PLOS ONE

RESEARCH ARTICLE

Shorter constant work rate cycling tests as proxies for longer tests in highly trained cyclists

Chantelle du Plessis[1,2,3]*, **Mark Andrews**[2], **Lachlan J. G. Mitchell**[2], **Jodie Cochrane Wilkie**[1], **Trish King**[2], **Anthony J. Blazevich**[1]

1 Centre of Human Performance, School of Medical and Health Sciences, Edith Cowan University, Joondalup, Western Australia, Australia, **2** Performance Science Unit, Queensland Academy of Sport, Nathan, Queensland, Australia, **3** Queensland Academy of Sport, Sport Performance Innovation and Knowledge Excellence, Nathan, Queensland, Australia

* chantelle.duplessis@dtis.qld.gov.au

Citation: du Plessis C, Andrews M, Mitchell LJG, Cochrane Wilkie J, King T, Blazevich AJ (2022) Shorter constant work rate cycling tests as proxies for longer tests in highly trained cyclists. PLoS ONE 17(5): e0259034. https://doi.org/10.1371/journal.pone.0259034

Editor: Julien Louis, Liverpool John Moores University School of Sport and Exercise Sciences, UNITED KINGDOM

Received: October 10, 2021

Accepted: March 23, 2022

Published: May 23, 2022

Data Availability Statement: All data csv and R script files are available from the Dryad database (https://doi.org/10.5061/dryad.76hdr7sxv).

Funding: The authors received no specific funding for this work.

Competing interests: The authors have declared that no competing interests exist.

Abstract

Severe-intensity constant work rate (CWR) cycling tests simulate the high-intensity competition environment and are useful for monitoring training progression and adaptation, yet impose significant physiological and psychological strain, require substantial recovery, and may disrupt athlete training or competition preparation. A brief, minimally fatiguing test providing comparable information is desirable. **Purpose** To determine whether physiological variables measured during, and functional decline in maximal power output immediately after, a 2-min CWR test can act as a proxy for 4-min test outcomes. **Methods** Physiological stress ($\dot{V}O_2$ kinetics, heart rate, blood lactate concentrations ($[La^-]_b$)) was monitored and performance fatigability was estimated (as pre-to-post-CWR changes in 10-s sprint power) during 2- and 4-min CWR tests in 16 high-level cyclists ($\dot{V}O_{2peak} = 64.4 \pm 6.0$ ml·kg^{-1}·min^{-1}). The relationship between the 2- and 4-min CWR tests and the physiological variables that best relate to the performance fatigability were investigated. **Results** The 2-min CWR test evoked a smaller decline in sprint mechanical power (32% vs. 47%, *p*<0.001). Both the physiological variables (r = 0.66–0.96) and sprint mechanical power (r = 0.67–0.92) were independently and strongly correlated between 2- and 4-min tests. Differences in $\dot{V}O_{2peak}$ and $[La^-]_b$ in both CWR tests were strongly associated with the decline in sprint mechanical power. **Conclusion** Strong correlations between 2- and 4-min severe-intensity CWR test outcomes indicated that the shorter test can be used as a proxy for the longer test. A shorter test may be more practical within the elite performance environment due to lower physiological stress and performance fatigability and should have less impact on subsequent training and competition preparation.

Introduction

Regular monitoring of both athlete performance and performance fatigue levels (i.e., physiological and psychological) are necessary to manage recovery and training load, to test the effects of interventions such as technique or equipment alterations, and to maximise physiological adaptation. To do so, specific tests that reflect the energetic demands of the task or event of interest, with sufficient precision are needed to detect relevant and meaningful changes. Appropriate testing protocols that can be used frequently without negatively impacting subsequent, prescribed training sessions or competition preparation, are therefore required.

Constant work rate (CWR) cycling tests are widely used to assess and monitor physiological and functional performance capacity in various athlete (i.e., time trial, pursuit, bunch race, sprint events; etc.), clinical and rehabilitation environments. In athlete environments, these tests are typically performed at intensities within the severe domain (i.e., greater than the critical power threshold) for durations ranging 2–15 min [1]. Their aim is to evoke a maximal effort that achieves the highest sustained average power output for the duration of the test, with minimal or no functional decline in mechanical power. In cycling, an athlete's ability to generate high power outputs during these tests should ultimately translate to a faster bicycle velocity in the field (e.g., during a time trial), which is critical to performance success. However, the maintenance of a high mechanical work rate (power output) requires a high muscle contractile force production at fast muscle shortening speeds, and therefore a high adenosine triphosphate (ATP) turnover rate and metabolic energy cost [2–4]. Consequently, these high work rates are associated with the accumulation and/ or depletion of fatigue-related metabolites such as decreasing intramuscular phosphocreatine concentrations ([PCr]) and increasing muscle lactate, adenosine diphosphate ([ADP]), inorganic phosphate ($[P_i]$), or hydrogen ion ($[H^+]$) accumulation as well as the continual rise in the rate of oxygen consumption ($\dot{V}O_2$) until $\dot{V}O_{2max}$ is attained [5, 6]. This unstable cellular metabolic environment can impact function at multiple sites within the muscle excitation-contraction coupling process at the sarcomere level and influence efferent output by the central nervous system (for reviews see [7–9]). Regardless of the mechanism, muscle function will be compromised irrespective of a participant's voluntary effort capacity when exercising within the severe-intensity domain, leading to fatigue [10–13].

To monitor (and maximise) physiological adaptation, needle muscle biopsies or phosphonuclear magnetic spectroscopy can provide clear insights into muscular metabolic changes occurring during fatiguing CWR exercise. However, these methods are invasive, expensive, and not easily accessible, and are therefore traditionally impractical in the elite sporting environment. Alternatively, the temporal pulmonary rate of oxygen consumption ($\dot{V}O_2$) profile may indirectly provide insights into the energetic state of the muscle [6, 11, 14, 15]. For example, slower O_2 onset kinetics can reflect a greater O_2 deficit, which is associated with greater substrate-level phosphorylation and anaerobic metabolism (i.e., decreased [PCr] and increased blood lactate concentration), resulting in greater homeostatic disturbance and reduced exercise tolerance. Assessing $\dot{V}O_2$ kinetics during CWR tests can thus provide considerable insight into the energetic state of the muscle, allowing assessment of the effectiveness of training programs as a whole and other interventions (e.g., biomechanical).

Although the measurement of key physiological factors underlying test performances are essential, there is also a need to determine the most relevant outcomes relating to performance success: the functional performance outcome. Since the goal of a CWR test is to maintain a constant work output, fatigue assessment is problematic as no external power loss occurs (unless the limit of tolerance, or exhaustion, is reached). One solution is to perform a maximal, movement-specific sprint test immediately after a CWR test to assess the muscle's capacity for maximal, explosive output [16–19]. Greater decrements in maximal sprint power have been observed as the duration (30 s–10 min) of prior exercise is increased (when performed at 60–98% of the mechanical power output at $\dot{V}O_{2max}$) [16, 17, 20]. Assuming that athletes are highly motivated to produce maximal effort and are familiar with the testing procedures, the functional loss in maximal sprint power immediately after a CWR test should provide information about the functional state of the muscles; and, therefore, information about the task fatigability.

Submaximal (60–90% of the mechanical power at $\dot{V}O_{2max}$) exercise tests are commonly used to predict maximal cycling performance (e.g. YMCA, Astrand-Ryhming, Physical Work Capacity 170, etc.) [21, 22]. Yet to truly translate controlled laboratory test results to field performance, the conditions under which the physiological limitations are manifested should be simulated [19]. Maximal effort laboratory tests are therefore needed to accurately reflect competition intensities. However, highly fatiguing tests require hours, or days, of recovery due to resulting physiological and psychological deficits and may disrupt an athlete's training schedule. Consequently, it is of interest to coaches and athletes to determine whether the data of shorter, less fatiguing tests provide comparable information to longer, more fatiguing tests.

The main purpose of this study was to determine whether the physiological variables measured during a shorter CWR test (2 min, 50% of the complete test duration) as well as the functional mechanical capacity measured immediately after it can be used as proxies for the fatigability results obtained in a longer (4-min) test. Because fatigue assessment is problematic during CWR tests, a secondary aim was to assess the relationship between the physiological changes, particularly $\dot{V}O_2$ kinetics, measured during the CWR tests and the decline in maximal sprint power measured after the CWR tests. Cycling was chosen as the model within which to test the hypothesis as it is a widely used exercise testing and training modality with both sporting and clinical applications, as well as being task-specific to the track cycling population that formed the current study cohort. We hypothesised that both the measured physiological variables and functional decline in the shorter test would be of lesser magnitude, and be associated with the outcomes of the longer test.

Materials and methods

Participants

Sixteen highly trained male (*n* = 13) and female (*n* = 3) cyclists (age 18.7 ± 2.2 y; height 180.8 ± 8.0 cm; mass 73.2 ± 10.1 kg; $\dot{V}O_{2peak}$ 64.4 ± 6.0 $ml \cdot kg^{-1} \cdot min^{-1}$; estimated mechanical power at $\dot{V}O_{2peak}$ 353.3 ± 58.9 W), highly accustomed with the performance testing described in this study, volunteered to participate. All participants were involved in an Australian State Institute of Sport Track Cycling program, completed ≥4 cycling and two resistance training sessions a week, and were free from injury at the time of data collection. All cyclists had ≥2 years' experience in the high-performance environment and were familiar with high-intensity ergometer testing. Written informed consent was given prior to participation and the study was approved by the Human Research Ethical Committee of Edith Cowan University (project number 2019-00505-DUPLESIS).

