W′ Recovery Kinetics during Variable-Pace Exercise: Investigating the Effects of Inherent Variability and Dynamic Changes in the Power-Duration Relationship.

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I certify that all material in this thesis which is not my own work has been identified and that any material that has previously been submitted and approved for the award of a degree by this or any other University has been acknowledged.

Abstract

The parameters of the power-duration relationship, critical power (CP) and W′ can be used to accurately predict severe-intensity (>CP) exercise performance. Both endurance-based sports such as cycling and team sports involve severe-intensity exercise. Thus, the optimization of severe-intensity exercise performance is highly relevant. It is advantageous if athletes can monitor their energy usage and energy availability either during an event or in retrospect, in order to inform tactics and pacing strategy. Mathematical models of energy expenditure have been developed, based on the CP concept and designed to measure the dynamic balance of W′ (W'_{BAL}) during exercise. The accuracy of the current W'_{BAL} models is equivocal and may be influenced by day-to-day variability in estimates of CP and W′. Additionally, it is known that dynamic changes in the power-duration parameters can occur during exercise – such changes are currently unaccounted for in the W'_{BAL} models. The purpose of this thesis was two-fold. Firstly, to investigate the accuracy with which the current W'_{BAL} models were able to characterise W'_{BAL} and the influence of inherent variability in CP and W′ on the accuracy of the W'_{BAL} models. Secondly, to examine whether dynamic changes in the power-duration parameters occurred during team sport type exercise. **Study 1**: W'_{BAL} was modelled for a 16.1-km road TT, using both the point (Best individual fit; BIF) estimates of CP and W′ and the upper and lower 95% CIs of both parameters. Upon completion of the 16.1-km TT, predicted end W'_{BAL} was -14.7 ± 26.4, -0.82 ± 5.52, and -14.2 ± 20.0 kJ for Morton's W'_{BAL} model ($W'_{BAL\text{-}MORTON}$), the integral W'_{BAL} model ($W'_{BAL\text{-}INT}$) and the differential W'_{BAL} model ($W'_{BAL\text{-}ODE}$) respectively, with no significant differences ($P > 0.05$) between models. When accounting for the 95% CIs of CP and W′, the 'bandwidth' in predicted end W'_{BAL} was equivalent to 278, 134 and 292% of starting W′ (W'_0) for the $W'_{BAL\text{-}MORTON}$, $W'_{BAL\text{-}INT}$ and $W'_{BAL\text{-}ODE}$ models respectively. These results indicate that: (i) The current W'_{BAL} models have poor predictive accuracy and; (ii) That inherent variability in the power-duration parameters significantly influences the accuracy of the W'_{BAL} models. **Study 2**: CP, W′ and the speed at which W′ recovered following full depletion (W'_{REC}) were measured in a fresh condition (no exercise prior to fatiguing bout) and following; (i) one 40 min block and; (ii) two 40 min blocks separated by a 15 minute 'half-time' interval, of simulated match play. CP and W'_{REC} did not significantly decline ($P > 0.05$) relative to the fresh condition following either 40 or 80 min of match play. W′ was significantly lower ($P < 0.05$) in comparison to baseline in

both the 40- and 80-min conditions but did not significantly differ ($P > 0.05$) between the 40- and 80-min conditions, indicating that the 15-minute recovery interval permitted full recovery of W′. The above results indicate that significant dynamic changes in the power-duration parameters do not occur during team sport type exercise. Taken collectively, the findings of both studies inform us of potential sources of error in W'_{BAL} modelling.

Table of contents

List of Tables

List of Figures

List of Symbols and Abbreviations

2MT	2-Minute all-out test
3MT	3-Minute all-out test
Δ	Difference
$\tau_{W'}$	Time constant of W′ recovery
ATP	Adenosine triphosphate
BIF	Best individual fit
BLa	Blood lactate
CI	Confidence interval
CNS	Central nervous system
CO_2	Carbon dioxide
CV	Coefficient of variation
CP	Critical Power: Asymptote of the power-duration relationship
CT	Critical torque
EMG	Electromyography
EP	End power
GET	Gas exchange threshold
H^+	Hydrogen ion
IST	Intermittent sprint test
K^+	Potassium ion
MVC	Maximal voluntary contraction
$m\dot{V}O_2$	Muscle oxygen uptake
NIRS	Near infrared spectroscopy
O_2	Oxygen
P	Power
PCr	Phosphocreatine
pH	Potential of hydrogen
PO	Power output
R-AOT	Repeat all-out test
RPM	Revolutions per minute

