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Road cycle TT performance: Relationship to the power-duration model and association with FTP

Original Investigation

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1 ABSTRACT

2 **Purpose:** To determine the accuracy of critical power (CP) and W' (the curvature constant of the power-duration relationship) derived from self-paced time-trial (TT) prediction trials 3 4 using mobile power meters to predict 16.1-km road cycling TT performance. This study also aimed to test the agreement between functional threshold power (FTP) and CP. Methods: 5 6 Twelve competitive male cyclists completed an incremental test to exhaustion, a 16.1-km 7 road TT, an FTP test, and 4–5 self-paced TT bouts on a stationary bike within the lab, using mobile power meters. **Results:** CP and W' derived from the power-duration relationship 8 closely predicted TT performance. The 16.1-km road TT completion time ($26.7 \pm 2.2 \text{ min}$) 9 10 was significantly correlated with the predicted time-to-completion (27.5 \pm 3.3 min, r= 0.89, P < 0.01). CP and FTP were not significantly different (275 ± 40 W vs. 278 ± 42 W, P > 0.05); 11 12 however, the limits of agreement between CP and FTP were 30 to -36 W. Discussion: The 13 findings of this study indicate that CP and W' determined using mobile power meters during maximal, self-paced TT prediction trials can be used to accurately predict 16.1-km cycling 14 15 performance, supporting the application of the CP and W' for performance prediction. However, whilst we demonstrated that the FTP was not significantly different from CP, the 16 17 limits of agreement were too large to consider FTP and CP interchangeable. 18

19 Key words: Critical power; functional threshold power; power meter; power-duration20 relationship; time-trial

21 MAIN TEXT INTRODUCTION

The ability to perform high-intensity (i.e., within the severe-intensity domain) exercise is 22 described by the hyperbolic relationship between power output (PO) and time to the limit of 23 tolerance (T_{lim}) (Jones, Vanhatalo, Burnley, Morton, & Poole, 2010; Morton, 2006). The 24 power asymptote of this relationship is termed the critical power (CP), which reflects the 25 highest work rate that can be sustained without a progressive loss of intramuscular and 26 27 systemic homeostasis (Black, Jones, Kelly, Bailey, & Vanhatalo, 2016; Poole, Ward, Gardner, & Whipp, 1988; Poole, Ward, & Whipp, 1990; Vanhatalo et al., 2016). The 28 29 curvature constant of this relationship, W', represents a fixed amount of work that can be completed above CP before Tlim (Moritani, Nagata, deVries, & Muro, 1981; Poole et al., 30 1988; Poole et al., 1990; Vanhatalo et al., 2016). During exercise above CP, the tolerable 31 duration of exercise is predictable according to the following equation (derived from the 32 power-duration relationship): 33

34

$$T_{\rm lim} = W' / (P - CP) \qquad [Eqn. 1]$$

where P is a given severe-intensity PO. Determination of the power-duration relationship is,
therefore, of considerable value for understanding high-intensity exercise tolerance and for
predicting athletic performance (Jones et al., 2010; Morton, 2006).

38

Previous research has demonstrated that determination of the power-duration relationship
permits accurate estimation of laboratory-based exercise performance (Chidnok et al., 2012;
Chidnok et al., 2013; Hill, Poole, & Smith, 2002; Murgatroyd, Ferguson, Ward, Whipp, &
Rossiter, 2011) and predicts field-based cycling performance (Black, Durant, Jones, &
Vanhatalo, 2014; Smith, Dangelmaier, & Hill, 1999). However, it should be noted that these
field-based investigations predicted performance using regression equations derived from

time-trial (TT) performance and CP rather than incorporating both CP and W' in a prediction
equation:

$$T_{lim} = (W - W')/CP$$
 [Eqn. 2]

When exercising within the severe-intensity domain, knowledge of the 2-parameter CP model
(eqn. 2) permits a more accurate determination of exercise performance (Jones et al., 2010;
Morton, 2006).

