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Journal of Science & Cycling
Breakthroughs in Cycling & Triathlon Sciences

Original Article

Performance analysis in high-level virtual cycling: data from the 2023 Zwift® UCI Cycling E-Sports World Championships

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Received: 11 April 2025 **Accepted:** 21 August 2025 **Published:** 9 September 2025

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Abstract

This study aimed to characterize the performance at the 2023 UCI Cycling E-Sports World Championships in 18 women and 27 men competing in this three-race knockout series with a direct elimination finale. We evaluated their power profile, critical power (women: 249 ± 29 W; men: 362 ± 26 W) and W′ (women: 14.4 ± 1.5 kJ; men: 23.5 ± 4.2 kJ) over the 12 months preceding the competition and during the event. Energy depletion during races was analyzed using Bartram's W′ balance models. Women and men advancing to the next race developed respectively ~15% and ~16% more power (W/Kg) compared to those eliminated in Race 1, for durations of ≤1 min ($p < 0.001$). In women, similar W′ depletion was observed in Race 1 and Race 2 ($p = 0.35$). In men, greater depletion was observed at the end of Race 1 compared to Race 2 (8 ± 8% difference, $p = 0.007$). The direct-elimination format of Race 3, involving repeated sprints, led to lower W′ depletion for both sexes. The results suggest that power developed for efforts up to 60 seconds and the ability to recover across races are pivotal for performance at the 2023 Cycling E-Sports World Championships.

Keywords

Virtual Cycling; W′; Critical Power; W'Balance; Mixed-Reality e-Sports.

1 Introduction

In 1921, the first road cycling world championships were held in Copenhagen. One-hundred years later, the first virtual cycling world championships took place, representing a new milestone in the cycling history. In 2023, the third UCI Cycling E-Sport World Champion title was contested on February 18th on the Zwift® platform (Zwift Inc. Long Beach, CA). A total of 87 women and 86 men from 27 countries participated in the competition, which consisted of three races. The first two races were a knockout format: after Race 1 (13.8 km), the top 30 men and the top 30 women cyclists advanced to Race 2 (8.5 km). The top 10 cyclists for each sex category competed for victory in the third race (12.5 km). One absolute novelty in this edition was the introduction of an elimination format for the final: one cyclist was eliminated each ~1.5 km. After the 7th elimination, the last 3 cyclists competed for victory. The three races were separated by only 15 min of rest.

In virtual cycling, the main factor determining speed is the power output developed relative to body weight, which mostly explains performance in this discipline (Westmattelmann, Stoffers, Sprenger, Grotenhermen, & Schewe, 2022). However, sex-specific data on the performance of high-level competitors is lacking (Westmattelmann et al., 2022). One useful methodology could be the analysis of their record power profile, as previously done in road cyclists (Mateo-March et al., 2022; Valenzuela et al., 2022). Furthermore, data derived from the power-duration relationship could also be useful for analyzing individuals' performance (Monod & Scherrer, 1965). In particular, it would be possible to evaluate their critical power (CP), *i.e.* the value of the power-duration curve asymptote, theoretically corresponding to the maximal sustainable metabolic steady state during exercise. The limited amount of work that can be performed above CP is represented by the W′ (expressed in joules; Jones, Burnley, Black, Poole, & Vanhatalo, 2019). The evaluation of CP and W′ offers valuable insights into performance analysis, and the advantage to be computed with power data.

Besides power output capacities, race strategy could play a key role in performance. In high-level competitions such as the UCI Cycling E-Sports World Championships (UCI E-Sports WCS), some platform-specific gameplay features (e.g., virtual "equipment" and "power-ups" available) are standardized. Thus, race strategy would mainly consist of i) the ability to take advantage of the front rider(s) slipstream, ii) to accelerate at the most opportune moment, starting a breakaway or for the final sprint and, importantly, iii) to successfully manage energy depletion and W′ reserve throughout the race(s). Following these considerations, and taking into account the stochastic nature of cycling races (Millour, Lajoie, & Domingue, 2022), race strategy and energy depletion could be visualized using the W′ balance models (Bartram, Thewlis, Martin, & Norton, 2022; Skiba, Chidnok, Vanhatalo, & Jones, 2012; Skiba, Fulford, Clarke, Vanhatalo, & Jones, 2015). W′ balance models assume that W′ progressively decreases when exercising at power outputs higher than CP and recovers following a mono-exponential kinetics when pedaling below CP. The predicted recovery rate varies across models, and it is based on a constant of recovery (τ, for a review see Skiba & Clarke, 2021). However, these models present some limitations: for example, they are less accurate for long durations of exercise due to the possible effect of accumulated fatigue (Millour et al., 2022). Nevertheless, W′ balance models could be useful in studying how cyclists manage their efforts during short races (Millour et al., 2022), such as the 2023 UCI E-Sports Zwift® WCS.

In this study, we evaluated the power profile (before and during the competition), and computed performance analysis data based on power output (Bartram W' balance model; Bartram, Thewlis, Martin, & Norton, 2018; Bartram et al., 2022) to better understand the characteristics and race strategies of cyclists competing in the 2023 Zwift® UCI E-Sports WCS, comparing cyclists who advanced in the different races vs. those who were eliminated. Due to the short format of the competitions (<18 simulated km culminating in a final sprint), we hypothesized that, for both women and men, successful E-sport cyclists advancing through the races of the World Championships would be able to present greater maximal power output for short durations (≤60 seconds) than the eliminated ones. Assuming that maximal effort is necessary to advance to the next race, we also expected W′ balance model to display values close to zero at the end of the first but not the second and third races, because incomplete recovery would prevent athletes from performing similarly to a fresh state.

2 Material and Methods

2.1 Participants

Before the competition, all cyclists taking part in the 2023 UCI E-Sports WCS on Zwift® were invited to participate in the present study. A total of 18 women (1.69 ± 0.09 m, 58 ± 7 kg, 34 ± 10 year) and 27 men (1.78 ± 0.05 m, 67 ± 5 kg, 31 ± 5 years old) agreed to participate. All the participants were informed of the aims, methods, and data treatment procedures relative to the study, and written informed consent was obtained. The study was approved by the Nantes University Ethics Committee (CERNI n°14012023) and met the requirements of the Declaration of Helsinki (2013) for research on humans (except registration on a publicly available database).

