = 0.2, medium = 0.5, and large = 0.8, Cohen ranges (Wassertheil and Cohen 1970). Effect sizes for 1-way analysis of variance are reported as partial eta squared ($\eta^2 p$), using the small (<.13), medium (.13–.25), and large (>.25) interpretation for effect sizes (Bakeman R. 2015). Significance was set at alpha ≤ .05 (2-tailed) for all analyses. Data analysis was conducted using the statistical package for the social sciences (SPSS, version 26).

Results

HIGHR Versus LOWR Cyclists Within the Same Age Category

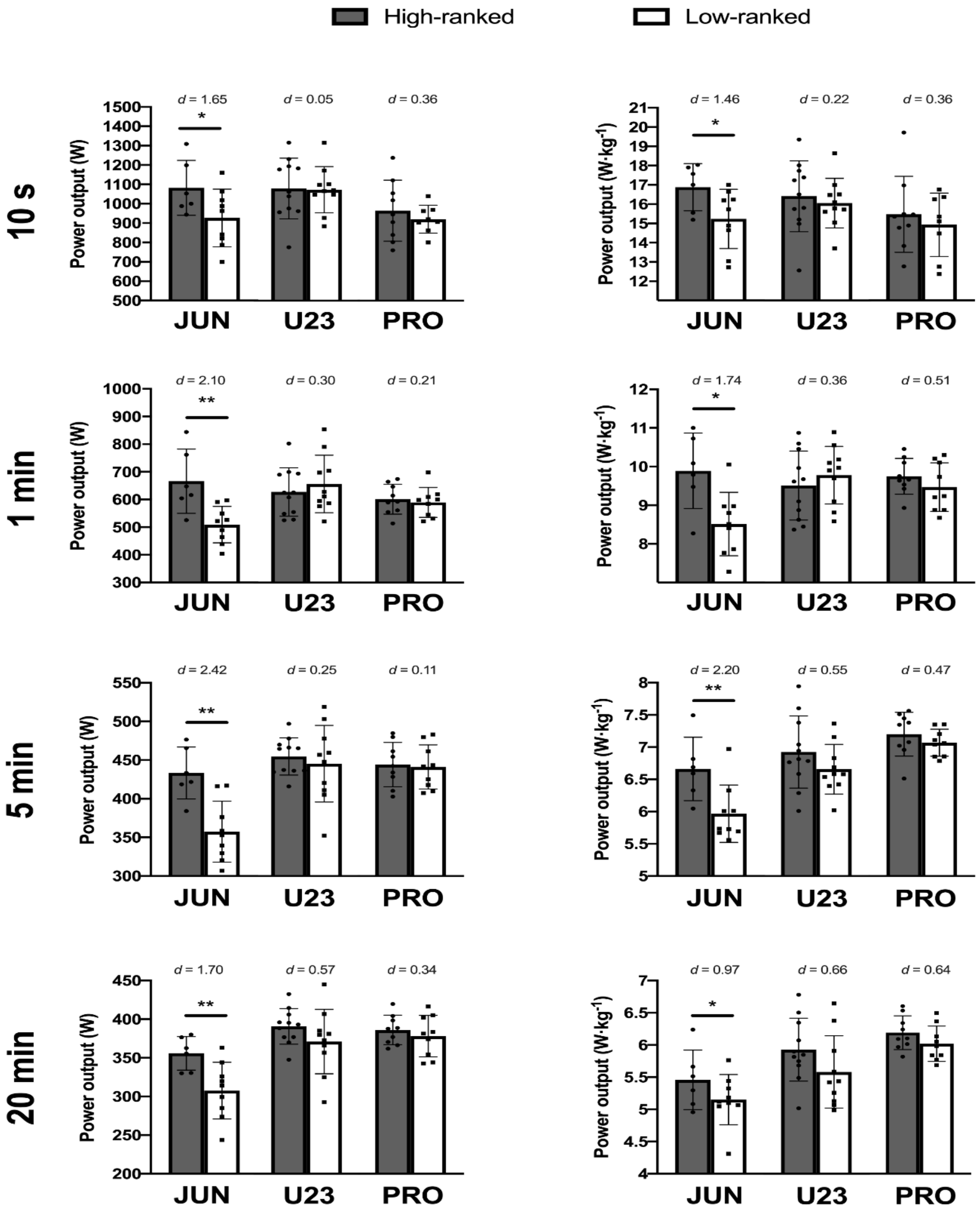
Differences in anthropometric and field-derived physical performance parameters between HIGHR and LOWR cyclists within the same age category are shown in Table 1 and Figures 1 and 2. In JUN, body mass, absolute RPOs, and relative RPOs were higher in HIGHR compared with LOWR (d = 0.97–2.20, large; P = .097–.001) (Table 1 and Figure 1). HIGHR and LOWR JUN did not differ in the percentage decline of RPOs after a prior accumulated work, except for the percentage decline of RPO-10 s after 40 $kJ \cdot kg^{-1}$, which was significantly lower in HIGHR compared with LOWR (d = 1.61, large; P = .041) (Figure 2). In the U23 and PRO groups, significant differences between HIGHR and LOWR cyclists were reported only for the percentage decline in RPOs after 30–50 $kJ \cdot kg^{-1}$ (d = 0.77–1.74, moderate–large; P = .096–.004) (Figure 2).

Table 1: *Differences in Anthropometric Characteristics Between HIGHR and LOWR JUN, U23, and PRO Climbers*

	JUN				U23				PRO			
	HIGHR	**LOWR**	***P***	***d***	**HIGHR**	**LOWR**	***P***	***d***	**HIGHR**	**LOWR**	***P***	***d***
Age (years)	18.3 ± 0.1	17.9 ± 0.5	0.100	1.01	19.9 ± 1.0	20.5 ± 0.7	0.279	0.57	29.7 ± 4.0	27.0 ± 2.8	0.122	0.77
Height (cm)	178 ± 8	174 ± 5	0.306	0.65	180 ± 6	181 ± 7	0.815	0.11	173 ± 6	177 ± 6	0.177	0.67
Weight (kg)	66 ± 7	60 ± 4	0.085	1.01	67 ± 6	67 ± 8	0.818	0.10	62 ± 4	62 ± 4	0.662	0.21
BSA (m^2)	1.8 ± 0.1	1.7 ± 0.1	0.174	0.87	1.9 ± 0.1	1.9 ± 0.2	0.858	0.08	1.8 ± 0.1	1.8 ± 0.1	0.643	0.22

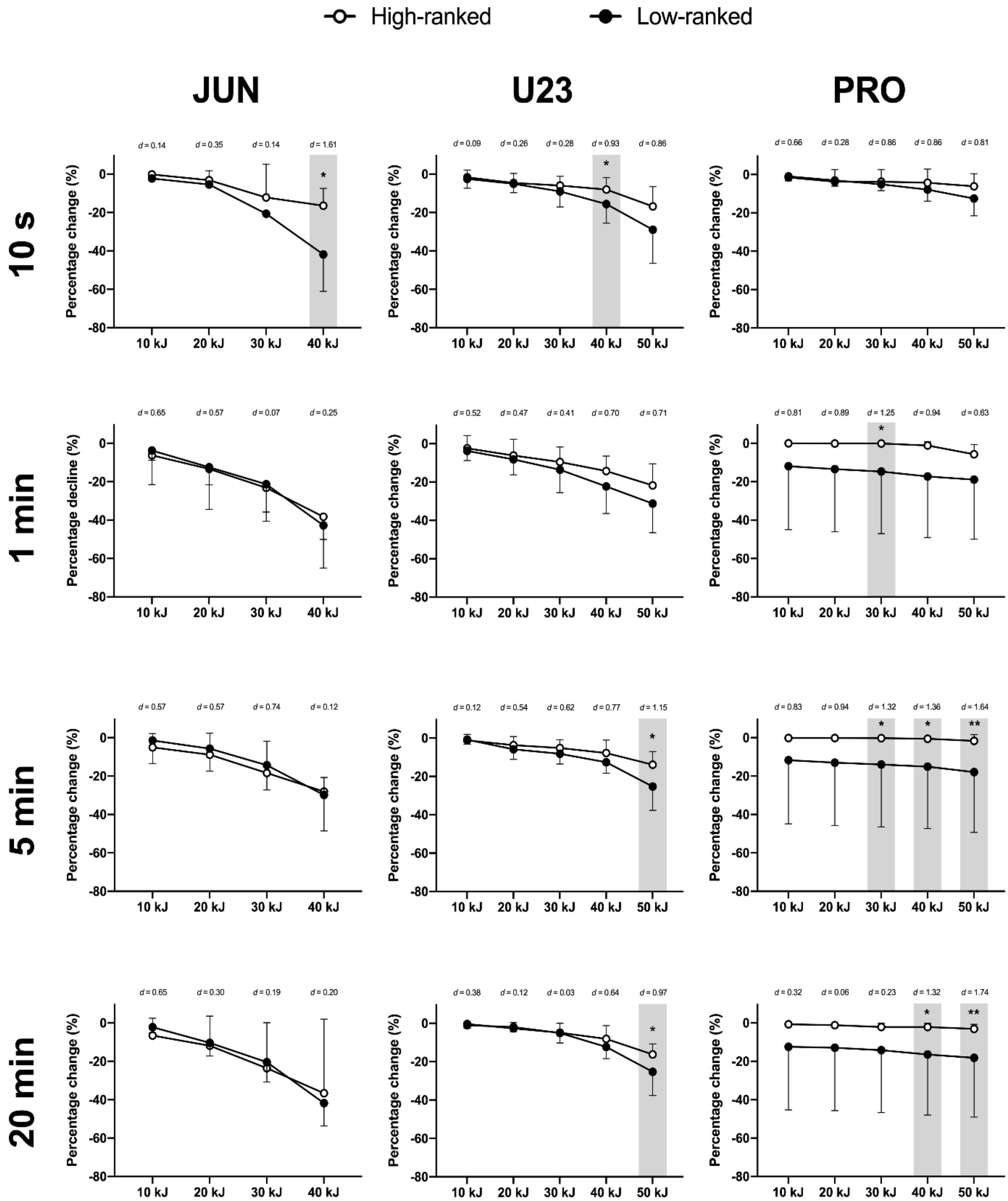
Abbreviations: BSA, body surface area; HIGHR, high ranked; JUN, junior; LOWR, low ranked; PRO, professional; U23, under 23.

***Figure 1**: Differences in absolute and relative RPOs (RPO-10 s, RPO-1 min, RPO-5 min, and RPO-20 min) between high- and low-ranked JUN, U23, and PRO climbers. The effect sizes are reported as Cohen d.*



*Abbreviations: JUN indicates junior; PRO, professional; RPO, record power output; U23, under 23. Significant difference between the 2 performance levels within the same category: *P < .05; **P < .01.*

Figure 2*: Differences in percentage decline of record power outputs after 10, 20, 30, 40, and 50 kJ·kg*$^{-1}$ *between high- and low-ranked JUN indicates U23, and PRO climbers. The effect sizes are reported as Cohen d.*



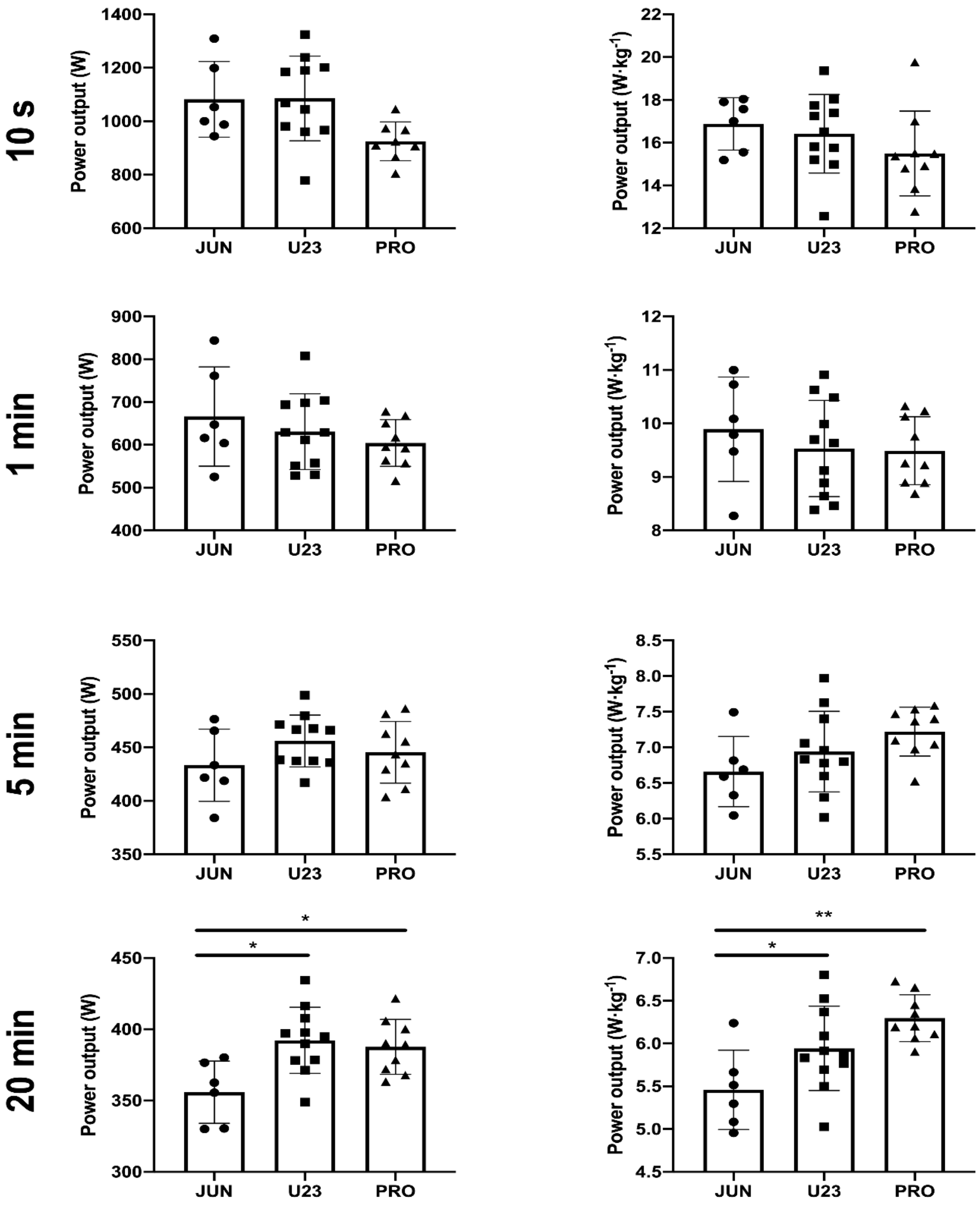
*Abbreviations: JUN indicates junior; PRO, professional; U23, under 23. Significant difference between the 2 performance levels within the same category: *P < .05; **P < .01.*

HIGHR Cyclists Between-Categories Comparison

Differences in field-derived physical performance parameters between HIGHR JUN, U23, and PRO cyclists are shown in Figures 3 and 4.

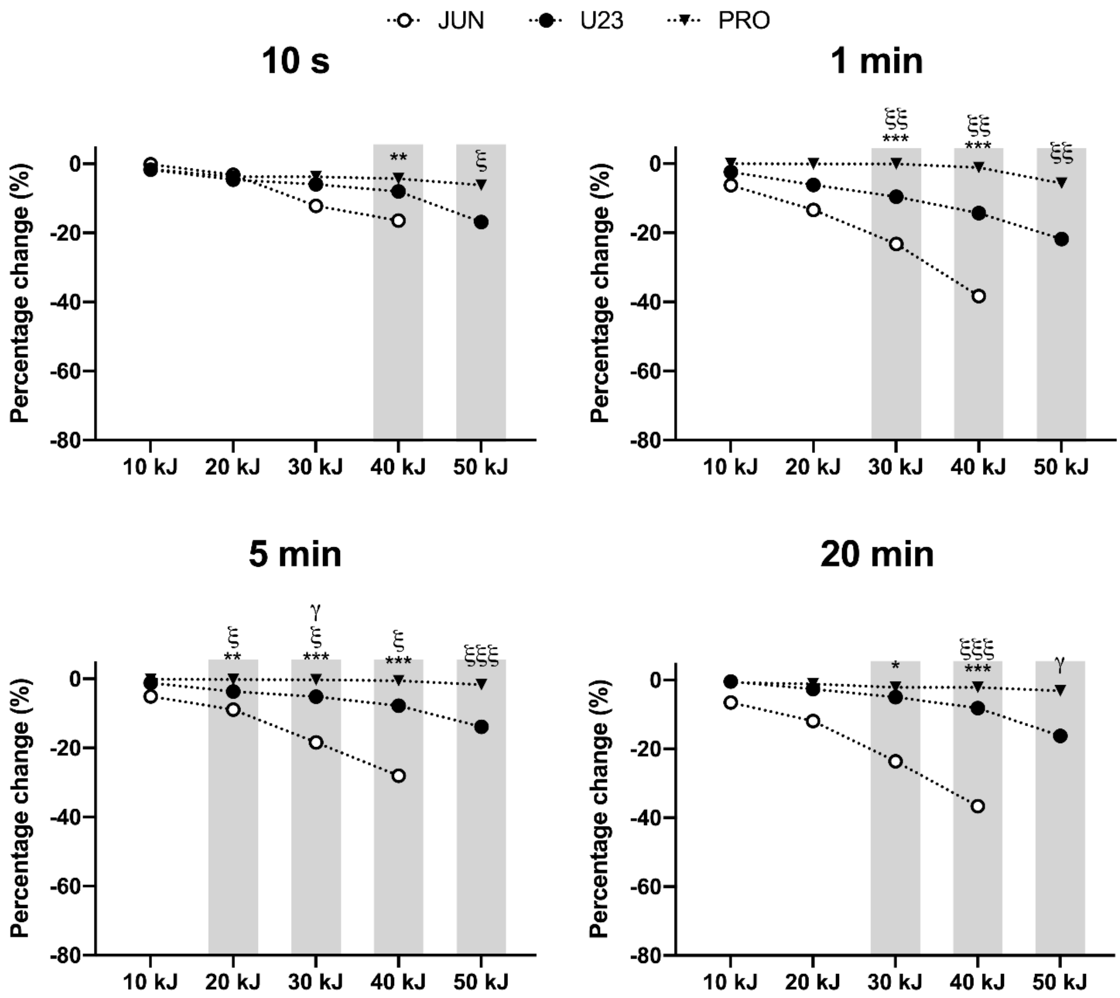
JUN HIGHR presented lower absolute and relative RPO-20 min (η2p=.34−.38, large; *P* = .099–.001) (Figure 3) and higher percentage decrease in RPOs after prior accumulated work compared with U23 and PRO HIGHR (η2p=.28−.68, large; *P* = .060–.001). Absolute and relative RPOs did not differ between U23 and PRO HIGHR, while percentage decrease in RPOs after prior accumulated work was the only parameter differentiating U23 and PRO HIGHR, with PRO declining less in relative RPO-1 min, RPO-5 min, and RPO-20 min after 20–50 $kJ \cdot kg^{-1}$ (η2p=.28−.68, large; *P* = .090–.001) (Figure 4).