51

Despite evidence supporting CP as a powerful determinant of endurance performance (Black 52 et al., 2014; Smith et al., 1999), its application has been hindered by the need for specialist 53 54 equipment, and the arduous and time consuming protocol, which requires the performance of several (\sim 3–5) maximal trials spanning \sim 2–15 minutes in duration (Jones et al., 2010; Hill et 55 al., 2002; Poole et al., 1988; Vanhatalo, Doust, & Burnley, 2007). However, the advent of 56 57 commercially available power meters, that are both valid and reliable (Bertucci, Duc, Villerius, Pernin, & Grappe, 2005; Gardner et al., 2004), provide the opportunity to assess the 58 59 power-duration relationship using equipment widely available to cyclists. The use of a cyclemounted power meter in combination with a static trainer enables the power-duration 60 relationship to be derived using a series of self-paced maximal TTs where the cyclist is able 61 62 to control the gear, cadence, and pacing strategy, more accurately replicating conditions in the field relative to the conventionally used constant work rate time-to-exhaustion trials 63 (Hopkins, Schabort, & Hawley, 2001; Jeukendrup, Saris, Brouns, & Kester, 1996; Laursen, 64 65 Francis, Abbiss, Newton, & Nosaka, 2007). Previous research has demonstrated the utility of cycle-mounted power meters to estimate CP in the field (Karsten, Jobson, Hopker, Jimenez, 66 & Beedie, 2014; Karsten, Jobson, Hopker, Stevens, & Beedie, 2015). However, it remains 67 unclear whether the power-duration relationship derived from TTs using cycle-mounted 68

power meter equipment commonly used by cyclists can accurately predict performance in thefield.

71

72	The functional threshold power (FTP) is a popular index of fitness used among cyclists to
73	provide an estimate of the maximal sustainable (~1 h) PO (Gavin et al., 2012). Equivalent to
74	95% of the mean PO sustained during a maximal self-paced 20-min TT (Allen & Coggan,
75	2006), determination of the FTP can be incorporated into training rides with relative ease.
76	However, despite recent research reporting correlations between FTP (derived from the 20-
77	min TT) and $\dot{V}O_2$ max (Denham, Scott-Hamilton, Hagstrom, & Gray, 2017) and the so-
78	called individual 'anaerobic threshold' (Borszcz, Tramontin, Bossi, Carminatti, & Costa,
79	2018), there is little evidence to support the physiological underpinnings of the FTP and no
80	previous work has established its ability to predict performance.

81

The purpose of this study was: 1) to determine the accuracy with which 16.1-km road cycling TT performance may be predicted by CP and *W*' derived using a road-bike, static trainer and a cycle-mounted power meter; and 2) to assess the agreement between CP and FTP. We hypothesised that the CP and *W*' can be used to accurately predict 16.1-km road cycling TT performance; that FTP would be correlated with 16.1-km road cycling TT performance; and that CP and FTP would be positively correlated and not significantly different from one another.

89

90 MATERIALS AND METHODS

91 Subjects

Twelve healthy, club-level cyclists (mean \pm SD: age, 25 ± 7 years, height 1.80 ± 0.05 m, 92 body mass 75.6 ± 5.9 kg) volunteered and gave written informed consent to participate in this 93 study, which had been approved by the University of Exeter Research Ethics Committee. 94 This study conformed to the principles of the World Medical Association Declaration of 95 Helsinki. Subjects reported to all testing sessions well-hydrated, having avoided strenuous 96 exercise and caffeine ingestion for 24 h and 3 h prior to testing, respectively. All subjects 97 98 were provided with general recommendations on maintaining adequate hydration prior to arrival. Testing was performed at the same time of day (\pm 90 min) for each subject and 99 100 separated by at least 24 h.