SD	Standard deviation
SEE	Standard error of the estimate
T_{lim}	Time taken to attain exercise intolerance
TT	Time trial
TWD	Total work done
$\dot{V}CO_2$	Carbon dioxide output
V_E	Minute Ventilation
$\dot{V}O_2$	Oxygen uptake
$\dot{V}O_{2Max}$	Maximal oxygen uptake
$\dot{V}O_{2Peak}$	Peak oxygen uptake
W > CP	Work performed above CP
W'	Curvature constant of the power-duration relationship
W'_0	W' at time t = 0
W'_{BAL}	W' Balance
$W'_{BAL\text{-}INT}$	Integral W' balance model
$W'_{BAL\text{-}MORTON}$	Morton’s W' balance model
$W'_{BAL\text{-}ODE}$	Ordinary differential equation W' balance model
W'_{REC}	W' Recovery
WEP	Work performed above end power

Declarations

The material contained within this thesis is original work, conducted and written by the author.

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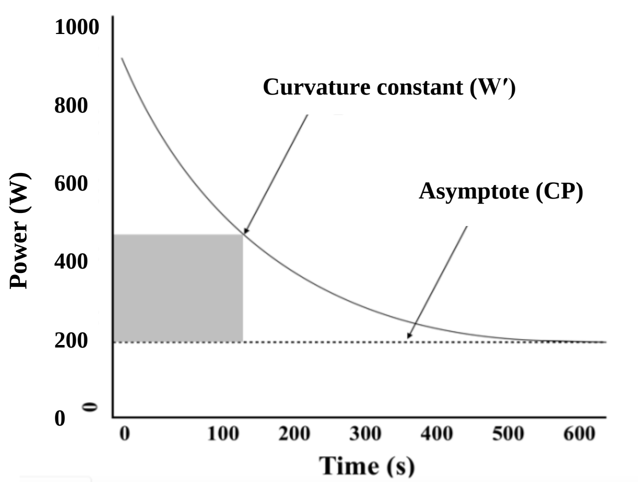
Chapter 1: Introduction

The relationship between work rate e.g., power output (PO) and the time over which it can be sustained (Figure 1) is hyperbolic (Monod and Scherrer., 1965; Moritani et al., 1981; Poole et al., 1988). The asymptote of the power-duration relationship is termed critical power (CP) and demarcates the boundary between the heavy and severe-intensity domains (Jones et al., 2008a; Jones et al., 2010; Poole et a., 2016). The curvature constant of the power-duration relationship, W′, is representative of the work capacity above CP and its magnitude is constant, regardless of the rate at which it is expended (Jones et al., 2010; Poole et al., 1988). Partial recovery of W′ takes place at sub-CP work rates (Ferguson et al., 2010; Skiba and Clarke., 2021). The recovery of W′ (W'_{REC}) is curvilinear, characterised by a fast initial recovery phase followed by a slowing in the rate of recovery (Ferguson et al., 2010; Caen et al., 2019). It is important to note that W'_{REC} is dependent on the intensity of sub-CP exercise, such that W′ will recover more quickly at lower intensities (Ferguson et al., 2010; Skiba et al., 2012).