Figure 3: *Differences in absolute and relative RPOs (RPO-10 s, RPO-1 min, RPO-5 min, and RPO-20 min) between high-ranked JUN, U23, and PRO climbers.*



Abbreviations: JUN indicates junior; PRO, professional; RPO, record power output; U23, under 23. Significant difference between the 2 categories: *P < *.05;* **P < *.01.*

***Figure 4**: Differences in percentage decline of record power outputs after 10, 20, 30, 40, and 50 kJ·kg^{-1} between high-ranked JUN, U23, and PRO climbers.*



Abbreviations: JUN indicates junior; PRO, professional; U23, under 23. Significant difference between JUN and PRO: *P < *.05;* **P < *.01;* ***P < *.001. Significant difference between JUN and U23:* $^{\gamma}$P < *.05. Significant difference between U23 and PRO:* $^{\xi}$P < *.05;* $^{\xi\xi}$P < *.01;* $^{\xi\xi\xi}$P < *.001.*

Discussion

To the best of our knowledge, this is the first study analysing field-derived physical performance parameters of JUN, U23, and PRO cyclists. This study revealed differences between HIGHR and LOWR climbers within the same age category as well as between HIGHR climbers of different age categories. The main finding of this study was that field-derived physical performance parameters discriminating HIGHR and LOWR climbers differed between age categories. Specifically, superior absolute and relative RPOs characterize HIGHR JUN climbing specialists, while superior durability differentiates HIGHR U23 and PRO climbers from LOWR. The secondary finding of this study was that in HIGHR climbers, aerobic parameters and durability were lower in JUN compared with U23 and PRO, while only durability differed between U23 and PRO.

HIGHR Versus LOWR Cyclists Within the Same Age Category

In JUN, absolute and relative RPOs were higher in HIGHR compared with LOWR climbers, while no differences in the decline in RPOs after a certain amount of prior work were reported. Conversely, in U23 and PRO, no differences in field-derived physical parameters calculated before prior accumulated work (i.e., absolute and relative RPOs) were found, while durability after 30, 40, and 50 $kJ \cdot kg^{-1}$ was superior in HIGHR compared with LOWR climbers. These findings, in line with our initial hypothesis, indicate that durability plays a pivotal role in competition success in PRO and U23 categories but not in JUN. A possible reason could be that, because of the longer distance and duration per race, U23 and PRO presented higher work per race (~36 and 45 $kJ \cdot kg^{-1}$, respectively) compared with JUN (~15 $kJ \cdot kg^{-1}$) (Gallo et al. 2022). In this perspective, psychophysiological mechanisms contributing to durability are stressed and therefore play a crucial role in determining competition success only in the longer U23 and PRO races but not in JUN races. On the other hand, in JUN, only the traditional physiological parameters normally determined in a rested state (i.e., maximal oxygen consumption, lactate threshold, gross efficiency), and their linked physiological attributes (i.e., stroke volume, haemoglobin content, aerobic enzyme activity, muscle capillary density, etc) (Joyner and Coyle 2008) play an important role in determining competition success. Van Erp et al. reported higher durability in HIGHR compared with LOWR PRO climbers, but they also reported higher relative RPO-5 min and relative RPO-20 min in HIGHR compared with LOWR. This could be due to the lower competitive level of the LOWR PRO cyclists considered by van Erp et al. with respect to those considered in the present study (Van Erp et al. 2021).

The fact that both absolute and relative RPOs did not discriminate between HIGHR and LOWR U23 and PRO climbers should be contextualized within the very high values recorded, and it should not be interpreted as an irrelevance of these parameters for competition success in these categories. Rather, the values of these parameters should be read as a sort of benchmark values for climbers to compete at U23 Continental and PRO levels (eg, RPO-20 min ≥ 5.6 W·kg^{-1} and ≥ 6.1 W·kg^{-1} for U23 Continental and PRO, respectively). In JUN, on the other hand, even the absolute RPOs determine competition success. This might sound surprising as it is the relative and not the absolute power which is correlated with uphill performance (Antón et al. 2007). However, as elevation gain per distance unit is lower in JUN (~6 m·km^{-1}) compared with U23 and PRO races (~12 m·km^{-1}), (Gallo et al. 2022) a possible explanation could be that JUN climbers have also to be stronger than competitors on the flat sections of the races, given that these represent a larger proportion of races compared with U23 and PRO. In fact, it has recently been shown that prior higher external and internal workload and intensity negatively affect power output on a climb (Leo et al. 2022). Hence, cyclists who have higher absolute power output may be able to ride at lower percentage of their physiological values on the flat sections, saving more energy to outperform their competitors in the successive uphill sections. As even body mass resulted higher in HIGHR JUN compared with LOWR JUN, a possible contributing factor to the superior absolute HIGHR JUN's RPOs could be a higher lean muscle mass, as reported to be correlated with absolute power output (Khordi et al. 2021). This difference in lean muscle mass between HIGHR JUN and LOWER JUN could also be related to maturation status given the height of the groups is moderately different, suggesting that anthropometrics could be relevant in discriminating performance within this category (Kordi et al. 2021). In addition to the lower elevation gain per distance unit, the shorter duration per race in JUN category (Gallo et al. 2022) could mean that a higher body weight (i.e, lean muscle mass) could be less of a hindrance in the JUN compared with U23 and PRO categories.

HIGHR Cyclists Between-Categories Comparison

HIGHR JUN presented lower absolute and relative RPO-20 min compared with both U23 and PRO, while no differences were found for any other variable measured in a rested state (i.e, absolute and relative RPO-10 s, RPO-1 min, and RPO-5 min). This suggests that, for JUN climbers transitioning to U23 or PRO categories, practitioners should foster training aiming to improve aerobic over anaerobic adaptations, as the latter are already at the same level of HIGHR U23 and PRO climbers. This is in line with our previous study (Gallo et al. 2022) showing that JUN recorded lower long-duration RPOs (from 5 to 180 min), but similar short-duration RPOs (from 1 to 60 s) compared with U23 and PRO.

HIGHR JUN climbers also presented lower durability after certain amounts of prior work (depending on the RPOs considered) compared with their U23 and PRO counterparts. As discussed above, this could be due to the JUN's lower duration and work per race, (Gallo et al. 2022) stressing these physical attributes at a lower level during competition.

Interestingly, durability was the only parameter that differentiated HIGHR U23 and PRO climbers, with PRO climbers declining less in relative RPO-1 min, relative RPO-5 min, and relative RPO-20 min after certain amounts of prior work. This is in line with Leo et al's study that showed that during a 5-day cycling multistage race, absolute and relative RPOs were not different between PRO and U23 cyclists, but PRO cyclists showed higher relative RPOs after a certain amount of prior accumulated work than U23 (Leo et al.2021). Therefore, when HIGHR climbers move from JUN to U23 or PRO or from U23 to PRO, training strategies aiming to improve this physical attribute should be implemented. Even if models to explain fatigue during prolonged endurance cycling (eg, neuromuscular fatigue, energy supply, energy depletion, psychological behaviors, motivational behaviors, etc) have been proposed (Abbiss and Laursen 2003), further investigations are needed to clearly establish the actual psychophysiological determinants of durability, considering maintenance of gross efficiency, muscle fiber type, resistance to mental fatigue, and nutritional and fluid intake, among the possible contributing factors (Passfield et al. 2000, Vikmoen et al. 2017, Filipas et al. 2019, Jeukendrup AE 2011) Starting from a conceptual framework where physiological attributes of durability have been clarified, future studies have to investigate the best training strategies to improve this attribute.

Limitations

The main limitation of this study is the small sample size. However, considering the highly competitive level of the participants included, even reaching our relatively small sample size in each age category was difficult, given the conflict of interests in sharing power output data between cycling teams. Another limitation of this study, given its ecological approach, is that no standardized efforts were performed for each mean maximal power after each level of prior work completed. As a consequence of this, it could be that maximal efforts were not done for all the time durations considered (ie, 10 s, 1 min, 5 min, and 20 min) after a certain amount of work completed (ie, 10, 20, 30, 40, and 50 $kJ \cdot kg^{-1}$). Furthermore, the same levels of prior accumulated work can be reached through different duration and intensity efforts. As the physiological mechanisms (central and/or peripheral) linked to fatigue depend on the intensity domain in which exercise is performed (Burnely and Jones 2018), we cannot exclude that the same amount of work completed at different intensities lead to a different percentage decline in power output (ie, durabiliy). In this scenario, the higher percentage decline in RPOs after the different levels of work observed in JUN compared with both U23 and PRO could be a consequence of the JUN higher internal training and racing intensities compared with both U23 and PRO (Gallo et al. 2022). Finally, power output data were collected with different power meter brands. Even if the accuracy of these instruments in power calculation was previously verified and validated (Maier et al. 2017), there could be a small difference in between all the brands used by the different cyclists.

Practical Applications

The fact that superior durability is associated with competition success in U23 and PRO but not in JUN suggests that practitioners and talent scouts should not only consider race results and classical physiological qualities but also this physical attribute when selecting JUN climbers to move up to U23 and PRO categories. Introducing standardized tests evaluating the percentage decline of maximal mean power output over different durations could be a useful practical solution.

Given the difference in physical attributes between HIGHR climbers of different age categories, JUN climbers transitioning to U23 or PRO should improve both predominantly aerobic relative parameters (RPO-20 min) and durability, whereas U23 climbers transitioning to PRO should focus on improving durability.

Conclusions

Differences in field-derived physical performance parameters between HIGHR and LOWR cyclists within the same age category showed that superior parameters measured in a rested state (absolute and relative RPOs) characterize HIGHR versus LOWR JUN climbers, whereas superior durability is the main feature differentiating HIGHR and LOWR U23 and PRO climbers. This suggests the value of evaluating durability when selecting cyclists moving from JUN to U23 or from JUN and U23 to PRO category. The differences between HIGHR cyclists of different categories suggest that JUN climbers should improve both aerobic parameters in a rested state and durability when moving to U23 and PRO categories, while the focus for U23 transitioning to PRO category should be the improvement of durability

STUDY 3

Differences in Training Characteristics Between Junior, Under 23 and Professional Cyclists

Gallo G, Leo P, Mateo-March M, Giorgi A, Faelli E, Ruggeri P, Mujika I, Filipas L. Differences in Training Characteristics Between Junior, Under 23 and Professional Cyclists. Int J Sports Med. 2022 Dec;43(14):1183-1189.

Abstract

Purpose: The aim was to compare the training characteristics of junior, under 23 and professional road cyclists. **Methods:** Training data collected during the 2019 competitive season of thirty male cyclists, divided into three age-related categories (JUN; U23; PRO), were retrospectively analysed for training characteristics, external and internal training load. **Results:** Higher duration per training session were observed in PRO (2.6±0.3 h) compared to both U23 (2.2±0.3 h; $P<0.001$) and JUN (2.0±0.2 h; $P<0.001$). Elevation gain per distance was higher in PRO (13.8±1.9 m·km^{-1}) compared to U23 (10.6±0.9 m·km^{-1}; P=0.001) and JUN (6.7±0.3 m·km^{-1}; $P<0.001$), and in U23 compared to JUN ($P<0.001$). Annual total work was lower in JUN (3694±467 kJ·kg^{-1}) compared to U23 (5268±746 kJ·kg^{-1}; P=0.001) and PRO (5759±1103 kJ·kg^{-1}; $P<0.001$). eTRIMP per hour was higher in JUN (151±40) compared to both U23 (115±23; P=0.003) and PRO (112±22; P=0.013). JUN spent more training time at medium and high heart rate intensity zones compared to U23 and PRO ($P<0.05$). **Conclusions:** JUN training sessions were shorter, induced higher internal load and included less elevation gain per distance compared to U23 and PRO. U23 and PRO presented similar eTRIMP per hour and internal intensity distribution, but PRO training sessions were longer than U23.

Introduction

In the past decades road cycling training was strongly based on volume parameters (i. e. distance, duration) and also perception of effort due to technological limitations. However, technological innovation and digitalization has led to an increased use of mobile power meters and heart rate (HR) monitors to prescribe and monitor cycling training programs. Power output (PO) and HR data provide more detailed information about the external (i. e. the objective measure of the work that an athlete completes) and internal (i. e. the individual psychophysiological response to cope with the external load) training characteristics, respectively (Impellizzeri et al. 2019).

International road cycling events, governed by the Union Cycliste Internationale (UCI), are divided in three age-related categories: junior (JUN; 17–18 years), under 23 (U23; 19–23 years), and professional (PRO;>23 years). Some previous studies already described external and internal training characteristics of PRO men and women (Van Erp et al. 2020) and U23 men (Leo et al. 2020) cyclists. However, to the best of our knowledge, no studies have reported training characteristics of JUN cyclists yet. In a recent study, the cross-sectional differences in external and internal race demands between JUN, U23 and PRO have been investigated (Gallo et al. 2022). They showed a progressively increase of volume parameters per race (distance and duration) as the category levels-up: volume per race was higher in PRO compared to U23, and in U23 compared to JUN. As a plausible consequence of this, JUN cyclists competed at a higher mean internal intensity (i. e. eTRIMP per hour) compared to both U23 and PRO. Accordingly, JUN spent a higher percentage of race times at high internal intensities (i. e. 80−89% and 90−100% $HR^{peak)}$ compared to U23 and PRO. Conversely, U23 and PRO accumulated a higher percentage of race times in low internal intensity zones (i. e. 50–59%, 60–69% and 70–79% of HR_{peak}) compared to JUN. Even if U23 and PRO presented very similar external and internal race characteristics, PRO races have a higher duration compared to the U23, suggesting that durability could be a peculiar feature that differentiates PRO from both JUN and U23 cyclists. It is not known, however, whether these different racing patterns correspond or not to similar differences in training characteristics.

To the best of the authors’ knowledge, a cross-sectional analysis of both external and internal training characteristics in JUN, U23 and PRO has not yet been carried out.

Therefore, the aim of this study was to compare the external and internal training characteristics of the three UCI age-limited road cycling categories: JUN, U23 and PRO. The results of this descriptive study could help coaches and practitioners to reflect on: (i) whether the current training strategies are or not the most appropriate to achieve success in each age-related category; (ii) whether current differences in training strategies across categories promote or not the development of a long and successful professional career; (iii) identifying different training strategies to target different physiological factors determining performance.

Materials and Methods

Participants

Thirty male cyclists, divided into the three age-related categories ruled by the UCI (JUN, n=10; U23, n=10; PRO, n=10) participated in this study. Anthropometric characteristics of the participants are reported in Table 1. Each category cohort was composed of cyclists riding for the same team. The competitive level of all three groups was high within their category: the JUN group won the Italian national team seasonal ranking and included a rider who won the silver medal at UCI Road World Championships; five out of ten U23 cyclists became professional within two seasons after the one considered in the present study; the PRO group ranked in the top ten in the World Tour team seasonal ranking. In JUN and U23 cohort, cyclists featured more individualistic goals, even if a team tactical approach is traditionally decided before each race. On the other hand, cyclists included in PRO group had a specific role within their team: four general classification contenders and six climbers domestiques.

Table 1*. Anthropometric characteristics of the participants, divided by age-category. Data are presented as mean ± SD.*

	JUN	**U23**	**PRO**	***P***	**ES**
Age (years)	17.2 ± 0.5	19.7 ± 0.3*	27.7 ± 1.4$^{*,\#}$	< 0.001	0.776
Height (cm)	179 ± 2	181 ± 2	182 ± 2	0.860	0.011
Mass (kg)	65.8 ± 6.4	65.1 ± 5.2	66.7 ± 7.0	0.519	0.049
BMI (kg/m^2)	20.5 ± 0.8	19.9 ± 1.2	20.0 ± 1.4	0.527	0.048

*Abbreviations: JUN, junior; U23, under 23; PRO, professional. *, Significantly different from JUN ($P < 0.05$). $^{\#}$, Significantly different from U23 ($P < 0.05$).*

The study design and procedures were approved by the local research ethics and followed the ethical principles for medical research involving human participants set by the World Medical Association Declaration of Helsinki. Participants were provided with written instructions outlining the procedures and risks associated with the study and gave informed written consent.

Experimental design

For each category, the 2019 season (1st October 2018–31st September 2019) was taken into consideration for data analysis. Session characteristics, HR, and PO data were collected during training using a commercially available cycling software platform (WKO5, TrainingPeaks LLC, Boulder, USA). All data were visually checked for erroneous data, and incomplete data files due to technological issues (e. g. flat battery of a power meter) were removed when necessary. If one of the 2 main variables (i. e. PO, HR) was missing for a given training session but no erroneous data were present within the given session, the data set was still analyzed using the available variables.

Training characteristics

Training duration, distance, and elevation gain were recorded using two different power meter head units: JUN and U23 used Garmin Edge 520, while PRO used Garmin Edge 810 (Garmin, Schaffhausen, Switzerland). It has been previously shown that the analyzed variables were relatively consistent within devices of this brand if, as in our case, the same setting was used (i. e. elevation correction) (Menaspà et al. 2014). In addition, the total annual number of training sessions was also recorded. The percentage of the annual days spent in training (training days percentage) and the elevation gain per distance ratio were also calculated.

External load

External load characteristics were calculated based on PO data collected with portable power meters: JUN, Garmin Vector 3 (Garmin, Schaffhausen, Switzerland); U23, SRAM Red eTap (SRAM, Red, Spearfish, South Dakota, USA); PRO, Power2max (Saxonar GmbH, Waldhufen, Germany). The accuracy of these instruments in power output measurement was previously validated (Maier et al. 2017). All riders were informed about the importance of the zero-offset calibration of power meters and were instructed to perform it before every ride according to the manufacturer’s recommendations.

Annual training work was derived summing the total work accumulated during each training session, calculated with the following formula:

$$\text{total work [kJ]} = \text{power output [W] duration [s]}/1000$$

External training intensity was calculated using the annual total work, total work per training session and total work per hour. Each of these parameters were normalized for the cyclists’ body mass. Training intensity distribution was evaluated considering the percentage of training time spent at different power output bands of 0.75 $W\cdot kg^{-1}$, from<0.75 to>7.50 $W\cdot kg^{-1}$, as already done in previous studies (Sanders et al. 2019).

Internal load

Internal load characteristics were assessed based on HR data collected with portable HR monitors connected with a chest strap (Garmin, Schaffhausen, Switzerland) with a 1 Hz sampling rate. Internal training load was calculated using Edwards’ TRIMP (eTRIMP) (Edwards S. 1994). eTRIMP was calculated based on time spent in the five pre-defined HR zones multiplied by a zone-specific arbitrary weighting factor: zone 1, 50–59% HR_{peak} (multiplication factor 1); zone 2, 60–69% HR_{peak} (factor 2); zone 3, 70–79% HR_{peak} (factor 3); zone 4, 80–89% HR_{peak} (factor 4); and zone 5, 90–100% HR_{peak} (factor 5).

HR_{peak} was defined as the highest HR recorded during the season. eTRIMP was considered as annual training eTRIMP, eTRIMP per training session and eTRIMP per hour. Training intensity distribution was evaluated considering the percentage of time spent in the same five HR zones used for the eTRIMP calculation and described above.

Statistical analysis

All data are presented as mean±standard deviation. For each variable, outliers which were more than three standard deviations from the mean of the respective group were excluded from further analysis. Assumptions of statistical tests such as normal distribution and sphericity of data were checked with Shapiro-Wilk and Mauchly's tests, respectively. Greenhouse-Geisser correction to the degrees of freedom was applied when violation to sphericity was present. To compare the mean of all variables between the three groups, one-way analysis of variance (ANOVA) was performed when normality assumption was met, otherwise Kruskal-Wallis H test was performed. Depending on whether assumption of homogeneity of variance was met or not (Levene test), Bonferroni or Games-Howell post-hoc test was performed, respectively. Significance was set at 0.05 (two-tailed) for all analyses. Effect sizes (ES) for one-way ANOVA are reported as partial eta squared and for Kruskal-Wallis H test as epsilon squared, using the small (<0.13), medium (0.13–0.25) and large (>0.25) interpretation for effect size (Bakeman R. 2015). The effect sizes for each post-hoc comparison are reported as Cohen d or Hedge g using the 0.2=small, 0.5=moderate, 0.8=large, Cohen's interpretation (Wassertheil and Cohen 1970). Data analysis was conducted using the statistical package for the social sciences, version 26 (SPSS Inc., Chicago, IL, USA).

Results

Training characteristics

Training characteristics for the three age-categories are reported in Table 2. There was a significant large effect of category among the three groups for all the parameters considered. Post-hoc tests showed that training days were higher in U23 compared to both PRO (P=0.005) and JUN (P<0.001), but did not differ between PRO and JUN. Training days percentage were lower in PRO compared to both U23 and JUN (P<0.001), but did not differ between U23 and JUN. Duration per training session and distance per training session were higher in PRO compared to both U23 and JUN (P<0.01) but did not differ between U23 and JUN. Annual training distance, annual elevation gain and elevation gain per distance, were higher in PRO compared to U23 and JUN, and in U23 compared to JUN (P<0.01). Effect sizes for each comparison are reported in Table 3.

