Cycling performance is superior for time-to-exhaustion versus time-trial in endurance laboratory tests.

Sarah L. Coakley[1] and Louis Passfield[1]

[1]Endurance Research Group, School of Sport and Exercise Sciences, University of Kent, Kent, UK.

Preferred running head: Time-to-exhaustion versus time-trial performance

🖂Address for correspondence:

Professor Louis Passfield

School of Sport and Exercise Sciences,

University of Kent,

Kent,

ME4 4AG

England

Email: L.Passfield@kent.ac.uk

Abstract

Time-to-exhaustion (TTE) trials are used in a laboratory setting to measure endurance performance. However, there is some concern with their ecological validity compared with time-trials (TT). Consequently, we aimed to compare cycling performance in TTE and TT where the duration of the trials was matched. Seventeen trained male cyclists completed three TTE trials at 80, 100 and 105% of maximal aerobic power (MAP). On a subsequent visit they performed three TT over the same duration as the TTE. Participants were blinded to elapsed time, power output, cadence and heart rate (HR). Average TTE was 865 ± 345 s, 165 ± 98 s and 117 ± 45 s for the 80, 100 and 105% trials respectively. Average power output was higher for TTE (294 ± 44 W) compared to TT (282 ± 43 W) at 80% MAP ($P < 0.01$), but not at 100 and 105% MAP ($P > 0.05$). There was no difference in cadence, HR, or RPE for any trial ($P > 0.05$). Critical power (CP) was also higher when derived from TTE compared to TT ($P < 0.01$). It is concluded that TTE results in a higher average power output compared to TT at 80% MAP. When determining CP, TTE rather than TT protocols appear superior.

Keywords: pacing; critical power; endurance performance

Introduction

Constant power output time-to-exhaustion (TTE) and self-paced time-trials (TT) are well-established cycling performance tests (Jeukendrup, Saris, Brouns & Kester, 1996; Paton & Hopkins, 2001; Schabort, Hawley, Hopkins, Mujika & Noakes, 1998). They are commonly used to monitor progression and detect changes following experimental interventions. The ecological validity of using TTE to assess endurance performance has been questioned (Jeukendrup & Currell, 2005). For instance, Marino (2012) and Tucker et al. (2006) suggest cyclists rarely maintain a constant power output to volitional exhaustion in competition. In contrast, the TT attempts to replicate a competitive situation in the laboratory, allowing athletes to self-regulate their pace in response to physiological demands (Palmer, Hawley, Dennis & Noakes, 1994; Tucker et al., 2006). Furthermore, it has also been established that the variability of TT is much lower and its repeatability superior to the TTE test (Jeukendrup et al., 1996; Laursen, Francis, Abbiss, Newton & Nosaka, 2007). Consequently, it is unclear whether power output for maximal TTE and TT performances under standardised conditions are directly comparable.

One of the more common uses of a TTE is to determine critical power (CP) from a series of exhaustive performance trials (Dekerle, Vanhatalo & Burnley, 2008; Hill, 1993; Monod & Scherrer, 1965). These trials are recommended to last between 2 to 15 min (Dekerle et al., 2008). Additionally, the maximum work done in a specified time period (e.g., the highest average power output/velocity in a TT format) has been used (Galbraith, Hopker, Jobson & Passfield, 2011; Galbraith, Hopker, Lelliott, Diddams & Passfield, 2014; Karsten, Jobson, Hopker, Stevens & Beedie, 2015). Using CP can help an athlete calculate appropriate pacing strategies and as a result it should be derived from the highest achievable performances (Jones, Vanhatalo, Burnley, Morton & Poole, 2010). The interchangeable use of TTE and TT protocols presumes that these tests are equivalent for determining CP. However, the possible influence of using a specified duration TT rather than TTE on the subsequent CP has not been assessed in trained cyclists.

The aim of this study was to compare average power output in TTE and TT, when trials are performed over the same duration. We also compared CP calculated from TTE and TT performance. We hypothesised that in comparison to TTE, the suggested difference in ecological validity of the TT would alter the power output cyclists were able to sustain, and in turn change calculated CP.

Methods

Participants

Seventeen trained male road cyclists were recruited as participants for this study (mean ± SD: age = 31 ± 9 y, body mass = 70.7 ± 9.9 kg, with a maximal aerobic power (MAP) of 366 ± 52 W and maximal oxygen uptake ($\dot{V}O_{2max}$) of 60.4 ± 8.4 $ml \cdot kg^{-1} \cdot min^{-1}$). All participants had been involved in a minimum of 250 km or 10 h of cycle training per week. Participants were excluded if they were on any medication, reported heart problems, exercise-induced asthma or an injury that would interfere with testing. All participants gave their written informed consent to participate in this study that had been approved by the University of Kent's ethics committee.