2.2 Design

Riders competed remotely, using their own bike (with standard handlebar) and heart rate chest strap (HR) which was mandatory. The same smart-trainer (Kickr V6, Wahoo Fitness, Atlanta, USA) was provided by Zwift® to all cyclists. A strict protocol was put in place before, during and after the championship in order to avoid any forms of cheating and to improve the reliability of the power output measurement (Richardson, Smith, & Berger, 2022; Thorne, 2022). In detail, a few weeks before the event, cyclists were required to complete the ZADA Power Test on the Zwift® platform using both the provided smart trainer (Wahoo Kickr V6) and their personal power meter. This standardized protocol, which included several maximal efforts (2 min, 4 min, 12 min, and two 15 s sprints), was designed to assess the athlete's performance profile and verify consistency between the two power measurement devices. Both devices were then mandatorily used during the official competition to ensure data integrity and fairness. Body mass and height of cyclists were also measured and verified by video 1 hour before the start of the race by all competitors. Power data and heart rate data were sent to Zwift® for verification after the races. Finally, the UCI and Zwift®, in collaboration with the International Testing Agency, implemented a structured Anti-Doping program: cyclists had to provide a timetable where they could be tested 7 days before and 7 days after the competition. The altimetric profile of the competition is presented in Supplemental Material S1.

2.3 Methodology

A survey was administered using the LimeSurvey platform to collect quantitative and qualitative data capturing the individual characteristics. We investigated nationality, cycling discipline(s) practiced, current training volume, years of road/track/mountain-bike and virtual cycling experience, number of races completed in 2022, preferred race characteristics, and perceived physical fitness during the World Championships. Additionally, answers to questions relative to perceived motivation, and advantages and limitations of indoor virtual cycling compared to outdoor cycling were also collected. To analyze the record power profile of athletes, we retrieved the power data of all races performed on the Zwift® platform by the participants over the 12 months preceding the competition. The best performances in terms of mean relative (i.e., in W per kg of body mass) and absolute power (in W) for periods of 15 s, 30 s, 1 min, 5 min and 20 min were then extracted. The associated absolute maximal heart rate was also retrieved from the same race. The records of 1 min, 5 min and 20 min were used to calculate CP and W′ based on the two-parameter work-time linear model (Equation 1; (Muniz-Pumares, Karsten, Triska, & Glaister, 2019)):

$$W = W' + (CP \times t)$$

Equation (1)

Where *W* represents the work performed for a given exercise duration. W′ is the work capacity above CP, calculated as the area under the curve above CP. CP is the Critical Power estimated as the y-intercept of the linear relationship extrapolated from the data when the time to exhaustion (t) approaches infinity and *t* is the time to exhaustion at a specific power output.

During the 3-races competition, power output and HR data were recorded over all the races. Additionally, rate of perceived exertion (CR-10 scale; Borg, 1982) was recorded by participants after each race. In addition to the record power profile (i.e., calculated from data over the last 12 months), we also calculated the best power outputs developed during the competition. Data were computed in terms of relative and absolute power for periods of 15 s, 30 s, 1 min and 5 min. Then, based on the parameters estimated in Equation 1 (CP and W′), the Bartram's model (Bartram et al., 2022) was used to estimate the depletion and reconstitution of W' during the races from successive 1-s segments of W' depletion (power output > CP; Equation 2) and reconstitution (power output < CP, Equation 3):

$$W'_{bal} = W'_{start} - [(PO - CP) \times u]$$

Equation (2)

$$W'_{bal} = W' - (W' - W'_{start}) \times e^{-(u)/\tau}$$

Equation (3)

Where W'_{start} is the W'_{bal} at the start of the segment (equal to W'_{bal} at the end of the previous segment), *PO* is the power output (in Watts) and *u* is the duration of the segment.

The constant τ was calculated as follows:

$$\tau = 2287.2 \times (CP - PO)^{-0.688}$$

Equation (4)

Where CP-PO corresponds to the instantaneous difference between the CP of the cyclist and the power output during each recovery segment.

The final sum of the W′ balance after iterating through all the segments or iterations provides the net W′ balance or the total change in anaerobic work capacity (W′) over each second.

The Bartram model was selected over the original integral or differential W′ balance models (Skiba et al., 2012, 2015) because it incorporates an adapted recovery time constant (τ) specifically calibrated for elite cyclists, who recover faster than what could be predicted by the previous models. This adaptation has been shown to improve the ecological validity of W′ balance estimates in short, high-intensity race formats comparable to the UCI E-Sports WCS, thereby providing a more accurate representation of W′ balance dynamics in our study population.

2.4 Statistical Analysis

All results are expressed as mean ± SD in text, tables, and figures. All analyses reported in the present section were computed separately for women and men. The normal distribution of all variables was tested using Shapiro-Wilk tests. CP and W′ were extracted using linear models for each participant, and the model fit was evaluated. Correlation analyses (Pearson's r) were run between overall ranking at the competition and power record profile (in W/kg), CP and W′. To compare advancing and eliminated cyclists for each race, independent samples t-tests were used on anthropometrical, physiological, and race data. Of note, because age data were available for all competitors and not only for our sample, we run an additional t-test for age in all advancing *vs.* eliminated cyclists. For record power profile and the power output data from the competition, repeated measures ANOVAs were conducted for each race, with effort duration (15s, 30s, etc.) as within-subject factor and group (advancing vs. eliminated) as between-subjects factor. For the W′ balance models, to detect differences in terms of minimal W′ reached between races, we computed i) paired-samples t-tests between Race 1 and Race 2 in cyclists that competed in Race 2 and ii) repeated-measures ANOVA (Race 1, 2 and 3 as within-subject factor) in cyclists that competed in Race 3. For all ANOVAs, Q-Q plots of residuals and sphericity were checked. Post-hoc tests were carried out in case of significant main effect or interaction using the Tukey correction. Effect sizes (d and η2p) were calculated when significant differences were found (Cohen, 1988). The magnitude of the differences was interpreted as trivial (d < 0.2), small (d < 0.5), moderate (d < 0.8), and large (d ≥ 0.8). For η2p, the difference was interpreted as small (η2p > 0.01), medium (η2p > 0.06), and large (η2p > 0.14) effects. The threshold for α was set at 0.05. Analysis was performed in the R environment (Rstudio V2023.06.0+421 and Jamovi V2.2.5).