Data collection

Experimental design. A within-subject repeated measured experimental design was used, and data were collected across two days separated by at least 48 h, but at the same time of day. Participants were asked to keep a food and training diary and replicate this 24 h prior to each laboratory visit. On the first visit, an industry-modified incremental step test [23] (called "2-in-1" test) was completed which included a submaximal step test to lactate threshold (approximately 4 $mmol \cdot l^{-1}$ blood lactate concentration, $[La^-]_b$) followed by a 4-min constant work rate (CWR) test where the cyclist's highest sustained average power output and cadence were measured. The 4-min CWR test was selected to imitate a track cyclist's pursuit time trial race (i.e., an individual pursuit across 4 km for men, and 3 km for women). Test reliability has been demonstrated both within and between days across six weeks in well trained cyclists [24]. A 10-s maximal cycle sprint was performed before (PRE-CWR$_{4min}$) and immediately after (POST-CWR$_{4min}$) the 4-min CWR test to assess the loss in maximal mechanical functional capacity (i.e., task fatigability). The maximal rate of oxygen uptake ($\dot{V}O_{2peak}$), $\dot{V}O_2$ kinetics, heart rate, and $[La^-]_b$ were measured to indicate physiological stress, i.e., to infer the chemo-energetic state of the muscles across the 4-min CWR test. On the second visit, a shorter (2-min) CWR test was completed at the same intensity as the 4-min test, with a maximal 10-s sprint also performed before (PRE-CWR$_{2min}$) and after (POST-CWR$_{2min}$). A 2-min duration was selected as i) participants were highly familiar with this duration as it is regularly performed during training sessions, ii) to ensure a 'steady state' for $\dot{V}O_2$ kinetic measurements as $>$2 min exercise within the severe-intensity domain is required [25], and iii) pilot testing demonstrated it was less fatiguing than a 3- or 4-min test. The submaximal ramp test was not completed during this visit.

Experimental procedures. *Visit 1*: *"2-in-1" test*. On Visit 1, participants were required to use their own pedals and cycling cleats and the seat, handlebar positions and crank length of a stationary electromagnetically braked cycle ergometer (LODE Excalibur, Groningen, Netherlands) were adjusted to match the participant's own track racing bicycle. They were required to perform a 15-min standardised warm-up where the intensity was self-selected within recommended ranges of power output. This included a 5-min low-intensity bout between 50–150 W, a 5-min short ramp (increment duration and power self-selected) between 125–350 W and a 6-s maximal seated sprint. After a 5-min active recovery between 50–100 W, a non-fatigued 10-s all-out seated sprint (a "non-fatigued sprint", PRE-CWR,$_{4min}$) was performed (see Fig 1). All warm-up intensities were recorded and then repeated on Visit 2.

Participants then performed a modified $\dot{V}O_{2max}$ test, i.e., the "2-in-1" test, currently employed in the State Institute system in Australia [23]. This test comprised two components (a submaximal step stage and a 4-min CWR test) that were separated by a self-selected 20-min active or passive rest. The first component involved 5–7 × 5-min stages of increasing intensity to lactate threshold, starting at 100 W (women) or 150 W (men) and increasing by 25 W (women) and 50 W (men). $[La^-]_b$ samples were taken from the earlobe and analysed (Lactate

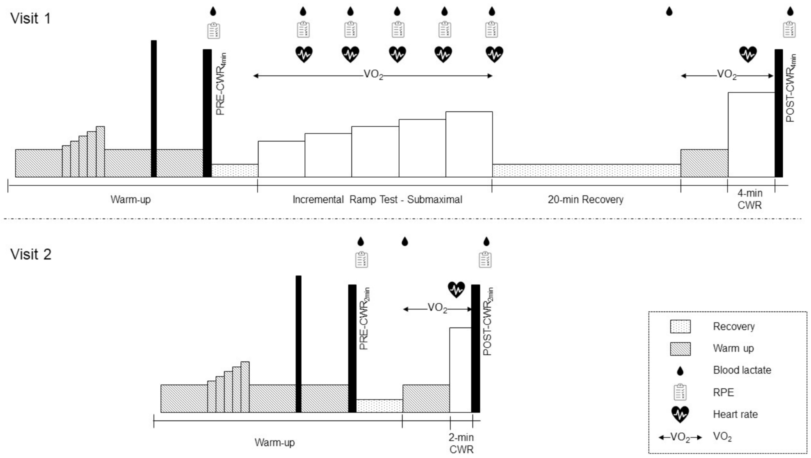

Fig 1. Outline of experimental protocol for the first and second visits to the laboratory.

https://doi.org/10.1371/journal.pone.0259034.g001

Pro2, Kyoto, Japan) during the 4th minute of each stage, and the test ceased when $[La^-]_b$ exceeded 4 mmol·l^{-1}. $\dot{V}O_2$ and carbon dioxide production ($\dot{V}CO_2$) data were continuously collected using a ParvoMedics metabolic cart system (ParvoMedics TrueOne 2400 diagnostic system, USA) and averaged over 10-s windows during the last 2 min of each stage. Heart rate was continuously measured (RS800 Polar Heart Rate Monitor, Finland) and rating of perceived exertion (RPE [26]) was obtained at the end of each stage.

Following the 20-min recovery (active or passive), a $[La^-]_b$ sample was required to be <2.5 mmol.l^{-1}. In the rare case that the $[La^-]_b$ sample was greater, a further 5-min recovery was imposed to ensure the participant was adequately recovered. A short, low-intensity warm-up of 5 min at a self-selected intensity (50–100 W) was then mandated before the 4-min CWR test was performed. The participants were familiar with performing this severe-intensity CWR test and therefore strongly encouraged to provide a maximal but evenly paced effort, and to maintain the target cadence for the duration of the test. The target cadence and power (and therefore the appropriate torque factor load) were recommended through consultation with the high-performance coaches and considering each participant's recent (<6 months) race history; see 'Torque Factor Load Setting for the CWR Test' section below for a detailed description of the methodological considerations. Note that the target power was an initial recommendation, and the aim was to attain the highest average sustained power output even if it resulted in a small cadence variation (typically of less than 5 rpm). A head unit secured to the ergometer provided visual feedback on both cadence and power. Participants were instructed to remain seated throughout the test. Torque and angular velocity (and power) data were sampled every 2° of each pedal stroke by the LODE ergometer mechanical system, and subsequently averaged per pedal revolution. The average power and cadence of the 4-min CWR test were calculated and used as reference for testing on Visit 2. $\dot{V}O_2$, $\dot{V}CO_2$ and heart rate data were continuously collected throughout the 4-min CWR test.

At the immediate conclusion of the 4-min CWR test, without pause, a 10-s all-out seated sprint (a "fatigued sprint", POST-CWR$_{4min}$) was performed [18, 19]. No pause was allowed after the 4-min CWR test to prevent recovery of central or peripheral aspects of fatigue. A cycling-specific maximal sprint was selected to assess fatigue (i.e., rather than a knee extension, leg press or other test) to prevent any perseveration effect (i.e., a motor pattern interference) influencing the test performance, which may occur when movement patterns differ between tasks [27, 28]. Blood was obtained from the ear lobe before and 1, 3, 5 and 7 min after the sprints that followed the CWR tests. $[La^-]_b$ was analysed within 15 s using the Lactate Pro2 analyser and the peak $[La^-]_b$ value retained for further analysis. RPE was obtained immediately following PRE-CWR and POST-CWR.

Visit 2: *2-min CWR test*. On Visit 2, participants completed the pre-test preparations and 15-min warm-up as on Visit 1. Similarly, for the conclusion of the warm-up, a 10-s all-out seated sprint ('non-fatigued', PRE-CWR$_{2min}$) was completed. However, the submaximal incremental ramp test of the "2-in-1" test from Visit 1 was not completed during Visit 2. After 5 min active recovery (50–100 W), participants were equipped with the same metabolic mouthpiece and then performed a 2-min CWR test at the same intensity (i.e., the same torque factor, cadence and power) as the 4-min CWR test. This 2-min CWR test was also immediately followed by a 10-s all-out seated sprint effort ('fatigued', POST-CWR$_{2min}$). $\dot{V}O_2$, $\dot{V}CO_2$, heart rate, $[La^-]_b$ and RPE data were collected as in the 4-min CWR test.

Methodical considerations. *Ergometer specifications*. All sprint components of the warm-up were completed in the cadence-dependent linear mode (i.e., in 'Wingate' isoinertial mode) of the ergometer with a torque factor load of 0.6 Nm·kg^{-1}. All warm-up and recovery components as well as the submaximal incremental ramp test were completed using a constant power mode of the ergometer, which allows the power output to be set independent of the freely chosen cadence.