The heavy-intensity domain consists of work rates above the gas exchange threshold (GET), and below CP (Lansley et al., 2011). GET can be defined as the intensity at which carbon dioxide output ($\dot{V}CO_2$) begins to increase more rapidly than oxygen uptake ($\dot{V}O_2$) (Beaver et al., 1986;Jones & Poole., 2005). Within the heavy-intensity domain, muscle metabolism will attain a steady state, such that muscle phosphocreatine [PCr], blood lactate [BLa], and muscle pH will stabilise (Jones & Vanhatalo., 2017; Parker-Simpson et al., 2015). The oxygen uptake ($\dot{V}O_2$) response to heavy-intensity exercise is characterised by a biexponential function (Jones et al., 2011). Specifically, following an initial delay of 10-20s, reflective of the time taken for deoxygenated blood to reach the pulmonary capillary network, there is an exponential increase in $\dot{V}O_2$ – this is supplemented by the so called 'slow component', delaying the attainment of a steady state of $\dot{V}O_2$ (Burnley and Jones., 2007; Jones et al., 2011; Wilkerson & Jones., 2007). At work rates above CP within the severe-intensity domain, W′ is depleted: muscle [PCr] continuously decreases, [BLa] increases inexorably, and maximal oxygen uptake ($\dot{V}O_{2max}$) is attained prior to, or at exhaustion (Chidnok et al., 2012; Lansley et al., 2011). Therefore, CP can be defined as a critical metabolic threshold, above which a progressive loss of systematic and intramuscular homeostasis will occur, resulting in substantially reduced exercise tolerance (Jones et al., 2008a; Jones et al., 2010; Jones & Vanhatalo., 2017; Poole et al., 2016).

The 2-parameter critical power model can be used to predict either the work rate that can be sustained for a given time or the time over which a given work rate can be sustained, assuming that the work rate remains above CP (Jones et al., 2010: Poole et al., 1988; Vanhatalo et al., 2011b).

$$T_{lim} = W' / (PO – CP) \qquad \textbf{(1)}$$

Where T_{lim} is the time for which the work rate can be sustained, W′ is the fixed work capacity above CP, PO is power output (work rate), and CP is representative of the boundary between the heavy and severe-intensity domains.

The 2-parameter model has been demonstrated to accurately predict T_{lim} in cycling exercise in which the work rate is close to the 'middle' of the range i.e., between maximum sustainable work rate and CP, of supra-CP work rates (1% difference between actual and predicted T_{lim} at a PO corresponding to ~150 % of CP) [Pallares et al., 2020]. However, the predictive accuracy of the 2-parameter model was reduced at both higher and lower work rates (86 and 6% difference between actual and predicted T_{lim} at work rates of ~295 and 102 % of CP respectively) [Pallares et al., 2020]. The time over which CP itself can be sustained exhibits considerable variability (~20-40 minutes) [Poole et al., 2016]. Additionally, the formulation of the 2-parameter model is such that, as the time asymptote approaches zero, the work rate tends toward infinity i.e., the work rate that could theoretically be sustained for that time would attain a non-physiological value (Chorley & Lamb., 2020). Morton. (1996) developed a novel 3-parameter CP model in order to attempt to address the above issues. In the 3-parameter model, the maximum attainable work rate is proportional to the remaining W′ (Morton., 1996). It has since been demonstrated that the 3-parameter model yields significantly lower values of CP in comparison to the 2-parameter model and, in so doing, yields unusually high estimates of W′ (Bergstrom et al., 2014). Due to the debatable validity of the parameter estimates and the lack of need of a model to cover extremely small time durations, the 3-parameter model is not commonly used in research (Chorley & Lamb., 2020).

A prominent limitation of 2-parameter CP model is that it cannot be applied to exercise which involves variable pacing, as the model only accounts for the expenditure and not the recovery of W′ (Jones & Vanhatalo., 2017). Exercise intensity within endurance events is likely to be variable due to tactical considerations and changes in terrain / conditions (Brickley et al., 2007; Jones & Vanhatalo., 2017; Kirby et al., 2021). Additionally, team sports involve rapid changes in exercise intensity, such that athletes are required to perform repeated high-intensity (> CP) efforts, interspersed with low intensity (< CP) periods and some passive rest periods (Bishop & Claudius., 2005; Bishop & Edge., 2006; Spencer et al., 2004). Accordingly, novel CP-based mathematical models have been developed, designed to characterise the dynamic balance of W′ (W'_{BAL}) during intermittent high-intensity exercise which is defined in the present thesis as exercise in which work rate alternates above and below CP exercise (Morton & Billat., 2004; Skiba et al., 2012; Skiba et al., 2014b). Theoretically, the W'_{BAL} models can be used to track energy expenditure and energy availability during events and/or in retrospect, helping to inform tactics and pacing strategy (Morton & Billat., 2004; Skiba et al., 2012; Skiba et al., 2014b; Skiba & Clarke., 2021).

