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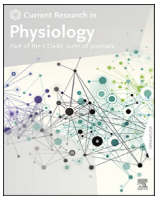

A comparative analysis of critical power models in elite road cyclists

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ABSTRACT

The aims of this study were to compare four different critical power model's ability to ascertain critical power and W′ in elite road cyclists, while making comparison to power output at respiratory compensation point, work rate ($J{\cdot}sec^{-1}$) at W_{max}, and the work done above critical power during the W_{max} test in relation to the W’. Ten male, elite endurance cyclists ($VO_{2max} = 71.9 \pm 5.9$ ml $kg^{-1}{\cdot}min^{-1}$) all familiar with critical power testing, participated in 3 testing sessions comprising 1. 15-s isokinetic (130 rpm) sprint, 1-min time trial, a ramp test to exhaustion, 2–3. a 4-min and/or 10-min self-paced maximal time trial separated by at least 24-h but limited to a 3-week period. The main findings show that all critical power models provided different W’ ($F_{(1.061,8.486)} = 39.07$, $p = 0.0002$) and critical powers ($F_{(1.022,8.179)} = 32.31$, $p = 0.0004$), while there was no difference between each model's critical power and power output at respiratory compensation point ($F_{(1.155,\ 9.243)} = 2.72$, $p = 0.131$). Differences between models or comparisons with respiratory compensation point were deemed not clinically useful in the provision of training prescription or performance monitoring if the aim is to equal work rate at compensation point. There was also no post-hoc difference between work completed at W_{max} (kJ) ($p = 0.890$) and W′ using the nonlinear-3 model. Further research is required to investigate the physiological markers of intensity associated with respiratory compensation point and critical power work rate and the bioenergetic contribution to W’.

1. Introduction

In sport the term ‘critical’ pertains to being of crucial importance to the successful outcome of the individual(s) sporting endeavour, and is likely inclusive of technical, physical, physiological, and psychological performance capability. In mathematics ‘critical’ refers to the transition from one state to another. The ‘Critical Power’ concept (Monod and Scherrer, 1965; Moritani et al., 1981) uses the relationship between work and time, employing various protocols to estimate the transition between exercise intensity domains, specifically, the transition between the heavy domain, where a metabolic steady state can be maintained, and the severe domain where a metabolic steady state does not occur (Vanhatalo et al., 2011). In the transition between these domains there is much debate (Galán-Rioja et al., 2020) over the synonymy between physiological measures and critical power, and ultimately performance within a range of sports.

Initially, the concept identified critical power as an intensity that could persist indefinitely (Monod and Scherrer, 1965). Logically, this suggests an intensity below ventilatory threshold and categorised as ≤ easy. However, the boundless nature is unrealistic (Hill, 1993) and time to exhaustion or sustainable work at the critical power is between 20 and 30-mins (Brickley et al., 2002; Jenkins and Quigley, 1990). This duration combined with reported steady state blood lactate values during the final 20-mins of such time efforts (8.9 ± 1.6 mM (Jenkins and Quigley, 1990)) supports an intensity categorisation in the severe intensity domain. Controlling work rate (W) at such a predetermined level means corresponding physiological values are considerably higher during prolonged efforts (Hill et al., 2002) where ability to sustain work at $\sim VO_{2\ max}$ might be deemed more valuable.

Even so, numerous works have identified significant relationships between critical power and aerobic capability (Chorley et al., 2020; Jones et al., 2010), anaerobic threshold (Moritani et al., 1981), and respiratory compensation point (Bergstrom et al., 2013; Dekerle et al., 2003; Keir et al., 2018), all taken from short stage incremental ramp style tests. However, contradictory evidence suggests that critical power is not a surrogate for respiratory compensation point (Leo et al., 2017) or the onset of blood lactate (Housh et al., 1991) where intensity was greater for critical power than a constant blood lactate of 4 mM (Clingeleffer et al., 1994). Such discrepancies could be explained via differences in protocols combined with participant capability, where small 15 W min^{-1}

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increments, as opposed to 25 and 35 W min^{-1}, to determine work rate at respiratory compensation point did not differ from critical power in recreational cyclists (Keir et al., 2018). However, inferring training work rates from a physiological perspective while utilising short duration incremental tests might be quite limited even though correlated with time trial performance (Amann et al., 2004).