Torque factor load setting for the CWR test. Since the 4-min CWR test was designed to imitate a pursuit race in which bicycle gears are fixed and power output is highly cadence-dependent, the cadence-dependent mode of the ergometer was selected with careful consideration of the torque factor load setting. Note that in conjunction with the coach and athlete input, one of two processes was followed to determine test target power output and cadence, and therefore the appropriate torque factor load:

For the minority of participants ($n = 5$) who used power meters on their track bicycles, the target power and cadence were set to their most recent Individual Pursuit power output and cadence. For the remaining participants, the $\dot{V}O_2$ during the last 2-min of each submaximal workload of the "2-in-1" test was averaged. Based on the linear regression equation of the submaximal $\dot{V}O_2$ and power output, the $\dot{V}O_{2peak}$ (determined from the cyclists' previous test conducted within the last year) was used to predict the mechanical power output at $\dot{V}O_{2peak}$. The target power output of CWR test was estimated between 105–110% of this mechanical power output at $\dot{V}O_{2peak}$, with the estimation based on previous research [29, 30] and retrospective analysis of all athlete data collected in the "2-in-1" test at the State Sports Institute in the three years preceding testing.

The torque factor load was subsequently calculated as:

$$Torque(Nm \cdot kg^{-1}) = [Power(W) \div Angular\ \ velocity(rad \cdot s^{-1})] \div Body\ \ mass(kg)$$

with power being the predicted 4-min CWR test power output, and angular velocity calculated as:

$$2\pi\ \ x\, cadence(revoluions \cdot s^{-1})$$

Data analysis

Physiological variables. $\dot{V}O_{2peak}$, minute ventilation (VE_{peak}), the respiratory exchange ratio (RER_{peak}), and heart rate (HR_{peak}) were calculated as the highest average values attained over any 30-s interval during both the 2- and 4-min CWR tests. The mean response time (MRT) represented the time taken from the baseline to achieve 63% of the final response $\dot{V}O_2$, and was estimated for both the 2- and 4-min CWR tests using a mono-exponential model fitted to each $\dot{V}O_2$ data set, as follows [11, 15, 31, 32]:

$$\dot{V}O_{2(t)} = \dot{V}O_{2\ Baseline} + \dot{V}O_{2\ Amplitude}\ \ x(1 - e^{-(t \div MRT)})$$

where $\dot{V}O_{2(t)}$ is the $\dot{V}O_2$ at any time point, $\dot{V}O_{2\ \mathrm{Baseline}}$ is the baseline $\dot{V}O_2$ calculated as the 1-min average $\dot{V}O_2$ before the start of the 2- and 4-min CWR tests, $\dot{V}O_{2\ \mathrm{Amplitude}}$ is calculated as the difference between the steady state $\dot{V}O_2$ asymptote and baseline, and ($1\text{-}e^{-\ (\mathrm{time}\ \div\ \mathrm{MRT})}$) is the exponential function that describes the rate of $\dot{V}O_2$ rise towards the steady state amplitude. For each participant, the Microsoft Excel solver function was used as an iterative fitting procedure to solve for the smallest sum of squares differences between the projected $\dot{V}O_{2(t)}$ (calculated using the exponential function) and the experimental data [11]. $\dot{V}O_{2\ \mathrm{Baseline}}$ was used as a fixed parameter and the $\dot{V}O_{2\ \mathrm{Amplitude}}$ and the estimated MRT parameters for the 2- and 4 min CWR tests were subsequently computed.

The estimated MRT for the 2-min CWR test was factored since a steady-state (required for the exponential function above) could not always be clearly defined for $\dot{V}O_2$ data collected during the 2-min CWR test. That is, in addition to calculating MRT for the 4-min CWR test from Visit 1 (with a clearly defined steady-state), the first 2-min of the same $\dot{V}O_2$ data set was used separately to calculate the 2-min MRT. The linear relationship (i.e., the slope and intercept) between the MRT of the first 2-min of the 4-min CWR test and the MRT of the 4-min CWR test was subsequently calculated for all individuals. This slope and intercept were then used to correct the MRT for the standalone 2-min CWR test from Visit 2:

$$Corrected\ MRT_{2min} = (MRT_{2min}\ x\ slope) + intercept$$

Mechanical variables. The functional decline in mechanical power output was determined by the fatigue-related decrements in peak and average power between the PRE-CWR and POST-CWR sprints. Only the first 8 s of the 10-s all-out sprints were used to remove any change in effort as the test neared completion. In addition, the peak cadence decrement during the sprints were calculated as indicators of the velocity-specific effect of the functional decline.

It should be noted that PRE-CWR was performed from a stationary start whereas POST-CWR was performed without delay from a rolling start following the 2- and 4-min CWR tests (i.e., the starting pedalling rates of the sprints were different). Because the cadence of the 4-min CWR test was not known until after its completion, a PRE-CWR sprint from a rolling start (at the cadence of the 4-min CWR test, and therefore the cadence of the start of the POST-CWR sprint) could not be completed. To eliminate the confounding effects of the pedalling rate (and therefore the staring condition) on fatigue estimation, the average power was also calculated for a pedal rate-specific region [33]. This region consisted of the minimal-to-maximal cadence range recorded during POST-CWR and compared to PRE-CWR within this region (see Fig 5).

Statistical analysis

All statistical analyses were performed using R software package (v 1.4). Data are presented as mean ± standard deviation, statistical significance was accepted at an alpha level of 0.05, and 95% confidence intervals (CI) with upper and lower limits were computed. Preliminary tests assessed and verified all test assumptions of multivariate normality (mvnormtest), multicolinearity (rstatix), homogeneity of variances (rstatix), and sphericity of the data, where relevant.

One-way repeated measures ANOVAs were used to test for differences between the 2- and 4-min CWR tests for i) the physiological variables obtained during the CWR tests [peak oxygen consumption ($\dot{V}O_{2peak}$), estimated mean $\dot{V}O_2$ response time (MRT), peak heart rate (HR_{peak}), peak respiratory exchange ratio (RER_{peak}), peak minute ventilation relative to body mass (VE_{peak}), and peak blood lactate concentration ($[La^-]_{b,peak}$), as well as the perceived exertion (RPE)], and ii) changes in mechanical variables obtained during sprints performed before and after the CWR tests [peak power ($\Delta Power_{peak}$), average power ($\Delta Power_{av}$), average power calculated during the pedal-rate-specific region of POST-CWR ($\Delta Power_{av,PRS}$), and peak cadence ($\Delta Cadence_{peak}$)].

Pearson's correlations were computed to quantify the linear relationships between the physiological and mechanical variables between the 2- and 4-min CWR tests. These were interpreted as r: 0.10–0.39, weak; 0.40–0.69, moderate; 0.70–0.89, strong and 0.90–1.00 very strong relationship [34]. The standard error of the estimate (SEE) of the regression was used to assess the accuracy of the 2-min test's data to predict the outcomes of the 4-min test. Smaller SEEs represent a smaller prediction error. To assist in the interpretation of the statistical confidence, the relative SEE was presented as a percentage of the 4-min CWR test mean: SEE (%) = (SEE ÷ mean) × 100.

Relationships between the physiological and fatigue estimates were analysed using a fixed-slopes linear mixed effect model approach using R package lmerTest [35]. Visual inspection of residual plots confirmed that linear modelling assumptions were met. The response variable was the relative change in average power ($W \cdot kg^{-1}$) between the sprints across the 2- and 4-min CWR tests (i.e., the performance fatigue estimate). The fixed effects were the physiological variables ($\dot{V}O_{2peak}$, $[La^-]_{b,peak}$, MRT, HR_{peak}, RER_{peak}) as well as the duration (i.e., 2- and 4-min) of the CWR test. The random effect was set for the individual participants to account for intraindividual dependencies interindividual heterogeneity.

Results

2-and 4-min CWR test descriptive outcomes

CWR tests were completed at 109 ± 0.1% of the predicted mechanical power output at $\dot{V}O_{2peak}$ (ranging 1.03 to 1.18% relative intensities) as determined from the incremental step test. Average power output and cadence for the 2- and 4-min CWR cycling tests were 384.0 ± 67.2 W (5.2 $W \cdot kg^{-1}$) and 106.6 ± 4.0 rpm vs. 383.4 ± 67.7 W (5.2 $W \cdot kg^{-1}$) and 105.5 ± 7.1 rpm, respectively.

Physiological variables and perceived exertion between 2- and 4-min CWR tests

No differences were observed in MRT or RER_{peak} between the 2- and 4-min tests ($p>0.05$) (Table 1), although $\dot{V}O_{2peak}$ indicated a trend towards significance ($p = 0.083$). Differences were observed in HR_{peak} ($p = 0.022$), $[La^-]_{b,peak}$ ($p = 0.019$), VE_{peak} ($p = 0.003$) and RPE ($p<0.001$). Moderate to very strong correlations were found between 2- and 4-min CWR tests for all physiological variables (ranging from $r = 0.66$ for MRT to $r = 0.96$ for $\dot{V}O_{2peak}$), but not for RPE ($r = -0.21$) (Fig 2). Participants reached the same fraction of $\dot{V}O_{2peak}$ at the end of the 2-min CWR test (93.4 ± 2.6%) as at the 2-min point of the 4-min CWR test (92.4 ± 2.8%) (Fig 3). In some cases, the 2-min CWR test was too short to clearly show a $\dot{V}O_2$-time asymptote. Therefore, the MRT from the 2-min CWR test was corrected from 34.9 ± 6.1 s to 36.5 ± 5.1 s based on the linear relationship between the estimated MRT in the first 2-min of the 4-min

Table 1. Physiological variables and perceived exertion observed in the 2-and 4-min CWR tests (*n* = 16).