3 Results

The complete report on quantitative and qualitative data is consultable at https://osf.io/9rbg6/?view_only=0b4a484340d841ae98446267b52f5d91.

3.1 Participants Characteristics

Cycling experience was 9 ± 7 years for women and 13 ± 6 years for men. All participants except 3 women reported competing in outdoor cycling. Seven women and seven men from the study sample were current professional or ex-professional cyclists (including one male professional triathlete). Most of athletes trained primarily outdoor, with 67% of women and 56% of men spending more than 10 h/week training outside, while the percentage of cyclists training more than 10h/week indoor was 22% for the women and 26% for the men. Years of experience in virtual racing ranged from 1 to 4 years for women and 2 to 4 years for men. Only 28% of women declared virtual racing as their favorite virtual cycling activity compared to training and free riding, while for men the percentage favoring races as their preferred virtual cycling activity was 85%. The number of Zwift® races performed during the twelve months preceding the World Championships was 72 ± 29 races for women and 140 ± 66 races for men. In comparison, 28% of women and 37% of men reported competing in more than 20 outdoor races per year, while the percentage of cyclists competing in more than 50 indoor virtual races was 33% (women) and 63% (men). Preferred virtual race distance was different between women and men, with the latter presenting higher participation in races longer than 30 km (44% vs. 78%). Interestingly, in our sample, no women participated in Zwift® races longer than 60 km.

A complete report on the computation of CP and W′ with the individual data and the goodness of fit for CP models for each participant and the list of smart-trainer, powermeter and HR monitor brands used by athletes habitually during the 12 months preceding the race is accessible at https://osf.io/9rbg6/?view_only=0b4a484340d841ae98446267b52f5d91. The record power output profile over the 12 months preceding the race for women and men is reported in Table 1. For both women and men, the overall ranking position was correlated with power records for durations of 15 s, 30 s, 1 min, 5 min (in W/kg), and W′ (in kJ/kg; all $p < 0.05$) but not with durations of 20 min, nor with CP. For men, the overall ranking position was also correlated with age, with younger cyclists occupying the top places of the ranking ($r = 0.587$, $p = 0.001$).

Table 1. Absolute (W or kJ) and relative (W/kg or kJ/kg) power output record profile of different effort durations ranked by percentiles (p) for women and men.

Women (N = 18)										
	p10		**p25**		**p50**		**p75**		**p90**	
	W	*W/kg*	*W*	*W/kg*	*W*	*W/kg*	*W*	*W/kg*	*W*	*W/kg*
15 s	524	9.3	589	10.9	674	12.2	741	12.9	811	13.2
30 s	470	8.1	513	9.4	576	10.1	603	10.4	659	10.9
1 min	407	6.9	421	7.7	455	8.0	493	8.5	502	8.7
5 min	267	4.9	284	5.1	308	5.3	331	5.6	339	5.8
20 min	227	4.2	245	4.4	259	4.6	278	4.7	285	4.8
CP	218	4.0	235	4.2	245	4.4	265	4.6	273	4.6
	kJ	*kJ/kg*	*kJ*	*kJ/kg*	*kJ*	*kJ/kg*	*kJ*	*kJ/kg*	*kJ*	*kJ/kg*
W′	9.9	0.2	11.8	0.2	14.9	0.3	17.3	0.3	18.7	0.3
Men (N = 27)										
	p10		**p25**		**p50**		**p75**		**p90**	
	W	*W/kg*	*W*	*W/kg*	*W*	*W/kg*	*W*	*W/kg*	*W*	*W/kg*
15 s	868	13.5	905	13.9	1003	14.7	1099	15.9	1174	17.4
30 s	741	11.4	792	11.8	851	12.8	938	13.5	988	14.2
1 min	600	9.4	635	9.6	677	10.3	738	10.7	768	11.0
5 min	405	6.4	436	6.6	464	6.8	491	7.0	501	7.2
20 min	338	5.4	374	5.5	382	5.6	396	5.9	415	6.0
CP	323	5.1	356	5.2	362	5.3	373	5.6	395	5.8
	kJ	*kJ/kg*	*kJ*	*kJ/kg*	*kJ*	*kJ/kg*	*kJ*	*kJ/kg*	*kJ*	*kJ/kg*
W′	18.5	0.3	21	0.3	23	0.4	25.9	0.4	28.7	0.4

CP: Critical Power, W′: work that can be performed above the critical power

3.2 World-Championship Performance Analysis

The first woman completed the 13.8 km of Race 1 in 18 min 05 s, while the first man finished in 16 min 48 s. In Race 2 (8.5 km), time to cross the finish line was 12 min 23 s for the first woman and 11 min 32 s for the first men. Finally, in Race 3, the winner for the women finished in 18 min 04 s, whereas the winner for the men finished in 16 min 11 s.

3.3 Characteristics of Advancing vs. Eliminated Cyclists

From our sample of 18 female participants, 10 advanced to Race 2 and 5 advanced to Race 3. Among the 27 male participants, 13 advanced to Race 2 and 6 advanced to Race 3. Differences between advancing and eliminated cyclists in anthropometrical, physiological and race data are presented in Table 2. Analyzing all competitors in the race we found that in men age did not differ between eliminated (33 ± 6 y) and advancing (31 ± 5 y) cyclists in race 1 ($p = 0.10$, $d = 0.40$, 95%CI [−0.05, 0.86]), while in race 2 the difference (32 ± 5 y vs 29 ± 3 y) was at the α-threshold, but with a large effect size ($p = 0.05$, $d = 1.01$, 95%CI [0.18, 1.85]). In women, no differences were observed in race 1 (34 ± 9 y vs 36 ± 8 y; $p = 0.37$, $d = 0.21$, 95%CI [−0.24, 0.66]) or race 2 (37 ± 8 y vs 35 ± 8 y; $p = 0.45$, $d = 0.30$, 95%CI [−0.49, 1.10]). Differences between advancing and eliminated cyclists in power output record profile over the 12 months before the competition are reported in Supplemental Materials S1.