101

102 Design

Subjects visited the laboratory on 9-10 occasions, and completed a 16.1-km road-based TT 103 over a 6-week period during pre-season and a minimum of 72 h between testing sessions. All 104 subjects completed: (i) an incremental test to determine peak oxygen uptake ($\dot{V}O_{2peak}$), the 105 106 gas exchange threshold (GET) and peak aerobic PO; (ii) 4-5 TT prediction trials for determination of the power-duration relationship; (iii) a 20-min TT for determination of FTP; 107 and (iv) a 16.1-km road TT (performed mid-way through the testing protocol). Following the 108 initial incremental test, all tests were randomised (excluding the 16.1-km road TT), and 109 performed on the subjects own road-bike with PO and work done measured via a mobile 110 power meter integrated into the rear wheel (PowerTap G3 Hub, CycleOps, Madison, USA) 111 connected wirelessly to a data logger (Edge 500, Garmin, Chicago, USA). The PowerTap G3 112 device was calibrated according to manufacturer's instructions prior to each test. The 113 road-bike was loaded onto a static trainer (Elite Volare Trainer Mag Alu, Fontaniva, Italy) for 114 the prediction trials (test ii) and 20-min TT (test iii), during which maximal resistance was 115 116 placed upon the rear wheel. The trainer resistance (set at arbitrary units of '5') and tyre

pressure (110 psi) was checked prior to each test. All laboratory-based tests were performed
in similar environmental conditions (temperature, 18–20°C; relative humidity, 45–55%).
Subjects were provided with visual and verbal feedback regarding the elapsed distance
completed, distance remaining as well as the elapsed work done and work remaining during
the laboratory TTs to replicate feedback typically received during TT efforts performed in the
field.

123

124 Incremental test

125 On the first laboratory visit, subjects performed a ramp-incremental cycling test for the 126 determination of the GET, peak aerobic PO and the peak oxygen uptake on an electronically 127 braked cycle ergometer (Lode Excalibur Sport, Groningen, the Netherlands). The $\dot{V}O_{2peak}$ 128 was required as a validation criterion of a maximal test during the experimental trials (as 129 described below).

130

131 Determination of the power-duration relationship

CP and W were estimated via 4–5 (4 trials, n = 6; 5 trials, n = 6) self-paced, maximal TTs to 132 obtain a range of times between ~2 and 15 min. This range of work rates was selected to 133 ensure participants were exercising within the severe-intensity domain, which was verified by 134 the measurement of VO₂ during each trial. Subjects were instructed to complete a target total 135 work as quickly as possible with the shortest trial completed within ~ 2 min and the longest 136 lasting <15 min, with two trials spaced equally in between, with a minimum 5 min separating 137 the shortest and longest trials (Bishop, Jenkins & Howard, 1998). Prior to each trial, each 138 subject performed a standardised warm-up at a work rate below GET, followed by 5 min of 139

passive rest. Subjects then completed a further 3 min of pedalling at their preferred cadence 140 but with no resistance on the rear wheel. Subjects were familiarised to the maximal 141 self-paced TTs and specific conditions of the task. Subjects performed a minimum of 2 TTs 142 of a set amount of work to result in completion in \sim 5–7 min until the difference in repeated 143 TT duration was <1.3% (Sparks et al., 2016). These trials were not included in the subsequent 144 data analysis. As a quality control measure of the mathematical modelling of the 145 146 power-duration parameters, a priori criteria were set for the standard errors associated with the CP and W', such that if the standard errors exceeded 5% and 10%, respectively, after 4 147 148 prediction trials, additional trials were completed until the standard error of estimate (SEE) was considered acceptable. Any prediction trials where the end-exercise $\dot{V}O_2$ was <95 % of 149 the subject's ramp test determined $\dot{V}O_{2peak}$ were excluded from the modelling of the 150 power-duration relationship. In the one instance where this occurred, the participant was 151 willing to revisit the laboratory to re-perform this trial. 152

153

154 Determination of the functional threshold power

Following the same experimental setup as described for the prediction trials, the FTP test started with 3 min of baseline pedalling at <90% GET at preferred cadence, followed by a 20min maximal, self-paced TT. The FTP was defined as 95% of the mean PO achieved during the 20-min TT (Allen & Coggan, 2006). All subjects reported completing the FTP test as part of their regular training regime.