	2-min	4-min	Mean Difference [95% CI]	p-value	r [95% CI]	SEE	SEE (%)
$\dot{V}O_{2peak}$ ($ml \cdot kg^{-1} \cdot min^{-1}$)	60.1 ± 5.9	64.4 ± 6.0	4.2 [3.3, 5.2]	0.083	0.96 [0.88, 0.98]	1.8	2.8
MRT (s)	36.5 ± 5.1 [†]	35.5 ± 5.7	-1.0 [-3.4, 1.3]	0.767	0.66 [0.25, 0.87]	4.4	12.4
RER_{peak}	1.15 ± 0.07	1.16 ± 0.05	0.01 [-0.01, 0.03]	0.500	0.77 [0.45, 0.92]	0.03	2.6
HR_{peak} (bpm)	181.5 ± 9.0	188.6 ± 8.5	7.1 [3.7, 10.5]	0.022[*]	0.75 [0.39, 0.91]	5.8	3.1
$[La^-]_{b,peak}$ ($mmol \cdot l^{-1}$)	9.5 ± 2.1	11.7 ± 2.9	2.2 [1.2, 3.1]	0.019[*]	0.76 [0.43, 0.91]	1.9	16.3
VE_{peak} ($l \cdot kg^{-1} \cdot min^{-1}$)	1.9 ± 0.3	2.3 ± 0.3	0.4 [0.3, 0.5]	0.003[*]	0.83 [0.57, 0.94]	0.2	8.7
RPE (6–20 Borg scale)	15.8 ± 1.5	18.8 ± 0.7	3.0 [2.1, 4.0]	<0.001[*]	-0.21 [-0.64, 0.31]	0.8	4.4

Data presented as mean ± standard deviation. SEE: Standard error of the estimate; smaller SEE represents a smaller prediction error. SEE (%): SEE relative to 4-min CWR test mean. MRT: Estimated mean response time; time taken to reach 63% of the $\dot{V}O_2$ asymptote.

[†] Corrected mean response time: MRT corrected by the relationship between the MRT of the 4-min CWR test and the first 2-min within the 4-min CWR test.

[*] $p<0.001$, significant difference between the 2- and 4-min CWR tests.

https://doi.org/10.1371/journal.pone.0259034.t001

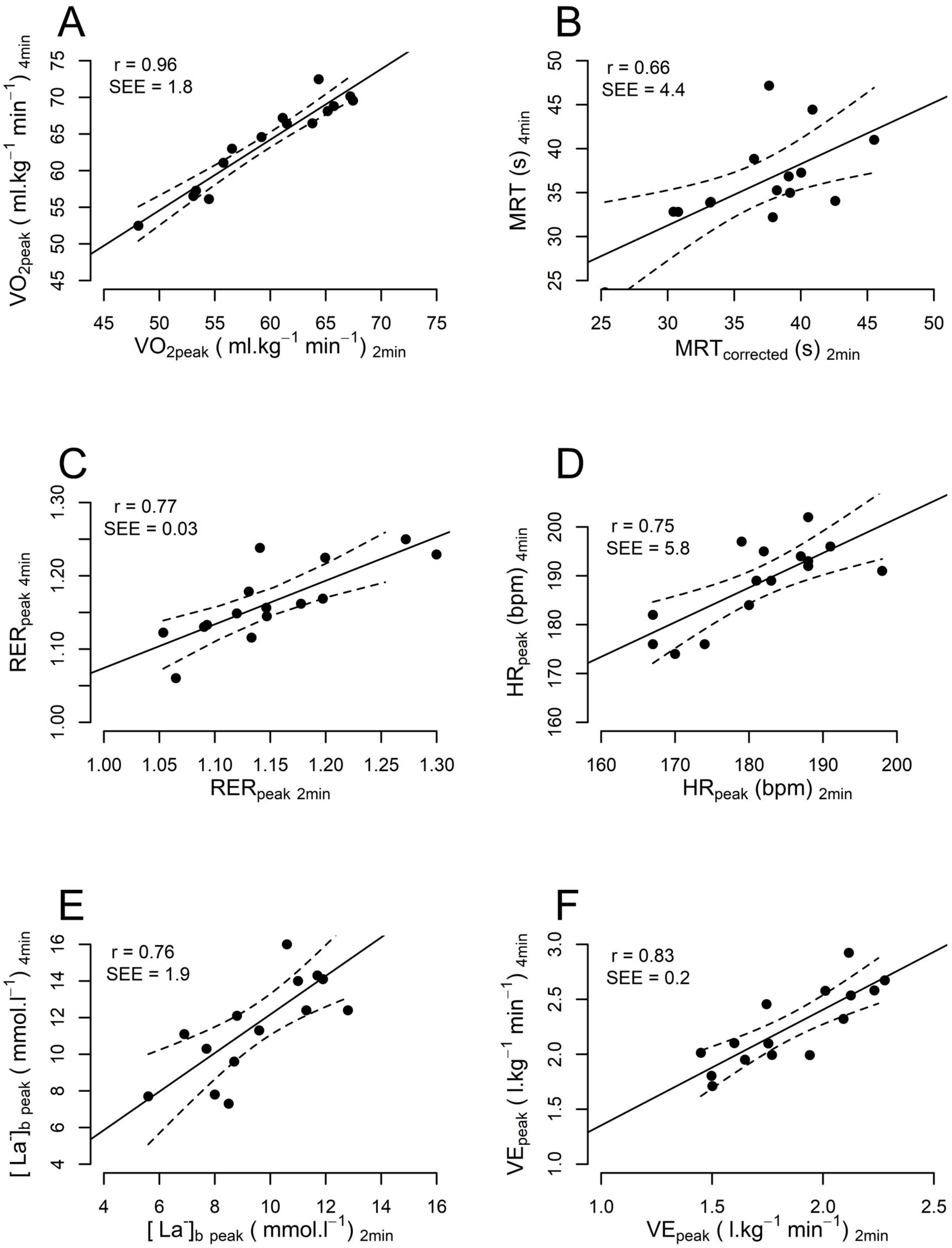

Fig 2. Relationships between physiological changes induced by 2- and 4-min CWR tests. Correlation and absolute standard error of the estimates (SEE) between the CWR tests are displayed on the top left corner of each graph. Dotted lines indicate the 95% CI. Moderate to very strong relationships were observed between physiological variables obtained during the 2- and 4-min CWR tests.

https://doi.org/10.1371/journal.pone.0259034.g002

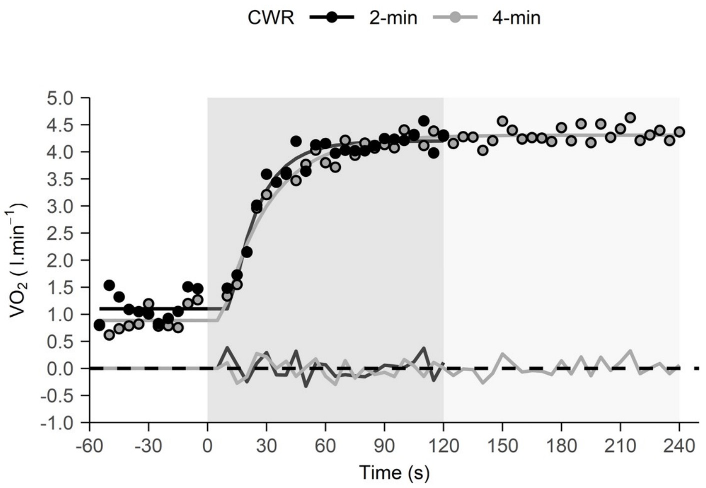

Fig 3. $\dot{V}O_2$**-time profiles for 2- and 4-min CWR tests in a representative participant performed on different days.** $\dot{V}O_2$ kinetics are inferred by the mean response times (Corrected MRT_{2min} = 25.3 s vs. MRT_{4min} = 23.6 s) and the $\dot{V}O_2$ steady state, as fitted by a mono-exponential function which were similar for both tests. The bottom black and grey lines represent the residuals. The darker and lighter grey shaded regions show the 2- and 4-min CWR test durations, respectively.

https://doi.org/10.1371/journal.pone.0259034.g003

CWR test and the estimated MRT of the 4-min test: [Corrected MRT_{2min} = 0.845 (MRT_{2min}) + 7.02].

Mechanical variables of the sprints performed before and after the 2-and 4-min CWR tests

The average powers of PRE-CWR_{2min} and PRE-CWR_{4min} sprints were similar (p = 0.319) and presented with a very strong correlation and small SEE (Table 2). The average powers of POST-CWR_{2min} and POST-CWR_{4min} sprints were different (p<0.001) but demonstrated a strong correlation and small SEE. Changes (Δ) in mechanical variables from the sprints

Table 2. Differences in mechanical variables recorded during sprints performed before (PRE-CWR) and after (POST-CWR) the 2-and 4-min CWR tests (*n* = 16).