Study Design

Each participant completed three laboratory tests on a cycle ergometer (Computrainer Pro, Racer Mate Inc., Seattle. WA, USA) on separate days with at least 48 h between each test. Prior to all tests participants were instructed to be well hydrated, and to avoid food, strenuous exercise and alcohol for 3 h, 24 h and 48 h respectively. The three laboratory tests consisted of (1) $\dot{V}O_{2max}$ test, (2) three x TTE, (3) three x TT. Participants used their own bicycles for testing, equipped with a bicycle power meter to measure and record power output (PowerTap Elite Wheel, CycleOps, Madison, USA) and a magnet to measure cadence. Prior to testing the power meter's zero offset was calibrated according to the manufacturer's guidelines.

Procedures

$\dot{V}O_{2max}$ *test.* Participants completed a maximal incremental exercise test to determine their $\dot{V}O_{2max}$ and associated MAP. The test started at 150 W and increased by 20 W every min until volitional exhaustion was reached or the participant was no longer able to maintain the required work rate. The volume of oxygen ($\dot{V}O_2$), carbon dioxide ($\dot{V}CO_2$) and expired gas ($\dot{V}_E$) were monitored throughout the tests using an online gas analysis system (Cortex Biophysik, Leipzig, Germany). Heart rate (HR) was recorded continuously using the cortex system. A capillary blood sample was collected from the fingertip 1 min after testing and analysed for lactate concentration (Biosen C-line, EKF diagnostic, Barbleben, Germany). The participants' MAP and $\dot{V}O_{2max}$ were calculated as the highest average achieved during the last 30 s.

Performance trials. Participants returned to the laboratory on two further occasions to complete three x TTE and three x TT. The TT were always performed on the final laboratory visit as their duration was based upon performance in the preceding TTE trials. The TTE protocol was as described by Karsten et al. (2015). Participants performed the TTE at power outputs equivalent to ~ 80, 100 and 105% of MAP with 30 min recovery between trials. Trials were performed in this fixed order and each was preceded by a 5 min warm up at 150 W. Galbraith et al. (2014) have previously established that this protocol allows sufficient recovery between trials. The intensities for the trials were set using the cycle ergometer, but actual power values recorded from the power meter were used for analysis. Participants were instructed to adopt their preferred cadence and maintain the target power for as long as possible. Verbal encouragement was provided, however, participants were not given feedback on their elapsed time, power output, cadence and HR. The participants' TTE was reached when despite encouragement their cadence fell 10 $rev{\cdot}min^{-1}$ below their preferred cadence for 10 s or more. The TTE was recorded to the nearest second (s). For their final visit participants completed three x TT of the same duration as previously recorded for the TTE trials at 80, 100 and 105% MAP. Testing was performed as for TTE in the same fixed order with 30 min recovery between trials. Each trial was preceded by a 5 min warm up at 150 W. Prior to each TT participants were informed of the duration they had achieved in the corresponding TTE trial and asked to complete the maximum work possible in this same time. During the TT, participants were free to change their cadence and ergometer resistance in order to complete as much work as possible. As with their TTE trials, verbal encouragement was provided but they were not given feedback on their elapsed time, power output, cadence and HR. Capillary blood samples were collected 1 min after each TTE and TT. Borg's (1970) 6-20 rating of perceived exertion (RPE) was recorded at 1 min and 5 min of exercise for TTE and TT at 80% MAP. In addition, at 1 min and 5 min of the TTE trial at 80% the participants' estimated time limit (ETL) was recorded as described by Garcin, Coquart, Robin and Matran (2011) and previously validated by Coquart et al. (2012). Participants were asked 'how long would you be able to perform an exercise at this intensity to exhaustion' and they estimated this using a 1-20 scale (1 = 'more than 16 h'; 20 = 'less than 2 min') (Garcin et al., 2011).

Statistical Analysis

A two-way repeated measures ANOVA was conducted to assess differences between TTE and TT for average power output, cadence, HR and RPE. Where a significant main effect between trials was indicated, a paired samples t-test with a Bonferroni correction was conducted to evaluate differences between trials. This analysis was also used to compare CP and W′ parameters derived from TTE and TT performances using three CP models: a hyperbolic model, linear work-time model (Linear-TW) and a second linear model (Linear-P). A hyperbolic model was generated from a non-linear regression between average power output and TTE (Equation 1). A Linear-TW model was generated from a linear regression between total work, expressed in Joules (J), and TTE (Equation 2). A linear-P model was generated from a linear regression between average power output and the inverse of TTE (Equation 3).

$$TTE = W' / (P - CP) \tag{1}$$

$$TW = W' + CP \cdot TTE \tag{2}$$

$$P = W' (1/TTE) + CP \tag{3}$$

Where TTE is time-to-exhaustion, W′ is the curvature constant, P is power output, CP is critical power and TW is total work.

Pearson's correlation was used to examine the relationship between TTE and the measures of RPE and ETL gathered after 1 min and 5 min in the 80% MAP trial. Analysis was conducted using the SPSS statistical software package (IBM SPSS Statistics, Rel, 22.0, SPSS, Inc, Chicargo, USA). R (R Core Team., 2014) was used to analyse the average power output for each decile (10%) for both TTE and TT. Statistical significance was accepted if $P < 0.05$ was found. Values are reported as the mean ± standard deviation (SD) unless stated otherwise.