160

161 *16.1-km road TT*

The TT was performed in Exeter (Devon, UK), on a dry day, with minimal wind, and an 162 ambient air temperature of ~14°C. All subjects were familiar with the 16.1-km road TT route 163 which they used regularly as part of club training sessions. The course initially directed 164 participants out by ~7 km before making a U-turn and covering the same course in the 165 opposite direction. There was minimal elevation, or variation in gradient or terrain throughout 166 the trial (Figure 1). Subjects followed their normal pre-competition warm-up, and were 167 168 instructed to perform maximally during the 16.1-km TT and not to draft. All subjects performed the TT on the same day, within the same hour. To reduce the possibility of 169 170 drafting, start times were separated by a 1-min interval and assigned based on previous TT performance, so that the fastest cyclist started first. Time-to-completion was recorded to the 171 nearest second and PO was used to calculate total work done (time integral x difference in 172 PO). All subjects completed the 16.1-km TT on their own individual road bike, which were 173 all of a similar high-standard, fitted with the same power meter device that was used for 174 laboratory assessments such that 12 power meters of the same model were used throughout 175 the study. 176

177

178 Breath-by-breath gas analysis

During all laboratory tests, pulmonary gas exchange was measured breath-by-breath using an online gas analyser (Mobile Jaegar Oxygen Pro, Hoechberg, Germany). The analyser was calibrated before each test with gases of known concentration, and a calibration syringe of known volume (3-L; Hans Rudolph, KS).

183

184 Data Analysis

The CP and W' parameters were estimated using 3 models: the hyperbolic power-time (P-T_{lim}) model (eqn. 1); the linear work-time (W-T_{lim}) model, where total work done is plotted against time (eqn. 3); and the linear inverse-of-time (1/T_{lim}) model, where PO is plotted against the inverse of time (eqn. 4):

189

$$W = CP \cdot T_{\lim} + W' \tag{Eqn. 3}$$

190

$$\mathbf{P} = \mathbf{W}' \cdot (1/T_{\text{lim}}) + \mathbf{C}\mathbf{P}$$
 (Eqn. 4)

The power (P) during the TTs was defined as the mean PO measured across the duration of 191 the trial. The SEE associated with the CP and W' was expressed as coefficient of variation 192 (CV%). The "total error" associated with the modelling of the power-duration parameters 193 was calculated as the sum of the CV% associated with the CP and W'. The sum of the CV% 194 was optimised for each individual by selecting the model with the smallest and highest total 195 error (eqn. 1, 3 or 4) to produce the "best individual fit" (BIF) and "worst individual fit" 196 (WIF) parameter estimates (Black, Jones, Bailey, & Vanhatalo, 2015; Black et al., 2016). The 197 BIF and WIF parameter estimates were then used to predict 16.1-km road TT performance 198 199 retrospectively by using eqn. 2 and the individual total work done which was measured for each subject. 200

201

202 Statistical analysis

203 One-way analysis of variance was used to assess differences in: (i) power-duration 204 parameters between models (eqn. 1–3), and; (ii) $\dot{V}O_{2peak}$ achieved in the ramp incremental 205 test, prediction trials, and the FTP test. Paired samples *t*-tests and Bland-Altman analyses 206 were used to assess differences and agreement between the actual and predicted 16.1-km road 207 TT performance times, between CP and FTP, and between BIF and WIF models. Similarity

between actual and predicted time-trial performance as well as between CP and FTP was also 208 assessed via the mean bias. Mean bias was calculated as the difference between this estimated 209 value and the 'true' value of the parameter being estimated as expressed as a percentage of 210 the true variable. The prediction of TT performance using FTP was assessed via regression 211 analysis. Paired samples t-tests and Bland-Altman analyses were used to assess differences 212 and agreement between the actual and predicted 16.1-km road TT performance times using 213 214 the FTP. Pearson's product moment correlation coefficients were used to assess relationships between 16.1-km road TT performance and the GET, VO_{2peak}, CP, and FTP. For calculation 215 216 of effect size, Cohen's d was used for paired t-tests. Statistical significance was accepted when P < 0.05 and data are presented as mean \pm SD. 217

218

219 **RESULTS**

220 16.1-km road TT performance

Subjects completed the 16.1-km road TT in 26.7 ± 2.2 min. The mean PO and cadence were
222 296 ± 38 W and 94 ± 6 rpm, respectively. Total work done in the road TT was 467 ± 39 kJ.
The group mean pacing strategy is displayed in Figure 1.