Importantly, time to exhaustion at power outputs associated with respiratory compensation point elicited compliance for 20.53 ± 5.70 min (Moral-González et al., 2020) which is similar to those of critical power (Brickley et al., 2002; Jenkins and Quigley, 1990) and might suggest that ramp style protocols provide similarly useful data about performance capability at set power outputs regardless of corresponding physiological response.

An additional component of the critical power model(s) is the W' (pronounced W-Prime) described as a supra-critical power tolerance (Ferguson et al., 2010). Unlike critical power, W′ is independent to work rate, is finite (Vanhatalo et al., 2011), and was previously linked to maximal oxygen deficit and/or anaerobic capacity (Miura et al., 1999; Moritani et al., 1981; Nebelsick-Gullett et al., 1988; Vandewalle et al., 1989). However, by its very definition one must assume that W′ encompasses an aerobic component between critical power and VO_{2max}, referred to as the VO_2 slow component (Vanhatalo et al., 2011). A big contributing factor to such a measure would include participants ability to sustain $VO_{2\ max}$ (Coats et al., 2003) and the ensuing build-up of fatigue inducing metabolites (Ferguson et al., 2010). At the very least there is likely to be considerable inter-athlete differences in what constitutes W', making it difficult to understand or measure.

Determination of critical power and W′ is possible via a number of models, including the linear-time work (Linear-TW) model (Moritani et al., 1981), the linear-power (Linear-P) model (Hughson et al., 1984), the nonlinear 2-parameter (nonlinear-2) model (Poole et al., 1988), and the nonlinear 3-parameter (nonlinear-3) model (Hugh Morton, 1996). Early work suggested that the linear models overestimated critical power (Hill, 1993) and there was an inverse relationship between models reporting high critical powers and low W′ and vice versa (Housh et al., 1991). High correlations between all models for critical power and long-term ventilatory threshold (20–40 min) has been shown (Gaesser et al., 1995) suggesting generic usefulness for endurance performance differentiation amongst athletes, but also as a means of monitoring training. However, inference to physiological development is limited and only the nonlinear-3 model provided non-significance when compared with long-term ventilatory threshold. Subsequent work in moderately trained non-cyclists supports the value of the nonlinear-3 model for determining critical power and W' (Bergstrom et al., 2014) from shorter duration ramp style protocols typically used for assessing athletes.

The aims of this study were to compare four different critical power model's ability to ascertain critical power and W′ in elite road cyclists, while making comparison to power output at respiratory compensation point, work rate ($J{\cdot}sec^{-1}$) at W_{max}, and the work done above critical power during the W_{max} test in relation to the W'. It is hypothesised that work rate associated with respiratory compensation point will not differ from critical power but differences between models will occur. As W′ includes proportional representation from maximal aerobic capability work rate at W_{max} will relate positively. This is the first study to assess differences between critical power models within an elite cyclists population, that considers individual variability, while presenting a novel method indicating the propensity of aerobic and anaerobic contribution to W'.

2. Methods

2.1. Participants

Ten male, nationally-internationally competitive endurance cyclists (3–15 years racing/training experience, age = 25 ± 5 years; height = 178.7 ± 3.5 cm; weight = 70.3 ± 7.7 kg; VO_{2max} = 71.9 ± 5.9 ml $kg^{-1}{\cdot}min^{-1}$) all familiar with critical power testing, participated in 3 laboratory testing sessions comprising: 1. 15-s isokinetic (130 rpm) sprint on a Cyclus 2 ergometer (Avantronic, Leipzig, Germany), 1-min time trial, plus a ramp style test to exhaustion; and 2–3. A 4-min or 10-min self-paced maximal time trial separated by at least 24-h but limited to a 3-week period. Thus, the efforts (1, 4, and 10-min) used to calculate critical power were in line with previous research on elite cyclists (Bartram et al., 2017). All participants provided written consent in accordance with the University Human Ethics Committee.