Results

Technical issues resulted in incomplete data for two participants for the 80% trial, one participant for the 100% and one participant for the 105% trial. These participants were excluded from the analysis and data is presented for the remaining thirteen participants (mean ± SD: age = 33 ± 9 y, body mass = 72.1 ± 10.1 kg, MAP = 366 ± 57 W, $\dot{V}O_{2max}$ = 60.1 ± 9.6 ml·kg·min^{-1}).

Comparison between performance trials

Average TTE was 865 ± 345 s, 165 ± 98 s, 117 ± 45 s, for the 80, 100 and 105% MAP trials respectively. As shown in Figure 1, average power output was significantly higher for TTE compared with TT at 80% MAP (294 ± 44 W vs. 282 ± 43 W respectively; $P < 0.01$). There were no significant difference in average power output for TTE and TT performances at 100% and (353 ± 62 W vs. 359 ± 74 W) and 105% (373 ± 63 W vs. 374 ± 61 W) MAP respectively ($P > 0.05$) (Figure 1).

Insert Figure 1 near here

Calculated CP was higher when derived from TTE compared to TT performances (*P* < 0.05). Whereas, calculated W′ was lower when derived from TTE compared to TT performances (*P* < 0.05). There was no significant difference between the three CP models when CP (*P* = 0.07) and W′ (*P* = 0.22) were calculated (Table 1).

*** Insert Table 1 near here ***

Physiological and perceptual measures

No difference was found between trials for HR and cadence at 80, 100 and 105% MAP (*P* > 0.05). There was also no significant difference between trials for RPE at 80% MAP (*P* > 0.05). However, blood lactate was a significantly higher for the TTE (10.79 ± 3.10 mmol·L^{-1}) compared to TT (8.10 ± 2.20 mmol·L^{-1}) after the 80% MAP trial, (*P* < 0.01), but not after trials at 100 and 105% MAP (*P* > 0.05). The relationship between TTE and measures taken of RPE and ETL after 1 min and 5 min at 80% MAP were not significant (*P* > 0.05). There was no correlation between RPE and ETL at 1 min and 5 min of the TTE trial (*P* > 0.05) (Table 2).

*** Insert Table 2 near here***

Pacing strategies

Figure 2 compares the average power outputs for each 10% segment of the TTE and TT at 80, 100 and 105% MAP. As evident from Figure 2, participants’ starting pacing strategy was higher for the TT compared to the TTE for each of the three intensities.

*** Insert Figure 2 near here ***

Discussion

The main finding from this study was that average power output for TTE was higher when compared to the TT at 80%, but not at 100% and 105% MAP. This in turn meant that calculated CP was higher when derived from TTE compared to TT. Although we hypothesised a difference between TT and TTE would be found, we anticipated that TTE would result in a lower average power output than TT due to its suggested lack of ecological validity. The higher average power output and CP found for TTE challenges the notion that this type of performance test lacks useful ecological validity (Jeukendrup & Currell, 2005; Marino, 2012). Criticism of TTE trials has also focused on their inherent variability and has resulted in a shift towards the use of TT instead (Jeukendrup & Currell, 2005). The findings of this study indicate that TTE should not be disregarded as a useful measure of performance in the laboratory.

Comparative data on TTE and TT performances are limited (Amann, Hopkins & Marcora, 2008; Ham & Knez, 2009; Thomas, Stone, St Clair Gibson, Thompson & Ansley, 2013). Moreover, previous studies were not designed to compare performance in TTE and TT directly, but rather to evaluate the effects of pacing (Ham & Knez, 2009; Thomas, Stone, Thompson, St Clair Gibson & Ansley, 2012) or of changing the inspired oxygen concentration (Amann et al., 2008) on performance. Ham and Knez (2009) report that performance for TTE and TT appears to be similar. In addition, Amann et al. (2008) found a similar sensitivity for both test protocols when detecting changes in performance, with differences in inspired oxygen concentration. In contrast to the present study, Thomas et al. (2013) reported a higher average power output during self-paced compared to even-paced cycling trials. However, this was only found for some participants, with nine out of fifteen cyclists unable to complete the same distance as their self-paced trial when the mean intensity was fixed. It is also important to note too that the higher average power output for TTE in the present study was found only for the longest trial at 80% MAP, where the average duration was 865 ± 345 s. No difference was found in the higher intensity trials ≥ 100% MAP that lasted ≤ 165 ± 98 s. Amann et al.

(2008) compared TTE and TT performance with a trial that lasted approximately half the length of the 80% trial in the present study (458 s). Thus, their findings of comparable TTE and TT performances are consistent with the results from the present study for the shorter duration trials. However, the performance trials of Ham and Knez (2009) and Thomas et al. (2012) were notably longer than the present study (2880 s and 1920 s respectively). As a result, other factors, such as pacing and feedback may have influenced the comparisons between previous studies and the present study.