W′ recovery kinetics have a high degree of inter-individual variability (Skiba and Clarke., 2021). A previous study found that the rate at which W′ recovered exhibited a significant positive association with both CP and $\dot{V}O_{2Max}$ and a negative association with fat mass (Chorley & Lamb., 2020). Accordingly, it is likely that some of the observed variability in W′ recovery kinetics is attributable to physiological factors (Chorley and Lamb., 2020l; Skiba and Clarke 202). However, it is also important to consider that the accuracy of the current W'_{BAL} models may contribute to the variability in W′ recovery kinetics, indeed, a number previous studies have demonstrated that predictive accuracy of the current W'_{BAL} models is equivocal (Bartram et al., 2018; Broxterman et al., 2016; Caen et al., 2019; Caen et al., 2021; Chorley et al., 2019; Lievens et al., 2020; Townsend et al., 2017). Therefore, it is important that further work be carried out in order to: (i) further examine the accuracy with which the different W'_{BAL} models can characterise W'_{BAL} during exercise, and; (ii) investigate factors that may contribute to variability in W′ recovery kinetics.

Chapter 2: Literature Review

Historical development of the CP concept

In an attempt to understand the physiological underpinnings of muscle fatigue in relation to athletic performance, Hill. (1925) constructed velocity-time curves, using world record times over a range of distances in running, cycling, swimming and rowing. It was observed that the velocity-time relationships for the above sports were hyperbolic (Hill, 1925). Later, Monod & Scherrer. (1965) plotted work rate against maximum sustainable duration for synergistic small muscle mass exercise in skeletal muscle, observing hyperbolic relationships for both dynamic and static work. CP was defined as the maximum work rate that 'could be sustained for a long time, without fatigue', corresponding to the asymptote of the curve of the work-time relationship (Monod & Scherrer., 1965). It is important to note that it has long since been established that fatigue development does occur at sub-CP work rates, albeit at a far slower rate and via different mechanisms to severe-intensity work rates (Black et al., 2016b). More specifically, at supra-CP work rates, fatigue is primarily driven by changes in the metabolic melieu of the working muscle, i.e., accumulation of fatigue-related metabolites which results in a reduced response to neural drive (Amann., 2011; Horstrup & Bangsbo., 2017). At sub-CP work rates, fatigue development is predominantly attributable to a reduction in central nervous system (CNS) drive (Amann., 2011). A second parameter, W′, was defined as a finite energetic reserve which would be depleted at work rates above CP, corresponding to the curvature constant of the work-time relationship (Monod & Scherrer., 1965). Mathematically, the relationship was expressed in the following form (Monod & Scherrer., 1965).

$$W_{lim} = (W' + CP) * T_{lim} \qquad \textbf{(1)}$$

Where T_{lim} = time taken for exhaustion to occur and W_{lim} = amount of work performed upon reaching T_{lim} (Monod & Scherrer., 1965). Moritani et al. (1981) subsequently demonstrated that the CP concept could be applied to whole body exercise, specifically cycle ergometry, concluding that it was possible to accurately calculate the time over which a given work rate (*P*), could be sustained, using the following equation.

$$T_{lim} = W' / (P\text{-}CP) \qquad \textbf{(2)}$$

The CP concept has since been applied to other sports such as running, swimming and rowing (Di Prampero et al., 2008; Kachouri et al., 1996; Shimoda & Kawakami., 2005).

Poole et al. (1988) later investigated the physiological response to exercise at and just above CP. Data from a series (5 or more) of constant work rate (CWR) tests to exhaustion, lasting between 2 and 15 minutes, was used to construct hyperbolic power-duration curves, from which CP was derived using the following hyperbolic formulation of the CP model, originally developed by Whipp et al. (1982).

$$W' = (P\text{-}CP) / T_{lim} \qquad \textbf{(3)}$$

Subsequently, subjects performed 2 further CWR tests, at CP and at 5% above CP [Poole et al., 1988).