The power profiles for data extracted from the UCI E-Sports WCS are presented in Figure 1. In women, for Race 1 there was no significant group effect or group × effort duration interaction (all $p > 0.05$) in terms of absolute power. When normalizing by body mass, a significant effort duration × group interaction was observed ($\eta 2p = 0.502$, $p < 0.001$). The relative power output of the advancing women was greater than the eliminated ones for efforts of 15 s, 30 s, and 1 min (Figure 1B). In Race 2, a significant group effect was observed in both absolute ($p = 0.026$; $\eta 2p = 0.481$) and relative power ($p < 0.001$; $\eta 2p = 0.756$), indicating an overall better performance for the advanced vs. eliminated cyclists (Figure 1A-B). For men, in Race 1 both absolute and relative power outputs showed significant time × effort duration interaction [$p < 0.001$; $\eta 2p = 0.493$ (W) and $\eta 2p = 0.52$ (W/kg)]. Advancing cyclists displayed greater values than eliminated cyclists for efforts between 15 s and 1 min (Figure 1C-D). However, no significant difference was observed for Race 2 ($p > 0.05$). The perceived physical fitness for the competition (on a scale from 1 to 10) was 8 ± 2 [range: 5-10] for women and 9 ± 2 [range: 5-10] for men. Normalizing average power at the race by the CP, in race 1 average intensity was similar between men (93 ± 6%) and women (96 ± 7%; $p = 0.21$, $d = −0.37$, 95%CI [−0.99, 0.25]). In race 2, women showed higher values (104 ± 7%) than men (89 ± 4%; $p < 0.001$, $d = −2.35$, 95%CI [−3.60, −1.14]). In race 3, no difference was observed (men: 92 ± 9%, women: 94 ± 12%; $p = 0.79$, $d = −0.15$, 95%CI [−1.52, 1.22]).

Table 2. Comparison of participants anthropometrical, physiological and race data between the cyclists advancing to the next race and the eliminated ones.

Women (n=18)			**Advancing**	**Eliminated**	**p-value**	**d (95% CI)**
Anthropometrical data						
	Age (yr)	Race 1	35 ± 8	32 ± 9	0.41	0.40 (-0.56; 1.34)
		Race 2	34 ± 10	36 ± 7	0.75	-0.21 (-1.45; 1.05)
	Body mass (kg)	Race 1	55 ± 6	61 ± 6	0.08	-0.89 (-1.88; 0.14)
		Race 2	57 ± 7	53 ± 5	0.36	0.62 (-0.72; 1.89)
	Height (cm)	Race 1	168 ± 6	169 ± 11	0.87	0.08 (-1.01; 0.85)
		Race 2	170 ± 7	166 ± 6	0.39	0.65 (-0.70; 1.92)
Physiological data						
	CP (W)	Race 1	242 ± 17	259 ± 38	0.23	-0.59 (-1.54; 0.39)
		Race 2	243 ± 20	241 ± 16	0.89	0.09 (-1.16; 1.32)
	CP (W/kg)	Race 1	4.41 ± 0.27	4.25 ± 0.26	0.24	0.58 (-0.40; 1.53)
		Race 2	4.28 ± 0.31	4.54 ± 0.16	0.14	-1.04 (-2.41; 0.43)
	W′ (kJ)	Race 1	15.35 ± 3.82	13.32 ± 3.11	0.24	0.58 (-0.40; 1.53)
		Race 2	17.66 ± 1.58	13.03 ± 4.11	**0.047**	**1.49 (-0.15; 3.02)***
	W′ (kJ/kg)	Race 1	0.28 ± 0.06	0.22 ± 0.06	0.06	0.95 (-0.10; 1.96)
		Race 2	0.31 ± 0.03	0.24 ± 0.06	**0.041**	**1.54 (-0.12; 3.10)***
Race data						
	Mean power (W)	Race 1	226 ± 18	253 ± 27	**0.023**	**-1.19 (-2.24; -0.09)**
		Race 2	264 ± 26	235 ± 18	0.08	1.26 (-0.29; 2.71)
	Mean power (W/kg)	Race 1	4.1 ± 0.21	4.17 ± 0.23	0.53	-0.30 (-1.24; 0.65)
		Race 2	4.63 ± 0.27	4.42 ± 0.08	0.12	1.09 (-0.40; 2.48)
	Cadence (rpm)	Race 1	87 ± 5	92 ± 5	0.06	-0.99 (-2.04; 0.10)
		Race 2	83 ± 8	84 ± 9	0.86	-0.12 (-1.35; 1.13)
	HR (bpm)	Race 1	165 ± 7	180 ± 9	**0.001**	**-1.85 (-3.07; -0.57)**
		Race 2	166 ± 19	172 ± 8	0.51	-0.44 (-1.69; 0.86)
	HR (%max)	Race 1	85 ± 3	90 ± 2	**<0.001**	**-2.15 (-3.50; -0.77)**
		Race 2	85 ± 8	89 ± 1	0.31	-0.69 (-1.97; 0.67)
Men (n=27)			**Advancing**	**Eliminated**	**p-value**	**d (95% CI)**
Anthropometrical data						
	Age (yr)	Race 1	29 ± 5	34 ± 4	**0.009**	**-1.09 (-1.95; -0.22)**
		Race 2	25 ± 4	32 ± 4	**0.01**	**-1.74 (-3.20;-0.19)**
	Body mass (kg)	Race 1	68 ± 5	67 ± 5	0.73	0.13 (-0.63; 0.89)
		Race 2	67 ± 5	68 ± 6	0.73	-0.19 (-1.29; 0.91)
	Height (cm)	Race 1	178 ± 6	179 ± 5	0.811	-0.09 (-0.85; 0.66)
		Race 2	179 ± 4	177 ± 7	0.61	0.29 (-0.83; 1.38)
Physiological data						
	CP (W)	Race 1	364 ± 26	360 ± 26	0.65	0.18 (-0.58; 0.93)
		Race 2	364 ± 30	364 ± 25	0.99	0.01 (-1.10; 1.11)
	CP (W/kg)	Race 1	5.38 ± 0.26	5.37 ± 0.30	0.92	0.04 (-0.71; 0.80)
		Race 2	5.42 ± 0.22	5.35 ± 0.30	0.67	0.25 (-0.87; 1.34)
	W′ (J)	Race 1	25.79 ± 3.70	21.42 ± 3.62	**0.005**	**1.19 (0.30; 2.06)**
		Race 2	25.54 ± 3.05	26.01 ± 4.42	0.83	-0.12 (-1.21; 0.98)
	W′ (kJ/kg)	Race 1	0.38 ± 0.03	0.32 ± 0.04	**<0.001**	**1.53 (0.54; 2.47)**
		Race 2	0.38 ± 0.03	0.38 ± 0.04	0.98	0.01 (-1.08; 1.10)