Table 2: *Training characteristics of the three age categories.*

	JUN	U23	PRO	*P*	ES
Training days (n)	225 ± 17	268 ± 40*	232 ± 6#	< 0.001	0.508
Annual duration (hours)	450 ± 74	572 ± 57*	631 ± 50*	< 0.001	0.620
Training percentage (%)	86 ± 2	89 ± 6	75 ± 2*,#	< 0.001	0.712
Duration per training session (hours)	2.00 ± 0.22	2.20 ± 0.28	2.60 ± 0.24*,#	< 0.001	0.561
Annual distance (km)	12817 ± 2105	15268 ± 1515*	17670 ± 1441*,#	< 0.001	0.586
Distance per training session (km)	56.7 ± 5.5	57.8 ± 8.7	74.3 ± 8.1*,#	< 0.001	0.543
Annual elevation gain (km)	80.2 ± 19.8	167.6 ± 23.5*	255.0 ± 32.5*,#	< 0.001	0.924
Elevation gain per distance ($m \cdot km^{-1}$)	6.7 ± 0.3	10.6 ± 0.9*	13.8 ± 1.9*,#	< 0.001	0.844

Data are presented as mean ± SD.

*Abbreviations: JUN, junior; U23, under 23; PRO, professional. *, Significantly different from JUN (P < 0.05). #, Significantly different from U23 (P < 0.05).*

***Table 3**: Effect sizes for the comparisons between junior, under 23 and professional cyclists.*

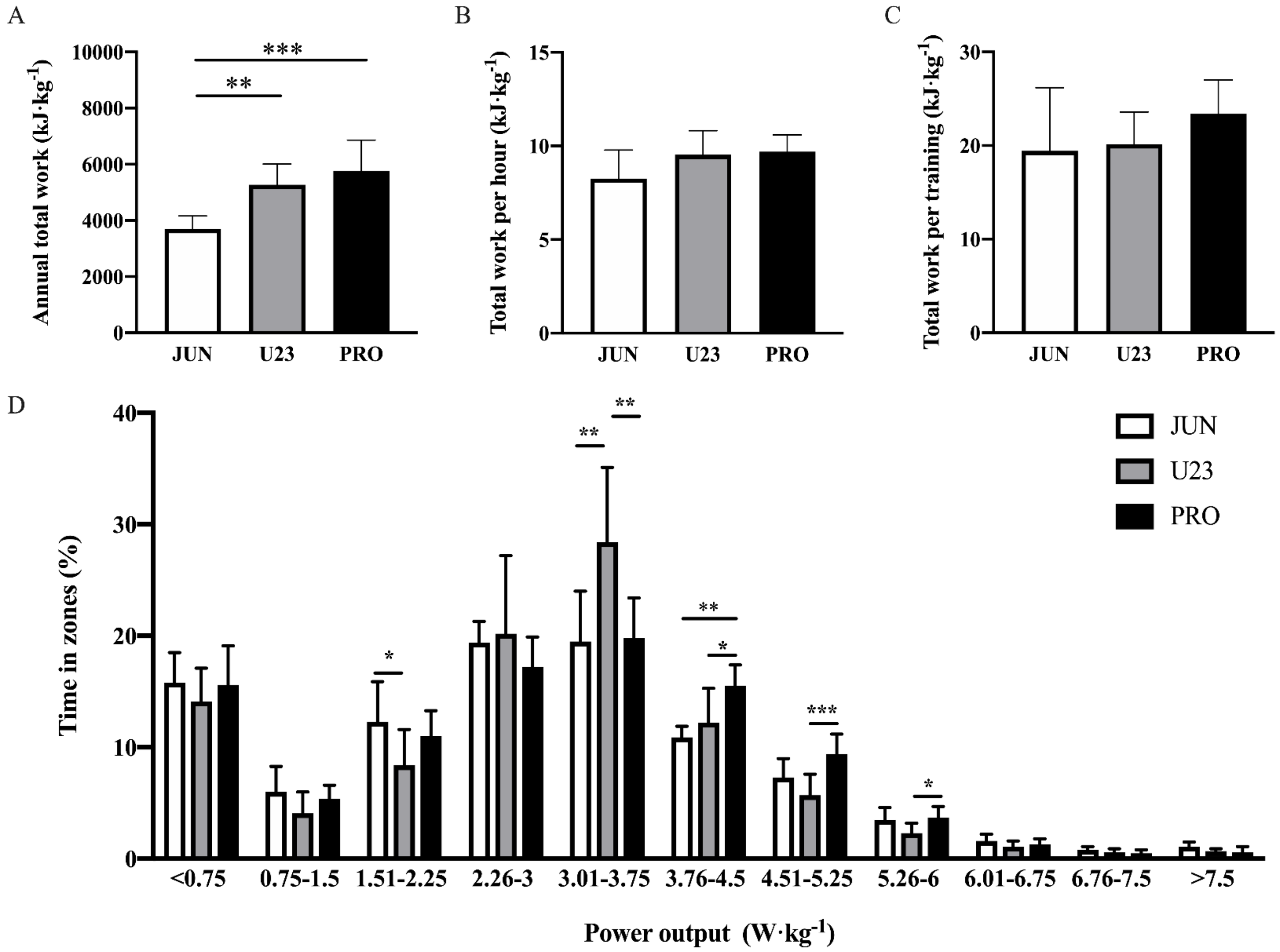
	JUN-U23	JUN-PRO	U23-PRO
Training days	1.40	0.55	1.26
Annual duration	1.85	2.87	1.10
Training percentage	0.56	5.57	3.22
Duration per training session	0.79	2.61	1.53
Annual distance	1.34	2.69	1.62
Distance per training session	0.15	2.54	1.96
Annual elevation gain	4.03	6.50	3.08
Elevation gain per distance	5.92	5.31	2.20
Annual total work	2.53	2.44	0.52
Total work per hour	0.90	1.16	0.16
Total work per training	0.13	0.73	0.93
Time in zone <0.75 $W \cdot kg^{-1}$	0.60	0.06	0.46
Time in zone 0.75-1.5 $W \cdot kg^{-1}$	0.90	0.33	0.82
Time in zone 1.51-2.25 $W \cdot kg^{-1}$	1.15	0.43	0.93
Time in zone 2.26-3 $W \cdot kg^{-1}$	0.16	0.94	0.57
Time in zone 3.01-3.75 $W \cdot kg^{-1}$	1.56	0.07	1.60
Time in zone 3.76-4.5 $W \cdot kg^{-1}$	0.56	3.03	1.28
Time in zone 4.51-5.25 $W \cdot kg^{-1}$	0.89	1.20	2.00
Time in zone 5.26-6 $W \cdot kg^{-1}$	1.19	0.19	1.47
Time in zone 6.01-6.75 $W \cdot kg^{-1}$	0.91	0.54	0.40
Time in zone 6.76-7.5 $W \cdot kg^{-1}$	0.67	1.00	0.33
Time in zone >7.5 $W \cdot kg^{-1}$	1.26	1.10	0.26
Annual eTRIMP	0.61	0.75	1.07
eTRIMP per hour	1.10	1.21	0.13
eTRIMP per training	1.83	0.28	1.97
Time in zone 50-59%	1.73	4.98	2.08
Time in zone 60-69%	2.43	3.67	0.96
Time in zone 70-79%	1.08	2.23	0.59
Time in zone 80-89%	3.16	3.08	0.34
Time in zone 90-100%	2.69	3.83	1.08

Abbreviations: JUN, junior; U23, under 23; PRO, professional.

External load

External load characteristics are presented in Fig. 1. There was a large significant difference in annual total work between the three groups ($P<0.001$, ES=0.560). Post-hoc test showed that annual total work was lower in JUN compared to U23 and PRO ($P<0.01$), while did not differ between U23 and PRO. Total work per hour and total work per training session did not differ between the three groups. The power output training intensity distribution showed large differences among the three groups ($P<0.05$, ES=0.239–0.458). Percentage of time spent between 1.51 and 2.25 $W \cdot kg^{-1}$ was higher in JUN compared to U23 ($P=0.040$); between 3.01 and 3.75 $W \cdot kg^{-1}$ was higher in U23 compared to JUN ($P=0.004$) and PRO ($P=0.005$); between 3.76 and 4.50 $W \cdot kg^{-1}$ was higher in PRO compared to U23 ($P=0.011$) and JUN ($P=0.001$); between 4.51 and 6.00 $W \cdot kg^{-1}$ was higher in PRO compared to U23 ($P<0.05$). Effect sizes for each comparison are reported in Table 3.

__Figure 1__: External training characteristics of junior, under 23 and professional cyclists. (a) Annual training work, (b) total work per hour, (c) total work per training session, (d) power output distribution as percentage of training time spent in different power bands.



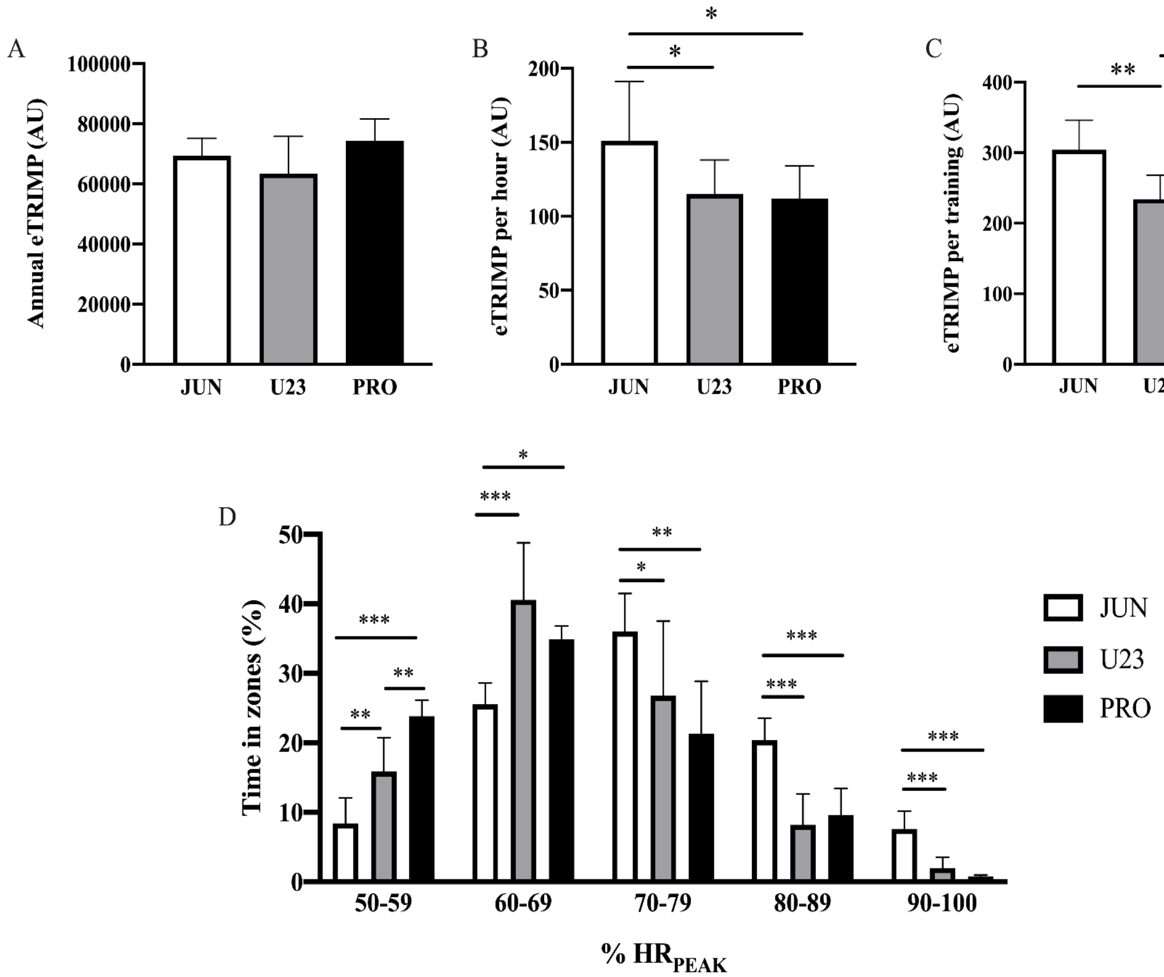
Abbreviations: JUN, Junior; U23, Under 23; PRO, Professional.

Significant difference between the groups (, P<0.05; **, P<0.01; ***, P<0.001).*

Internal load

Internal load characteristics are presented in Fig. 2. No significant differences between groups were found for annual eTRIMP. However, there were large differences among the three groups for eTRIMP per training session and eTRIMP per hour (P<0.05, ES=0.176–0.370). The post-hoc analysis revealed that eTRIMP per training session was lower in U23 compared to PRO (P=0.003) and JUN (P=0.006) but did not differ between JUN and PRO. eTRIMP per hour was higher in JUN compared to U23 (P=0.003) and PRO (P=0.013) but did not differ between U23 and PRO. Training intensity distribution showed large differences among the three categories (P<0.05, ES=0.343−0.732). Percentages of training time spent at medium and high intensity zones (70–79% HR_{peak}; 80–89% HR_{peak}; 90–100% HR_{peak}) were higher in JUN compared to U23 and PRO (P<0.05), but did not differ between U23 and PRO. Conversely, percentages of training time spent at low intensity zones (50–59% HR_{peak}; 60–69% HR_{peak}) were lower in JUN compared to U23 and (P<0.05). In addition, percentage of training time spent at 50–59% HR_{peak} was also higher in PRO compared to U23 (P=0.007). Effect sizes for each comparison are reported in Table 3.

Figure 2*: Internal training characteristics of junior, under 23 and professional cyclists. (a) Annual training eTRIMP, (b) eTRIMP per hour, (c) eTRIMP per training session, (d) heart rate distribution as percentage of training time spent in different heart rate zones.*



Abbreviations: JUN, Junior; U23, Under 23; PRO, Professional.

Significant difference between the groups (, P<0.05; **, P<0.01; ***, P<0.001).*

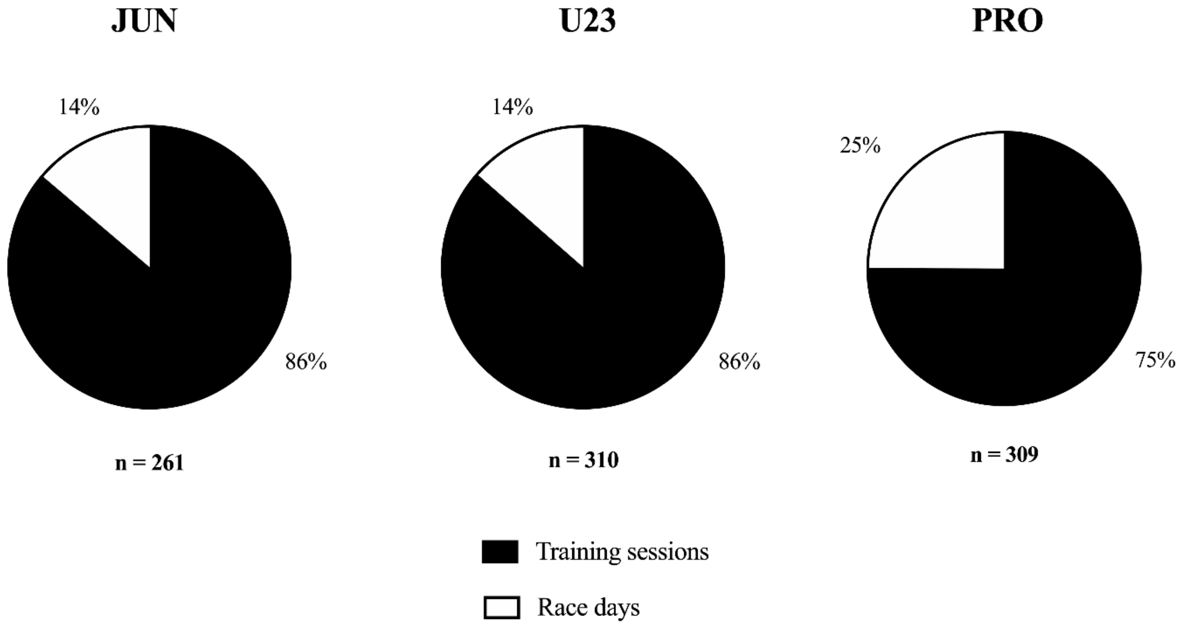
Discussion

This is the first study to present a cross-sectional comparison of external and internal training load characteristics of the three UCI age-limited road cycling categories: JUN, U23 and PRO. The results highlighted large differences for several training characteristics among the three categories: JUN training sessions were shorter, with higher internal intensity and included less elevation gain per distance compared to U23 and PRO training sessions. During training sessions, JUN, U23 and PRO produced a similar work per hour, however PRO performed longer training session than JUN and U23.

Training characteristics

The number of training sessions per year was higher in U23 compared to both JUN and PRO, with no differences between JUN and PRO. Total number of training and competition days per year was lower in JUN compared to both U23 and PRO, but was similar between U23 and PRO. Accordingly, PRO spent a lower percentage of exercise days per year in training compared to both JUN and U23 (Fig. 3). Therefore, while JUN spent less days per year on the bike, the difference in training days observed between U23 and PRO was due to the higher percentage of days spent in races in PRO compared to U23, while the opposite happened for training. This could be the consequence of the common practice of many professional cyclists of using races to increase their fitness and performance level. Due to the lower financial possibilities of team sponsors and race calendar restrictions, this practice is less common in U23. Hence, training planning and periodization could play a more important role in building fitness and increasing performance level in U23, while a proper selection of race calendar and an adaptation of the training schedule to the race calendar are likely to play a pivotal role in PRO.

***Figure 3**: Proportion of training sessions (black area) and race days (white area) per year in junior, under 23 and professional cyclists.*



Duration and distance per training session was higher in PRO compared to both JUN and U23, while did not differ between JUN and U23. This is in line with longer duration and distance per race observed in PRO compared to U23 and JUN (Gallo et al.2022), suggesting that coaches adopted the training specificity concept (i. e. adapting training volume and intensity to race demands).

Total annual elevation gain, and elevation gain per distance progressively increase as the category levels-up. Even this trend is consistent with differences in race demands observed among these three categories (Gallo et al. 2022). Elevation gain per distance was very similar between training and racing for each category, suggesting that coaches voluntarily adjust training terrain according to the race demands of each category, confirming the adoption of the training specificity concept throughout categories.

External load

Annual total work resulted lower in JUN compared to both U23 and PRO, mainly due to a lower annual duration. Total work per hour did not significantly differ between the three groups, however, JUN reported largely lower values with a P value near to alpha level compared both to U23 (P=0.135) and PRO (P=0.085) The same external workload differences among these three categories have been observed in races (Gallo et al. 2022). The lower total work per hour observed in JUN cyclists could be a natural consequence of their lower capacity to produce PO between 5 and 180 min compared to U23 and PRO (Gallo et al. 2022). In fact, cycling training is usually prescribed using individual physiological anchors (e. g. percentage of HR_{peak} or percentage of PO at the lactate or ventilatory threshold). Thus, at the same relative intensity prescribed by coaches, JUN might produce a lower absolute PO compared to U23 and PRO. Accordingly, the power intensity distribution showed a left-ward shift between 1.51 and 6.00 $W \cdot kg^{-1}$ for JUN compared to both U23 and PRO. The same trend, also observed in racing PO distribution, is in line with JUN's lower capacity to produce PO in the moderate, heavy, and severe exercise intensity domains compared to both U23 and PRO (Gallo et al. 2022). On the other hand, the same percentage of training time spent at PO>6.00 $W \cdot kg^{-1}$ across the three categories could be the consequence of a similar capacity to produce PO in the force-velocity exercise intensity domain across the three categories (Gallo et al.2022), combined with JUN's shorter duration of training sessions compared to U23 and PRO. The fact that U23 accumulated more time between 3.01 and 3.75 $W \cdot kg^{-1}$ compared to PRO, while the opposite happened between 3.76 and 6.00 $W \cdot kg^{-1}$, could be due to a higher capacity to produce PO after prior amount of total work (i. e. superior durability) in PRO compared to U23 (Gallo et al. 2022).