2.2. Laboratory testing

On visiting the laboratory, participants were measured for height (SECA 213 stadiometer, Hamburg, GER) and body weight (SECA 876, Hamburg, GER) prior to commencing testing on their own bicycle fitted to a smart trainer (all data logged at 1 Hz using a Garmin Edge 530 (Garmin, Schaffhausen, Switzerland)) compatible with their own bicycle (Wahoo KICKR, Wahoo Fitness, Atlanta, GA, USA; Elite Suito, Fontaniva, ITA; and Tacx Neo Smart T2800, Wassenaar, NL). All trainers were compared to the Verve InfoCrank (InfoCrank Classic, Verve Cycling, Perth AUS) prior to undertaking the study. The InfoCrank has been shown to be valid and reliable previously (Maier et al., 2017) and our own pre-testing comparison with the cranks and trainers to be used provided mean CV (%) over a range of power outputs (200–500 W) of 0.64% for the Tacx Neo, 0.49% for the Wahoo KickR, and 1.64% for the Elite Suito. All trainers were deemed acceptable for use as per standards described within the literature (Hopkins et al., 2009).

Session 1: Prior to the 1-min time trial participants performed a self-selected, pre-approved warm-up as per a competitive scenario of this duration-intensity. Once individual warm-up was completed participants indicated when they were ready, whereupon they were required to reach a cadence of 80 rpm and a power output of 200 W. At this point the 1-min time trial commenced and participants were required to ride as hard (self-selected pacing strategy) as possible for a 1-min period to obtain the best overall average power output.

On completion of the 1-min time trial participants undertook a 5-min active recovery (<150 W), followed by 20-mins of passive recovery prior to commencing the ramp style test. As previous work (Schneider and Berwick, 1997) has shown reductions of, but no uncoupling of V_E from VCO_2 following 1-min maximal exercise, where determination of power output at the respiratory compensation point was not significantly different it was felt 25-mins recovery between tests was appropriate. The ramp test subsequently commenced at 150 W and increasing 30 W min^{-1} until the participant could no longer maintain the required power output (Macdermid and Stannard, 2012). Throughout this test, heart rate (Garmin Edge 530 plus HRM strap), expired air (ParvoMedics Trueone 2400, ParvoMedics, Salt Lake City, UT, USA), and power output were measured. Expired air data averaged every 15-s enabled calculation of peak oxygen consumption and respiratory compensation point as per the methods used previously (Lucia et al., 2000). Two researchers independently determined respiratory compensation point using the criteria of an increase in both VE:VO2 and VE:VCO2 and a decrease in PETCO2. The latter being used to extrapolate work rate at this physiological intensity for comparison with critical power. $VO_{2\ max}$ was classified as the highest 1-min epoch during the final minutes of the test with the corresponding power output identified as W_{max}. The latter being used for comparison with critical power, converted to kJ to compare with W'. Work done (kJ) above respiratory compensation point until W_{max} was reached was also calculated used to determine the ratio of the W'.

Session 2–3: Participants completed either a 4-min or 10-min time trial in randomised order and separated by 24-h (Karsten et al., 2017). Participants were informed of time trial order 24-h prior to testing to allow mental preparation for the effort required. After being weighed and measured participants performed a self-selected, pre-approved warm-up as per a competitive scenario of this duration-intensity. Once individual warm-up was completed participants indicated when they were ready, whereupon they were required to reach a cadence of 80 rpm and a power output of 200 W. At this point the time trial commenced and participants rode as hard (self-selected pacing strategy) as possible for the designated period to obtain the best overall average power output.

Mean power output data from the aforementioned time trials was used to calculate critical power and W-prime (W′) via four differing methods as previously reported and presented in Table 1. The linear models form a linear curve where the slope and Y-axis provide the critical power and W′ respectively in the case of the Linear-TW model, and vice versa in the case of the Linear-P model. The non-linear models form a hyperbolic curve with the asymptote being the critical power and the area between this asymptote and the curve providing the W’. To avoid the assumption that all of the W′ can be depleted in an instant the Nonlinear-3 model introduces the parameter P_{max} (maximum instantaneous power). The Linear models tend to produce higher critical power values, while the nonlinear-models produce higher W’ values, but may also produce the closest critical power compared with RCP (Bull et al., 2000; Gaesser et al., 1995).