As the 80% trial lasted longer than 2 min, the divergent performance between TTE and TT may be explained by differences in pacing strategy. For events like this an even-paced strategy such as that enforced in the TTE is often suggested to result in greater performances (Atkinson, Davison, Jeukendrup & Passfield, 2003; de Koning, Bobbert & Foster, 1999; Foster et al., 1993; Ham & Knez, 2009). These studies suggest that a high variation in pace, only possible in a TT, is associated with a reduction in performance. For example, Ham and Knez (2009) found that participants whose relative starting strategy was > 105% of their average speed performed worse overall. Cangley, Passfield, Carter and Bailey (2011) noted in their field study that cyclists find it difficult to adopt a specified pacing strategy even when it is known to be superior. Therefore, to evaluate the participants pacing strategy in the present study we calculated the average power output sustained for each decile (10%) of both TTE and TT at 80, 100 and 105% MAP. This power output distribution is plotted showing 95% confidence intervals for a within subject design (Morey, 2008) in Figure 2. Figure 2 (a) clearly suggests the participants misjudged their pacing strategy for the TT at 80% MAP. In comparison with the TTE trial, participants can be seen to adopt a higher average power output initially in the TT. This fast start appears to result in a progressive decline in power output throughout the TT leading to lower average power output when compared to the TTE. This pattern in pacing has also been seen in previous research and was associated with a poorer TT performance (Foster et al., 1993; Mattern, Kenefick, Kertzer & Quinn, 2001).

During TTE trials it is normal practice not to provide feedback on elapsed time or power output (e.g. Galloway & Maughan, 1997). Therefore, to standardise comparisons in the present study no feedback was provided during either the TTE or TT performances. Previous studies that have blinded participants to any external feedback are inconsistent (Faulkner Arnold & Eston, 2011; Jones et al., 2013; Mauger, Jones & Williams, 2009; Micklewright, Papadopoulou, Swart, & Noakes, 2010; Wilson, Lane, Beedie & Farooq, 2012). For instance, Wilson et al. (2012) investigated the effects of no feedback, accurate feedback, false feedback and false negative feedback on 10-mile TT cycling performances. Their results showed no significant differences in completion times and average power outputs when the four different feedback conditions were compared. In contrast, Faulkner et al. (2011) found that completion time as well as pacing strategies were significantly slower when participants were blinded to feedback, compared to accurate or delayed feedback conditions. Nonetheless, it is common for participants in TT to be provided with their elapsed and remaining time, or distance, and sometimes power output too. According to Marcora's (2008) psychobiological model, the absence of any of these key variables can have a negative impact on performance and subsequently reduce the ecological validity of TT performances. As a result, this lack of feedback may explain the absence of a notable end spurt that is often observed in previous TT performances (e.g. Thomas et al., 2012). However, the difference in total work done for the TTE and TT in the 80% MAP trial was ~10 kJ (by multiplying trial duration by average power output and converting to kJ). Therefore, it seems improbable that the end spurt can account for this ~10 kJ difference in work done observed between TTE and TT in the 80% MAP trials. Further studies are needed to determine the effect of feedback on the pacing strategy and how this influences TTE and TT performances. In addition, Jones et al. (2015) proposed that other factors, such as emotion regulation or motivation, could also influence performance when no feedback is provided. Although the mechanisms responsible for these factors are unknown (Jones et al., 2015).

The exact reason for the higher average power output in TTE at 80% MAP remains to be explained. While a learning effect can influence performance, in our study twelve out of thirteen participants demonstrated a higher average power output for the first performance trial (TTE) compared to second (TT). It seems that early in exercise even our well-trained cyclists found it difficult to gauge their perception of effort and how long it can be sustained until exhaustion. In the present study we measured RPE at 1 min and 5 min for both TTE and TT at 80% MAP and ETL at the same time points for TTE only. There were no differences in RPE between TTE and TT indicating that participants did not perceive that they were starting faster in the TT. This conclusion is reinforced by the observation that neither measures of RPE or ETL correlated with the duration of the 80% MAP TTE trial. These findings are consistent with previous studies that have shown a fast start can result in a decrease in speed and overall performance (Ham & Knez, 2009). These findings also highlight the related limitation of perceptual scales as identified in a review (Coquart et al., 2012). Interestingly, HR was not different when comparing TTE and TT at any of the three intensities either, suggesting that it may be similarly limited. But, blood lactate after TTE at 80% MAP was higher than for TT. Combined, this data suggests that the participants perceived the effort to be similar in both trials, but were able to sustain a greater power output and induce a greater metabolic stress in the 80% MAP TTE trial. Previous research has found a TTE type even paced strategy to be more physiologically and psychologically demanding when compared to self-paced TT (Billat, Slawinski, Daniel & Koralsztein, 2001; Lander, Butterly & Edwards, 2009). This is evidenced by an increase in core body temperature and blood lactate responses (Billat et al., 2001; Lander et al., 2009). The TT allowed athletes to self-regulate and vary their pace in response, whereas the TTE trials resulted in a premature termination of exercise (Lander et al., 2009; Marino, 2012).