224

225 Ramp incremental test

During the ramp incremental test, subjects attained a peak aerobic PO of 427 ± 34 W and a \dot{VO}_{2peak} of 4.73 ± 0.49 L·min⁻¹ (63.5 ± 6.5 ml·kg⁻¹·min⁻¹). The GET occurred at 2.08 ± 0.28 L.min⁻¹ and 157 ± 32 W. The \dot{VO}_{2peak} measured during the ramp incremental test was not different from the end-exercise \dot{VO}_2 measured during the prediction trials (4.83 ± 0.46 L.min⁻¹) and the FTP test (4.81 ± 0.48 L.min⁻¹; *P*=0.59). The \dot{VO}_{2peak} (*r*= -0.70, *P*<0.01) and peak PO (*r*= -0.84, *P*<0.01) during the ramp incremental test were significantly correlated with 16.1-km road TT performance (i.e. completion time), but no relationship was observed between TT performance and the GET (r= -0.31, P=0.33).

234

235 *Power-duration parameters*

During the maximal, self-paced TT prediction trials, mean PO ranged from 246 to 528 W, 236 which resulted in completion times ranging from 84 to 789 s. Importantly, VO_{2peak} was 237 238 attained during all trials, confirming that each trial was performed within the severe-intensity domain and, thus could be used to establish the power-duration relationship (Burnley & 239 240 Jones, 2007; Hill et al. 2002). The mean cadence during the TT prediction trials was 94 ± 5 rpm, and was not significantly different to the preferred cadence selected during the ramp 241 incremental test or the 16.1-km road TT (P=0.77). Group mean CP and W' estimated using 242 the BIF were 275 ± 42 W and 20.0 ± 7.0 kJ, respectively. When using the WIF, CP (273 ± 42 243 W) and W' (20.6 \pm 8.2 kJ) were not significantly different from BIF estimates (P=0.69, 244 d=0.04). In addition, there were no differences between equations 1, 3 and 4 in CP or W' 245 estimates (P=0.79; Table 1), which indicated low levels of random error within the prediction 246 trial data (Hill & Smith, 1994). There was no difference between predicted TT performance 247 using the BIF or WIF (BIF: 27.5 \pm 3.3 min vs. WIF: 27.8 \pm 2.9min, P=0.45, d=0.12). The 248 BIF parameter estimates were obtained from the P-T_{lim} model in 2 subjects and from the 249 1/T_{lim} and W-T_{lim} in 6 and 4 subjects, respectively. The WIF parameter estimates were 250 251 obtained from the P-T_{lim} model in 7 subjects and from the 1/T_{lim} and W-T_{lim} in 1 and 4 subjects, respectively. However, whilst the actual TT performance $(26.7 \pm 2.2 \text{ min})$ was not 252 different to that predicted from the BIF model (P=0.13, d=0.29), there was a significant 253 difference between actual performance and the prediction derived from the WIF model 254 (P=0.02, d=0.47). Therefore, BIF model parameters were used in further analyses. The 255 predicted time-to-completion underestimated actual TT performance with a mean bias of -49 256

257 \pm 104 s which corresponded to 2.9% of actual TT performance (Figure 2b). The CP was 258 inversely correlated with 16.1-km road TT performance (*r*= -0.89, *P*<0.01; Figure 3a). No 259 significant relationship was observed between *W*' and TT performance (*r*= 0.43, *P*=0.16). The 260 16.1-km road TT completion time was significantly correlated with the predicted time (27.5 \pm 261 3.3min) to completion (*r*= 0.88, *P*<0.01; Figure 2a).