2.3. Statistical analysis

Descriptive data (mean, standard deviation, range) were calculated for variables measured during the laboratory ramp test and all dependent variables over the time trials.

Overall differences between model's ability to determine the power output at critical power were compared with power output at respiratory compensation point. Post-hoc multiple comparisons were made (Sidak's test) between respiratory compensation point and all models, plus between models. Similarly, one-way ANOVA with post-hoc multiple comparisons (Sidak's test) was used to compare the W′ estimates generated by each model and make comparison between the work completed at W_{max} (kJ)and the magnitude of the W’.

Further analysis using Bland-Altman enabled visual comparison between respiratory compensation point and critical power as determined by each model and/or agreement between models through bias ± SD and 95% limits of agreement. All statistical analyses were performed using Graphpad Prism (V7.0).

3. Results

Mean ± SD values from the ramp style test to determine aerobic capability included VO_{2max} 71.3 ± 5.9 ml $kg^{-1} \cdot min^{-1}$, HR_{peak} 188 ± 10 bpm, W_{max} 418 ± 45 W or 5.97 ± 0.66 W kg^{-1}, ventilatory threshold 267 ± 28 or 3.81 ± 0.43 W kg^{-1}, respiratory compensation point 340 ± 30 W or 4.86 ± 0.53 W kg^{-1}.

Data from the self-paced maximal effort time trials provided mean ± SD power outputs of 572 ± 77, 412 ± 43, 361 ± 40 W or 8.11 ± 0.42, 5.87 ± 0.43, and 5.14 ± 0.48 W kg^{-1} for 1-min, 4-min and 10-min, respectively. Corresponding average cadence (rpm) and heart rate during these time trials were 105 ± 8, 99 ± 7 and 93 ± 5 rpm, and 172 ± 7, 180 ± 9, and 180 ± 6 bpm, respectively.

Using the power data from the 1-4-10-min time trials provided significant overall differences between models for critical power ($F_{(1.022,8.179)} = 32.31$, $p = 0.0004$), with significant ($p < 0.001$) post-hoc differences for all pairings (Fig. 1 A) and trivial-moderate effect size differences (Fig. 1C). Overall significant differences were also found for W’ ($F_{(1.061,8.486)} = 39.07$, $p = 0.0002$) with significant ($p < 0.001$) post-hoc differences for all pairings (Fig. 1B) and medium-large effect size differences (Fig. 1D).

Table 1
Formulas used to calculate CP and W’ for various CP models.

Critical Power Model	Model Equation
Linear-TW (Hughson et al., 1984)	$W_{lim} = W'+(CP*t)$
Linear-P (Moritani et al., 1981)	$PO = W'*(1/t) + CP$
Nonlinear-2 (Poole et al., 1988)	$t = W'/(PO-CP)$
Nonlinear-3 (Hugh Morton, 1996)	$t = (W'/PO-CP) + (W'/CP-P_{max})$

Where, W_{lim} = Maximum amount of work able to be completed in an effort; W’ = Watt-Prime; CP = Critical Power; t = Time(s); PO = Power output; P_{max} = Maximum instantaneous power output.

Comparison of critical power obtained from each model and compared with the power output at respiratory compensation point provided no overall differences ($F_{(1.155, 9.243)} = 2.72$, $p = 0.131$) with no significant ($P < 0.05$) post-hoc difference between respiratory compensation point and each model. Effect size with 95% confidence interval, differences were trivial for Linear-TW (0.11, −0.82–1.03) and Linear-P (−0.17, −1.09–0.76), and medium for nonlinear-2 (0.30, −0.64–1.22) and nonlinear-3 (0.45, −0.51–1.56). Further visual analysis comparing model critical power with respiratory compensation point through Bland-Altman plots analysis (Fig. 2A–D) where bias ± SD (95% Limits of agreement) were 4.0 ± 33.6 (−61.9-69.9) W, −6.0 ± 33.4 (−71.4-59.4) W, 10.7 ± 34.2 (−36.4-77.7), and 16 ± 35.4 (−53.4-85.4) W for Lin-TW, Lin-P, nonlinear-2, and nonlinear-3, respectively.