We specified TTE and TT performance trials that are typical of those used to determine CP. Dekerle et al. (2008) suggest that the determination of CP should be made from trials ranging between 2 to 15 min. The duration of the trials in our study ranged from ~ 1 to 14 min.

However, it should also be noted that the average time difference between the 100 and 105% MAP trials was only ~ 48 s. In their review, Jones et al. (2010) suggest that CP can be used to enable athletes to set appropriate pacing strategies and predict performance. Consequently, it is important that CP is determined accurately from the highest achievable performances, to ensure optimal pacing strategies are set. CP was calculated from three different models (hyperbolic, Linear-TW, Linear-P). No differences were found between models for calculated CP or W′. However, the difference in CP estimates between models was close to significance ($P = 0.07$). The findings from our study demonstrate that a ~ 16 W higher value ($P < 0.05$) for CP is obtained when TTE rather than TT performances are used. In addition, W′ was significantly lower for TTE (~ 2 kJ) compared to TT. Therefore, the results may suggest that CP and W′ are inversely related to each other, depending on the type of performance test performed. This inverse relationship has been previously found following training (Jenkins & Quigley, 1992; Vanhatalo, Doust & Burnley, 2008), as well as differences in pacing strategy (Bailey, Vanhatalo, DiMenna, Wilkerson & Jones, 2011; Jones, Wilkerson, DiMenna, Fulford & Poule, 2008), and prior warm up (Jones, Wilkerson, Burnley, & Koppo, 2003). Nevertheless, Vanhatalo, Jones and Burnley (2011) note that an increase in CP, and reduction in W′ is related to an improvement in overall endurance performance. Whereas, an increase in W′ and a reduction in CP will only enhance high intensity, short duration performances (Vanhatalo et al., 2011). Therefore, future studies should use a TTE test protocol to maximise calculated power output when determining CP.

Conclusion

In conclusion, average power output for TTE was greater than for TT at 80% MAP. There was no significant difference in average power output for shorter high intensity TTE and TT at 100 and 105% MAP. The reason for the lower TT performance at 80% MAP may be related to competitive cyclists pacing strategy by starting too fast. Early in exercise it appears that even competitive cyclists are not sensitive to the perceptual cues that inform their effort and ability to estimate how long it can be sustained. The higher average power output achieved during TTE performance also results in a higher calculated CP from those trials compared with TT. Therefore, researchers are advised to adopt a TTE test protocol to maximise calculated power output when determining CP.

Acknowledgements

The authors would like to thank the cyclists who volunteered to participate in this study.

References

Amann, M., Hopkins, W.G., & Marcora, S.M. (2008). Similar sensitivity of time to exhaustion and time-trial time to changes in endurance. *Medicine and Science in Sports and Exercise,* 40, 574-578.

Atkinson, G., Davison, R., Jeukendrup, A., & Passfield, L. (2003). Science and cycling: current knowledge and future directions for research. *Journal of Sports Sciences*, 21, 767-787.

Bailey, S.J., Vanhatalo, A., DiMenna, F.J., Wilkerson, D.P., & Jones, A.M. (2011). Fast-start strategy improves VO_2 kinetics and high-intensity exercise performance. *Medicine and Science in Sports and Exercise,* 43, 457-467.

Billat, V.L., Slawinski, J., Daniel, M & Koralsztein, J.P. (2001). Effect of free versus constant pace on performance and oxygen kinetics in running. *Medicine and Science in Sports and Exercise,* 33, 2082-2088.

Borg, G (1970). Perceived exertion as an indicator of somatic stress. *Scandinavian Journal of Rehabilitation medicine,* 2, 92-98.

Cangley, P., Passfield, L., Carter, H., & Bailey, M. (2011). The effect of variable gradients on pacing in cycling time-trials. *International Journal of Sports Medicine,* 32, 132–136.

Coquart, J.B., Eston, R.G., Noakes, T.D., Tourny-Chollet, C., L'hermette, M., Lemaître, F & Garcin, M. (2012). Estimated time limit: a brief review of a perceptually based scale. *Sports Medicine,* 42, 845-855.

de Koning, J.J., Bobbert, M.F, & Foster, C. (1999). Determinants of optimal pacing strategy in track cycling with an energy flow model. *Journal of Science and Medicine in Sport,* 2, 266 277.

Dekerle, J., Vanhatalo, A., & Burnley, M. (2008). Determination of critical power from a single test. *Science and Sports,* 23, 231-238.

Faulkner, J., Arnold, T., & Eston, R.G. (2011). Effects of accurate and inaccurate distance feedback on performance markers and pacing strategies during running. *Scandinavian Journal of Medicine and Science,* 21 (6), e176-183.

Foster, C., Synder, A.C., Thompson, N.N., Green, M.A., Foley, M., & Schrager, M. (1993). Effect of pacing strategy on cycling time trial performance. *Medicine and Science in Sports and Exercise*, 25, 383-388.