	Sprint	Sprint	Mean Difference [95% CI]	p-value	r [95% CI]	SEE	SEE (%)
	2-min CWR	4-min CWR					
Change in variable							
$\Delta Power_{peak}$ (W)	-379.1 ± 153.9*	-553.2 ± 215.9*	174.1 [124.0, 224.3]	< 0.001**	0.92 [0.79, 0.97]	85.1	15.4
$\Delta Power_{ave}$ (W)	-305.2 ± 83.2*	-455.8 ± 126.1*	150.6 [111.1, 190.0]	< 0.001**	0.83 [0.56, 0.94]	73.5	16.1
$\Delta Power_{ave,PRS}$ (W)	-420.7 ± 113.1*	-540.7 ± 164.4*	120.0 [79.7, 160.2]	< 0.001**	0.89 [0.71, 0.96]	76.9	14.2
POST-CWR sprints							
POST-CWR_{ave} (W)	657.1 ± 131.7	499.9 ± 97.5	-157.2 [125.4, 189.0]	< 0.001**	0.91 [0.76, 0.97]	42.6	8.5
POST-CWR_{ave} (W)	760.7 ± 139.3	583.5 ± 121.8	177.1 [141.9, 212.4]	< 0.001**	0.89 [0.70, 0.96]	59.8	10.2

Data presented as mean ± standard deviation. SEE: Standard error of the estimate; smaller SEE represents a smaller prediction error. SEE (%): SEE relative to 4-min CWR test mean. Δ: Changes between sprints performed before and after CWR tests. $Power_{ave,PRS}$: Average power during the pedal rate-specific region, i.e., specific to the cadence range of the fatigued sprint performed after the CWR tests.

*: Significant difference between sprints performed before and after CWR tests, p<0.001.

**: Significant difference between changes in sprints across the 2- and 4- min test durations, p<0.001.

https://doi.org/10.1371/journal.pone.0259034.t002

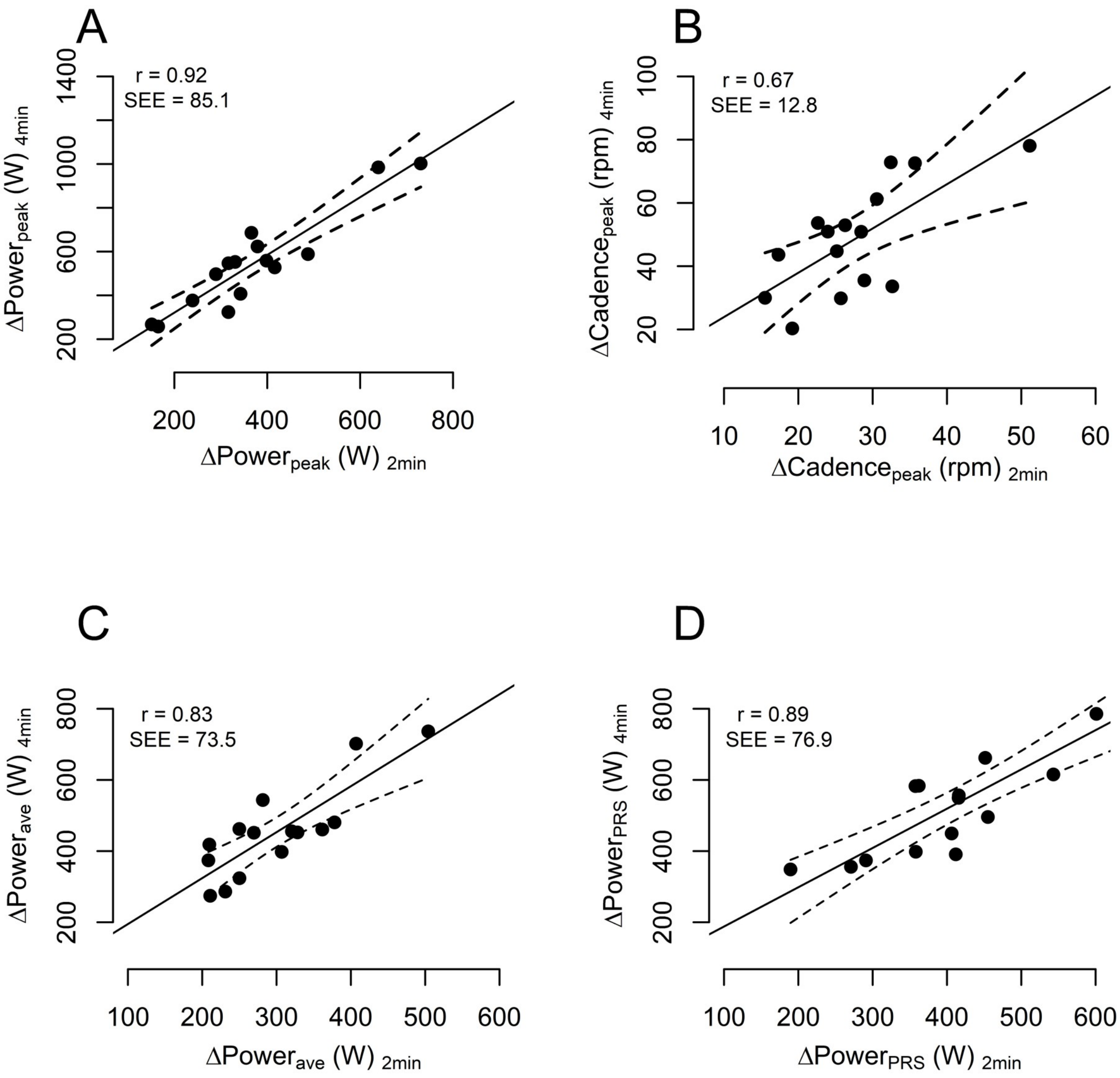

Fig 4. Relationships between 2-min and 4-min CWR tests for changes in (Δ) mechanical variables obtained in the sprints. Correlation and standard error of the estimates (SEE) between the CWR tests are displayed on the top left corner of each graph. Dotted lines indicate 95% CIs. Moderate to very strong relationships were observed between mechanical variables obtained during the 2- and 4-min CWR tests.

https://doi.org/10.1371/journal.pone.0259034.g004

performed before and after the 2-min CWR test were significantly smaller ($p<0.001$) than changes in the sprints performed before and after the 4-min CWR test. Strong correlations were observed in mechanical variables between the 2 and 4-min test (ranging from r = 0.83 for ΔPower_{ave} to r = 0.92 for $\Delta\text{Power}_{peak}$) (Fig 4). Larger SEEs were found for ΔPower_{ave} in pre-to-post CWR tests than POST-CWR_{ave} (Table 2) and, as described in the Discussion, in many cases the POST-CWR sprint power alone may be the most relevant variable for use. The power- and torque-cadence relationships of the sprints performed before and after the CWR tests indicated a downward shift in the fatigued conditions (Fig 5). Irrespective of some individual variation, an overall trend of a functional mechanical decline in sprint capacity after the longer vs. the shorter test is indicated (Fig 6).