Internal load

eTRIMP per training session was lower in U23 compared to both JUN and PRO, while it did not differ between JUN and PRO. The lower value observed in U23 could be due to their higher number of training sessions completed per year compared to the other two categories. eTRIMP per hour was higher in JUN compared to both U23 and PRO. Accordingly, JUN spent more percentage training time at medium and high internal intensities (70–79%, 80−89% and 90−100% HR_{peak}) compared to U23 and PRO, while U23 and PRO accumulated more percentage of time at low intensities (50–59% and 60–69% HR_{peak}). A similar difference in the intensity distribution across these three categories was observed in races, suggesting that training volume and intensity of each category has been adapted to their respective race demands (Gallo et al. 2022). The same approach was reported in two studies by the same research group, which compared race demands and training characteristics of professional men and women road cyclists (Sanders et al. 2019, Van Erp et al. 2020).

The intensity distribution was similar between U23 and PRO, except for percentage of time accumulated between 50–59% HR_{peak}, which was higher in PRO compared to U23. This, combined with a longer duration per training session in PRO compared to U23, and in line with the differences in race demands (Gallo et al. 2022), suggests that PRO focused more on longer low intensity workouts.

Limitations

The main limitation of this study is the low sample size and that all athletes for each category are part of only one team. Therefore, the data reported in this study could not be necessarily extended to all the teams and cyclists included in each category. However, including training data of more than one team for each age-category has not been feasible in this study due to conflicts of interest and data liability rules.

Lastly, cyclists in PRO group were only general classification contenders and climbers domestiques. Future studies with a larger sample size that could include different riders' specialization (e. g. sprinters, classics specialists, etc.) need to be performed to understand whether or not cyclists' role influences training characteristics.

Practical applications

From a practical point of view, the training characteristics reported in this study could be seen from three different perspectives: (i) are these the best training strategies to get the best race results in each category? (ii) are these the best training strategies to promote the development of a long-term and successful professional career? Concerning training to get the best race results in each category, it is unknown whether the best strategy to improve longer-duration lower-intensity endurance performance is longer-duration lower-intensity training or not. In the same way, it is still unknown if the best way to improve shorter-duration higher-intensity endurance performance is shorter-duration higher-intensity training. In fact, with respect to prescribing training to improve endurance performance, Laursen stated that "there's more than one way to skin a cat" (Laursen PB 2004). This means that many of the positive endurance training adaptations beneficial for endurance performance of various durations and intensities (e. g. mitochondrial oxidative capacity, fat oxidation, glucose transport capacity) could be obtained through both longer-duration lower-intensity and short-duration high-intensity training. Even for what concern durability, it is unclear whether low-intensity durability (i. e. preserving the capacity to produce PO after prior long-duration moderate-intensity exercise) is improved by long-duration low-intensity training. Therefore, even if all three groups involved in our study obtained success in their respective category, it is not possible to assert that the training specificity they adopted was a successful strategy, as cyclists might already possess outstanding pre-season fitness and performance level which might allow them to achieve success independently from the training pattern adopted.

For what concerns training to promote the development of a long-term and successful professional career, the present descriptive data do not allow to assess whether the strategy adopted in each category was the more appropriate. Only one longitudinal study correlated training characteristics and physical performance throughout the three UCI age-related categories. In this case study, Pinot and Grappe reported that the total annual duration and training load correlated with improvements in recorded POs in a world-class cyclist over a period of six years (2 years in JUN, 1 year in U23, 3 years in PRO) (Pinot and Grappe 2015). Despite this study suggesting that increasing volume and training load over the years might be a successful strategy to improve physical performance, further investigations are needed. Given the cross-sectional design of our study, it remains unclear whether a superior long-term combination of volume and intensity exists to improve endurance performance longitudinally.

Conclusions

JUN training sessions were shorter, induced higher internal load and included less elevation gain per distance compared to U23 and PRO. U23 and PRO presented similar eTRIMP per hour and internal intensity distribution, but PRO training sessions were longer than U23. The same differences in training characteristics across these three age-related cycling categories have also been reported for race demands, suggesting that training volume and intensity of each age category have been adapted to their respective race demands. However, given the descriptive nature of this study, it remains unknown whether this is the best training strategy to get race results in each category and/or to promote the development of a long and successful professional career.

STUDY 4

The Day-by-Day Periodization Strategies of a Giro d'Italia Podium Finisher

Gallo G, Mateo-March M, Fuk A, Ruggeri P, Codella R, Faelli E, Filipas L. The Day-by-Day Periodization Strategies of a Giro d'Italia Podium Finisher. Accepted on Int J Sports Physiol Perform.

Abstract

Purpose: The aim of this study was to describe the day-by-day training and racing characteristics in preparation to Giro d'Italia of one world class road cyclists who achieved a place on the podium in the final general classification of the Giro d'Italia. **Methods:** Day-by-day power meter training and racing data of one road cyclists (age: 25 years; relative maximum oxygen consumption: 81 ml·min-1 ·kg-1; relative 20-min record power output: 6.6 W·kg-1) of the 152 days leading up to the podium in the Giro d'Italia final general classification were retrospectively analysed. Daily load, daily volume and overall and daily intensity distribution were considered.

Results: During training, a pattern alternating 'hard days' versus 'easy days' was observed, as significant amounts of medium or high intensity or load were not performed for more than two consecutive days. This pattern was achieved combining high volume (> 4 hrs) with significant amount of medium and high intensity within the same training sessions. During training, when training load and intensity increased, the density of 'easy days' augmented. In one-week stage races and Giro d'Italia three to eight consecutive days with significant amounts of medium and high intensity were performed. A high number of training sessions with small amounts of medium and high intensity volume were observed: 38 days accumulating 3-10 min at medium intensity and 29 days spending 1-9 min at high intensity.

Conclusions: These data provide novel insights about the day-by-day periodization strategies leading to a top 3 in Giro d'Italia general classification.

Introduction

Training characteristics of professional road cyclists have been previously reported only as annual mean, periodical mean (e.g winter and spring) or weekly periodization. Training characteristics of junior (Gallo et al. 2022. Gallo et al. 2023), However, similar overall and weekly volume and intensity distribution could be completed in very different ways of combining volume, intensity, and recovery both between consecutive days and within the same training session. These day-by-day different combinations could lead to different strain, biological signals and training adaptations (Foster C. 1998). Therefore, the aim of this study was to describe the day-by-day training and racing characteristics of the 152 days preceding the achievement of the podium in Giro d'Italia final general classification in one world-class road cyclist. Reporting this data could give useful insights to coaches and practitioners as well as acknowledge day-by-day training strategies adopted by a successful world class road cyclist to be tested in future scientific studies.

Material and Methods

Participant

One professional road cyclist (age: 26 years; body mass: 64 kg; height: 173 cm; relative maximum oxygen consumption: 81 ml·min-1·kg-1; relative 20-min record power output: 6.6 W·kg−1) was included in this study. The study design and procedures were approved by the research ethics committee of the Università degli Studi di Milano (approval number 52/20, attachment 4) and followed the ethical principles for medical research involving human participants set by the World Medical Association Declaration of Helsinki. The participant gave informed written consent.

Experimental design

Daily training and racing data power data of the 152 days (December-May) preceding the beginning of the Giro d'Italia in which the participant achieved the podium in the final general classification were considered. The race schedule of the athlete was reported. Races were classified based on relative importance for the rider (A, main goal; B, secondary goal; C, preparation race), days of race and level of the race according to the Union Cycliste Internationale classification. In addition, also the day-by data of Giro d'Italia were reported.

Data processing

Power output from training and races was daily collected using a portable power meter (Power2max, Saxonar GmbH, Waldhufen) that was zeroed before every ride. Precision and accuracy of this power meter were reported in a previous study (Maier et al. 2017). Data were saved and organized using a cycling performance software analyzer (WKO5; TrainingPeaks LLC). For each day, the inclusion criteria for power data were that the sum of time spent in power zones was at least 80% of the daily total duration. When the daily sum of time spent in power zones was >80% but did not reach 100% of the daily total duration, time spent in each zone were increased proportionally. For the ten days in which duration but not power data were recorded, only daily duration was reported.

Volume, load, and intensity distribution

Volume was considered as the duration of the training sessions or races. Load was reported as total amount of work done calculated with the following formula:

$$\text{Total work(kJ)} = \text{Power output(W)} \times \text{duration(s)}/1000.$$

Intensity distribution was calculated using a three-zone power-based model: functional threshold power (Coggan A. 2003) was used to separate zone 2 and zone 3, as it has been shown to be a valid surrogate of the lactate threshold in trained cyclists (Valenzuela et al. 2018). Functional threshold power was estimated by subtracting the 5% to the highest mean of 20-min power output recorded in race or training 13 and was updated on an annual basis. The 85% of the functional threshold power was used to separate zone 1 and zone 2 because it represents a percentage exercise intensity close to the first lactate and ventilatory threshold in professional road cyclists (Coggan A. 2003; Mujika and Padilla 2001). Time spent in zone 1 was considered as low intensity training (LIT), time in zone 2 as medium intensity training (MIT), and time in zone 3 as high intensity training (HIT). To give context when analysing the day-by-day data, we also reported the overall intensity distribution.

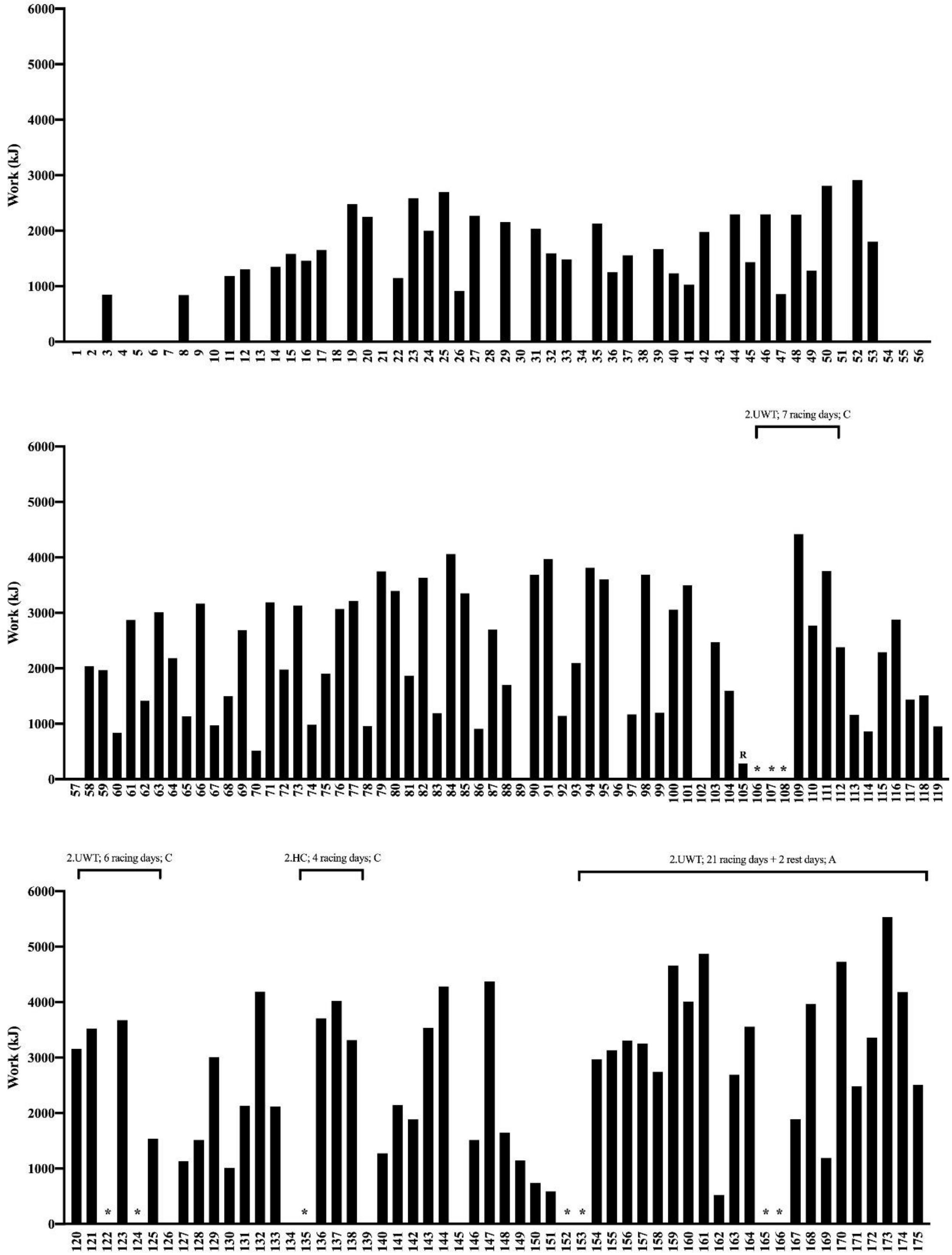
Results

The day-by-day load is reported in Figure 1.

The day-by-day time spent in LIT, MIT and HIT are reported in Figure 2.

The distributions of the time accumulated in MIT and HIT during single training sessions are reported in Figure 3a and 3b.

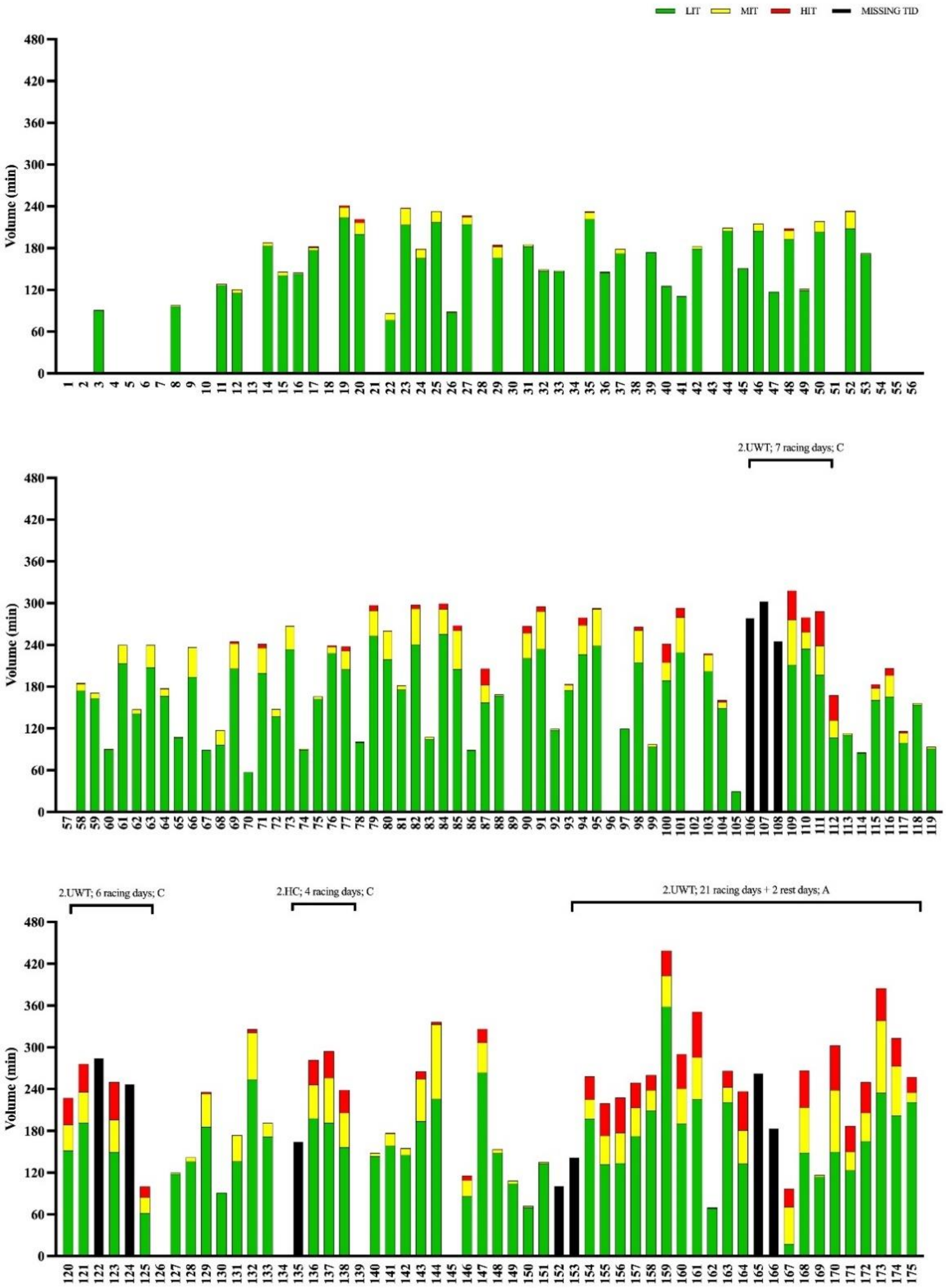
Figure 1*: Day-by-day load of a world-class level cyclist in preparation to and during Giro d'Italia.*



Abbreviations: 2.HC, hors catégorie stage race; 2.UWT, UCI World Tour stage race.

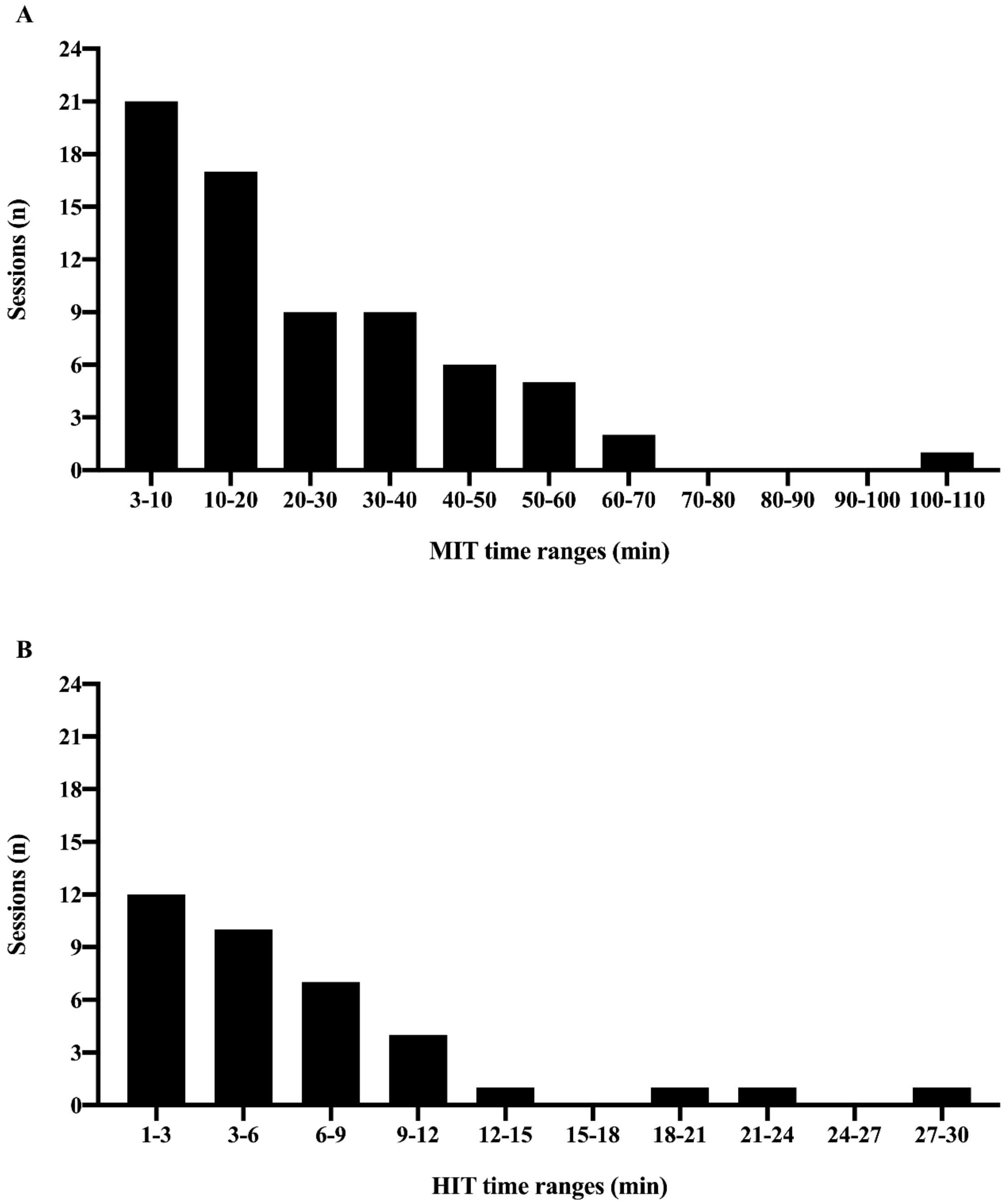
Asterisks indicates the days in which training intensity distribution is missing.