Galbraith, A., Hopker, J., Lelliott, S., Diddams, L., & Passfield, L. (2014). A single-visit field test of critical speed. *International Journal of Sports Physiology and Performance,* 9 (6), 931-935.

Galbraith, A., Hopker, J.G., Jobson, S.A., & Passfield, L. (2011). A novel field test to determine critical speed. *Journal of Sports Medicine and Doping Studies*, 1, 2161-0673.

Galloway, S.D., & Maughan R.J. (1997). Effects of ambient temperature on the capacity to perform prolonged cycle exercise in man. *Medicine and Science in Sports and Exercise*, 29, 1240–1249.

Garcin, M., Coquart, J.B., Robin, S., & Matran, R. (2011). Prediction of time to exhaustion in competitive cyclists from a perceptually based scale. *The Journal of Strength and Conditioning Research*, 25 (5), 1393-1399.

Ham, D.J., & Knez, W.L. (2009). An evaluation of 30-km cycling time trial (tt30) pacing strategy through time-to-exhaustion at average tt30 pace. *The Journal of Strength and Conditioning Research*, 23, 1016-1021.

Hill. D.W. (1993). The critical power concept. *Sports Medicine,* 16, 237-254.

Jenkins, D.G., & Quigley, B.M. (1992). Endurance training enhances critical power. *Medicine and Science in Sports and Exercise,* 24, 1283-1289.

Jeukendrup, A., Saris, W.H., Brouns, F., & Kester, A.D (1996). A new validated endurance performance test. *Medicine and Science in Sports and Exercise,* 28, 266-270.

Jeukendrup, A.E., & Currell, K. (2005). Should time trial performance be predicted from three serial time-to-exhaustion tests? *Medicine and Science in Sports and Exercise,* 37, 1820.

Jones, A.M., Vanhatalo, A., Burnley, M., Morton, R.H., & Poole, D.C. (2010). Critical power: Implications for determination of VO_{2max} and exercise tolerance. *Medicine and Science in Sports and Exercise,* 42, 1876–1890.

Jones, A.M., Wilkerson, D.P., DiMenna, F., Fulford, J., & Poule, D.C. (2008). Muscle metabolic responses to exercise above and below the ‘critical power’ assessed using 31P-MRS. *American Journal of Physiology, Regulatory, Integrative and Comparative Physiology*, 294, R585-R593.

Jones, A.M., Wilkerson, D.P., Burnley, M., & Koppo, K. (2003). Prior heavy exercise enhances performance during subsequent perimaximal exercise. *Medicine and Science in Sports and Exercise*, 35, 2085-2092.

Jones, H.S., Williams, E.L., Bridge, C.A., Marchant, D., Midgley, A.W., Micklewright, D., & Mc Naugthon, L.R. (2013). Physiological and psychological effects of deception on pacing strategy and performance: a review. *Sports Medicine*, 43, 1243-1257.

Jones, H.S., Williams, E.L., Marchant, D., Sparks, S.A., Midgley, A.W., Bridge, C.A., & Mc Naughton, L. (2015). Distance-dependent association of affect with pacing strategy in cycling time trials. *Medicine and Science in Sports and Exercise*, 47 (4), 825-832.

Karsten, B., Jobson, S.A., Hopker, J., Stevens, L., & Beedie, C. (2015). Validity and reliability of critical power field testing. *European Journal of Applied Physiology*, 115 (1), 197-204.

Lander, P.J., Butterly, R.J., & Edwards, A.M. (2009). Self-paced exercise is less physically challenging than enforced constant pace exercise of the same intensity: influence of complex central metabolic control. *British Journal of Sports Medicine*, 43, 789-795.

Laursen, P.B., Francis, G.T., Abbiss, C.R., Newton, M.J., & Nosaka, K. (2007). Reliability of time-to-exhaustion versus time-trial running tests in runners. *Medicine and Science in Sports and Exercise*, 39, 1374-1379.

Marcora, S.M. (2008). Do we really need a central governor to explain brain regulation of exercise performance. *European Journal of Applied Physiology*, 104, 929-931.

Marino, F.E. (2012). The limitations of the constant load and self-paced exercise models of exercise physiology. *Comparative Exercise Physiology*, 7, 173-178.

Mattern, C.O., Kenefick, R.W., Kertzer, R., & Quinn, T.J. (2001). Impact of starting strategy on cycling performance. *International Journal of Sports Medicine*, 22, 350-355.

Mauger, A.R., Jones, A.M., & Williams, C.A. (2009). Influence of feedback and prior experience on pacing during a 4-km cycle time trial. *Medicine and Science in Sports and Exercise*, 41(2), 451-458.

Micklewright, D., Papadopoulou, E., Swart, J., & Noakes, T. (2010). Previous experience influences pacing during 20 km time trial cycling. *British Journal of Sports Medicine*, 44, 13: 952-960.

Monod, H., & Scherrer, J. (1965). The work capacity of a synergic muscular group. *Ergonomics*, 8, 329-338.