262

263 Functional threshold power

The group mean PO during the 20-min FTP test was 292 ± 44 W, which corresponded to an 264 265 FTP of 278 ± 42 W (Figure 4). The FTP was not significantly different to CP (275 ± 42 W, P=0.57, d=0.07; Figure 2c; 2d). The FTP predicted TT performance with a mean difference 266 of 60 s (3.8% difference, P=0.99). The FTP was positively correlated with the CP (r=0.92, 267 P < 0.01; Figure 2c) with a mean bias of -3 ± 17 W (1.3%; Figure 2d). The deducted 5% of 268 work output during the 20-min FTP test was not significantly correlated with the W' (r=0.42, 269 P=0.26). The FTP was inversely correlated with 16.1-km TT completion time (r=-0.87, 270 *P*<0.01; Figure 3b). 271

272

273 DISCUSSION

274 The current study assessed the accuracy with which road cycling TT performance may be predicted by the parameters of the power-duration relationship (i.e., CP and W) derived using 275 equipment commonly used by cyclists for training. The main finding of this study was that 276 consistent with our primary hypothesis, the power-duration relationship established in the 277 laboratory provided a prediction that was not statistically different from, and was strongly 278 279 correlated with, actual 16.1-km road TT performance. In agreement with our second hypothesis, the FTP was correlated with, and not different from, the CP, but the limits of 280 agreement between CP and FTP were relatively large (+10.9 to -13.1%). Collectively, these 281

findings substantiate the scientific foundations for the translation of laboratory-based

assessments of the power-duration relationship to predict athletic performance in the field.

However, the FTP should not be considered interchangeable with CP and the physiological

285 justification for the FTP protocol remains questionable.

286

Previous research has shown that the CP alone is a strong predictor of field based cycling 287 performance (Black et al., 2014; Smith et al., 1999). However, knowledge of the 288 289 power-duration parameters (i.e., CP and W') derived from the 2-parameter CP model (eqn. 2) should permit a more accurate determination of exercise performance >CP (i.e. within the 290 severe intensity domain, Jones et al., 2010; Morton, 2006). To test this assumption, we used 291 the 2-parameter CP model to predict 16.1-km road TT performance, which is typically 292 performed at a mean PO slightly above CP (Brickley, Dekerle, Hammond, Pringle, & Carter, 293 2007). Indeed, the PO sustained during the 16.1-km TT (~296 W) was 7.8% greater than CP 294 295 and 6.7% greater than FTP. This is in agreement with previous research showing that a power 296 output at or close to CP can be maintained for ~20-60 min (Brickley et al., 2002; Bull et al., 2000; Housh et al., 1989; McLellan and Cheung, 1992). In addition, we showed that the 2-297 parameter CP model provided a prediction that was not statistically different from, and was in 298 close agreement with, actual TT performance. The prediction underestimated the 16.1-km TT 299 duration by ~2.9% (Figure 3), which is similar to TT test-retest reliability for trained cyclists 300 301 performing in a laboratory setting (1.3–3.2%, Sparks et al., 2016).

302

303 Despite the 2-parameter CP model (r=0.88) having a superior predictive capability compared

to traditional performance parameters including $\dot{V}O_{2peak}$ (r=0.70), ramp test peak PO (r=

0.84) and GET (r= -0.31), a similarly accurate performance prediction was provided based on

306 CP alone (r= 0.89). It should, however, be noted that knowledge of the power-duration 307 relationship and the total work to be completed permits the estimation of performance 308 according to equation 2. In contrast, knowledge of the CP without knowledge of either, or 309 both, W' or total work to be completed necessitates the use of a regression equation to predict 310 performance which is specific to a particular course and distance (Black et al., 2014). It may, 311 therefore, be prudent to predict TT performance using the CP and W' rather than the CP or 312 FTP alone.

313

In this study, we replicated the current procedures that are recommended to and adopted by 314 athletes and coaches for measuring FTP (Allen & Coggan, 2006). The FTP, which is 315 equivalent to 95% of the PO achieved during a maximal self-paced 20-min TT, is popular 316 among cyclists to determine "sustainable PO for 1 hour", to distinguish between performance 317 capabilities and to track changes in fitness (Gavin et al., 2012). We observed no significant 318 319 difference and a statistically high level of agreement, between CP and FTP suggesting that 320 the FTP may provide a practical means of estimating CP outside the laboratory. Given the strong relationship between CP and FTP (r=0.92), and the similar trial duration of the FTP 321 protocol and the 16.1-km TT, it is unsurprising that the FTP (~278 W) was in close 322 agreement with the mean PO sustained during the 16.1-km TT and correlated with TT 323 completion time (r= -0.87). However, it is important to note that the limits of agreement 324 between CP and FTP in this study (+30 to -36 W) may be considered too large to be 325 practically meaningful for athletes and coaches, and that the agreement between the two 326 327 variables is likely to be coincidental rather than mechanistically linked.