$\dot{V}O_2$ and [BLa] reached stable values in the test at CP and all participants achieved the target time of 24 minutes, i.e., they did not attain exhaustion, however, during the supra-CP test, $\dot{V}O_{2max}$ was attained and [Bla] increased inexorably, until exhaustion occurred [T_{lim} of 17.7 ± 1.2 minutes] (Poole et al., 1988). Therefore, it was concluded that CP represented a physiological threshold, separating the heavy and severe-intensity domains (Poole et al., 1988).

Physiological bases of CP and W′

As highlighted in chapter 1, muscle metabolism and pulmonary $\dot{V}O_2$ stabilise at work rates below CP: there is no progressive PCr breakdown, [Bla] will not increase inexorably, such that the rate of production will equal the rate of clearance and pulmonary $\dot{V}O_2$ will stabilise (Burnley and Jones., 2007; Jones et al., 2008a; Skiba., 2014). In other words, energy supply from substrate level phosphorylation attains a steady state (Poole et al., 2016). In contrast, at work rates above CP at which W′ is depleted, muscle metabolism fails to stabilise - muscle PCr and pH decrease, alongside an accumulation of blood lactate [Bla], reaching their minimum and maximum values respectively at the limit of tolerance (Jones & Vanhatalo., 2017).The magnitude of the $\dot{V}O_2$ slow component will continually increase until $\dot{V}O_{2Max}$ is attained such that pulmonary $\dot{V}O_2$ increases inexorably toward its maximum value, signalling that exhaustion is imminent (Black et al., 2016b; Burnley and Jones., 2007). A reduction in muscle excitability occurs alongside the increase in metabolic and ionic perturbations (Black et al., 2016b). Evidence from previous studies suggests that the reduction in excitability is due to an increase in interstitial potassium [K^+] within t-tubules, resulting in weakened propogation of the action potential along the surface membrane (Cairns et al., 1997; McKenna., 1992; McKenna et al., 2008). Additionally, an increase in extracellular [K^+] depolarizes the cell membrane, eliciting a reduction in the amplitude of the action potential leading to impaired force production (Cairns et al., 1997; McKenna., 1992; McKenna et al., 2008). It has been demonstrated that the concentrations of intramuscular metabolites attained at exhaustion within the severe-intensity domain are similar, independent of the length of the exercise bout (Black et al., 2016b). In contemporary terms, CP is defined as that which demarcates the boundary between the heavy and severe-intensity domains, i.e., separating steady-state and non-steady-states of muscle metabolism (Black et al., 2016b; Jones et al., 2008a; Poole et al., 2016).

Traditionally, W′ has been considered to represent an ‘anaerobic work capacity’, consisting of energy derived from high energy phosphates and anaerobic glycolysis, coupled with a small amount of aerobic energy from O_2 bound to myoglobin. (Monod & Scherrer., 1965; Moritani et al., 1981; Poole et al., 2016). Vanhatalo et al. (2011a) showed that W′ was proportional to the $\dot{V}O_2$ slow component, reflecting a loss of muscle efficiency in the form of an increase in the volume of O_2 required for a given work rate to be sustained. There is evidence to suggest that W′ is responsive to interventions known to effect anaerobic exercise performance (Miura et al., 1999; Muira et al., 2000). Specifically, W′ increases following oral creatine supplementation, and decreases as a result of glycogen depletion, with neither intervention effecting CP (Miura et al., 1999; Miura et al., 2000). Additionally, W′ has been shown to decrease in response to hyperoxic conditions, and following endurance exercise training, alongside corresponding increases in CP (Gaesser and Wilson., 1988; Vanhatalo et al., 2010), thus suggesting a possible inverse relationship between CP and W′. Parker-Simpson et al. (2015), found that there was a significant inverse correlation between the change in W′ and the change in CP in normoxic vs hypoxic conditions. Suggesting that the changes in W′ in response to interventions, may be related to changes in CP (Parker-Simpson et al., 2015). Mitchell et al. (2018) noted that CP was significantly correlated with both the proportion of type I muscle fibers and the degree of muscle capillarity. Type 1 fibers possess characteristics that favour oxidative metabolism, such as higher mitochondrial content and capillary supply vs type II fibers (Schiaffino and Reggiani., 2011). Surprisingly, previous studies have found that the magnitude of W′ was not significantly correlated with the proportion of either type I or type II muscle fibers (Mitchell et al., 2018; Vanhatalo et al., 2016). Therefore, it is overly simplistic to consider CP and W′ as separate aerobic and anaerobic parameters respectively, and neither can be accounted for by a single physiological index (Jones et al., 2010; Poole et al., 2016; Skiba, 2014).