Comparison of W′ obtained from each model and compared with W_{max} converted to kJ provided overall differences ($F_{(1.483, 11.86)} = 24.32$, $p = 0.0001$) with non-significant post-hoc differences between W_{max} and nonlinear-3 model ($p = 0.890$). While comparison between respiratory compensation point and W′ from each model produced overall significant difference ($F_{(1.409, 11.28)} = 126.5$, $p < 0.0001$) with post-hoc differences ($p < 0.0001$) between each model W′ and respiratory compensation point. Further analysis using effect size with 95% confidence interval for comparison between W’ and W_{max}, provided small differences for nonlinear-3 (0.41, −0.54–1.32) and large for Linear-TW (2.72, −1.34–3.85), Linear-P (3.43, 1.85–4.68), nonlinear-2 (1.56, 0.44–2.52) and nonlinear-3 (0.45, −0.51–1.56). Bland-Altman visual analysis (Fig. 2) highlights negative proportional bias, where bias ± SD (95% limits of agreement) were 1.95 ± 6.95 (−11.68–15.58) W.

The difference between the minute work-rate at RCP and W_{max} during the W_{max} test was expressed as a percentage of the mean W′ derived from the four CP models for each individual. The remaining fraction of the W′ was composed of the work completed at and above W_{max}. Expressed as a percentage of W′ these comprised 30.3 ± 13.2 (18.6–56.2) % and 69.7 ± 13.2 (43.8–81.4) % of the W’, respectively (Fig. 4).

4. Discussion

The aims of this study were to compare four different critical power model's ability to ascertain critical power and W′ in elite road cyclists, while making comparison of critical power to power output at respiratory compensation point, and work rate ($J \cdot sec^{-1}$) for W′ with that performed above critical power during the W_{max} test. The main findings show that: (a) all critical power models provided significantly different W′ and critical powers; (b) there was no significant difference between each model's critical power and power output at respiratory compensation point; (c) differences between models or compared to respiratory compensation point were not clinically useful in the provision of training prescription or performance monitoring if the aim is to equal work rate at compensation point; and (d) converting W_{max} test to work done (kJ) was not significantly different to W′ using the nonlinear-3 model.

To date, research comparing critical power models has used what would be considered untrained cyclists (Jeukendrup et al., 2000) and findings may not be applicable to the elite group. The participants in the dataset presented can be classified as well-trained to world-class cyclists (Jeukendrup et al., 2000) based on the range for VO_{2max} (4.39–5.66 L min^{-1}, or 60.0–79.1 ml $min^{-1} \cdot kg^{-1}$) and W_{max} (340–505 W, or 5.04–7.07 W kg^{-1}). As such, critical power and W’ data presented (Fig. 1A and B) provides additional support to the work of others (Bartram et al., 2017) anticipating elite cyclists capability. This is important as the efficacy of calculating such data in regards to cyclists seasonal progress (Passfield et al., 2017) through automated analysis of training and racing data (Karsten et al., 2014) via online training applications