Figure 2*: Day-by-day time spent in LIT, MIT and HIT by a world-class level cyclist in preparation to and during Giro d'Italia.*



Abbreviations: 2.HC, hors catégorie stage race; 2.UWT, UCI World Tour stage race. Black bars are the day in which training intensity distribution is missing.

***Figure 3**: Distributions of the time accumulated in MIT (A) and and HIT (B) during single training sessions of a world-class level cyclist in preparation to and during Giro d'Italia during single training sessions.*



Abbreviations: MIT, Medium intensity training; HIT, High intensity training.

Discussion

Combining high volume and medium-high intensity within the same training sessions

When looking at Figure 1 and 2 it looks like the cyclists adopted a pattern alternating ‘hard days’ and ‘easy days’, when considering both load and times spent in zones. In fact, he never performed 3000 kJ or an important amount of MIT and HIT for more than two consecutive days. Moreover, every time he performed one or two consecutive days in which he goes over these thresholds, the following day he never exceeded 2500 kJ or performed significant amount of MIT or HIT. Significant amount of MIT and HIT were consistently performed during long training sessions: > 4 hours. Following the training specificity principle (Hawley JA 2008), future studies should investigate whether combining high volume and medium-high intensity within the same training session could be an effective training strategy to improve durability (a key determinant of success in road cycling, (Van Erp et al. 2020)) compared to performing them in two different days.

Interestingly, when training load and intensity were increased (from day 60 onwards) there was a concomitant increase in the number of training sessions with duration of less than 2 hours and little or no medium or high intensity performed. This seems to highlight the importance alternating hard days and easy days especially when load and intensity are increased.

When looking at all the stage races the cyclist performed, it looks clear as they represent consecutive hard days without easy days in between, with almost always high amounts of both MIT and HIT associated with quite long durations (> 3 hours) (Figure 1 and 2). According to the principle of training specificity, it could be that performing consecutive hard days in one-week stage races could be an effective strategy to stimulate recovery capacity in preparation for Giro d’Italia.

High-intensity training micro-doses

The cyclist performed 38 training sessions accumulating 3 to 20 min in MIT, while 32 sessions with time spent in MIT > 20 min (Figure 3A). When considering HIT, he performed 29 training sessions accumulating 1 to 9 min in HIT, while only 8 sessions with time spent in HIT > 10 min (Figure 3B). Therefore, it seems clear that, in addition to some training session with a specific focus on MIT and/or HIT, a relevant number of training sessions with MIT and/or HIT micro-doses was performed. Given the retrospective nature of this study, we do not know whether the cyclist performed these MIT and HIT micro-doses as a part of the training schedule or because of the stochastic nature of road cycling (e.g. slope changes, accelerations). Future studies could investigate whether performing frequently micro-doses of MIT and HIT could give an additional stimulus for positive adaptations without compromising recovery.

Practical Applications

This case study gives unique insights into day-by-daymicrocycle periodization strategiesy of a world-class cyclist who achieved a top 3 in the Giro d'Italia final general classification. Future studies could test whether these microcycle training strategies are or not the most effective to increase performance in road cyclists and endurance athletes.

Conclusions

In the preparation to a Giro d'Italia final general classification podium achievement, during training, a world-class road cyclists alternated 'hard days' and 'easy days', combining high-volume with important amount of MIT and HIT within the same sessions. with not exceeding significative amount of MIT, HIT or training load for more than two consecutive days. When training load and intensity increased, the density of ‘easy days’ also increased. During 4-7 days stage races and Giro d’Italia, 3 to 8 consecutive days with high amounts of volume accumulated at MIT and HIT were performed. In training, he combined high-volume with important amount of MIT and HIT within the same sessions. During training periods, while he performed some days performing significant amount of MIT and HIT, he also completed many sessions accumulating small amounts (micro-doses) of these intensities.

STUDY 5

Performing high-intensity training following prolonged exercise impacts durability-related adaptations

Gallo G, Rønnestad B, Sandbakk Ø, Skovereng K, Maunder E, Gotti D, Tallaksen L, Faelli E, Ruggeri P, Meloni A, Codella R, Filipas L. Under review on Med. Sci. Sports Exerc.

Abstract:

Purpose: Durability refers to resilience to the effects of prolonged exercise on physiological profiling characteristics. The aim of this study was to investigate if performing high-intensity training (HIT) at the end of long low-intensity training sessions enhances durability. **Methods:** Twenty trained cyclists were randomly allocated to one of two four-week training interventions (CON, n=10 and INT, n=10). INT performed HIT at the end of long low-intensity sessions, while CON performed HIT and long low-intensity sessions on separate days. Weekly training was matched for overall volume and time in zones. An incremental test to determine the first (VT1) and second (VT2) ventilatory thresholds, and a 5-min time trial (TT), was performed in a rested state (-rest) and after 2.5-h cycling (-2.5h) pre- and post-intervention. **Results**: Adaptations to VT1-rest favored CON ($\eta p2 = 0.14$), although this was not significant ($p = 0.101$). There was a greater improvement in VT2-rest in CON vs. INT ($p = 0.015$; $\eta p2 = 0.29$). Adaptations to VT1-2.5h favored INT ($\eta p2 = 0.19$), although this was not significant ($p = 0.057$), while no group differences in adaptations to VT2-2.5h were observed. Following prolonged exercise, VT1 was better maintained after INT vs. CON ($p = 0.015$; $\eta p2 = 0.29$). Group differences in this effect for VT2 were not significant, but there was a large effect size in favor of INT ($p = 0.058$; $\eta p2 = 0.19$). Adaptations to TT-rest and TT-

2.5h were not different between-groups. **Conclusions:** These data indicate the timing of HIT impacts adaptations related to durability in trained cyclists.

Introduction

Training for endurance sport aims to improve physiological determinants of performance: the maximal oxygen uptake ($\dot{V}O_2max$), fractional utilization of $\dot{V}O_2max$, indicated by intensity domain transitions, and movement economy (Joyner and Coyle 2008; Poole et al. 2016). These physiological profiling characteristics degrade during prolonged exercise (Stevenson et al. 2022; Clark et al. 2018; Passfield et al. 2000). The ability to sustain these characteristics during long-lasting competitions, also called durability (or fatigue resilience), has been proposed as an additional key factor for long duration endurance performance (Maunder et al. 2021; Jones AM 2023).

Road cycling is an endurance sport in which durability may play a significant role due to the long duration of competitions. Tactical considerations often require road cyclists to exert maximum effort towards the end of races, after more than two hours of continuous exercise (Peiffer et al. 2018; Van Erp et al. 2020). Recent studies examining personal record power outputs over fixed durations in the rested state, and when having already completed 40-50 $kJ \cdot kg^{-1}$ of prior work, have found the latter to better reflect race results among professional and under-23 road cyclists (Gallo et al. 2022; Muriel et al. 2022; Van Erp et al. 2021).

There is currently limited knowledge about effective strategies for improving durability. The principle of specificity suggests training routines closely aligned with the desired outcome (such as specific exercise tasks or performance criteria) yield effective results (Hawley JA. 2008). Consequently, incorporating high-intensity training (HIT) after prolonged exercise might enhance durability. However, this has not yet been assessed.

Therefore, the purpose of this study was to investigate if incorporating HIT at the end of long low-intensity training sessions is an effective method for enhancing durability in trained cyclists. Our hypothesis was that this approach would improve durability to a greater extent than a standard training intervention involving traditional HIT and long duration-low intensity sessions performed on separate days.

Methods

Participants

Twenty cyclists (16 male and 4 female) participated in this study. Inclusion criteria were as follows: (i) habitually training >5 $h \cdot week^{-1}$, (ii) training frequency ≥3 $sessions \cdot week^{-1}$, (iii) free of recent viral infection and musculoskeletal injury (>3 months), (iv) not suffering from cardiovascular disease, and (v) able to self-report a record power output over 20 min of >3 $W \cdot kg^{-1}$ body mass for males and >2 $W \cdot kg^{-1}$ body mass for females. These criteria were formally assessed during the first visit through a health and performance screening questionnaire. Participants were classified as “trained” according to McKay's participant classification framework for research in sport science (McKay et al. 2022). The study was administered from three locations, including 8, 6, and 6 subjects, respectively. The study design and procedures were approved by the research ethics committee of University of Milan (n° 52/20, attachment 4, 14 May 2020) and followed the ethical principles for medical research involving human participants set by the World Medical Association Declaration of Helsinki. Participants were provided with written instructions outlining the procedures and risks associated with the study and gave informed written consent.

Study design

An overview of the study design is shown in Figure 1. Participants initially completed a two-week pre-intervention training period focused on low intensity training (LIT), with one HIT session per week. Weekly volume during the pre-intervention period was matched to each participant’s previous four weeks (PRE-WEEKLY-VOL). During the pre-intervention period, participants performed one long LIT session per week of the same duration as the average duration of the four longest rides completed in the previous four weeks (PRE-LONG-VOL). During the pre-intervention period, participants visited the laboratory to perform a familiarisation 5 min time trial (TT). At the end of this period, participants performed two laboratory tests (see 'Physiological and performance testing') to estimate the first ventilatory threshold (VT_1), second ventilatory threshold (VT_2), and 5 min time trial TT power output in a rested state, and after 2.5 h of cycling at 90% of the initial VT_1 power output. Participants were then randomly allocated to a control (CON) or intervention (INT) group. The groups were matched for sex, PRE-WEEKLY-VOL, and percentage decrease in 5 min TT mean power output in the rested state vs. after 2.5 h of cycling. For the subsequent four weeks, participants performed a prescribed training programme, with no between-group differences in weekly frequency, volume, or intensity distribution. The only between-group difference was in the training sequence; that is, CON performed HIT in standalone (~1 h) training sessions, while INT performed HIT at the end of long low intensity sessions. In CON and INT, prescribed long sessions were 5% longer in duration than each individual's PRE-LONG-VOL, and the prescribed weekly training volume was 15% greater than each individual's PRE-WEEKLY-VOL. The physiological and performance tests were repeated after the four-week training intervention period to assess between-group differences in adaptations to power output at VT_1, power output at VT_2, and 5 min TT mean power output, in a rested state and after 2.5 h of cycling.

Figure 1: *Overview of the study design.*

Abbreviations: CON, control group: INT, intervention group.

Pre-intervention period

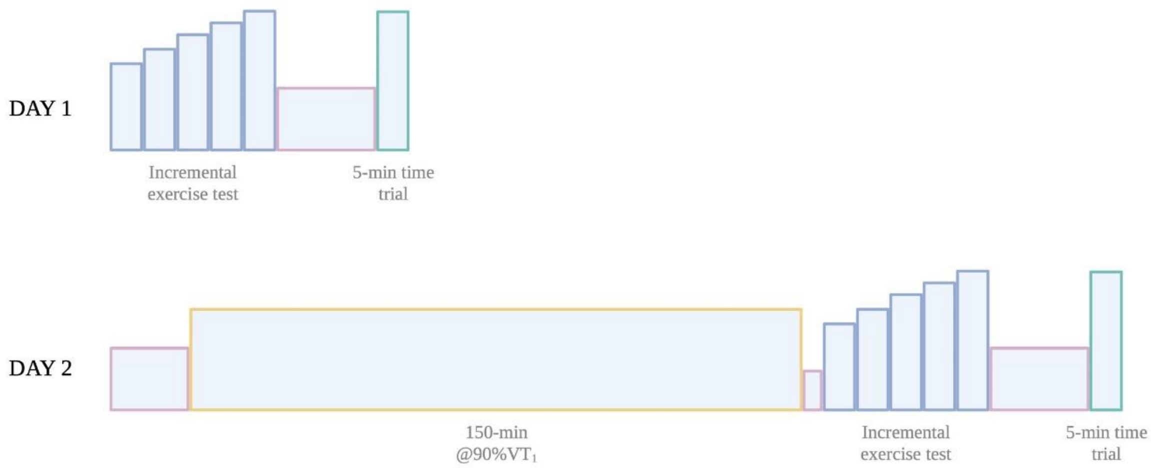
During the pre-intervention period, participants performed a standardized training programme with weekly volume equal to that of their previous four weeks (PRE-WEEKLY-VOLUME). The pre-intervention programme consisted of LIT (<2 h), one ~1 h HIT session per week, and one long LIT session per week of the same duration as PRE-LONG-VOL (Table 1). The LIT was prescribed using the Borg CR-10 scale (Borg G. 1998): LIT, 1-2, "easy, very easy" – "easy". The HIT session consisted of a 15 min warm up, 4 x 5 min repetitions performed at the maximum sustainable work intensity with 2.5 min recovery between-intervals, followed by a 15-min cool down. During the pre-intervention period, participants visited the laboratory to complete a familiarization 5 min TT. Briefly, after 60 min of low-intensity cycling (Borg CR-10 scale, 2-3, "easy"), participants rested for 2 min and then performed the 5-min TT with maximum effort. Participants were instructed to sustain the highest possible mean power output for the 5 min trial. Participants were allowed to see cadence, elapsed time, and real-time power output, but not mean power output.

Physiological and performance laboratory testing

Two days before test days, participants performed standardized low intensity training sessions (volume < 2 h; intensity: RPE 1-2 in the Borg CR-10 scale). Laboratory tests were performed on two separate days in the week before and after the training intervention (Figure 2). Participants arrived having recorded (or replicated) their 24-h diet. On testing days, an incremental submaximal cycling test with continuous collection of expired gases using indirect calorimetry (Centre 1: K5, COSMED, Rome, Italy; Centre 2 and 3: Vyntus CPX with mixing chamber, CareFusion, Hoechberg, Germany) was undertaken to determine power output and heart rate associated with VT_1 and VT_2. Tests were performed on participants' own road bicycles mounted on an indoor trainer in Centre 1 (Turno, Elite, Padova, Italy) or an electromagnetically-braked cycle ergometer (Excalibur Sport, Lode, Groningen, Netherland) adjusted according to each cyclist's preference for seat height, horizontal distance between tip of seat and bottom bracket, and handlebar position in Centre 2 and 3. After a 5-min warm-up at 100 W, cycling commenced at 150 W for males and 100 W for females, and the power output increased by 25 W every 5 min. The first (VT_1) and second (VT_2) ventilatory thresholds were calculated by identification of the $\dot{V}O_2$ associated with the first rise in the ventilatory equivalents for oxygen and carbon dioxide, respectively. These

$\dot{V}O_2$ values were converted to power outputs by linear regression of the $\dot{V}O_2$ vs. power output relationship using the last minute of $\dot{V}O_2$ data in each incremental stage. Heart rates at VT_1 and VT_2 were then quantified by linear regression of the power output vs. heart rate relationship, using the last minute of heart rate data of each stage (Stevenson et al. 2022). At the end of each step, a blood sample was taken from the earlobe for determination of blood lactate concentration (bLa^-) (Centre 1: Lactate Pro 2, Arkray Inc, Tokyo, Japan; Centre 2 and 3: Biosen C-line Lactate Analyzer, EKF Diagnostic GmbH, Barleben, Germany) and the whole-body rating of perceived exertion (RPE) was recorded using Borg 6 to 20 scale (Borg G. 1998). Once blood lactate concentration exceeded 4.0 $mmol{\cdot}L^{-1}$, participants recovered for 10 min at 100 W, and then performed a 5 min TT. Participants were instructed to achieve the highest possible mean power output during the 5 min. During the TT, participants were able to see cadence, elapsed time, and real-time power output, but not mean power output. Performance was quantified as mean power output. In addition, $\dot{V}O_{2peak}$ was calculated as the highest 30-s rolling average $\dot{V}O_2$. The incremental submaximal test and the 5-min TT were performed in a rested state on day one (VT_1-rest, VT_2-rest, TT-rest), and after a 150 min of cycling at 90% of VT_1 power output (calculated in day one) on day two (VT_1-2.5h, VT_2-2.5h, TT-2.5h). On day two, before starting the 150 min bout, participants warmed-up for 5 min at 100 W. After the 150-min exercise bout and before the incremental test, participants recovered for 2 min at 90 W. As it has been shown that carbohydrate ingestion influences durability (Clark et al. 2019), glucose was consumed at 60 $g{\cdot}h^{-1}$ during the 150-min exercise bout. Glucose was consumed in beverages made with plain water to achieve a standardized rate of fluid consumption (380 mL·h^{-1}). Expired gas and heart rate at 30 min and 150 min, were considered, and calculated as the average of the last minute preceding the relative time point. In addition, at these time points RPE was recorded. Durability was assessed as percent difference between VT_1-rest and VT_1-2.5h (ΔVT_1%), VT_2-rest and VT_2-2.5h (ΔVT_2%), TT-rest and TT-2.5h (ΔTT%).To minimise external influences on the trials, each participant completed pre- and post-intervention tests at the same time of the day (± 2 hours), after 7-8 hours of sleep, under similar environmental conditions (18-20 °C). Furthermore, day 1 and 2 were separated by the same number of days in pre and post-tests.

Figure 2*: Schematic representation of laboratory test sessions.*



Training intervention: CON vs. INT

The two groups completed an individualized four-week training intervention involving five sessions per week, with a weekly volume corresponding to +15% PRE-WEEKLY-VOL (Table 1). The interventions involved two HIT sessions per week, as either standalone, short duration (~1 h) training sessions (CON), or at the end of long duration (+5% PRE-LONG-VOL), LIT sessions (INT). The CON group also performed two long duration LIT sessions per week (+5% PRE-LONG-VOL). The two HIT sessions were separated by at least one day for CON and INT. The HIT consisted of 4-5 (four in week 1-2 and five in week 3-4) x 5 min work intervals separated by 2.5 min recovery. Participants were instructed to perform these intervals at the maximum sustainable work intensity, and aimed to achieve the maximum possible mean power output during each session. In both groups, the remaining LIT sessions did not exceed 2 h. Participants were allowed to perform a maximum of 3 h LIT per week in non-cycling endurance training (running, cross-country skiing, swimming), if they were already performing these activities before entering the study.

Training intensities were prescribed using the three-zone endurance training model proposed by Seiler and Kjerland [15]. LIT was defined as time spent below the heart rate associated with VT_1, medium intensity training (MIT) as time spent between the heart rates associated with VT_1 and VT_2, and HIT as time spent above the heart rate associated with VT_2. These zones were derived from the pre-intervention incremental test performed in the rested state. Training load was calculated as Lucia's TRIMP (Lucia et al. 2003). Heart rate and (if available) power output was used to monitor training intensity during all training sessions. Adherence to the training intervention was monitored using an online training platform (TrainingPeaks LLC, Winchester Cir, MA, USA).