Determination of the power-duration relationship

Traditionally, CP and W′ are determined using a series 3-5 of maximal severe-intensity constant work rate or self-paced trials performed on separate days, with the shortest and longest trials lasting ~2 and 15 minutes respectively e.g., Black et al. (2015), Brickley et al. (2002), Hill et al. (2002), and Morgan et al. (2018). CP and W′ can then be estimated using: (i) The hyperbolic p-t model (Equation 3) via non-linear regression ;(ii) the linear work-time model (Equation 1) by means of plotting total work done in each trial against time to completion and; (iii) the linear inverse of time model (Equation 4), where PO is plotted against the inverse of time (Black et al., 2015; Morgan et al., 2018):

$$P = W' * \left(\frac{1}{T_{lim}}\right) + CP \qquad \textbf{(4)}$$

Subsequently, the standard errors of the estimate (SEEs) associated with CP and W′ can be expressed as coefficients of variation (CVs) relative to the parameter estimates (CV %). The total error associated with each model is calculated as the sum of the CV% associated with CP and the CV% associated with W′. Parameter estimates from the model with the lowest total error, usually termed the best individual fit (BIF) model, are used (Black et al., 2015; Morgan et al., 2018).

Whilst a conventional power-duration relationship determination protocol can provide accurate and reliable estimates of both parameters, it is time consuming to conduct (Jones et al., 2010). Burnley et al. (2006) attempted to determine the power-duration relationship using a single 3-minute all-out test (3MT) against a fixed resistance. Participants performed 3 x 3MTs, from which end power (EP), analogous to CP (Vanhatalo et al., 2007; Vanhatalo et al., 2008), was calculated as the mean PO over the last 30 s of the test. Work done above end power (WEP), analogous to W′(Vanhatalo et al., 2007; Vanhatalo et al., 2008),, was calculated as the work performed at work rates greater than EP during the test. Subsequently, participants performed two constant work rate tests, one at a work rate of 15 W below EP and another at 15 W above EP. The supra-EP test elicited a physiological response consistent with severe-intensity exercise, specifically, blood lactate [BLa] and $\dot{V}O_2$ increased inexorably, with exhaustion occurring in 13 ± 7 minutes. Contrastingly, in the sub-EP trial the majority of participants (9/11) were able to continue exercise for 30 minutes, with [BLa] and $\dot{V}O_2$ attaining a steady state in 7/9 participants. Therefore, Burnley et al. (2006) concluded that EP was likely to be equivalent to CP. Later, Vanhatalo et al. (2007) compared EP and WEP derived from a 3MT with estimates of CP and W′ derived from a conventional CP determination protocol. There were no significant differences between EP and CP or W′ and WEP. Therefore, it was concluded that the 3MT could provide valid estimates of both CP and W′ (Vanhatalo et al., 2007).

Vanhatalo et al. (2008) later demonstrated that the 3MT was sensitive to training-induced changes in CP, specifically, EP significantly increased in comparison to baseline following completion of a 4-week high-intensity interval training program. More recently, in Clark et al. (2018) participants completed a 3MT in a fatigued state following 2 h of heavy-intensity constant work rate exercise. Participants subsequently performed constant work rate trials at 15 W above and 15 W below fatigued EP. In the sub-EP trial, [BLa] and $\dot{V}O_2$ attained a steady state, consistent with heavy-intensity behaviour. In the supra-EP trial, T_{lim} was 8.8 ± 6.2 minutes, indicating that the trial was performed in the severe-intensity domain. Thus, it was concluded that the 3MT could provide accurate estimates of CP and W′ in a fatigued state (Clark et al., 2018). In summary, it is now established that the 3MT can provide accurate, valid and reliable estimates of CP and W′ in both rested and fatigued conditions and is sensitive to training-induced changes in the power-duration relationship (Burnley et al., 2006; Clark et al., 2018; Vanhatalo et al., 2007; Vanhatalo et al., 2008).