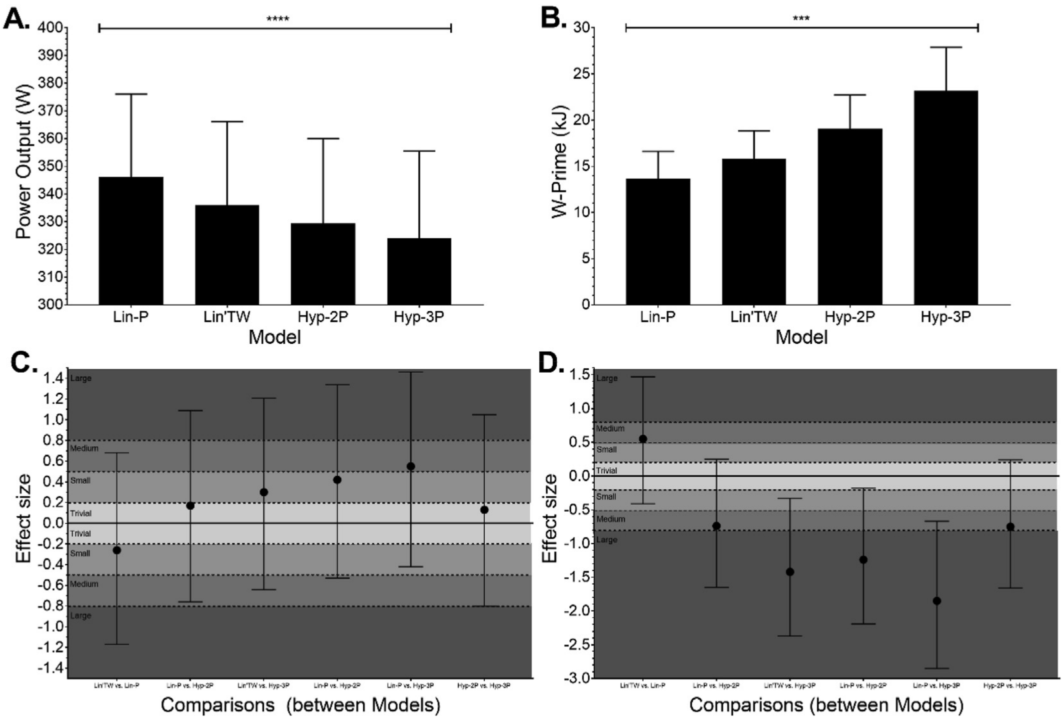

Fig. 1. Comparison between models for, A. Critical power mean ± SD, B. W′ mean ± SD, and effect size differences (Lower-Upper 95% CI) for pairing combinations for, C. Critical power, D. W'.

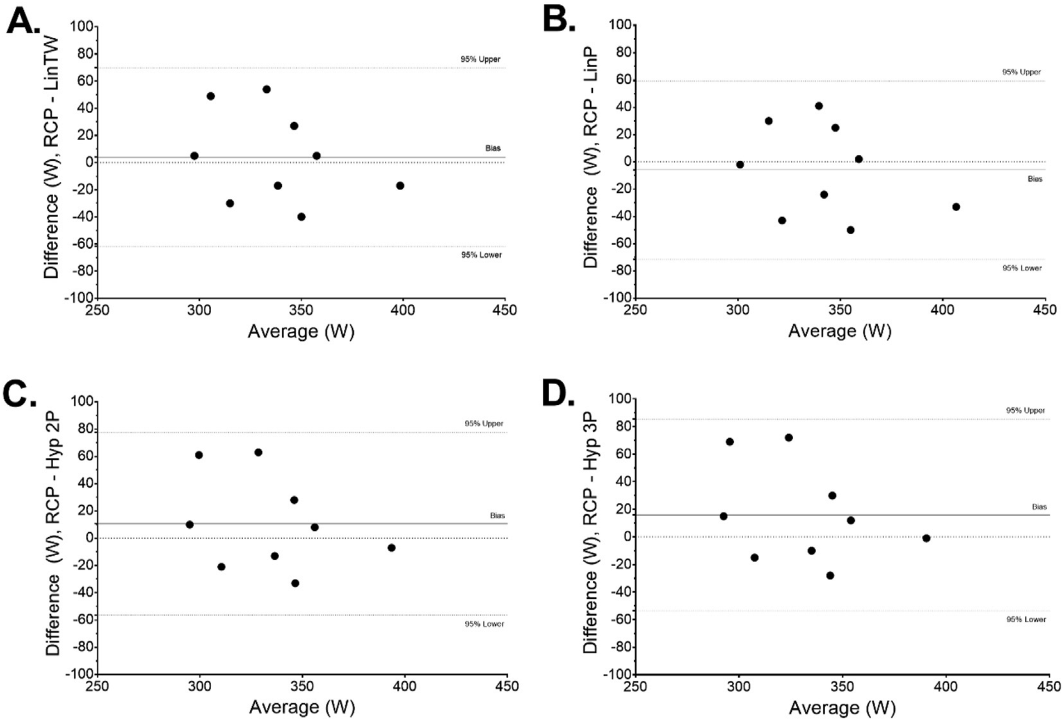

Fig. 2. Bland–Altman plots comparing respiratory compensation point with, A. Lin-TW, B. Lin-P, C. Nonlinear-2, and D. Nonlinear-3 data. The central bold-line represents the absolute average difference (bias) between measures, while the upper and the lower dotted lines represent 95% Limits of Agreement.

makes it widely accessible.