328

15

329	The W' (~20 kJ) accounted for a very small proportion (~4.3%) of the total work performed
330	during the 16.1-km TT (~466 kJ) and therefore, unsurprisingly, no significant relationship
331	was found bet'een the W' and the amount of work performed above FTP during the 20-min
332	TT. Whilst the physiological underpinnings of W' remain to be fully elucidated, it is
333	indicative of a finite amount of work that can be performed above CP, and is associated with
334	the $\dot{V}O_2$ slow component, depletion of muscle phosphocreatine, and the accumulation of
335	fatigue-related metabolites (Burnley & Jones, 2007; Poole, Burnley, Vanhatalo, Rossiter, &
336	Jones, 2016). Accordingly, during exercise above CP, exercise tolerance and/or performance
337	is defined by the magnitude of the W' and its rate of utilisation (Burnley & Jones, 2016;
338	Chidnok et al., 2013; de Souza et al., 2016; Skiba, Chidnok, Vanhatalo, & Jones, 2012).

339

Importantly, during exercise below the CP, the W' can be recovered at a rate dependent on the 340 intensity and duration of the recovery interval, such that a greater reconstitution occurs at 341 342 lower intensities and during longer duration recovery intervals (Burnley & Jones, 2016; 343 Chidnok et al., 2013; de Souza et al., 2016; Skiba et al., 2012). During the self-paced 20-min TT, subjects cycled for periods below their CP (Figure 4), which would have permitted some 344 reconstitution of the W'. However, we found mean W' (~20 kJ) to be higher than the group 345 mean '5% power-time integral' (~ 16.8 kJ) from the FTP test. This is likely explained by 'lost 346 time' spent below CP and the setting of a metabolic limit on the utilization of W' (Fukuba & 347 Whipp, 1999). Future research is warranted to compare the accuracy of performance 348 prediction by the 2-parameter CP model for continuous exercise (present study) against the 349 350 intermittent CP model (Morton & Billet, 2004) and the 'W' balance' model (Skiba et al., 2012) which account for fluctuations in PO including periods <CP. Furthermore, it should be 351 noted that the determination of the FTP is based on the arbitrary subtraction of 5% of the 352

mean power output during a 20-min TT. Indeed, the work performed above FTP was not
equivalent to *W'* thus questioning the physiological bases of the FTP protocol.

355

As mentioned above, the predictive accuracy of the power-duration relationship is influenced 356 357 by a number of factors. It is also important to note that the power-duration relationship is only applicable in the severe intensity domain where a number of additional factors have an 358 increasing important influence on performance and exercise tolerance (Black et al. 2017; 359 Burnley & Jones, 2007), such that attainment of the $\dot{V}O_{2max}$ must be considered an obligatory 360 criterion for a prediction trial to be included in mathematical modelling (Burnley & Jones, 361 2007; Hill et al. 2002). Furthermore, TTs have been reported to be more reliable than 362 constant work rate trials, and better reflect the demands of field-based competition (Hopkins 363 et al., 2001; Jeukendrup et al., 1996; Laursen et al., 2007). Therefore, in the current study, to 364 minimise the influence of performance variability on the power-duration relationship, all 365 exercise trials were self-paced, maximal TTs, where $\dot{V}O_{2peak}$ was attained, and to which 366 367 subjects were familiarised. Moreover, all exercise trials were performed on subjects' personal road bikes allowing each subject to freely control their gear, cadence, and pacing strategy, 368 thus accurately replicating conditions in the field. These considerations (i.e., matching of 369 trials, familiarisation, good reliability and consistent attainment of VO_{2peak}) ensured a good fit 370 of the experimental data to the model. 371

372

Previous research investigating the power-duration relationship has typically adopted a single model (i.e., $P-T_{lim}$, $1/T_{lim}$ or $W-T_{lim}$) for the estimation of the power-duration parameters. To examine the importance of (in)accuracies in the modelled fit to the experimental data we compared the 2-parameter models associated with the least (BIF) and most (WIF) total error

17

for each subject. Interestingly, and despite a good fit of each 2-parameter model to the
experimental data, the WIF significantly underestimated actual TT performance whereas no
significant difference was observed in actual and predicted performance using the BIF. The
findings of the current study, therefore, highlight the importance of model selection, and
support the adoption of the BIF model to ensure accurate prediction of performance (Black et
al., 2015).