Application of the CP concept to intermittent high-intensity exercise

Introduction to W'_{BAL} modelling

Morton and Billat. (2004) developed the first CP model for intermittent high-intensity exercise, based upon the two-parameter CP model. Morton's model ($W'_{BAL\text{-}MORTON}$) assumes that both the expenditure and recovery of W′ follow linear kinetics, and can be expressed in a bi-conditional form in order to monitor the dynamic balance of W′ (W'_{BAL}) during intermittent high-intensity exercise:

$$If\ P > CP,\ W'_{bal} = W'_{exp} - [(P_w - CP)t_w] \qquad \textbf{(3a)}$$

$$If\ P < CP,\ W'_{bal} = W'_{exp} + [(CP - P_r)t_r] \qquad \textbf{(3b)}$$

Where W'_{EXP} is the W'_{BAL} prior to the work/recovery interval, P_w and T_w, and P_r and T_r are the PO and duration of the work (w) and recovery (r) intervals, respectively (Morton and Billat. 2004). Subsequently, Ferguson et al (2010) investigated the nature of W′ recovery kinetics. Subjects performed severe-intensity exercise to T_{lim}, following 2, 6, and 15 minutes of recovery at 20 W, preceded by an initial bout of exhaustive severe-intensity exercise (Ferguson et al., 2010). Whilst there were no significant changes in CP vs the baseline (unfatigued) condition, W′ was significantly reduced following 2, 6 and 15 minutes of recovery (Ferguson et al., 2010). It was then observed that the speed of W′ recovery was greater in the initial vs the later recovery period, specifically, 37, 65, and 86% of W′ was recovered following 2, 6 and 15 minutes of recovery respectively (Ferguson et al., 2010). Therefore, Ferguson et al. (2010) concluded that W′ recovery kinetics were curvilinear.

Skiba et al. (2012) later sought to develop a new model ($W'_{BAL\text{-}INT}$), accounting for the curvilinear nature of W′ recovery kinetics, using integral calculus. Three key assumptions were made: (1) W′ expenditure commenced instantly when work rate exceeded CP; (2) W′ reconstitution began as soon as work rate fell below CP; (3) the reconstitution of W′ followed an exponential time course (Skiba et al., 2012). An equation was derived, in order to calculate W'_{BAL} at any given time during a about of intermittent high-intensity exercise:

$$W'_{bal} = W' - \int_0^t W'_{exp}.\, e^{\frac{-(t-u)}{\tau W'}}\, du \qquad \textbf{(4)}$$

Where W'_{EXP} is equal to the expended W′, *-(t-u)* is equal to time between segments in which W′ is expended, *du* denotes that integration has been performed with respect to *u* (initial time), and $\tau_{W'}$ is the time constant of W′ recovery (Skiba et al., 2012). In order to calculate $\tau_{W'}$, subjects performed exhaustive intermittent high-intensity exercise, specifically, 60 s intervals at a PO calculated to elicit exhaustion in 6 minutes (P6) + 50% of the difference between P6 and each subject's CP, separated by 30 s recovery intervals at a range of work rates (Skiba et al., 2012). In each case $\tau_{W'}$ was varied using an iterative process, such that W'_{BAL} was equal to 0 at T_{lim} - $\tau_{W'}$ was then plotted against the difference between CP and recovery interval power output (D_{CP}), the relationship between the two parameters assessed by means of regression analysis (Skiba et al., 2012). The following equation was formulated (derived from group-averaged data) in order to determine $\tau_{W'}$:

$$\tau_{W'} = 546.e^{(-0.01D_{CP})} + 316 \qquad \textbf{(5)}$$

Where D_{CP} is equal to the difference between mean recovery PO for a given bout, and CP (Skiba et al., 2012).