However, ascertaining purpose or reason of specific points of a model is vital to the success of any training programme. Critical power is thus associated with a variety of markers representing transitions from steady state metabolic (Moritani et al., 1981) or respiratory work (Bergstrom et al., 2013). The data presented supports the assumption that critical power, for all models, demarcates the transition from heavy to severe intensity exercise (Dekerle et al., 2003) via the respiratory compensation point and critical power output not being significantly different. The mean differences for RCP-Model (4, −6, 11, 16 W) for linear-TW, Linear-P, nonlinear-2, nonlinear-3, respectively, supports the linear compared to nonlinear models. This contradicts previous findings where linear models were found to overestimate critical power (Hill, 1993) and nonlinear-3 model provided more accurate prediction of critical power in relation to respiratory compensation point (Bergstrom et al., 2014). However, statistical analysis taking into account individual participants variability via effects size calculation (Fig. 1 C) and visual analysis (Bland and Altman, 1986) reveals clinically significant difference within individuals for all models and when compared with respiratory compensation point work rate (Fig. 2A–D). As such, if the aim of a test is to attain and prescribe individualised training from a work rate associated with respiratory compensation point, then critical power is not precise enough (mean bias is 6.25 ± 95% confidence interval of 26.3 W). This difference would be enough to influence time to exhaustion at either critical power or respiratory compensation (Brickley et al., 2002; Jenkins and Quigley, 1990; Moral-González et al., 2020) and thus influence performance prescribed at the set work rate. Alternatively, such error in training intensity led prescription would lead to sub-optimal training as a result of increasing time within a higher or lower domain than expected, while upsetting the polarised balance of training (Seiler and Kjerland, 2006). Additionally, post-hoc analysis between model comparison indicates significant differences (Fig. 1A) making comparison between different training applications tricky if the model used is not provided to the analysts, athlete, or coach.

Likewise, the supra-critical component (W′) of the critical power model provided an overall difference, where post-hoc comparison of between models were significantly different (Fig. 1B). This reiterates the importance of understanding which model is being used for any comparisons inter-intra athlete and understanding what it measures exactly in order to validate or perform useful training or performance analysis studies. As has previously been reported (Bergstrom et al., 2014), models predicting the highest critical power report the lowest W′ and vice versa. Specifically, nonlinear models underestimate critical power while reportedly overestimating W' (Bergstrom et al., 2014). The latter is based on the initial premise that W' was synonymous with anaerobic capability/capacity (Miura et al., 1999; Moritani et al., 1981), but more recently has been acknowledged as a combination of systems. As such, it reflects the ability to work beyond the critical power, sustain $VO_{2\ max}$ (Coats et al., 2003) and the associated metabolic fatigue (Ferguson et al., 2010) of supramaximal exercise over a finite period.

In acknowledging the fact that W′ is work done above critical power we considered and compared the work participants completed at W_{max} during the incremental ramp test. While there were no relationships and an overall difference between models, post-hoc testing showed that there was no difference between W' (nonlinear-3) and work at W_{max}. It is important to note because there is no statistical difference, this does not mean they are the same thing, but rather there was just no statistical difference between the numbers from the two tests. If further research establishes this maybe a ramp style test that takes 10–15 min is a more efficient use of elite athlete's time. However, just like respiratory compensation point comparison with critical power, on an individual level effect size limits of agreement (Fig. 1D) and the mean differences ± 95% CI (1.951 ± 5.544 kJ) with proportional bias (Fig. 3) deemed that work completed at W_{max} (kJ) is not useful to determine individual W'. It is recommended that future work investigates the efficacy of the means to determine anaerobic (ATP-PC and Glycolytic) and aerobic capability to establish the efficacy of critical power and W′ as a means of assessing bioenergetic capability.