Race data						
	Mean power (W)	Race 1	328 ± 23	344 ± 27	0.12	-0.63 (-1.41; 0.18)
		Race 2	319 ± 17	328 ± 29	0.46	-0.43 (-1.53; 0.71)
	Mean power (W/kg)	Race 1	4.88 ± 0.63	5.16 ± 0.62	0.25	-0.45 (-1.22; 0.33)
		Race 2	4.75 ± 0.24	4.81 ± 0.21	0.61	-0.30 (-1.39; 0.82)
	Cadence (rpm)	Race 1	86 ± 6	85 ± 8	0.73	0.13 (0.63; 0.89)
		Race 2	82 ± 6	80 ± 6	0.56	0.33 (-0.79; 1.42)
	HR (bpm)	Race 1	166 ± 9	166 ± 8	0.82	-0.09 (-0.84; 0.67)
		Race 2	166 ± 9	167 ± 5	0.69	-0.23 (-1.32; 0.88)
	HR (%max)	Race 1	85 ± 3	85 ± 3	0.53	-0.25 (-1.00; 0.52)
		Race 2	84 ± 2	86 ± 1	0.053	-1.21 (-2.48; 0.14)

Race 1: 10 women and 13 men from the study sample advanced to race 2; Race 2: 5 women and 6 men advanced to race 3. Physiological data refer to data collected over the 12 months preceding the race. CP: Critical Power; HR: Heart rate. *=lower bound confidence interval driven by an outlier with high W′ values in the eliminated group (19.68 kJ; 0.33 kJ/kg).

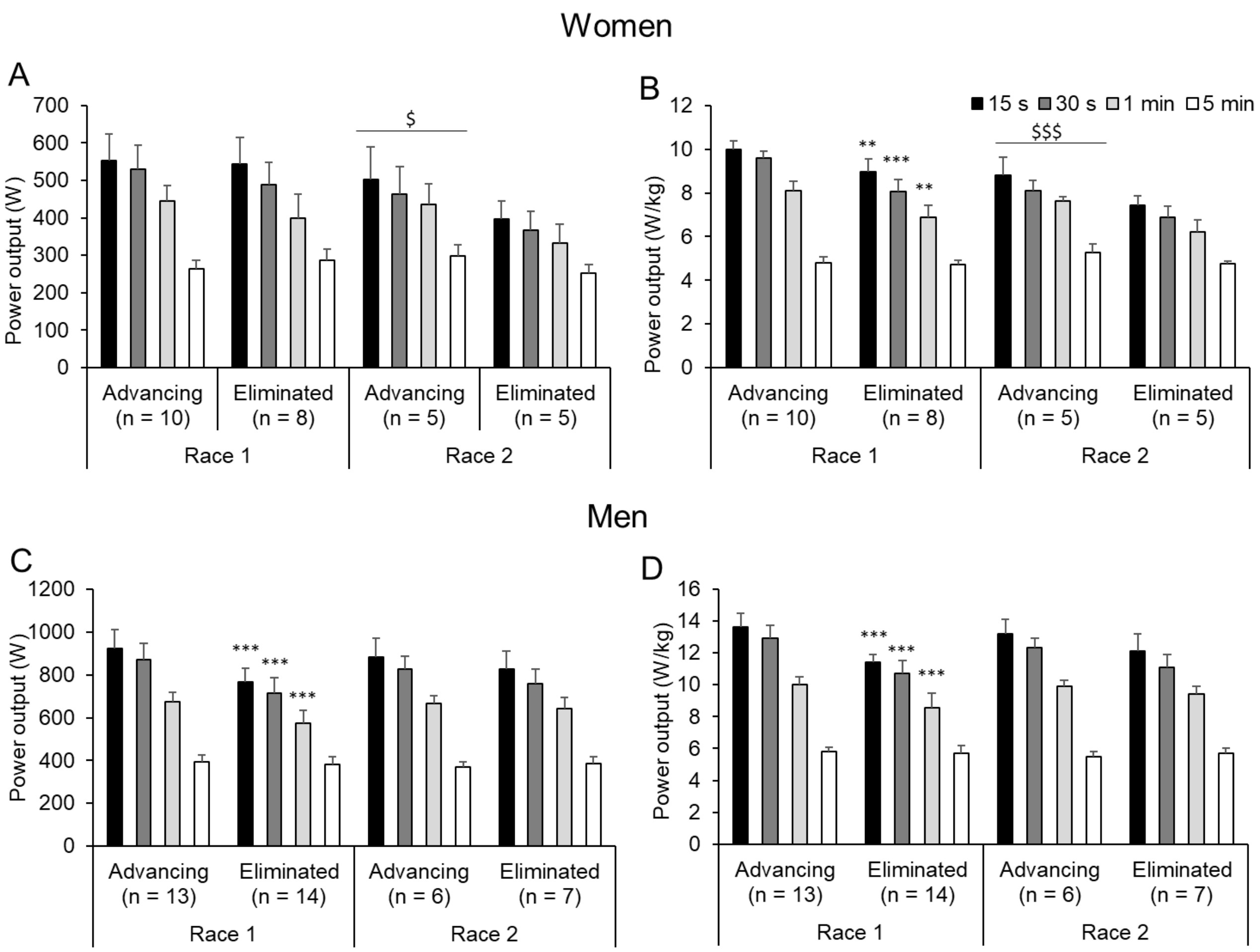

Figure 1. Comparison of mean maximal power outputs during the first and second races for women (Absolute: A, relative: B) and men (Absolute: C, relative: D) cyclists who advanced or were eliminated. *= significant difference from qualified cyclists. **: p < 0.01, ***: p < 0.001. $= significant main group effect (advancing vs. eliminated). $= p < 0.05, $$$= p < 0.001.