Table 1: *Example of the training program during pre-intervention and intervention period for a participant with 10 h as pre weekly volume and 240 min as pre long volume.*

PRE-INTERVENTION							
	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday	Sunday
CON/INT	60 min LIT	60 min LIT	60 min LIT	60 min with 4x5 min HIT	Rest	120 min LIT	240 min LIT
INTERVENTION							
	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday	Sunday
CON	Rest	255 min LIT	60 min LIT	60 min with 4x5 min HIT	Rest	60 min with 4x5 min HIT	255 min LIT
INT	Rest	60 min LIT	60 min LIT	235 min LIT + 4x5 min HIT	Rest	235 min LIT + 4x5 min HIT	60 min LIT

Abbreviations: CON, control group; INT, intervention group; LIT, low intensity training; MIT, medium intensity training; HIT, high intensity training.

Statistical analysis

All data are presented as mean ± standard deviation. Normal distribution and sphericity of data were checked and confirmed using the Shapiro-Wilk and Mauchly's tests, respectively. Baseline, pre-intervention values were compared between-groups using independent t-tests. Two-way analyses of variance (group and time as factors) were used to assess within-group and interaction effects for weekly volume, long ride duration, and weekly training frequency between the pre-intervention and intervention period. Two-way analyses of variance (group and time as factors) were used to assess within-group, between-group, and interaction effects for VT_1-rest, VT_1-2.5h, $\Delta VT_1\%$, VT_2-rest, VT_2-2.5h, $\Delta VT_2\%$, TT-rest, TT-2.5h, and $\Delta TT\%$. Two-way analyses of variance (group and time as factors) were used to assess within-group, between-group, and interaction effects for $\dot{V}O_2$, respiratory exchange ratio (RER), minute ventilation (VE), breathing frequency (BF), HR, RPE, and bLa^- during the step at 175 W in the rested state, after 2.5 h of exercise, and the percentage difference between these values. Two-way analyses of variance (group and time as factors) were used to assess within-group, between-group, and interaction effects for $\dot{V}O_2$, RER, HR, and RPE, at the 30 min and 150 min timepoints of the 150 min bout at 90% of VT_1 and percentage changes between the 30 min and 150 min timepoints. When a significant interaction effect was found, within-group contrast tests were carried out. Paired t-tests were performed to compare overall LIT, MIT, HIT and LuTRIMP of the intervention period between-groups. Effect sizes for repeated measures analyses of variance are reported as partial eta squared (η_p^2), and interpreted as trivial (<0.01), small (0.01-0.05) medium (0.05–0.13) or large (>0.13) (Bakerman R. 2005). Effect sizes for t-tests are reported as Cohen's d, and interpreted as trivial (<0.20), small (0.20–0.50), moderate (0.50–0.80), or large (>0.80) (Wassertheil and Cohen 1970). Significance was set at 0.05 (two-tailed) for all analyses. Statistical analysis was conducted using the Statistical Package for the Social Sciences, version 29 (SPSS Inc.).

Results

Pre-tests

There were no significant between-group differences in anthropometric, physiological, or performance variables at baseline (Table 2).

Table 2: *Anthropometric, physiological and performance characteristics after the pre-intervention period.*

	CON	**INT**	***P***
Age (years)	35.0 ± 13.6	34.2 ± 13.0	0.869
Height (cm)	179.3 ± 10.8	177.3 ± 9.4	0.597
Body mass (kg)	74.1 ± 14.3	73.0 ± 12.1	0.848
VO_2peak ($mL \cdot kg^{-1} \cdot min^{-1}$)	58.1 ± 12.1	58.1 ± 9.5	0.999
VT_1-rest (W)	206.2 ± 43.6	196.9 ± 38.2	0.553
VT_1-2.5h (W)	194.4 ± 42.1	184.0 ± 35.8	0.483
ΔVT_1 (%)	-5.8 ± 4.5	-7.0 ± 6.6	0.638
VT_2-rest (W)	250.7 ± 54.8	244.1 ± 45.6	0.727
VT_2-2.5h (W)	247.1 ± 61.0	235.5 ± 50.1	0.583
ΔVT_2 (%)	-1.9 ± 5.0	-5.5 ± 6.6	0.193
TT-rest (W)	337.3 ± 85.7	327.1 ± 69.3	0.729
TT-2.5h (W)	317.3 ± 75.9	307.3 ± 62.1	0.702
ΔTT (%)	-5.6 ± 3.3	-6.0 ± 4.0	0.814

Abbreviations: CON, control group; INT, intervention group; VO_2peak, peak oxygen consumption; VT_1, first ventilatory threshold; VT_2, second ventilatory threshold; TT, time trial.

Training characteristics

There were no significant main effects of group on weekly volume, long ride duration, or weekly training frequency. For weekly volume, no significant effect of time ($p = 0.064$; $\eta_p^2 = 0.18$), or group x time interaction was found ($p = 0.790$; $\eta_p^2 = 0.004$). For long ride duration, there was no effect of time ($p = 0.121$; $\eta_p^2 = 0.13$), or group x time interaction ($p = 0.863$; η_p^2

= 0.002). For weekly frequency, there was no effect of time ($p = 0.486$; $\eta_p^2 = 0.027$), while a significant moderate group x time interaction was observed ($p = 0.026$; $\eta_p^2 = 0.245$), as weekly frequency significantly increased in INT ($p = 0.040$) but not CON (Table 3). There were no significant between-group differences in LIT (CON: 1981 ± 710 vs INT: 2131 ± 627 min, p = 0.622, d = 0.22), MIT (CON: 177 ± 158 vs INT: 187 ± 176 min, p = 0.880, d = 0.06), or HIT (CON: 142 ± 49 vs INT: 129 ± 62 min, p = 0.621, d = 0.23) volume, or LuTRIMP (2762 ± 957 vs INT: 2832 ± 220 AU p = 0.852, d = 0.10).

Table 3: *Training characteristics during the pre-intervention and intervention periods.*

	CON			**INT**			***P* (ES)**		
	Pre-intervention	**Intervention**	**Δ**	**Pre-intervention**	**Intervention**	**Δ**	**Group**	**Time**	**Group x time**
Weekly volume (h)	8.4 ± 3.3	9.6 ± 3.3	1.3 ± 2.1	9.3 ± 2.9	10.3 ± 2.8	1.0 ± 3.0	0.527 (0.02)	0.064 (0.18)	0.790 (0.00)
Long ride duration (h)	2.9 ± 0.3	3.1 ± 0.3	0.2 ± 0.6	2.9 ± 0.3	3.1 ± 0.3	0.2 ± 0.4	0.927 (0.00)	0.121 (0.13)	0.863 (0.00)
Training frequency (sessions/week)	5.0 ± 0.6	5.6 ± 0.3	0.6 ± 1.1	6.2 ± 0.6	5.1 ± 0.3	-1.1 ± 1.9	0.460 (0.03)	0.486 (0.03)	0.026 (0.25)*

Abbreviations: CON, control group; INT, intervention group.

** indicates $p < 0.05$.*

Physiological and performance parameters in the rested state

A significant large main effect of time ($p = 0.03$; $\eta_p^2 = 0.40$), but no group x time interaction ($p = 0.101$; $\eta_p^2 = 0.14$), was observed for VT_1-rest. There was no main effect of time on VT_2-rest ($p = 0.154$), but a significant large group x time interaction was observed ($p = 0.015$; $\eta_p^2 = 0.29$), whereby a significant increase was observed in CON ($p = 0.009$) but not INT ($p = 0.411$). A significant large main effect of time ($p < 0.001$; $\eta_p^2 = 0.64$), but no group x time interaction ($p = 0.334$; $\eta_p^2 = 0.06$), was observed for TT-rest (Table 4, Figure 3). In the step at 175 W, there were no main effects of group, or group x time interactions, for $\dot{V}O_2$, RER, VE, BF, HR, RPE, or bLa^- (Supplementary Table 1). A significant effect of time was observed only for RPE ($p = 0.012$, $\eta_p^2 = 0.32$, Supplementary Table 1). At the 30 min time point of the 150 min bout at 90% of VT_1, there were no main effects of group, time, or group x time interactions, for $\dot{V}O_2$, RER, HR, or RPE (Supplementary Table 2).

Physiological and performance parameters after 2.5 hours

There was no significant main effect of time ($p = 0.216$), or group x time interaction ($p = 0.057$; $\eta_p^2 = 0.19$), for VT_1-2.5h. There was no main effect of time ($p = 0.580$), or group × time interaction ($p = 0.492$; $\eta_p^2 = 0.03$), for VT_2-2.5h. For TT-2.5h, a significant large main effect of time was observed ($p < 0.01$; $\eta_p^2 = 0.31$), but no group x time interaction ($p = 0.380$, $\eta_p^2 = 0.05$, Table 4, Figure 3). In the step at 175 W, there were no main effects of group, or group x time interactions, for $\dot{V}O_2$, RER, VE, BF, HR, RPE, or bLa^-. A significant effect of time was observed only for RPE ($p = 0.023$, $\eta_p^2 = 0.27$, Supplementary Table 1). At the 150 min time point of the 150 min bout at 90% of VT_1, there were no main effects of group, or group x time interactions, for any of the variables measured. A significant effect of time was observed only for RER ($p = 0.008$, $\eta_p^2 = 0.41$, Supplementary Table 2).

Supplementary Table 1: *Physiological and perceptual response during the step tests at 175 W.*

	CON			**INT**			***P* (ES)**		
	Pre-intervention	**Post-intervention**	**Δ**	**Pre-intervention**	**Post-intervention**	**Δ**	**Group**	**Time**	**Group x time**
VO_2-rest (ml · min^{-1})	2563 ± 331	2547 ± 299	-16 ± 320	2523 ± 89	2583 ± 174	60 ± 189	0.991 (0.00)	0.785 (0.00)	0.637 (0.02)
VO_2-2.5h (ml · min^{-1})	2714 ± 224	2639 ± 283	-76 ± 163	2653 ± 160	2683 ± 114	30 ± 63	0.942 (0.00)	0.564 (0.03)	0.190 (0.14)
ΔVO_2 (%)	7.0 ± 11.7	3.9 ± 5.4	-3.1 ± 12.7	5.2 ± 6.0	4.1 ± 5.2	-1.1 ± 9.0	0.795 (0.01)	0.527 (0.03)	0.754 (0.01)
VE-rest (L· min^{-1})	64.3 ± 10.9	64.6 ± 11.6	0.3 ± 9.1	68.5 ± 6.9	69.2 ± 5.6	0.6 ± 3.4	0.410 (0.06)	0.826 (0.01)	0.944 (0.00)
VE-2.5h (L· min-^{1})	71.4 ± 12.2	68.1 ± 13.3	-3.3 ± 6.1	74.9 ± 5.4	75.9 ± 6.8	1.0 ± 2.4	0.366 (0.08)	0.441 (0.06)	0.168 (0.17)
ΔVE (%)	11.6 ± 12.1	5.2 ± 4.9	6.4 ± 9.5	9.7 ± 6.4	9.8 ± 7.2	0.1 ± 7.2	0.738 (0.01)	0.235 (0.13)	0.217 (0.14)
BF-rest (1 · min^{-1})	31.1 ± 7.8	30.5 ± 7.1	-0.6 ± 7.2	29.2 ± 5.1	29.2 ± 6.4	0.0 ± 2.2	0.607 (0.02)	0.815 (0.00)	0.818 (0.00)
BF-2.5h (1 · min^{-1})	37.0 ± 9.8	37.5 ± 8.9	0.5 ± 5.4	33.8 ± 4.2	34.5 ± 4.6	0.6 ± 2.9	0.394 (0.05)	0.618 (0.02)	0.348 (0.05)
ΔBF (%)	19.1 ± 11.9	23.4 ± 16.5	4.3 ± 15.4	17.6 ± 15.4	20.9 ± 20.9	3.3 ± 13.1	0.794 (0.01)	0.304 (0.08)	0.895 (0.00)

RER-rest (AU)	0.97 ± 0.09	0.98 ± 0.10	0.01 ± 0.07	1.00 ± 0.08	1.00 ± 0.10	0.00 ± 0.07	0.469 (0.03)	0.785 (0.01)	0.636 (0.01)
RER-2.5h (AU)	0.87 ± 0.05	0.92 ± 0.10	0.04 ± 0.10	0.93 ± 0.06	0.96 ± 0.10	0.03 ± 0.05	0.124 (0.14)	0.089 (0.17)	0.747 (0.01)
ΔRER (%)	-9.1 ± 5.8	-6.2 ± 7.5	-2.9 ± 6.5	-6.9 ± 5.7	-3.9 ± 3.5	-3.0 ± 7.2	0.334 (0.06)	0.088 (0.17)	0.979 (0.00)
HR-rest (bpm)	131 ± 18	127 ± 17	3 ± 7	145 ± 18	144 ± 16	1 ± 5	0.089 (0.19)	0.168 (0.13)	0.586 (0.02)
HR-2.5h (bpm)	135 ± 18	135 ± 16	0 ± 10	150 ± 16	150 ± 13	0 ± 7	0.065 (0.22)	0.888 (0.00)	0.945 (0.00)
ΔHR (%)	3.6 ± 8.2	6.6 ± 4.8	3.0 ± 7.3	3.7 ± 4.0	4.8 ± 2.8	1.1 ± 4.3	0.727 (0.01)	0.199 (0.12)	0.546 (0.03)
RPE-rest (AU)	11.2 ± 2.7	10.6 ± 2.4	-0.7 ± 1.6	11.9 ± 2.7	10.7 ± 2.1	-1.2 ± 1.0	0.704 (0.01)	0.012 (0.32)*	0.253 (0.08)
RPE-2.5h (AU)	11.8 ± 2.9	11.0 ± 2.3	-0.8 ± 1.0	12.6 ± 2.2	12.1 ± 2.3	-0.4 ± 1.2	0.413 (0.04)	0.023 (0.27)*	0.483 (0.03)
ΔRPE (%)	7.3 ± 13.5	4.4 ± 7.2	-2.9 ± 14.4	7.2 ± 15.0	14.7 ± 18.2	7.4 ± 10.0	0.383 (0.05)	0.435 (0.04)	0.087 (0.16)
bLA^--rest (mMol/L)	1.4 ± 0.7	1.2 ± 0.4	-0.2 ± 0.4	2.1 ± 1.9	1.7 ± 1.0	-0.5 ± 1.0	0.323 (0.10)	0.153 (0.19)	0.565 (0.03)
bLA^--2.5h (mMol/L)	1.3 ± 0.7	1.1 ± 0.5	-0.2 ± 0.3	1.6 ± 1.3	1.6 ± 1.0	0.0 ± 0.3	0.452 (0.06)	0.290 (0.11)	0.385 (0.08)
ΔbLA^- (%)	-7.4 ± 16.5	-7.2 ± 18.8	-0.2 ± 7.0	-22.1 ± 16.0	-2.4 ± 16.6	-19.7 ± 30.2	0.526 (0.04)	0.147 (0.20)	0.154 (0.19)

Abbreviations: CON, control group; INT, intervention group; VO_2: oxygen consumption; VE, ventilation; BF, breath frequency; RER, respiratory exchange ratio; HR, heart rate. RPE, rating of perceived exertion; bLa^-, blood lactate concentration.

** indicates $p < 0.05$*

Supplementary Table 2*: Physiological and perceptual measurements at pre- and post-intervention during the 150min bout at 90% of the first ventilatory threshold.*

	CON			**INT**			***P* (ES)**		
	Pre-intervention	**Post-intervention**	**Δ**	**Pre-intervention**	**Post-intervention**	**Δ**	**Group**	**Time**	**Group x time**
VO_2-30min ($mL \cdot min^{-1}$)	2717 ± 502	2858 ± 573	140 ± 39	2333 ± 576	2460 ± 489	127 ± 30	0.136 (0.14)	0.117 (0.16)	0.935 (0.00)
VO_2-150min ($mL \cdot min^{-1}$)	2928 ± 464	2942 ± 507	14 ± 230	2422 ± 589	2591 ± 516	169 ± 365	0.094 (0.18)	0.241 (0.09)	0.316 (0.07)
ΔVO_2 (%)	8.5 ± 10.8	3.6 ± 6.5	-4.8 ± 11.0	4.1 ± 3.9	5.5 ± 7.3	1.4 ± 7.4	0.653 (0.01)	0.460 (0.04)	0.187 (0.11)
RER-30min (AU)	0.93 ± 0.05	0.94 ± 0.10	0.01 ± 0.01	0.95 ± 0.07	0.97 ± 0.08	0.02 ± 0.07	0.448 (0.04)	0.394 (0.05)	0.726 (0.01)
RER-150min (AU)	0.87 ± 0.05	0.89 ± 0.08	0.02 ± 0.03	0.90 ± 0.03	0.93 ± 0.06	0.03 ± 0.03	0.290 (0.08)	0.008 (0.41)*	0.510 (0.03)
ΔRER (%)	-6.5 ± 2.6	-5.0 ± 2.4	-1.5 ± 3.3	-5.8 ± 5.1	-3.7 ± 1.2	-1.4 ± 6.3	0.671 (0.01)	0.293 (0.08)	0.957 (0.00)
HR-30min (bpm)	134 ± 19	136 ± 16	2 ± 1	138 ± 9	138 ± 11	1 ± 5	0.655 (0.01)	0.730 (0.01)	0.460 (0.04)
HR-150min (bpm)	141 ± 15	142 ± 14	1 ± 10	144 ± 9	146 ± 11	2 ± 6	0.542 (0.03)	0.495 (0.03)	0.912 (0.00)

ΔHR (%)	5.8 ± 6.2	5.0 ± 4.9	-0.8 ± 4.8	4.3 ± 3.4	6.0 ± 2.5	1.6 ± 2	0.897 (0.00)	0.668 (0.01)	0.192 (0.11)
RPE-30min (AU)	9.8 ± 2.1	10.0 ± 1.5	0.3 ± 1.2	10.2 ± 2.5	10.0 ± 1.5	-0.2 ± 1.1	0.942 (0.00)	0.591 (0.02)	0.169 (0.12)
RPE-150min (AU)	12.3 ± 1.5	`12.0 ± 1.1	-0.3 ± 1.2	12.6 ± 2.5	12.4 ± 1.6	-0.1 ± 2.0	0.627 (0.02)	0.665 (0.01)	0.867 (0.00)
ΔRPE (%)	29.2 ± 21.4	22.1 ± 19.0	-7.1 ± 12.4	25.9 ± 24.2	31.8 ± 24.8	6.0 ± 21.9	0.756 (0.01)	0.898 (0.00)	0.157 (0.13)

Abbreviations: CON, control group; INT, intervention group; VO_2: oxygen consumption; RER, respiratory exchange ratio; HR, Heart Rate; RPE, rating of perceived exertion.

* indicates $p < 0.05$

Durability

No significant main effect of time ($p = 0.886$), but a large significant group x time interaction was observed for $\Delta VT_1\%$, ($p = 0.015$; $\eta_p^2 = 0.29$), whereby $\Delta VT_1\%$ decreased in INT and increased in CON (Table 4). No significant main effect of time ($p = 0.955$), or group x time interaction, was observed for $\Delta VT_2\%$ ($p = 0.058$; $\eta_p^2 = 0.19$). There was no significant main effect of time, or interaction group × time ($p = 0.272$; $\eta_p^2 = 0.08$), for $\Delta TT\%$ (Table 4, Figure 3). There were no significant main effects of group, time, or group x time interactions in the percentage changes for $\dot{V}O_2$, RER, VE, BF, HR, RPE and bLa^- in the steps at 175 W between the rested state and after 2.5 hrs, and no significant main effects of group, time, or time x group interactions for the percentage changes between the 30 min and 150 min timepoint during the 150 min bout at 90% of VT_1 for $\dot{V}O_2$, RER, HR, or RPE (Supplementary Table 1 and 2).