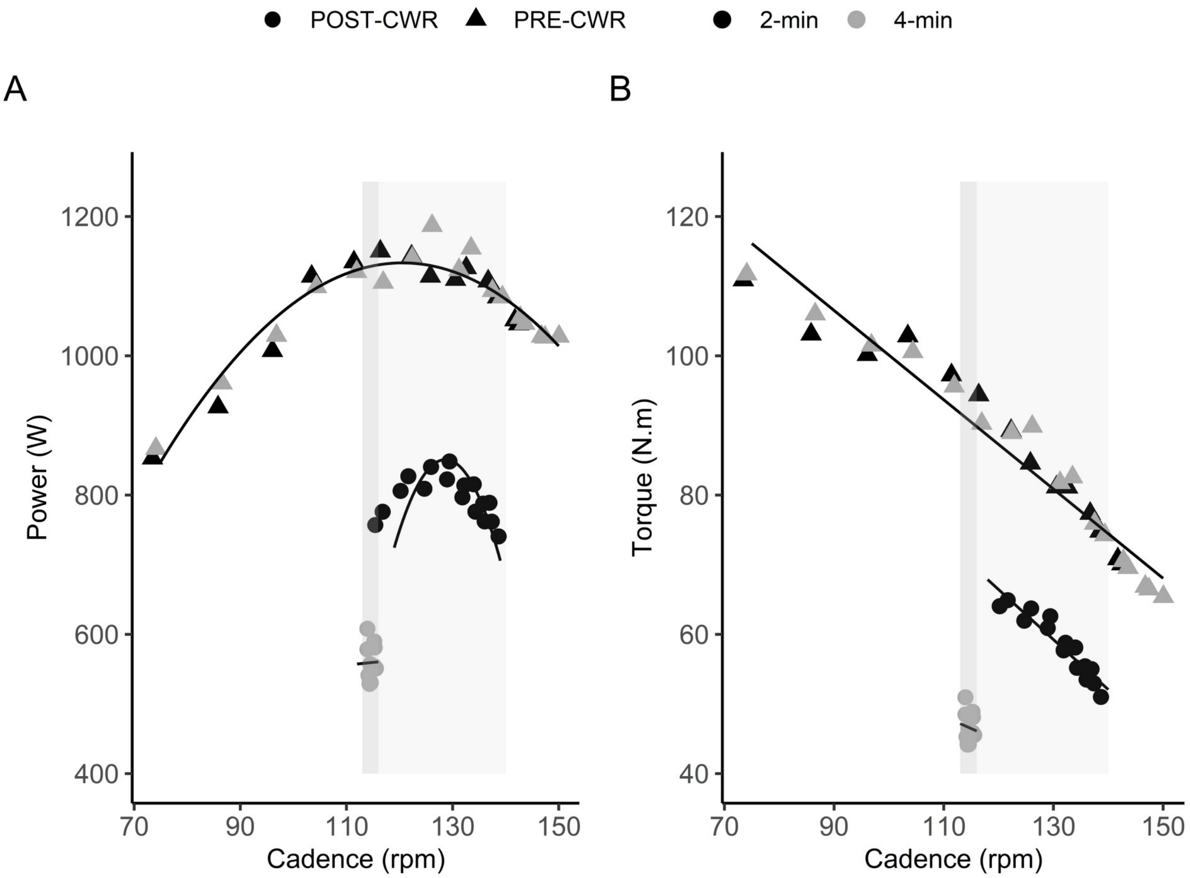

Fig 5. Power-cadence (left) and torque-cadence (right) relationships obtained in the sprints performed before and after the 2-min (black shapes) and 4-min (grey shapes) CWR tests from a representative subject. Triangles represent PRE-CWR sprints and the dots represent POST-CWR sprints. The downward shift of power- and torque-cadence relationships after CWRs demonstrate that power was severely compromised by the increase in CWR test duration. Shaded boxed regions represent the differences between the pedal rate ranges for POST-CWR$_{2min}$ (lighter grey region) and POST-CWR$_{4min}$ (darker grey region) zones used for ΔPower$_{ave,\ PRS}$ calculation.

https://doi.org/10.1371/journal.pone.0259034.g005

Physiological variables of the CWR tests vs. changes in sprint mechanical variables

The linear mixed model was generated as: ΔPower$_{ave}$ relative to body mass = ($0.07 \times \dot{V}O_{2peak}$) + ($0.14 \times [La^-]_{b,peak}$)–($0.01 \times$ MRT) + ($1.65 \times RER_{peak}$) + ($0.02 \times HR_{peak}$)–($1.26 \times$ CWR test duration) -5.49, with a random effect for individual participants. An ANOVA of the model revealed significant effects for $\dot{V}O_{2peak}$, $[La^-]_{b,peak}$ and CWR test duration ($p<0.05$). As a result, these physiological variables were found to be best related to the functional mechanical decline after the CWR tests.

Discussion

The main purpose of this study was to determine whether a shorter (2-min), severe-intensity constant work rate (CWR) cycling test could be used as a proxy for a longer (4-min) test. This CWR test was selected to simulate a 4-km pursuit time trial in track cycling where performance is influenced by the ability to mitigate reductions in the power output and tolerate the inevitable peripheral muscle fatigue developed at these high physiological work rates. The

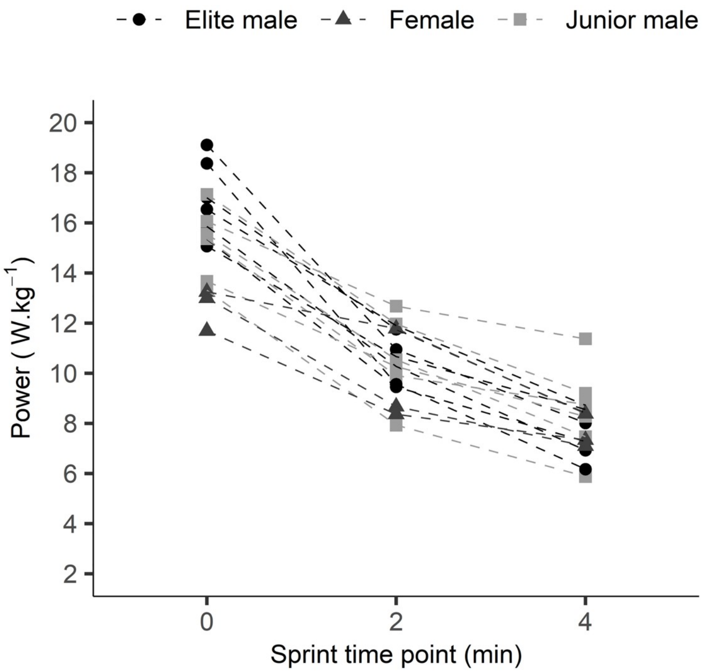

Fig 6. Peak power (relative to body mass) before and after the 2- and 4-min CWR tests for all participants. Irrespective of individual variation, a greater overall functional deficit was observed for the longer test duration. Sprint time point '0' represents the relative peak power in pre-CWR sprints whereas time points '2' and '4' represent the relative peak power in sprints performed after the 2-min and 4-min CWR tests, respectively. Shapes represent the different groups of cyclists: Black dots = elite men, light grey squares = junior (U19) men, dark grey triangles = women.

https://doi.org/10.1371/journal.pone.0259034.g006

findings confirmed our hypotheses. First, the CWR test of 50% of the original duration was sufficient to elicit substantial fatigue, as indicated by the significant loss in mechanical power, and this magnitude of reduction was strongly correlated with the power loss measured in the longer test. Both the physiological and mechanical variables (i.e., the fatigability estimates) were independently and strongly correlated between the CWR tests despite the tests being performed on different days, and thus being influenced by between-day variability. This highlights the comparable nature of the tests. Second, the differences in $\dot{V}O_{2peak}$, blood lactate concentration, and the duration of the CWR tests were strongly associated with the decline in mechanical power output measured across the sprints. Although no single physiological variable can be used to predict the loss in mechanical power (i.e., fatigability) independently, explosive sprints both before and after a shorter CWR test can allow an estimate of fatigue that would be obtained in the longer test, without causing the same extent of fatigue. Shorter CWR tests followed by maximal sprints may therefore be useful as a (regular) fatigue assessment and monitoring tool in athletic testing environments.

The participants completed 2- and 4-min CWR tests at 109% of their predicted mechanical power output at $\dot{V}O_{2peak}$, which reflected their individual track cycling pursuit power capacity. A decline of 32 ± 8% and 47 ± 9% in mechanical power (i.e., functional capacity) was caused by the 2- and 4-min CWR tests, respectively. Analogous to our findings, others [16, 17, 20, 36–38] have shown maximal power reductions of 25–32% after submaximal CWR cycling tests performed at 60–98% of the mechanical power reached at $\dot{V}O_{2peak}$ for durations of 3–10 min. It is likely that the greater (47%) decrease in power output after the 4-min CWR test in the present study reflects the higher workloads (e.g., 109% vs. 60–98% of the mechanical power output at $\dot{V}O_{2peak}$) and cadences (100–110 rpm vs. ~60–90 rpm), higher level of athletic training ability, and potentially, the different sprint modality used in the present study.

In addition to changes in functional mechanical power output, differences in the torque-angular velocity (or cadence) and power-angular velocity relationships during maximal cycling present valid estimates of performance fatigue [33, 38, 39]. As done by Capelli and colleagues [17] and Marcora and Staiano [10], we employed a cadence-dependent (isoinertial) mode on the cycle ergometer, allowing the participants to accelerate to a maximal cadence in each sprint. As illustrated in Fig 5, the linear torque-cadence and parabolic power-cadence relationships of the fatigued sprints shifted downwards, indicating that the athletes' functional performance abilities were severely compromised by the prior CWR tests; that is, they were highly fatigued [10, 33, 39]. This was particularly evident after the 4-min CWR test, in which the participants were unable to re-generate the same level of torque and angular velocity after the CWR tests despite producing maximal voluntary effort. One may therefore gain insight into task fatigability by imposing a maximal sprint immediately after a CWR test, where it would otherwise not have been quantified since there was no mechanical drop in power during CWR tests. More importantly, the shorter test was discernibly less strenuous and should thus have less impact on subsequent recovery and training. This possibility should be explicitly determined in a future study.

As the cycle sprints were used to predict the functional loss rather than muscle fatigue specifically, sprint cadence was not fixed to the cadence of the CWR test. Thus, the velocity-dependent effect of fatigue was not accounted for [36, 40]. Because a cadence-dependent mode was used, participants could increase cadence as a means of increasing power, which reflects the temporal and kinetic patterns obtained when using fixed gears on a track bicycle (where cadence must increase when power increases). Not only did the CWR tests compromise the maximal cadence achieved compared to a non-fatigued sprint, but the acceleration was also severely impacted. This is evidenced by similarities between the average CWR test cadence (105.5 ± 7.1 rpm) and peak sprint cadence (105.5 ± 11.1 rpm), which may partly be explained by the non-fatigued sprint commencing from a stationary start whilst the fatigued sprint commenced, without pause, at the final cadence of the CWR test (i.e., from a rolling start). To account for this limitation, we calculated the average difference in mechanical power for the 'pedal rate-specific region': the cadence range of the fatigued sprint. However, like the decline in peak power (32% and 47%), decrements in average power during the pedal rate-specific region were found after the 2- (37 ± 5%) and 4-min (51 ± 6%) CWR tests. Therefore, the functional performance outcomes were severely affected by both 2-and 4 min CWR tests even when partly accounting for velocity-dependent differences.