3.4 Differences Across Races

Figure 2 shows the W' balance for women and men during the three races, while Figure 3 represents the comparison between minimal W′ balance values reached during the three competitions in women and men. Race strategies for Race 1 and Race 2 showed a large energy expenditure in the final sprint where minimal W′ balance value was reached. Race 3 showed a different profile with repeated cycles of energy depletion and recovery for the advancing athletes due to its elimination format. In Race 1 (men) and 2 (women) some cyclists tried to start a breakaway, identified as a deflection in the energy curve toward the lower part of the graphic (Figure 2). These breakaways were not successful, and results were determined in the final sprint. For Race 3 in men, the winner adopted a different race strategy than the other cyclists from the start by executing an early solo breakaway and then maintaining a more even power output and a progressive decrease in W′ balance until the end of the race (dark line in Figure 2F).

Comparing Race 1 and 2 in women, no significant difference was found for minimal W′ balance [$p = 0.82$, $d = -0.08$ (-0.69; 0.55); Figure 3A]. In men, greater W′ depletion was found in Race 1 compared to Race 2 [$p = 0.007$, $d = 0.90$ (0.24; 1.54); Figure 3B]. When comparing Race 1, 2 and 3, a significant race main effect was found in both women ($p < 0.001$; $\eta 2p = 0.944$) and men ($p < 0.001$; $\eta 2p = 0.939$). In women, every race differed significantly from the other (Figure 3A). In men, similar minimal W′ values were found for Race 1 and 2, with Race 3 showing significantly lower W′ depletion than both Race 1 and 2 (Figure 3B).

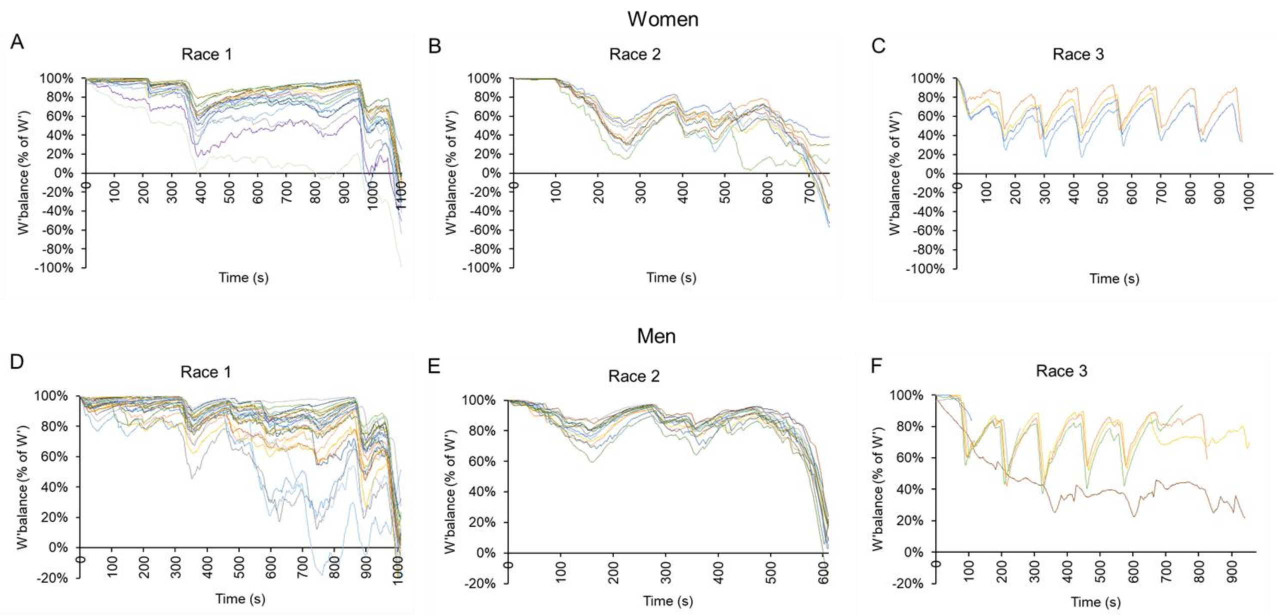

Figure 2. Analysis of the three races using the W' balance model of Bartram for women and men. Panel F: Race winner is the continuously declining W′ Balance trace.