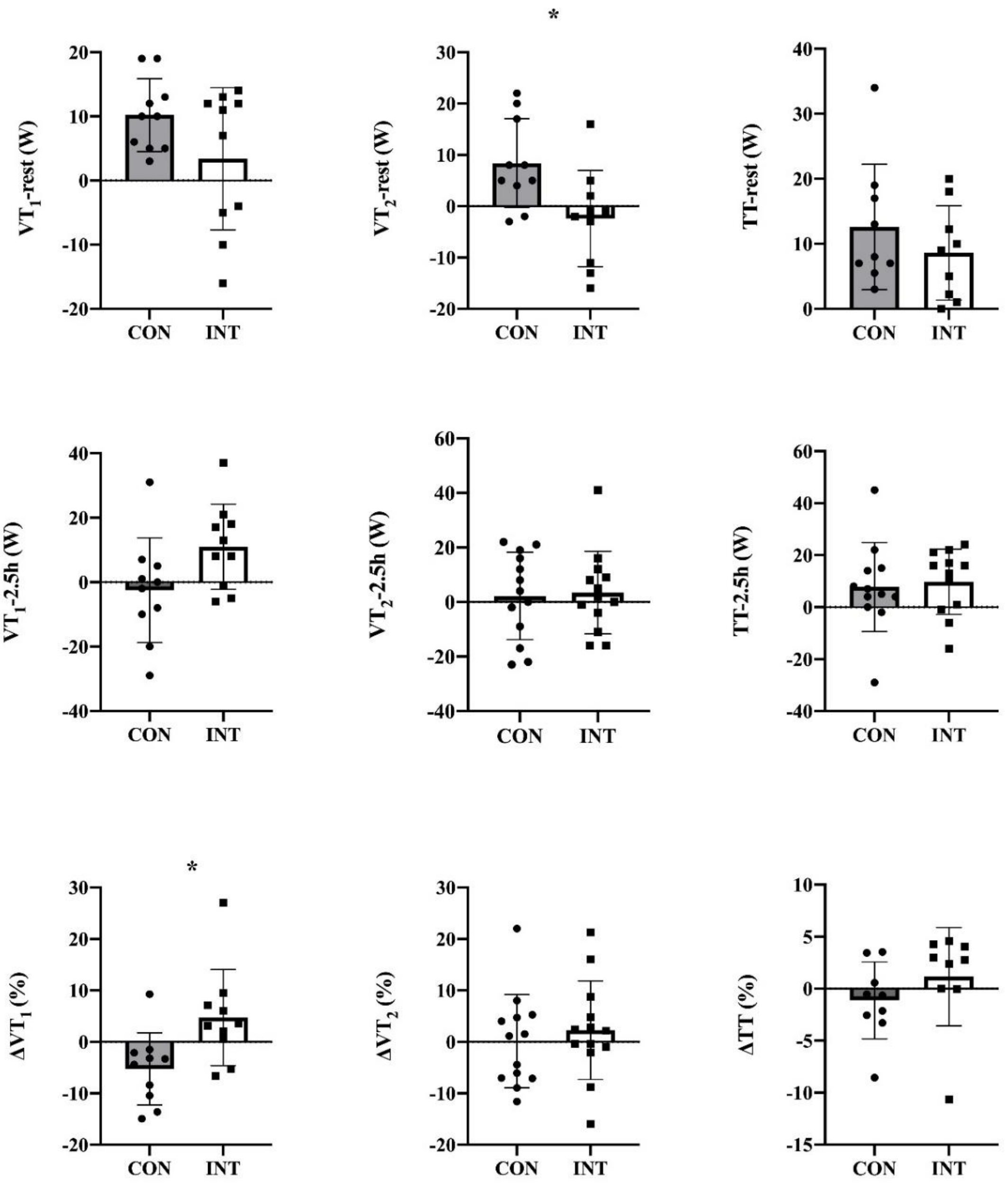
Table 4: *Physiological and performance characteristics at pre- and post-intervention.*

	CON			INT			*P* (ES)		
	Pre-intervention	Post-intervention	Δ	Pre-intervention	Post-intervention	Δ	Group	Time	Group x time
VT_1-rest (W)	206.2 ± 43.6	216.4 ± 41.7	10.2 ± 5.7	187.6 ± 31.3	191.0 ± 32.3	3.4 ± 11.1	0.205 (0.09)	0.003 (0.40)*	0.101 (0.14)
VT_1-2.5h (W)	194.4 ± 42.1	191.9 ± 39.1	-2.5 ± 16.3	173.5 ± 26.3	184.5 ± 22.0	11.0 ± 13.2	0.345 (0.05)	0.216 (0.08)	0.057 (0.19)
ΔVT_1 (%)	-5.8 ± 4.5	-11.1 ± 10.3	-5.3 ± 7.0	-7.0 ± 6.6	-2.3 ± 9.0	4.7 ± 9.3	0.227 (0.08)	0.886 (0.00)	0.015 (0.29)*
VT_2-rest (W)	250.7 ± 55.0	259.1 ± 50.1	8.4 ± 8.7	237. ± 35.8	235.0 ± 38.6	-2.4 ± 9.3	0.368 (0.05)	0.154 (0.11)	0.015 (0.29)*
VT_2-2.5h (W)	247.1 ± 61.0	246.6 ± 53.0	-0.5 ± 17.0	223.9 ± 35.9	228.5 ± 37.0	4.6 ± 15.6	0.341 (0.05)	0.580 (0.02)	0.492 (0.03)
ΔVT_2 (%)	-1.9 ± 5.2	-5.1 ± 5.8	-3.2 ± 5.9	-5.5 ± 1.9	-2.4 ± 2.1	3.1 ± 7.9	0.837 (0.00)	0.955 (0.00)	0.058 (0.19)
TT-rest (W)	343.8 ± 88.2	356.4 ± 92.0	12.6 ± 9.6	316.8 ± 53.8	325.4 ± 54.5	8.6 ± 7.2	0.419 (0.04)	<0.001 (0.64)*	0.334 (0.06)
TT-2.5h (W)	321.2 ± 79.4	327.8 ± 77.3	6.6 ± 19.3	295.7 ± 49.1	308.8 ± 57.1	13.1 ± 10.0	0.488 (0.03)	0.016 (0.31)*	0.380 (0.05)
ΔTT (%)	-6.4 ± 3.0	-7.5 ± 3.5	-1.1 ± 3.7	-6.5 ± 4.2	-5.3 ± 4.4	1.2 ± 4.7	0.497 (0.03)	0.990 (0.00)	0.272 (0.08)

Abbreviations: CON, control group; INT, intervention group; VT_1, first ventilatory threshold; VT_2, second ventilatory threshold; TT, time trial.

** indicates $p < 0.05$.*

Figure 3: *Changes in physiological and performance parameters between pre and post-intervention in control (CON) and intervention (INT) groups.*



*Abbreviations: VT_1, first ventilatory threshold; VT_2, second ventilatory threshold; TT, time trial. -rest indicates parameters measured in the rested state on day 1. -2.5hrs indicates parameters measured after 2.5 hours of cycling at low intensity on day 2. Δ% indicates the percent difference between -rest and -2.5hrs. * indicates $p < 0.05$*

Discussion

The aim of this study was to determine if performing HIT at the end of long, low-intensity training sessions is a superior method for improving durability in trained cyclists than shorter standalone HIT sessions. Our findings revealed some distinct differences in adaptations to physiological variables depending on the timing of HIT. Specifically, performing HIT in standalone short-duration sessions tended to favor adaptations in the rested state, while performing HIT at the end of LIT sessions tended to favor adaptations after 2.5 hours of low-intensity cycling. These results indicate that the timing of HIT has an impact on durability-related adaptations in trained cyclists.

Specificity of adaptations

We observed evidence of specificity of adaptations in both groups. For example, power output at VT_2-rest increased significantly more in CON compared to INT, with a large effect size (+8.4 ± 8.7 W vs. -2.4 ± 9.3 W). Adaptations to power output at VT_1-rest were not significantly different between-groups, although the average increase was higher in CON vs. INT (+10.2 ± 5.7 W vs. +3.4 ± 11.1 W) with a large effect size. In the assessments performed after 2.5 h of low intensity cycling, adaptations to power output at VT_1 were not significantly different between groups (CON: -2.5 ± 16.3 W vs. INT: +11.0 ± 13.2 W), but the effect size, in favor of INT, was large. Since no previous study has examined the specificity of adaptations on durability, our data are novel. Although not all findings showed statistically significant differences between groups, the overall direction of these findings (including the TT results) align with the principle of training specificity.[13] he data thus suggests that performing standalone HIT sessions is more beneficial for adaptations in the rested state, while HIT performed after long-duration low-intensity work tends to be more effective for adaptations after prolonged exercise. The superior adaptations obtained after prolonged exercise compared to rested state observed in INT, are similar to what was found in studies investigating the effects of adding strength training to ongoing endurance training in cyclists (Vikmoen et al. 2017) and cross-country skiers (Øfsteng et al. 2018).

Durability

We assessed durability as the percentage change VT_1, VT_2, and TT from the rested state to after 2.5 h of low-intensity exercise. Durability of VT_1 improved significantly more in INT than CON, as the magnitude of the reduction in VT_1 power output after prolonged exercise was reduced following INT (4.7 ± 9.3 %) but not CON (-5.3 ± 7.0 %). Adaptations to durability of VT_2 were not significantly different between-groups (INT: 3.1 ± 7.9 % vs CON: -3.2 ± 5.9 %), but there was a large effect size favoring INT. Durability of VT_1 and VT_2 improved in INT due to adaptations after 2.5 h of low-intensity exercise. Durability was 'worsened' in CON as improvements in the rested state were not observed after 2.5 h of exercise (Figure 3, Table 4). Thus, it should be noted that the absolute power output at VT_1 and VT_2 after 2.5 h in CON did not change, but due to improved VT_1 and VT_2 in the rested state, the magnitude of the reduction in these variables following prolonged exercise increased. The opposite occurred in INT, where no changes in the rested state and numerical improvements in VT_1 and VT_2 after 2.5 h reduced the effect of prolonged exercise on these variables. These findings suggest that when assessing the effects of a training intervention, considering adaptations both in a rested state and after prolonged exercise may provide more insights than solely relying on durability statistics. The effects of these different adaptation profiles on performance likely depends on the specific duration of the competition.

Adaptations to physiological ($\dot{V}O_2$, RER, VE, BF, HR, RPE and bLa^-) and perceptual (RPE) variables in the rested state and after 2.5 h, and the difference between these timepoints, were not different between-groups at the same absolute (175 W step) and relative (90% of VT_1) intensity (Supplementary Table 1 and 2). Therefore, we cannot make any inference about the physiological mechanisms underlying the observed specificity of adaptations in VT_1 and VT_2.

A previous study showed a strong positive relationship between a smaller decline in gross efficiency during prolonged exercise and durability.[5] However, in the present study, there were no differences between CON and INT in the development of (submaximal) $\dot{V}O_2$ costs during the prolonged cycling, which agrees with a cross-sectional study observing no relationship between conserving gross efficiency during prolonged cycling and durability measures (Almquist et al. 2023).

There is some indication that superior durability is related to glycogen availability (Clark et al. 2019). However, in our ecologically valid setting, with standardized glucose ingestion during the 2.5 hours of cycling, no differences in RER values were observed, which indicates no superior carbohydrate sparing effects in INT compared to CON. Future studies designed to establish the mechanistic cause of durability are warranted. These studies could investigate the relationship between adaptations in durability and in direct measures of muscle glycogen availability.

Previous studies have suggested that a higher magnitude of decoupling of the internal to external workload during prolonged exercise can be a marker of fatigue and durability (Smyth et al. 2022; Matomäki et al. 2023). However, in the present study, the superior improvement in durability of VT_1 in INT vs. CON was not accompanied by decreased decoupling in either the step at 175 W or during the 150 min bout. Although not significant, moderate to large effect sizes in favor of decreased decoupling were observed in CON compared to INT for changes between pre-post intervention for some variables ($\dot{V}O_2$, VE, RPE, bLa^-, Supplementary Table 1 and 2). This suggests caution should be taken when evaluating durability outcomes using decoupling. Future studies should investigate whether decoupling is a valid durability marker in different contexts.

Methodological consideration

While total training volume, training time spent in different intensity zones and total training load were similar between-groups, weekly training frequency decreased in INT, but not in CON, during the four-week intervention. We consider this as a practical outcome when combining high-volume and high-intensity within the same training sessions instead of on separate days, rather than a limitation when interpreting the results of the present study. There are to our knowledge no data showing effects of training frequency on endurance training adaptation when volume and intensity distribution are matched.

Conclusions

The present findings indicate that the timing of HIT has an impact on adaptations related to durability in trained cyclists. Specifically, performing HIT in standalone, short-duration (~1 h) sessions tends to favor physiological and performance adaptations in the rested state, while performing HIT after prolonged LIT sessions tends to favor such adaptations after multiple hours of exercise. These results can inform training programming and enable athletes to target the specific adaptations required to maximize performance in their respective events. Future research should build on this work by assessing the effects of HIT timing in interventions longer than four weeks, and investigate the underlying mechanisms behind durability-related adaptations.

SECTION THREE

MAIN FINDINGS AND FINAL CONSIDERATIONS

This thesis aimed to understand the impact of durability on competition success in Junior (JUN), Under 23 (U23) and Professional (PRO) male road cycling categories and to investigate effective training strategies to improve durability. Study 1 (chapter 2) investigate cross sectional differences in race demands between junior, under 23 and professional road cycling categories. Results showed as JUN races are shorter, more internally intense and included less elevation gain per distance unit compared to U23 and PRO races. U23 and PRO races present similar work demands per hour and record power outputs, but PRO races are longer than U23. This study suggested as durability is a requirement of growing importance when stepping up from JUN to U23 and from U23 to PRO. Study 2 (chapter 3) investigated the field-derived power performance parameters associate with competition success in road cycling climbing specialists of JUN, U23 and PRO categories. Superior absolute and relative RPOs at rested state characterize high-ranked vs low-ranked JUN climbing specialists. Superior durability characterized high-ranked U23 and PRO climbers compared with their low-ranked counterpart, as well as PRO versus U23 climbers high-ranked climbers. This study confirmed the hypothesis of durability is important for U23 and PRO but not JUN cyclists in determining competition success. Study 3 (chapter 4) reported cross sectional difference in training characteristics between JUN, U23 and PRO male road cyclists. JUN spent more training time at medium and high heart rate intensity zones compared to U23 and PRO. Higher duration per training session were observed in PRO compared to both U23 and JUN. Elevation gain per distance was higher in PRO compared to U23 and JUN, and in U23 compared to JUN. This study could suggest as the amount of high-volume low intensity training performed could explain the differences in durability between JUN, U23 and PRO male road cyclists. Study 4 (chapter 5) described the day-by-day training and racing characteristics in preparation to Giro d'Italia of one world class road cyclist achieved a place on the podium in the final general classification of the Giro d'Italia. During training, a pattern alternating 'hard days' versus 'easy days' was achieved combining high volume (> 4 hrs) with significant amount of medium and high intensity within the same training sessions instead of performing them apart in standalone training sessions. This observation led to design the experimental Study 5 (chapter 6), which investigated if a 4-weeks training intervention performing high-intensity training at the end of long low-intensity training sessions is more effective to enhance durability compared to perform high volume and high intensity in different days. The data revealed, performing high-intensity training in standalone short-duration sessions tended to favor adaptations in the rested state, while performing high-intensity training at the end of long low intensity trainings sessions tended to favor adaptations after 2.5 hours of low-intensity cycling. These results indicate that the timing of HIT has an impact on durability-related adaptations in trained cyclists.

Globally these data highlight: (i) the importance of durability for talent identification and long-term athlete development in road cycling; (ii) the possible benefit of performing high intensity training at the end of long low intensity sessions to improve durability which could be relevant to optimize performance in long duration sports, such as road cycling, ultra cycling and long distance triathlon.

REFERENCES

1. Abbiss CR, Laursen PB. Models to explain fatigue during prolonged endurance cycling. *Sports Med*. 2005;35(10):865–898.
2. Allen DG, Lamb GD, Westerblad H. Skeletal muscle fatigue: cellular mechanisms. *Physiol Rev*. 2008 Jan;88(1):287-332.
3. Almquist NW, Hansen J, Rønnestad BR. Development of Cycling Performance Variables and Durability in Female and Male National Team Cyclists: From Junior to Senior. *Med Sci Sports Exerc*. 2023 Nov 1;55(11):2053-2063.
4. Antón MM, Izquierdo M, Ibáñez J, Asiain X, Mendiguchía J, Gorostiaga EM. Flat and uphill climb time trial performance prediction in elite amateur cyclists. *Int J Sports Med*. 2007;43(2):161–167.
5. Bakeman R. Recommended effect size statistics for repeated measures designs. *Behav Res Methods*. 2005;37(3):379–384.
6. Bassett DR Jr, Howley ET. Limiting factors for maximum oxygen uptake and determinants of endurance performance. *Med Sci Sports Exerc*. 2000 Jan;32(1):70-84.
7. Bassett DR Jr. Scientific contributions of A. V. Hill: exercise physiology pioneer. *J Appl Physiol (1985).* 2002 Nov;93(5):1567-82.
8. Bishop D, Edge J, Goodman C. Muscle buffer capacity and aerobic fitness are associated with repeated-sprint ability in women. *Eur J Appl Physiol*. 2004 Aug;92(4-5):540-7.

9. Borg G. Borg's perceived exertion and pain scales. Champaign, IL: Human kinetics; 1998.
10. Burnley M, Jones AM. Power–duration relationship: physiology, fatigue, and the limits of human performance. *Eur J Sport Sci*. 2018;18(1):1–12.
11. Clark IE, Vanhatalo A, Bailey SJ, Wylie LJ, Kirby BS, Wilkins BW, Jones AM. Effects of Two Hours of Heavy-Intensity Exercise on the Power-Duration Relationship. *Med Sci Sports Exerc*. 2018 Aug;50(8):1658-1668.
12. Clark IE, Vanhatalo A, Thompson C, Joseph C, Black MI, Blackwell JR, Wylie LJ, Tan R, Bailey SJ, Wilkins BW, Kirby BS, Jones AM. Dynamics of the power-duration relationship during prolonged endurance exercise and influence of carbohydrate ingestion. *J Appl Physiol (1985).* 2019 Sep 1;127(3):726-736.
13. Clark IE, Vanhatalo A, Thompson C, Wylie LJ, Bailey SJ, Kirby BS, Wilkins BW, Jones AM. Changes in the power-duration relationship following prolonged exercise: estimation using conventional and all-out protocols and relationship with muscle glycogen. *Am J Physiol Regul Integr Comp Physiol*. 2019 Jul 1;317(1):R59-R67.
14. Coggan A. Training and racing using a power meter: an introduction. Lev II Coach Man; 2003.
15. Coyle EF, Sidossis LS, Horowitz JF & Beltz JD (1992). Cycling efficiency is related to the percentage of type I muscle fibers. *Med Sci Sports Exerc* 24, 782–788.
16. Coyle EF. Integration of the physiological factors determining endurance performance ability. *Exerc Sport Sci Rev*. 1995;23:25-63.
17. de Koning JJ, Noordhof DA, Lucia A, Foster C. Factors affecting gross efficiency in cycling. *Int J Sports Med*. 2012 Nov;33(11):880-5

18. De Pauw K, Roelands B, Cheung SS, De Geus B, Rietjens G, Meeusen R. Guidelines to classify subject groups in sport-science research. *Int J Sports Physiol Perform*. 2013;8(2):111–122.
19. Di Giulio C, Daniele F, Tipton CM. Angelo Mosso and muscular fatigue: 116 years after the first Congress of Physiologists: IUPS commemoration. *Adv Physiol Educ*. 2006 Jun;30(2):51-7.
20. Edwards S. The heart rate monitor book. *Med Sci Sport Exerc*. 1994;26(5):647.
21. Farrell PA, Wilmore JH, Coyle EF, Billing JE, Costill DL. Plasma lactate accumulation and distance running performance. *Med Sci Sports.* 1979 Winter;11(4):338-44.
22. Filipas L, Gallo G, Pollastri L, Torre AL. Mental fatigue impairs time trial performance in sub-elite under 23 cyclists. *PLoS One*. 2019;14(6):e0218405.
23. Foster C, Casado A, Esteve-Lanao J, Haugen T, Seiler S. Polarized Training Is Optimal for Endurance Athletes. *Med Sci Sports Exerc*. 2022 Jun 1;54(6):1028-1031.
24. Foster C. Monitoring training in athletes with reference to overtraining syndrome. *Med Sci Sports Exerc*. 1998 Jul;30(7):1164-8.
25. Gallo G, Leo P, March MM, Giorgi A, Faelli E, Ruggeri P, Mujika I, Filipas L. Differences in Training Characteristics Between Junior, Under 23 and Professional Cyclists. *Int J Sports Med*. 2022 Dec;43(14):1183-1189.
26. Gallo G, Mateo-March M, Gotti D, Faelli E, Ruggeri P, Codella R, Filipas L. How do world class top 5 Giro d'Italia finishers train? A qualitative multiple case study. *Scand J Med Sci Sports*. 2022 Dec;32(12):1738-1746.
27. Gallo G, Mateo-March M, Leo P, Campos-Donaire A, Gandia-Soriano A, Giorgi A, Faelli E, Ruggeri P, Codella R, Mujika I, Filipas L. Power Road-Derived Physical Performance Parameters in Junior, Under-23, and Professional Road Cycling Climbers. *Int J Sports Physiol Perform*. 2022 Apr 28;17(7):1094-1102.