Exploratory analysis comparing the difference in work completed during at W_{max} and respiratory compensation point during the W_{max} test is presented as a percentage of the W' (Fig. 4) and is proposed as a means to indicate aerobic/anaerobic contribution to the W'. Informal discussions with individual participants regarding performance capability and roles within their teams suggests that data presented in Fig. 4 does a good job indicating bioenergetic training status. It is postulated therefore, that those with low respiratory compensation points, and therefore likely CP, relative to W_{max} have greater anaerobic status. This means they are also more suited to sprinter classification, while those with higher respiratory compensation point and/or CP relative to W_{max} are more aerobically trained and suited to general classification (Chorley et al., 2020). Again, further research needs to investigate the aerobic-anaerobic contribution to W' depletion, where previously (Macdermid et al., 2018) it has been shown that oxygen deficit has reached a plateau (<1 L min^{-1}) by 60-s and that aerobic contribution to exercise is dominant after 30-s of all-out effort lasting 100-s.

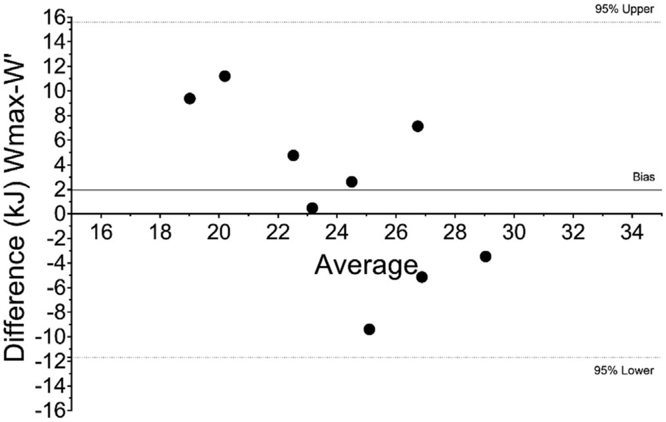

Fig. 3. Bland–Altman plots comparing W_{max} with W′ using the nonlinear-3 critical power model. The central bold-line represents the absolute average difference (bias) between measures, while the upper and the lower dotted lines represent 95% Limits of Agreement.

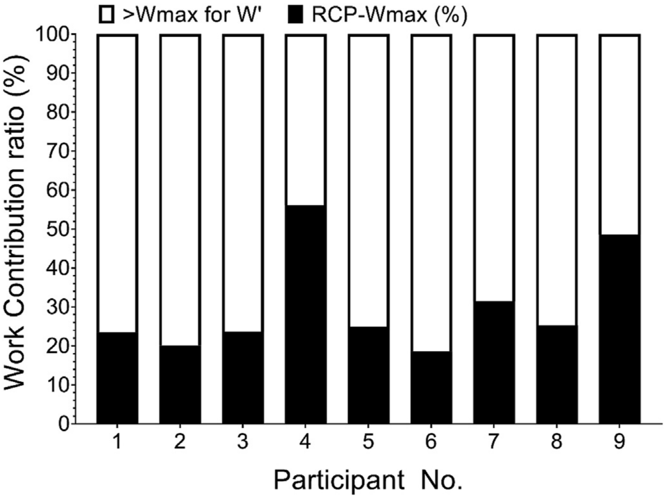

Fig. 4. Work contribution ratio (%) for work between respiratory compensation point and W_{max} during ramp test in relation to W′ for individual participants.

5. Conclusion

This study set out to compare four different critical power model's ability to ascertain critical power and W′ in elite road cyclists, while making comparison of critical power to power output at respiratory compensation point, and work rate (J·sec^{-1}) for W′ with that performed above critical power during the W_{max} test. While there were no differences between the work rate at respiratory compensation point and critical power determined by each model, the ability to produce comparable results was unachievable. More detailed analysis deemed work rate at critical power inappropriate to prescribe training at a physiological transition as per respiratory compensation point. Likewise, W′ was significantly different between models, not related to work rate at W_{max} or between critical power and W_{max} as determined from an incremental, short staged ramp test to exhaustion. Further research is required to investigate the physiological markers of intensity associated with respiratory compensation point and critical power work rate and the bioenergetic contribution to W'.

CRediT authorship contribution statement

Boris Clark: Conceptualization, Data curation, Formal analysis, Investigation, Project administration, Methodology, Validation, Writing – review & editing. **Paul W. Macdermid:** Formal analysis, Project administration, Methodology, Supervision, Validation, Writing – original draft, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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