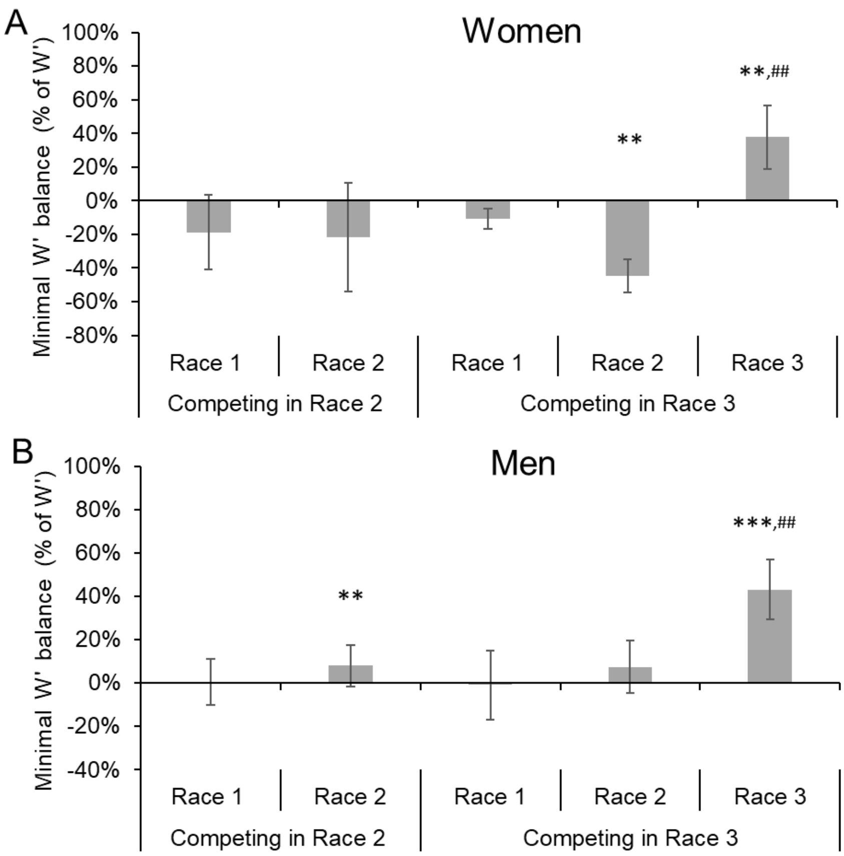

Figure 3. Comparison of minimal W′ balance reached by women (Panel A) and men (Panel B). Ten women and thirteen men competed in race 2. Five women and six men competed in race 3. *= significantly different from Race 1.**= $p < 0.01$, ***= $p < 0.001$. #= significantly different from Race 2. ##= $p < 0.01$.

4 Discussion

In the present study, we evaluated for the first time the power profile and performance of cyclists competing in the UCI E-Sports WCS. Comparing cyclists who advanced in the different races vs. those who were eliminated, differences emerged depending on the sex and race.

In Race 1, both women and men who advanced to Race 2 exhibited greater maximal power output for short durations (≤60 seconds), as hypothesized. However, in Race 2, power profile and W′values were greater in the advancing group only in women, with no differences in men.

We also hypothesized greater depletion in W′ balance at the end of Race 1 compared to the other races. This effect was found only in men. In women advancing to Race 3, greater depletion was observed in Race 2.

4.1 High-Level E-Cyclists Characteristics

None of the cyclists in our sample competed exclusively in virtual cycling, showing considerable experience in road cycling (~10 years), contrasting with the virtual cycling experience of four years or less. This was probably due to the novelty of this discipline (Bjärehed & Bjärehed, 2022; McIlroy, Passfield, Holmberg, & Sperlich, 2021; Westmattelmann, Grotenhermen, Sprenger, & Schewe, 2021). The approach to virtual cycling was different from road cycling, with cyclists accruing a large number of virtual competitions performed in a year, up to 267 races. This is not the case for other disciplines (e.g. Heron, Sarriegui, Jones, & Nolan, 2021; Stoop, Hohenauer, Vetsch, Deliens, & Clijsen, 2019), and might be unique to virtual cycling, where it is possible to perform several independent short races during a single day.

To better understand the performance level of the cyclists competing in the UCI E-Sports WCS, it is possible to use the power output record profile previously reported in professional women and men road cyclists as a benchmark (Mateo-March et al., 2022; Valenzuela et al., 2022). In women, the best cyclists in the present study (90th percentile) presented lower values compared to the 90th percentile of road cyclists (~10%) and were more similar to of road cyclists in the 75th percentile for 30-second and 1-minute durations (Mateo-March et al., 2022). For longer durations (5 and 20 minutes), they aligned more with the 50th percentile, within a ~3% difference (Mateo-March et al., 2022). Conversely, the record power outputs of the best men cyclists (90th percentile) were comparable to those of the best road cyclists for durations of 30 s and 1 min, within ~3% difference (Valenzuela et al., 2022). For longer durations of 5 min and 20 min, record power outputs of men in our 90th percentile were numerically lower than those of road cyclists (6% and 9% difference, respectively), being closer to those of professional road cyclists in the 50th percentile (Valenzuela et al., 2022). It is also important to note that differences between indoor and outdoor power measurements exists (e.g. Lipski, Spindler, Hesselink, Myers, & Sanders, 2022) and might limit the comparison across studies.

Nevertheless, assuming that the samples of Mateo-March *et al*. (2022) and Valenzuela *et al.* (2022) represent the top level cyclists, it is possible to make a few considerations: i) cyclists competing in the UCI E-Sports WCS displayed a power profile biased toward short durations of effort (i.e. ≤1 minute), ii) this was less evident in women, and that iii) taking road cycling as a reference, the level of the UCI E-Sports WCS was higher for the men than women. Consequently, there is an opportunity for developing the competitive aspects of e-sports cycling in women and adapting the training to the specificities of the discipline (e.g. relatively short efforts). As presented in Figure 2, these competitions were characterized by an important effort when the finish line was approaching. Indeed, cyclists possessing a greater ability to develop power over short efforts advanced throughout the races of the World Championships, as shown by the correlation between race ranking with power record for effort ≤5 minutes and W′, and the difference in power profile between advancing and eliminated cyclists in Race 1, where the largest selection was made. Moreover, minimal W′ balance was not different between advancing and eliminated cyclists, excluding a possible influence of race strategy on the results, supporting these conclusions. These findings have important implications for the future competitiveness of virtual cycling, as this discipline is expected to grow in popularity (Bjärehed & Bjärehed, 2022; McIlroy et al., 2021).

4.2 UCI Cycling E-Sports World Championships

Women advancing to Race 2 displayed a lower absolute mean power output compared to the eliminated ones. No difference was found in mean power output relative to body weight, which corroborates the conclusions from Westmattelmann et al. (2022) that power-to-weight ratio is a critical factor in competitive virtual cycling. The power profile obtained during the race showed that advancing women possessed greater ability to develop power for short durations (≤1 minute), and that these values were obtained during a final long sprint, as indicated by the W′ balance profile. Additionally, the lower HR during Race 1 and the record power output data suggest a better overall fitness of the advancing cyclists. Similarly, in Race 2, cyclists who advanced to the final were able to develop overall more power than the eliminated ones, with similar W′ depletion. Only race 2 showed a sex-based difference in intensity, with women presenting substantially higher normalized power values than men, and higher than their CP. These results could be explained by i) a greater W′ in the advancing group and possibly greater recovery capacity from Race 1, as suggested in a recent work on short-term recovery in cyclists (Dale, Muniz, Cimadoro, & Glaister, 2022), and ii) the higher demands of race 2 in women in terms of intensity. It has been previously reported that, despite similarities across cyclists in classical indicators of performance such as power at ventilatory thresholds, peak power output, or $\dot{V}O_{2max}$, lower fatigability was related to better race performance (Valenzuela et al., 2023). This lower fatigability manifested as the ability to develop high power outputs at different time points over the race and appeared particularly important in Race 3. The elimination format required competitors to develop high power outputs repeatedly despite the possible fatigue accumulated during Race 1 and 2. Indeed, women were unable to deplete their W′ reserve in Race 3 to the level of Race 2.