28. Hill AV. Athletic records. *Lancet*. 1925;5:481–486.

29. Holloszy JO, Coyle EF. Adaptations of skeletal muscle to endurance exercise and their metabolic consequences. *J Appl Physiol*. 1984;56:831–838.

30. Iaia FM, Hellsten Y, Nielsen JJ, Fernström M, Sahlin K, Bangsbo J. Four weeks of speed endurance training reduces energy expenditure during exercise and maintains muscle oxidative capacity despite a reduction in training volume. *J Appl Physiol* (1985). 2009 Jan;106(1):73-80.

31. Impellizzeri FM, Marcora SM, Coutts AJ. Internal and external training load: 15 years on. *Int J Sports Physiol Perform*. 2019;14(2):270–273.

32. Jeukendrup AE. Nutrition for endurance sports: marathon, triathlon, and road cycling. *J Sports Sci*. 2011;29(suppl 1):S91–S99.

33. Jones AM. The fourth dimension: physiological resilience as an independent determinant of endurance exercise performance. *J Physiol. 2023* Aug 22.

34. Joyner MJ (1991). Modeling: optimal marathon performance on the basis of physiological factors. *J Appl Physiol* 70, 683–687.

35. Joyner MJ, Coyle EF. Endurance exercise performance: the physiology of champions. J Physiol. 2008 Jan 1;586(1):35-44..

36. Kordi M, Parker Simpson L, Thomas K, et al. The relationship between neuromuscular function and the W′ in elite cyclists. *Int J Sports Physiol Perform*. 2021;16(11):1656–1662.

37. Laursen PB. Training for intense exercise performance: high-intensity or high-volume training? *Scand J Med Sci Sport*. 2010;20:1–10.

38. Leo P, Spragg J, Mujika I, Giorgi A, Lorang D, Simon D, Lawley JS. Power Profiling, Workload Characteristics, and Race Performance of U23 and Professional Cyclists

During the Multistage Race Tour of the Alps. *Int J Sports Physiol Perform*. 2021 Aug 1;16(8):1089–1095.

39. Leo P, Spragg J, Simon D, Lawley J, Mujika I. Climbing performance in U23 and professional cyclists during a multi-stage race. *Int J Sports Med*. 2022;43(2):161–167.
40. Leo P, Spragg J, Simon D, Lawley JS, Mujika I. Training characteristics and power profile of professional U23 cyclists throughout a competitive season. *Sports*. 2020;8(12):167.
41. Lucía A, Hoyos J, Santalla A, Earnest C, Chicharro JL. Tour de France versus Vuelta a España: which is harder? *Med Sci Sports Exerc*. 2003.
42. Lucía A, Hoyos J, Pérez M, Santalla A, Chicharro JL. Inverse relationship between VO2max and economy/efficiency in world-class cyclists. *Med Sci Sports Exerc*. 2002 Dec;34(12):2079-84.
43. Lucia A, Hoyos J, Pérez M, Santalla A, Earnest CP, Chicharro JL. Which laboratory variable is related with time trial performance time in the Tour de France? *Br J Sports Med*. 2004 Oct;38(5):636-40.
44. Lucia A, Hoyos J, Chicharro JL. Physiology of professional road cycling. *Sport Med.* 2001;31:325-337.
45. Maier T, Schmid L, Müller B, Steiner T, Wehrlin JP. Accuracy of cycling power meters against a mathematical model of treadmill cycling. *Int J Sports Med*. 2017; 38: 456- 461.
46. Mateo-March M, Valenzuela PL, Muriel X, Gandia-Soriano A, Zabala M, Lucia A, Pallares JG, Barranco-Gil D. The Record Power Profile of Male Professional Cyclists: Fatigue Matters. *Int J Sports Physiol Perform*. 2022 Mar 3;17(6):926-931.
47. Matomäki P, Heinonen OJ, Nummela A, Laukkanen J, Auvinen EP, Pirkola L, Kyröläinen H. Durability is improved by both low and high intensity endurance training. *Front Physiol*. 2023 Feb 16;14.

48. Maunder E, Seiler S, Mildenhall MJ, Kilding AE, Plews DJ. The Importance of 'Durability' in the Physiological Profiling of Endurance Athletes. *Sports Med*. 2021.
49. McKay AKA, Stellingwerff T, Smith ES, et al. Defining training and performance caliber: a participant classification framework. *Int J Sports Physiol Perform*. 2022; 17(2): 317- 331.
50. Menaspà P, Quod M, Martin DT, Peiffer JJ, Abbiss CR. Physical Demands of Sprinting in Professional Road Cycling. *Int J Sports Med*. 2015 Nov;36(13):1058-62.
51. Menaspà P, Impellizzeri FM, Haakonssen EC, Martin DT, Abbiss CR. Consistency of commercial devices for measuring elevation gain. *Int J Sports Physiol Perform*. 2014;9(5):884.
52. Menaspà P, Rampinini E, Bosio A, Carlomagno D, Riggio M, Sassi A. Physiological and anthropometric characteristics of junior cyclists of different specialties and performance levels. *Scand J Med Sci Sport*. 2012;22(3):392–398.
53. Menaspà P, Sassi A, Impellizzeri FM. Aerobic fitness variables do not predict the professional career of young cyclists. *Med Sci Sports Exerc*. 2010;42(4):805–812.
54. Menaspà P, Sias M, Bates G, La Torre A. Demands of world cup competitions in elite women's road cycling. *Int J Sports Physiol Perform*. 2017;12(10):1293–1296.
55. Mosso A. La Fatica. Firenze: *Giunti*, 2001
56. Mostaert M, Vansteenkiste P, Pion J, Deconinck FJA, Lenoir M. The importance of performance in youth competitions as an indicator of future success in cycling. *Eur J Sport Sci*. 2021;22(4):481–490.
57. Mujika I, Padilla S. Physiological and performance characteristics of male professional road cyclists. *Sports Med*. 2001;31(7):479-87.
58. Mujika, I., Padilla, S. Physiological and Performance Characteristics of Male Professional Road Cyclists. *Sports Med* 31, 479–487 (2001).

59. Muriel X, Mateo-March M, Valenzuela PL, Zabala M, Lucia A, Pallares JG, Barranco-Gil D. Durability and repeatability of professional cyclists during a Grand Tour. *Eur J Sport Sci*. 2022 Dec;22(12):1797-1804.
60. Noordhof DA, Øfsteng SJ, Nirenberg L, Hammarström D, Hansen J, Rønnestad BR, Sandbakk Ø. Performance-Determining Variables in Long-Distance Events: Should They Be Determined From a Rested State or After Prolonged Submaximal Exercise? *Int J Sports Physiol Perform*. 2021 May 1;16(5):647-654.
61. Øfsteng S, Sandbakk Ø, van Beekvelt M, Hammarström D, Kristoffersen R, Hansen J, Paulsen G, Rønnestad BR. Strength training improves double-poling performance after prolonged submaximal exercise in cross-country skiers. *Scand J Med Sci Sports*. 2018 Mar;28(3):893-904.
62. O'Toole ML, Douglas PS, Hiller WD. Lactate, oxygen uptake, and cycling performance in triathletes. *Int J Sports Med*. 1989 Dec;10(6):413-8.
63. Ouvrard T, Groslambert A, Ravier G, Grosprêtre S, Gimenez P, Grappe F. Mechanisms of performance improvements due to a leading teammate during uphill cycling. *Int J Sports Physiol Perform*. 2018;13(9):1215–1222.
64. Padilla S, Mujika I, Cuesta G, Goiriena JJ. Level ground and uphill cycling ability in professional road cycling. *Med Sci Sports Exerc. 1999*;31(6):878–885.
65. Passfield L, Doust JH. Changes in cycling efficiency and performance after endurance exercise. *Med Sci Sports Exerc*. 2000 Nov;32(11):1935-41.
66. Peiffer JJ, Abbiss CR, Haakonssen EC, Menaspà P. Sprinting for the Win: Distribution of Power Output in Women's Professional Cycling. *Int J Sports Physiol Perform*. 2018 Oct 1;13(9):1237-1242.

67. Péronnet F, Thibault G, Rhodes EC, McKenzie DC. Correlation between ventilatory threshold and endurance capability in marathon runners. *Med Sci Sports Exerc*. 1987 Dec;19(6):610-5..

68. Pinot J, Grappe F. A six-year monitoring case study of a top-10 cycling Grand Tour finisher. *J Sports Sci* 2015; 33: 907-914.

69. Pinot J, Grappe F. The record power profile to assess performance in elite cyclists. *Int J Sports Med*. 2011 Nov;32(11):839-44.

70. Poole DC, Burnley M, Vanhatalo A, Rossiter HB, Jones AM. Critical Power: An Important Fatigue Threshold in Exercise Physiology. *Med Sci Sports Exerc*. 2016 Nov;48(11):2320-2334.

71. Quod MJ, Martin DT, Martin JC, Laursen PB. The power profile predicts road cycling MMP. *Int J Sports Med*. 2010 Jun;31(6):397-401.

72. Rodríguez-Marroyo JA, Pernía R, Cejuela R, García-López J, Llopis J, Villa JG. Exercise intensity and load during different races in youth and junior cyclists. *J Strength Cond Res*. 2011;25(2):511–519.

73. Rønnestad BR, Hansen J, Stensløkken L, Joyner MJ, Lundby C. Case Studies in Physiology: Temporal changes in determinants of aerobic performance in individual going from alpine skier to world junior champion time trial cyclist. *J Appl Physiol* (1985). 2019 Aug 1;127(2):306-311.

74. Rønnestad BR, Lid OM, Hansen J, Hamarsland H, Mølmen KS, Nygaard H, Ellefsen S, Hammarström D, Lundby C. Heat suit training increases hemoglobin mass in elite cross-country skiers. *Scand J Med Sci Sports*. 2022 Jul;32(7):1089-1098. doi: 10.1111/sms.14156.

75. Rønnestad BR, Mujika I. Optimizing strength training for running and cycling endurance performance: A review. *Scand J Med Sci Sports*. 2014 Aug;24(4):603-12. doi: 10.1111/sms.12104.

76. Sallet P, Mathieu R, Fenech G, Baverel G. Physiological differences of elite and professional road cyclists related to competition level and rider specialization. *J Sports Med Phys Fitness*. 2006;46(3):361.

77. Sanders D, van Erp T. The Physical Demands and Power Profile of Professional Men's Cycling Races: An Updated Review. *Int J Sports Physiol Perform*. 2021 Jan 1;16(1):3-12.

78. Sanders D, Heijboer M, Hesselink MKC, Myers T, Akubat I. Analysing a cycling grand tour: can we monitor fatigue with intensity or load ratios? *J Sports Sci.* 2018;36(12):1385–1391.

79. Sanders D, Heijboer M. Physical demands and power profile of different stage types within a cycling grand tour. *Eur J Sport Sci*. 2019;19(6):736–744.

80. Schumacher YO, Mroz R, Mueller P, Schmid A, Ruecker G. Success in elite cycling: A prospective and retrospective analysis of race results. *J Sports Sci*. 2006 Nov;24(11):1149-56.

81. Shoenfeld Y, Shapiro Y, Hanne N, Drory Y, Kellermann JJ. Aerobic work capacity in sedentary men and active athletes in Israel. *Isr J Med Sci.* 1977 Mar;13(3):240-4.

82. Smyth B, Maunder E, Meyler S, Hunter B, Muniz-Pumares D. Decoupling of Internal and External Workload During a Marathon: An Analysis of Durability in 82,303 Recreational Runners. *Sports Med*. 2022 Sep;52(9):2283-2295.

83. Spragg J, Leo P, Swart J. The Relationship between Physiological Characteristics and Durability in Male Professional Cyclists. *Med Sci Sports Exerc*. 2023 Jan 1;55(1):133-140.

84. Stevenson JD, Kilding AE, Plews DJ, Maunder E. Prolonged cycling reduces power output at the moderate-to-heavy intensity transition. *Eur J Appl Physiol*. 2022 Dec;122(12):2673-2682.

85. Svendsen IS, Tønnesen E, Tjelta LI, Ørn S. Training, performance, and physiological predictors of a successful elite senior career in junior competitive road cyclists. *Int J Sports Physiol Perform*. 2018;13(10):1287–1292.

86. Valenzuela PL, Alejo LB, Ozcoidi LM, Lucia A, Santalla A, Barranco-Gil D. Durability in Professional Cyclists: A Field Study. *Int J Sports Physiol Perform*. 2022 Dec 15;18(1):99-103.

87. Valenzuela PL, Morales JS, Foster C, Lucia A, De La Villa P. Is the functional threshold power a valid surrogate of the lactate threshold? *Int J Sports Physiol Perform*. 2018;13:1293-1298.

88. Van Erp T, Sanders D, De Koning JJ. Training characteristics of male and female professional road cyclists: A 4-year retrospective analysis. *Int J Sports Physiol*. 2019 Nov 5;15(4):534-540.

89. Van Erp T, Sanders D, Lamberts RP. Maintaining Power Output with Accumulating Levels of Work Done Is a Key Determinant for Success in Professional Cycling. *Med Sci Sports Exerc*. 2021 Sep 1;53(9):1903-1910.

90. Van Erp T, Sanders D. Demands of professional cycling races: influence of race category and result. *Eur J Sport Sci*. 2020;21(5):666–677.

91. Vikmoen O, Rønnestad BR. A Comparison of the Effect of Strength Training on Cycling Performance between Men and Women. *J Funct Morphol Kinesiol*. 2021 Mar 17;6(1):29.

92. Vikmoen O, Rønnestad BR, Ellefsen S, Raastad T. Heavy strength training improves running and cycling performance following prolonged submaximal work in well-trained female athletes. *Physiol Rep*. 2017;5(5):e13149.

93. Wassertheil S, Cohen J. Reviewed work: Statistical power analysis for the behavioral sciences by Jacob Cohen. *Biometrics*. 1970;26(3):588.

SECTION FOUR

ATTESTATION OF AUTHORSHIP

I hereby declare that the work contained in this thesis has not been previously submitted either in whole or in part to qualify for any other academic award. I also certify that the thesis is my own work carried out during my candidature and that any assistance that I have received in my research work and in the preparation of this thesis has been acknowledged.

Gabriele Gallo

February 2024

ACKNOWLEDGEMENTS

Thanks to my tutor Professor Emanuela Luisa Faelli and to Professor Piero Ruggeri for giving me the opportunity to start this journey, and for trusting and supporting me in all the projects undertaken in these three years.

Thanks to Luca Filipas for the advice and time spent together working on all the projects.

Thanks to my AUT supervisor Ed Maunder for the advice and time spent working together on the projects during my year in New Zealand. Thanks also to all the people I met during my year spent in New Zealand, for the professionality and passion they put in sport science.

Thanks to all coauthors who gave an important contribution to complete the projects: Professor Roberto Codella, Manuel Mateo-March, Bent Ronnestad, Daniel Gotti, Andrea Fuk and many others.

Thanks to my family. Alessandra and all my friends.

LIST OF REFEREED JOURNAL PUBLICATIONS

Publication arising from thesis

- **Gallo G,** Leo P, Mateo-March M, Giorgi A, Faelli E, Ruggeri P, Mujika I, Filipas L. Cross-Sectional Differences in Race Demands Between Junior, Under 23, and Professional Road Cyclists. *Int J Sports Physiol Perform*. 2022 Mar 1;17(3):450-457.
- **Gallo G,** Mateo-March M, Leo P, Campos-Donaire A, Gandia-Soriano A, Giorgi A, Faelli E, Ruggeri P, Codella R, Mujika I, Filipas L. Power Road-Derived Physical Performance Parameters in Junior, Under-23, and Professional Road Cycling Climbers. *Int J Sports Physiol Perform*. 2022 Apr 28;17(7):1094-1102.
- **Gallo G**, Leo P, Mateo-March M, Giorgi A, Faelli E, Ruggeri P, Mujika I, Filipas L. Differences in Training Characteristics Between Junior, Under 23 and Professional Cyclists. Int J Sports Med. 2022 Dec;43(14):1183-1189.
- **Gallo G.** Mateo-March M, Fuk A, Faelli E, Codella R, Ruggeri P, Filipas L.

  The Day-by-Day Periodization Strategies of a Giro d'Italia Podium Finisher. Accepted on *Int J Sports Physiol Perform*.
- **Gallo G,** Rønnestad B, Sandbakk Ø, Skovereng K, Maunder E, Gotti D, Tallaksen L, Faelli E, Ruggeri P, Meloni A, Codella R, Filipas L. Performing high-intensity training following prolonged exercise impacts durability-related adaptations. Under review on *Med. Sci. Sports Exerc*.

Extra publications during candidature

- **Gallo G**, Bosio A, Martin M, Morelli A, Azzolini M, Guercilena L, Larrazabal J, Rampinini E. Relationships between training dose and record power outputs in professional road cyclists: insights and threats to validity. *Biol Sport*. 2023 Apr;40(2):485-495.
- **Gallo G,** Mostaert M, Faelli E, Ruggeri P, Delbarba S, Codella R, Vansteenkiste P, Filipas L. Do Race Results in Youth Competitions Predict Future Success as a Road Cyclist? A Retrospective Study in the Italian Cycling Federation. *Int J Sports Physiol Perform*. 2022 Apr 1;17(4):621-626.
- **Gallo G,** Geda E, Codella R, Faelli E, Panascì M, Ranieri LE, Pollastri L, Brighenti S, Molino L, Riba U, Luzi L, Ruggeri P, Filipas L. Effects of Bilateral Dorsolateral Prefrontal Cortex High-Definition Transcranial Direct-Current Stimulation on Physiological and Performance Responses at Severe-Intensity Exercise Domain in Elite Road Cyclists. *Int J Sports Physiol Perform*. 2022 Apr 21;17(7):1085-1093.
- **Gallo G,** Mateo-March M, Gotti D, Faelli E, Ruggeri P, Codella R, Filipas L. How do world class top 5 Giro d'Italia finishers train? A qualitative multiple case study. *Scand J Med Sci Sports*. 2022 Dec;32(12):1738-1746.
- **Gallo G,** Mateo-March M, Gotti D, Maunder E, Codella R, Ruggeri P, Faelli E, Filipas L. The Weekly Periodization of Top 5 Tour de France General Classification Finishers: A Multiple Case Study. *Int J Sports Physiol Perform*. 2023 Sep 14;18(11):1313-1320.
- **Gallo G**, Faelli E, Ruggeri P, Filipas L, Codella R, Plews D, Maunder E. Power output at the moderate-to-heavy intensity transition decreases in a non-linear fashion during prolonged exercise. Under review on *Eur J Appl Physiol*.