As illustrated by the loss in functional mechanical power, the present results show that a CWR test of 50% of the original duration was sufficient to induce fatigue, regardless of the exact mechanisms underpinning the fatigue (i.e., in the muscular, cardiovascular, or central nervous system) [13]. Moreover, strong correlations (r = 0.83–0.92) were found between the functional decline in power induced by the 2 and 4-min CWR tests within a prediction error (SEE) of 14–16%. (Fig 4). It is important to consider the SEE not only reflects variability in the post-CWR test performance, but also the variability of the pre-CWR test (i.e., it is a complex variable calculated as post–pre score), which may include the test commencing with different starting conditions than the post-CWR test. The opportunity thus exists to use the POST-CWR power alone (SEE = 8.5%) as long as one is confident that the athlete started the CWR in the same state as the previous test (i.e., through means of a PRE-CWR sprint, 2.7%

SEE). Nevertheless, due to the strong association between the 2-and 4-min CWR tests obtained in the present study, and despite the tests being done on different days, one can be confident that the functional decline estimated in the 2-min test is strongly reflective of that which would be obtained in a 4-min CWR test. Further research is required to specifically assess the systematic error between tests when they are performed on the same day with sufficient recovery, which was not possible in the present study.

In addition to the power loss, an important aim was to assess differences in the physiological demands between the CWR tests to provide insight into the energetic state of the muscles and their influence on the subsequent maximal mechanical power loss. All physiological variables increased in magnitude with a similar trajectory between the tests, which eventually resulted in a greater decrease in mechanical power after the 4-min CWR test. Strong relationships and small SEEs indicated that the physiological variables (e.g., $\dot{V}O_{2peak}$, RER and heart rate) obtained in the 2-min CWR test could be used to predict the outcomes of the 4-min CWR test, at least within a 2.6–3.1% error range (Fig 2). It was identified that neither the duration of the CWR test nor the fact that the CWR tests were performed on different days affected $\dot{V}O_2$ kinetics ($\dot{V}O_{2peak}$ $p = 0.08$ and MRT $p = 0.77$, and therefore the oxygen deficit) or RER_{peak} ($p = 0.50$).

Alternatively, significant increases were found in peak blood lactate concentration, peak heart rate and minute ventilation as well as RPE for the longer CWR test. It can be assumed that the greater rise in these physiological variables during the 4-min CWR test would be associated with a greater anaerobic metabolism (i.e., decreased [PCr] and increased muscle lactate concentrations and therefore [H^+] accumulation). This would result in a greater homeostatic disturbance and reduced exercise tolerance, or in our case, lead to a greater change in mechanical power output measured immediately after the 4-min CWR test [4–6, 12]. Other researchers have found that exhaustive cycling exercise within the severe-intensity domain, regardless of work rate or test duration, is associated with the same level of depletion of high energy phosphates [PCr] and the accumulation of [H^+], [ADP] and [Pi], as well as lactate due to the greater rate of glycolysis, and that the $\dot{V}O_2$ will continue to rise until reaching $\dot{V}O_{2max}$ (i.e., $\dot{V}O_2$ slow component) [4–6, 12]. This resulting cellular homeostatic imbalance can influence various components within the muscular (sarcomeric) excitation-contraction coupling process, resulting in a functional decline manifested as a reduced external functional power output [7, 8]. The findings from the mixed linear regression model suggest that $\dot{V}O_{2peak}$, peak blood lactate concentrations and the duration of the CWR tests were significantly associated with the decline in the average power measured across the sprints. Consequently, for the same power output within the severe intensity domain, exercising for a longer duration resulted in a greater instability of the internal metabolic environment, which was subsequently expressed as a greater loss in functional explosive power.

Whilst considering the predictive error, a shorter CWR test may provide a valid substitute for the longer tests, which are significantly physiologically and psychologically taxing and induce substantial residual fatigue. Although the exact temporal recovery response remains to be tested in future studies, the shorter test was more tolerable as it induced less fatigue and is not expected to substantively impact long-term athlete fatigue or training schedules. Consequently, it may be more frequently used in a training season (including at the start of a training session) to monitor performance and fatigue levels. The shorter test also introduces the possibility of completing multiple shorter tests within a single session to assess the effects of various interventions (such as bicycle-set up variations, recovery or nutritional interventions, etc.) and thus with reduced error imposed by between-day changes.

Conclusion

A severe- intensity CWR test lasting 50% of the original duration (i.e., 2 min vs. 4 min) may be used as a proxy for outcomes that would be obtained in a test of twice the duration. The present results demonstrate that the shorter CWR test was sufficient to evoke fatigue by detecting meaningful changes in physiological variables measured during, and maximal cycling power output measured immediately after, the 2-min CWR tests. However, the 2-min test was significantly less fatiguing and thus more physiologically and psychologically tolerable. One should consider the possibility of using a post-CWR sprint alone as the outcome variable to reduce the variability that is inherent within a change scores (pre-to-post) type of test. It is important, however, that a pre-CWR test be used to assess the athlete's physiological state and their readiness to perform and ensure they are within the normal testing variability. Laboratory tests that simulate competition intensities (such as an individual pursuit) can therefore be performed more regularly by using a shorter-duration CWR test that subsequently requires less recovery time and thus impacts subsequent training and competition preparation to a lesser extent, although the specific magnitudes of these effects require further study. Such tests could be used to monitor training adaptation or to assess the effects of acute and chronic interventions, such as changing bicycle-rider biomechanics, recovery or nutritional strategies, equipment, etc. In well trained athletes, it is likely that multiple tests could be conducted on the same day, assuming adequate recovery is provided, increasing testing efficiency. Additionally, as the capacity to produce and maintain high power outputs after a prior fatiguing exercise bout is essential for performance success, the ability to produce higher power output for a given level of fatigue or produce the same power after a CWR of higher mean power would indicate a performance improvement. Importantly, end-burst power following sustained, high-power cycling has implications for other track (e.g. Keirin or bunch races) and road cycling race events where a final sprint often dictates race outcomes.

Acknowledgments

The authors would like to thank all participants for volunteering their time to complete the study. We also thank Kirstin Morris and Katie McGibbon for valuable feedback on a draft version of the manuscript, and Shih Ching Fu for his statistical advice. This work was supported by the Industry Engagement Scholarship between the Queensland Academy of Sport's Sport Performance Innovation and Knowledge Excellence unit and Edith Cowan University.

Author Contributions

Conceptualization: Chantelle du Plessis, Mark Andrews, Anthony J. Blazevich.

Data curation: Chantelle du Plessis.

Formal analysis: Chantelle du Plessis, Lachlan J. G. Mitchell, Anthony J. Blazevich.

Investigation: Chantelle du Plessis.

Methodology: Chantelle du Plessis, Mark Andrews, Jodie Cochrane Wilkie, Anthony J. Blazevich.

Project administration: Chantelle du Plessis.

Resources: Chantelle du Plessis, Trish King.

Software: Chantelle du Plessis, Mark Andrews, Lachlan J. G. Mitchell.

Supervision: Mark Andrews, Trish King, Anthony J. Blazevich.

Visualization: Chantelle du Plessis, Lachlan J. G. Mitchell.

Writing – original draft: Chantelle du Plessis.

Writing – review & editing: Chantelle du Plessis, Mark Andrews, Jodie Cochrane Wilkie, Trish King, Anthony J. Blazevich.