Morey, R.D. (2008). Confidence intervals from normalized data: A correction to Cousineau (2005). *Tutorials in Quantitative Methods for Psychology*, 4(2), 61–64.

Palmer, G.S., Hawley, J.A., Dennis, S.C., & Noakes, T.D. (1994). Heart rate responses during a 4-d cycle stage race. *Medicine and Science in Sports and Exercise*, 26, 1278-1283.

Paton, C.D., & Hopkins, W.G. (2001). Tests of cycling performance. *Sports Medicine*, 31, 489-496.

Paton, C.D., & Hopkins, W.G. (2001). Tests of cycling performance. *Sports Medicine*, 31, 489-496.

R Core Team (2014). R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. URL http://www.R-project.org/.

Schabort, E.J., Hawley, J.A., Hopkins, W.G., Mujika, I., & Noakes, T.D. (1998). A new reliable laboratory test of endurance performance for road cyclists. *Medicine and Science in Sports and Exercise*, 30, 1744 – 1750.

Thomas, K., Stone, M., St Clair Gibson, A., Thompson, KG., & Ansley, L. (2013). The effect of an even-pacing strategy on exercise tolerance in well-trained cyclists. *European Journal of Applied Physiology*, 113, 3001-3010.

Thomas, K., Stone, M., Thompson, K.G., St Clair Gibson, A., & Ansley, L. (2012). The effect of self-even and variable-pacing strategies on the physiological and perceptual response to cycling. *European Journal of Applied Physiology*, 112, 3069-3078.

Tucker, R., Bester, A., Lambert, E.V., Noakes, T.D., Vaugham, C.L., & St Clair Gibson, A. (2006). Non-random fluctuations in power output during self-paced exercise. *British Journal of Sports Medicine*, 40, 912-917.

Vanhatalo, A., Doust, J.H., & Burnley, M. (2008). A 3-min all out cycling test is sensitive to a change in critical power. *Medicine and Science in Sports and Exercise*, 40, 1693-1699.

Vanhatalo, A., Jones, A.M., & Burnley, M. (2011). Application of critical power in sport. *International Journal of Sports Physiology and Performance*, 6, 128-136.

Wilson, M.G., Lane, A.M., Beedie, C.J & Farooq, A. (2012). Influence of accurate and inaccurate ‘split time’ feedback upon 10-mile time trial cycling performance. *European Journal of Applied Physiology*, 112, 231-236.

Table 1: Median and range: Critical power (CP) and W′ parameter estimates from the hyperbolic, Linear-TW and Linear-P models when derived from time-trials (TT) and time-to-exhaustion (TTE) trials. Standard error of the mean (SEM) for CP and W′ estimates derived from each model are also included. * Significant difference between trials; *P*<0.05.

		CP (W)	SEM	W′ (J)	SEM
TT					
	Hyperbolic	258 (189 – 336) *	12.50	11,857 (8889 – 19,952) *	888.67
	Linear-TW	259 (190 – 337) *	12.46	11,653 (9416 – 17,619) *	807.27
	Linear-P	261 (198 – 342) *	12.49	11,623 (6047 – 18,239)	1003.67
TTE					
	Hyperbolic	267 (194 – 347)	13.53	9999 (5956 – 29,080)	1693.83
	Linear-TW	268 (196 -347)	12.87	9479 (6037 – 18,194)	1068.67
	Linear-P	277 (207 – 347)	12.08	9517 (5986 – 16,100)	1099.32

Table 2: Mean (± SD): Blood lactate, heart rate (HR), cadence, ratings of perceived exertion (RPE) and estimated time limit (ETL) for time-trials (TT) and time-to-exhaustion (TTE) at 80, 100 and 105% of maximal aerobic power (MAP). * Significant difference between trials; $P < 0.05$.

	80%		100%		105%	
	TT	TTE	TT	TTE	TT	TTE
Blood lactate (mmol·L^{-1})	8.10 ± 2.20	10.79 ± 3.10 *	8.42 ± 3.13	8.76 ± 3.18	7.60 ± 2.07	7.89 ± 2.63
Average HR (bpm)	166 ± 11	167 ± 13	164 ± 11	163 ± 15	161 ± 14	163 ± 15
Average cadence (rpm)	96 ± 7	96 ± 10	97 ± 10	87 ± 12	96 ± 13	93 ± 13
RPE (1 min)	13 ± 2	13 ± 2	–	–	–	–
RPE (5 min)	16 ± 2	16 ± 2	–	–	–	–
ETL (1 min)	-	13 ± 3	–	–	-	–
ETL (5 min)	-	13 ± 4	–	–	-	–