383

384 Practical Applications

385 This study demonstrates that the laboratory-based estimate of the power-duration relationship, determined using equipment readily available to cyclists, enables the accurate 386 prediction of field-based cycling performance. It is recommended that athletes and 387 388 practitioners consider incorporating assessment of the power-duration relationship into their normal training routine to monitor fitness and predict performance. The predictive accuracy 389 can be improved by selecting the 2-parameter model that is associated with the lowest 390 modelling error (i.e. BIF). However, whilst we demonstrate, statistically, that FTP provides a 391 close approximate to CP, the limits of agreement are too large to consider FTP and CP 392 393 interchangeable. Therefore, considering the arbitrary definition of the FTP as 95% of mean PO during a 20-min TT, we recommend that FTP is used with caution and instead encourage 394 395 the use of the power-duration relationship for performance prediction.

396

397 Conclusion

The results of the present study demonstrate that the parameters of the power-duration
relationship, CP and *W*', provide a performance prediction that is not statistically significant

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400 from, and is closely correlated with, 16.1-km road cycling TT performance. The CP was more strongly associated with performance than the ramp test peak PO, peak oxygen uptake, 401 W', GET, and FTP, providing further evidence to support the predictive validity and 402 403 performance relevance of the CP. However, despite observing a close agreement between CP 404 and FTP, the limits of agreement were too large to consider these variables as equivalent. Furthermore, due to its arbitrary definition, and that no relationship was observed between 405 the work performed above FTP and W', the physiological relevance of the FTP is questioned. 406 Given the superior predictive capability of the power-duration relationship parameters 407 408 compared to other traditional physiological variables, we encourage applied practitioners and athletes to incorporate CP testing into their training and testing routine as an aid to monitor 409 fitness and predict performance. 410

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414

- 415 **Declaration of interest statement**
- 416 The authors report to conflict of interest.

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544 Figure and table captions

545 *Figure 1*

546 Group mean pacing strategy (white circles) during road 16.1-km time-trial (TT). The dashed 547 black line represents the mean critical power (CP) and the dashed grey line represents the 548 mean functional threshold power (FTP).

549

550 *Figure 2*

Correlation (A and C) and Bland–Altman analyses (B and D) for predicted and actual timetrial (TT) performance (s) and for critical power (CP) and functional threshold power (FTP). In panels A and C, the solid line is the best-fit linear regression, and the dashed line is the line of identity. Time trial performance was predicted using the 2-parameter power-duration model (i.e. CP and W'). In panels B and D (Bland–Altman plots), the dashed horizontal lines represent the 95% limits of agreement (LOA) and the solid black line represents the mean difference (MD) between the two measures.

558

559 *Figure 3*

560 Correlation between critical power (CP) and time-trial (TT) performance (panel A) and

561 functional threshold power (FTP) and TT performance (panel B). Panel C illustrates Bland-

- Altman analysis for predicted and actual time-trial (TT) performance (s). Time trial
- 563 performance was predicted using the FTP during linear regression. The solid black line
- represents the mean difference (MD) and the dashed horizontal lines represent the 95% limits

of agreement (LOA) between the two measures.

566

567 *Figure 4*

- 568 Group mean power output (PO) during 20 min functional threshold power (FTP) test. The PO
- 569 equivalent to critical power has also been included (dashed line).

- 570 *Table 1*
- 571 The parameter estimates derived from eqs. 1-3 and the best and worst individual fits for the
- time trials (TT). Total error indicates the sum of coefficients of variation (CV %) associated
- 573 with critical power (CP) and the curvature constant (W).