References

1. Craig JC, Vanhatalo A, Burnley M, Jones AM, Poole DC. Critical power: possibly the most important fatigue threshold in exercise physiology. In: Jerzy AZ, editor. Muscle and Exercise Physiology. Manhattan, United States: Elsevier; 2019. p. 159–81.
2. Fletcher JR, Groves EM, Pfister TR, MacIntosh BR. Can muscle shortening alone, explain the energy cost of muscle contraction in vivo? European Journal of Applied Physiology. 2013; 113(9):2313–22. https://doi.org/10.1007/s00421-013-2665-0 PMID: 23712215
3. Fenn WO. The relation between the work performed and the energy liberated in muscular contraction. The Journal of Physiology. 1924; 58(6):373–95. https://doi.org/10.1113/jphysiol.1924.sp002141 PMID: 16993634
4. Broxterman RM, Layec G, Hureau TJ, Amann M, Richardson RS. Skeletal muscle bioenergetics during all-out exercise: mechanistic insight into the oxygen uptake slow component and neuromuscular fatigue. Journal of Applied Physiology. 2017; 122(5):1208–17. https://doi.org/10.1152/japplphysiol.01093.2016 PMID: 28209743
5. Jones AM, Wilkerson DP, DiMenna F, Fulford J, Poole DC. Muscle metabolic responses to exercise above and below the "critical power" assessed using P-MRS. American Journal of Physiology-Regulatory, Integrative and Comparative Physiology. 2008; 294(2):R585–R93. https://doi.org/10.1152/ajpregu.00731.2007 PMID: 18056980
6. Hogan MC, Richardson RS, Haseler LJ. Human muscle performance and PCr hydrolysis with varied inspired oxygen fractions: a P-MRS study. Journal of Applied Physiology. 1999; 86(4):1367–73. https://doi.org/10.1152/jappl.1999.86.4.1367 PMID: 10194224
7. Fitts RH. Mechanisms of muscular fatigue. In: Poortmans JR, editor. Priciples of Exercise Biochemistry. 46. 3rd ed. Basel: Basel, Karger; 2004. p. 279–300.
8. MacIntosh BR, Holash RJ, Renaud J-M. Skeletal muscle fatigue–regulation of excitation–contraction coupling to avoid metabolic catastrophe. Journal of Cell Science. 2012; 125(9):2105–14. https://doi.org/10.1242/jcs.093674 PMID: 22627029
9. Fitts RH. Cellular mechanisms of muscle fatigue. Physiological Reviews. 1994; 74(1):49–94. https://doi.org/10.1152/physrev.1994.74.1.49 PMID: 8295935
10. Marcora SM, Staiano W. The limit to exercise tolerance in humans: mind over muscle? European Journal of Applied Physiology. 2010; 109(4):763–70. https://doi.org/10.1007/s00421-010-1418-6 PMID: 20221773
11. Whipp BJ, Rossiter HB. The kinetics of oxygen uptake: physiological inferences from the parameters. In: Jones A, Poole D, editors. Oxygen Uptake Kinetics in Sport, Exercise and Medicine. 1st ed. London: Routledge; 2005. p. 62–94.
12. Black MI, Jones AM, Blackwell JR, Bailey SJ, Wylie LJ, McDonagh ST, et al. Muscle metabolic and neuromuscular determinants of fatigue during cycling in different exercise intensity domains. Journal of Applied Physiology. 2017; 122(3):446–59. https://doi.org/10.1152/japplphysiol.00942.2016 PMID: 28008101
13. Abbiss CR, Laursen PB. Models to explain fatigue during prolonged endurance cycling. Sports Medicine. 2005; 35(10):865–98. https://doi.org/10.2165/00007256-200535100-00004 PMID: 16180946
14. Knight DR, Poole DC, Schaffartzik W, Guy HJ, Prediletto R, Hogan MC, et al. Relationship between body and leg VO2 during maximal cycle ergometry. Journal of Applied Physiology. 1992; 73(3):1114–21. https://doi.org/10.1152/jappl.1992.73.3.1114 PMID: 1400024
15. Poole DC, Jones AM. Oxygen uptake kinetics. Comprehensive Physiology. 2012; 2(2):933–96. https://doi.org/10.1002/cphy.c100072 PMID: 23798293
16. Sargeant A, Dolan P. Effect of prior exercise on maximal short-term power output in humans. Journal of Applied Physiology. 1987; 63(4):1475–80. https://doi.org/10.1152/jappl.1987.63.4.1475 PMID: 3693183
17. Capelli C, Antonutto G, Zamparo P, Girardis M, di Prampero PE. Effects of prolonged cycle ergometer exercise on maximal muscle power and oxygen uptake in humans. European Journal of Applied

Physiology and Occupational physiology. 1993; 66(3):189–95. https://doi.org/10.1007/BF00235092 PMID: 8477672

18. Froyd C, Millet GY, Noakes TD. The development of peripheral fatigue and short-term recovery during self-paced high-intensity exercise. The Journal of Physiology. 2013; 591(5):1339–46. https://doi.org/10.1113/jphysiol.2012.245316 PMID: 23230235
19. Coelho AC, Cannon DT, Cao R, Porszasz J, Casaburi R, Knorst MM, et al. Instantaneous quantification of skeletal muscle activation, power production, and fatigue during cycle ergometry. Journal of Applied Physiology. 2015; 118(5):646–54. https://doi.org/10.1152/japplphysiol.00948.2014 PMID: 25539940
20. Elmer SJ, Marshall CS, Wehmanen K, Amann M, McDaniel J, Martin DT, et al. Effects of locomotor muscle fatigue on joint-specific power production during cycling. Medicine and Science in Sports and Exercise. 2012; 44(8):1504–11. https://doi.org/10.1249/MSS.0b013e31824fb8bd PMID: 22343616
21. Lamberts RP, Swart J, Noakes TD, Lambert MI. A novel submaximal cycle test to monitor fatigue and predict cycling performance. British Journal of Sports Medicine. 2011; 45(10):797–804. https://doi.org/10.1136/bjsm.2009.061325 PMID: 19622525
22. Åstrand P-O, Ryhming I. A nomogram for calculation of aerobic capacity (physical fitness) from pulse rate during submaximal work. Journal of Applied Physiology. 1954; 7(2):218–21. https://doi.org/10.1152/jappl.1954.7.2.218 PMID: 13211501
23. Tanner R, Gore C. Physiological tests for elite athletes. 2 ed: Human kinetics; 2012.
24. Driller MW, Argus CK, Bartram JC, Bonaventura J, Martin DT, West NP, et al. Reliability of a 2-bout exercise test on a wattbike cycle ergometer. International Journal of Sports Physiology and Performance. 2014; 9(2):340–5. https://doi.org/10.1123/ijspp.2013-0103 PMID: 23920473
25. Jones AM, Vanhatalo A. The 'critical power'concept: applications to sports performance with a focus on intermittent high-intensity exercise. Sports Medicine. 2017; 47(1):65–78.
26. Borg GA. Psychophysical bases of perceived exertion. Medicine and Sience in Sports and Exercise. 1982.
27. Gottschall JS, Palmer BM. The acute effects of prior cycling cadence on running performance and kinematics. Medicine and Science in Sports and Exercise. 2002; 34(9):1518–22. https://doi.org/10.1097/00005768-200209000-00019 PMID: 12218748
28. Gurfinkel V, Levik YS, Kazennikov O, Selionov V. Locomotor-like movements evoked by leg muscle vibration in humans. European Journal of Neuroscience. 1998; 10(5):1608–12. https://doi.org/10.1046/j.1460-9568.1998.00179.x PMID: 9751133
29. Mildenhall M. The effect of acidosis on peak power after a simulated 4000-m individual pursuit on a bicycle ergometer. Auckland, New Zealand: Auckland University of Technology; 2019.
30. Craig NP, Norton KI. Characteristics of track cycling. Sports Medicine. 2001; 31(7):457–68. https://doi.org/10.2165/00007256-200131070-00001 PMID: 11428683
31. Hill DW, Poole DC, Smith JC. The relationship between power and the time to achieve VO2max. Medicine and Science in Sports and Exercise. 2002; 34(4):709–14. https://doi.org/10.1097/00005768-200204000-00023 PMID: 11932583
32. Whipp BJ, Ward SA, Rossiter HB. Pulmonary O2 uptake during exercise: conflating muscular and cardiovascular responses. Medicine and Science in Sports and Exercise. 2005; 37(9):1574–85. https://doi.org/10.1249/01.mss.0000177476.63356.22 PMID: 16177611
33. Gardner AS, Martin DT, Jenkins DG, Dyer I, Van Eiden J, Barras M, et al. Velocity-specific fatigue: quantifying fatigue during variable velocity cycling. Medicine and Science in Sports and Exercise. 2009; 41(4):904–11. https://doi.org/10.1249/MSS.0b013e318190c2cc PMID: 19276842
34. Schober P, Boer C, Schwarte LA. Correlation coefficients: appropriate use and interpretation. Anesthesia and Analgesia. 2018; 126(5):1763–8. https://doi.org/10.1213/ANE.0000000000002864 PMID: 29481436
35. Kuznetsova A, Brockhoff PB, Christensen RH. lmerTest package: tests in linear mixed effects models. Journal of Statistical Software. 2017; 82(1):1–26.
36. Beelen A, Sargeant A. Effect of fatigue on maximal power output at different contraction velocities in humans. Journal of Applied Physiology. 1991; 71(6):2332–7. https://doi.org/10.1152/jappl.1991.71.6.2332 PMID: 1778931
37. Marcora SM, Staiano W. The parabolic power–velocity relationship does not apply to fatigued states. European Journal of Applied Physiology. 2010; 109(4):787–8. https://doi.org/10.1007/s00421-010-1495-6 PMID: 20443022
38. Buttelli O, Vandewalle H, Peres G. The relationship between maximal power and maximal torque-velocity using an electronic ergometer. European Journal of Applied Physiology and Occupational Physiology. 1996; 73(5):479–83. https://doi.org/10.1007/BF00334427 PMID: 8803510

39. MacIntosh BR, Svedahl K, Kim M. Fatigue and optimal conditions for short-term work capacity. European Journal of Applied Physiology. 2004; 92(4):369–75. https://doi.org/10.1007/s00421-004-1177-3 PMID: 15241693

40. Burnley M. The limit to exercise tolerance in humans: validity compromised by failing to account for the power-velocity relationship. European Journal of Applied Physiology. 2010; 109(6):1225. https://doi.org/10.1007/s00421-010-1465-z PMID: 20373106