In Race 1, advancing men cyclists were characterized by a greater capacity to develop power over short durations than the eliminated ones, as evidenced by the record power output, the difference in W′ and the power output profile during the race. Not surprisingly, CP did not discriminate between advancing and eliminated cyclists: demarcating the boundary between heavy and severe intensity domains, CP is more related to efforts longer than the final sprint (Jones et al., 2019). In Race 2 advancing cyclists were younger than eliminated ones, which could translate to greater $\dot{V}O_{2max}$ and recovery capacity (Brown, Ryan, & Brown, 2007). Interestingly, there were no other differences between advancing and eliminated cyclists. We speculate that strategy could have played a key role in advancing to race 3 (e.g. sprinting at the right moment; Westmattelmann et al., 2022). While it is possible that accumulated fatigability was greater in eliminated cyclists, our race comparison on minimal W′ balance values in men challenges this hypothesis. The model, developed for high-level cyclists (Bartram et al., 2018, 2022), assumed complete recovery between races (i.e., athletes started the race at 100% value), consistently with a stabilization of recovery within 12 minutes (Dale et al., 2022). Importantly, this model did not take into account residual fatigue: for example, it could display full "readiness" (100%) while the "real" starting levels might be lower (e.g., 80%). These examples denote that the theoretical threshold of 0% within the model might be not achievable, otherwise it would imply an unrealistic W′ balance depletion of 120%. As we assumed maximal effort to be necessary to advance to the next race, the fact that for men the W′ depletion in Race 2 was lower to that of Race 1 likely suggests residual fatigue between races (Dale et al., 2022). As per the women group, Race 3 could not be compared to the other two races, because of the elimination format. However, it is interesting to notice that, in men, the race strategy adopted by the winner was different compared to the other cyclists (Figure 2). A risky but successful solo breakaway from the start of the race allowed a subsequent more even power distribution with a slow but progressive and greater depletion of W′ balance. Although due to ethical reasons we are not authorized to disclose personal data, we observed that the winner was no outlier in terms of CP and W′, with values close to the mean of the group. While in Race 1 selection was more likely dictated by physiological determinants, these results suggest that other factor determined performance in Race 2. As the level of men was closer to top level road cyclist, based on our results we speculate that as the competitive level of virtual cycling increases, physiological differences will decrease, with performance depending largely on other factors. This will give more and more responsibility to the virtual platforms, that controls the "physical law" of virtual cycling interface.

4.3 Limitations.

The main limitation of the study was that data of record power output to derivate the W′ model for each cyclist were not obtained in standardized conditions and not necessarily on the same smart trainer as the one used during the World Championship (Wahoo Kickr V6, see https://osf.io/9rbg6/?view_only=0b4a484340d841ae98446267b52f5d91), which could have an influence on the accuracy of the metrics derived from the record power-duration relationship (Leo, Spragg, Podlogar, Lawley, & Mujika, 2022). However, it was deemed as the best approach to collect data from participants around the globe, being challenging to perform in-person supervised tests in this population. Race data could be considered as more ecologically valid than laboratory testing and allowed us to accumulate large amount of datapoints (e.g. Morin et al., 2021), limiting the influence of extreme values on CP models computed. Indeed, over a period of 12 months, we analyzed data from ~70 races in women and 140 in men. Regardless, it could not reflect the fitness level of the participants at the time of the competition. In men, values approached zero showing that cyclists expressed their best performance according to the prediction of the model, partially supporting the validity of the model in this group. However, for some women, values largely dropped below zero. This could be due to the underestimation of CP and W′ due to lower datapoints compared to men. This limitation did not affect the race comparison, as data were analyzed within-subjects. The small sample size in some subgroup comparisons, such as female cyclists in race 2 ($n = 5$ per group), might have limited statistical power and increased the risk of type II error. Finally, as previously discussed, the τ estimated in currents W′ balance model resulted in full recovery after the 15 minutes of inactivity between races. Future studies are needed to develop model prediction of residual fatigability to adjust the model.

5 Practical Applications

Since 2023, the UCI E-Sports WCS have maintained a consistent race format, making the findings of the present study relevant for future editions. Cyclists targeting E-Sport competitions need to develop sustained power for efforts lasting under 20 min, as well as the ability to deliver maximal ultra-short bursts (around 1 min) during critical moments of the race. Low fatigability is also crucial: riders should (i) be able to repeat high-intensity sprints over time and (ii) optimize recovery to successfully complete multiple (e.g., three) short races within 2 h. The W′ balance model may serve as a valuable tool for guiding W′ depletion management during training and racing. In women, there remains considerable potential to increase both participation and the competitive standard in virtual cycling.

6 Conclusions

Virtual cycling is becoming an increasingly important discipline within competitive cycling, with growing participation and evolving performance demands. The present study offers valuable foundational data to better understand the physiological and performance factors specific to virtual cycling. These insights can inform future research as well as practical training and recovery strategies to optimize athlete preparation and success. Moreover, there remains significant potential to expand both the participation and competitive level of women in virtual cycling, highlighting important opportunities for development in this rapidly growing field.

Supplementary Materials: The following are available online at www.jsc-cycling.com/xxx, Figure S1: title, Table S1: title, Video S1: title.

Funding: GV is supported by a MITACS fellowship.

Acknowledgments: We want to thank all the cyclists participating in the present study for their time and for sharing their data.

Conflicts of Interest: The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, or in the decision to publish the results.

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