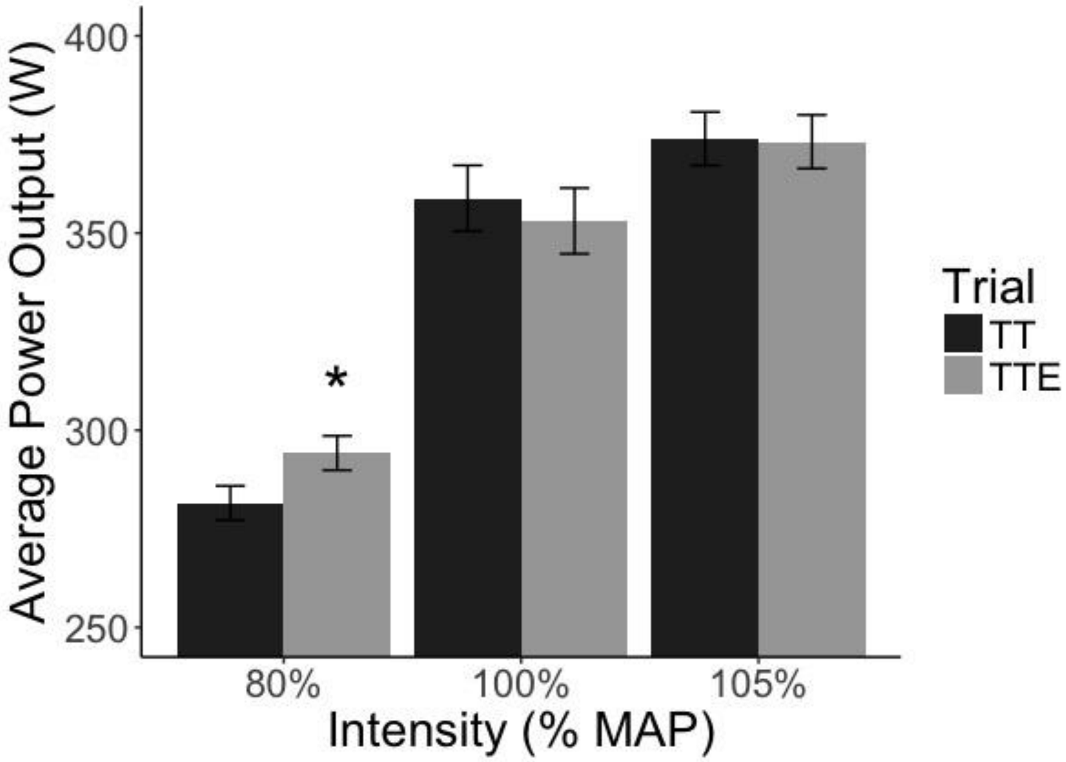

Figure 1: Average power output for time-trials (TT) and time-to-exhaustion (TTE) at 80, 100 and 105% of maximal aerobic power (MAP). Values are mean and 95% confidence intervals for a within subject design. *Significant difference between trials; $P < 0.05$.

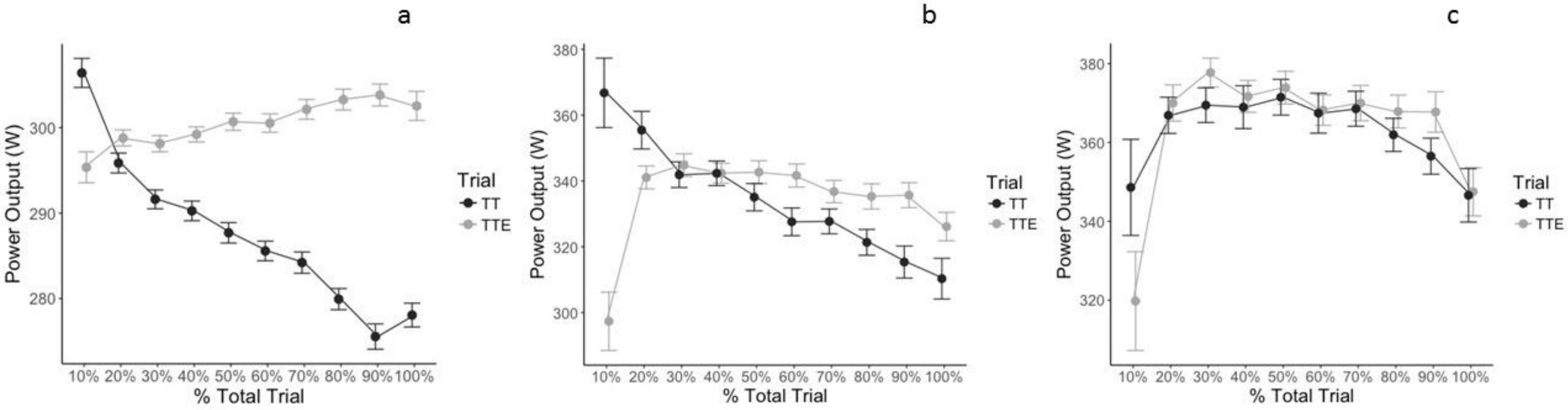

Figure 2: Power output averaged over each 10% segment of time-trial (TT) and time-to-exhaustion (TTE) at 80% (a), 100% (b) and 105% (c) of maximal aerobic power (MAP). Values are mean and 95% confidence intervals for a within subject design.