The $W'_{BAL\text{-}INT}$ model has some prominent limitations (Skiba and Clarke., 2021; Sreedhara et al., 2020). Specifically, the $W'_{BAL\text{-}INT}$ model assumes that the rate of W′ recovery is constant throughout an exercise bout, and therefore not dependent on the work rate of individual recovery intervals (Skiba et al., 2012). Additionally, Equation 4 cannot be solved until the conclusion of a bout (Skiba et al., 2012) and, therefore, cannot be used in real time during a training session or race, thus limiting the practical application of the $W'_{BAL\text{-}INT}$ model. In order to address the above concerns, Skiba et al. (2014b) developed a novel bi-conditional W'_{BAL} model ($W'_{BAL\text{-}ODE}$), assuming linear discharge and exponential recovery of W′:

$$If\ P \geq CP,\ W'_{bal} = W'_0 - [(P - CP)t] \qquad \textbf{(6a)}$$

$$If\ P < CP,\ W'_{bal} = W'_0 - W'_{exp}e^{\frac{-t}{\tau}} \qquad \textbf{(6b)}$$

Where W'_0 is equal to W′ at time, t = 0, t is equal to the duration of the work or recovery interval, W'_{EXP} is equal to the amount of W′ expended before the recovery interval, and τ is the time constant of W′ recovery given by the following equation:

$$\tau = W'_0 / D_{CP} \qquad \textbf{(7)}$$

Where D_{CP} is the difference between instantaneous recovery interval PO and CP (Skiba et al. 2014b).

The $W'_{BAL\text{-}ODE}$ model is easier to compute than the $W'_{BAL\text{-}INT}$ model due to its relative mathematical simplicity, in other words, the $W'_{BAL\text{-}ODE}$ model offers greater ease of use for athletes and coaches. (Skiba et al., 2012; Skiba et al., 2014b; Skiba & Clarke., 2021). Additionally, the time constant of W′ recovery used by the $W'_{BAL\text{-}ODE}$ model is dynamic (dependent on instantaneous D_{CP}) and thus theoretically more accurate than that used by the $W'_{BAL\text{-}INT}$ model (Skiba et al., 2012; Skiba et al., 2014b; Skiba & Clarke., 2021). It is important to note that the $W'_{BAL\text{-}ODE}$ model also has inherent limitations (Skiba & Clarke., 2021). Firstly, due to the assumption that depletion of W′ is linear (note: the $W'_{BAL\text{-}INT}$ model assumes a curvilinear depletion), the $W'_{BAL\text{-}ODE}$ model can over-predict the rate of W′ depletion, i.e., T_{lim} being reached prematurely (Skiba et al., 2014b; Skiba and Clarke., 2021). Secondly, the $W'_{BAL\text{-}ODE}$ model can be considered to be less flexible than the $W'_{BAL\text{-}INT}$ model in that it uses a ‘generic’ formulation for calculating the time constant of W′ recovery, assuming that τ is dependent solely upon W'_0 and D_{CP} (Skiba et al., 2014b). In other words, in its current formulation, the $W'_{BAL\text{-}ODE}$ model is more difficult to adapt for individual use whereas the $W'_{BAL\text{-}INT}$ model permits estimation of highly individualised time constants, via the process used to derive $\tau_{W'}$, described in Skiba et al., (2012).

Accuracy of the current W'_{BAL} models

The accuracy with which both the $W'_{BAL\text{-}INT}$ and $W'_{BAL\text{-}ODE}$ models are able to characterise W'_{BAL} and therefore predict exercise performance is equivocal (Skiba and Clarke., 2021). In Townsend et al. (2017), exhaustive high-intensity intermittent cycling exercise (9 work intervals of ~50s at a PO predicted to elicit exhaustion in 5 minutes, interspersed with ~45s recovery intervals, with a maximal sprint of 3-5s following every third work interval) was performed at sea level (250m) and at altitude (2,250m). The $W'_{BAL\text{-}INT}$ model underestimated W'_{REC} at altitude, specifically, predicted W'_{BAL} was significantly lower than 0 at T_{lim}, (-2.8 kJ), at sea level the predicted W'_{BAL} was not significantly different from zero [-0.9 kJ] (Townsend et al., 2017).
For the $W'_{BAL\text{-}ODE}$ model predicted W'_{BAL} at T_{lim} was not significantly different from zero at altitude (0.7 kJ) or at sea level (-1.3 kJ), in other words, the $W'_{BAL\text{-}ODE}$ model provided accurate characterisations of W'_{BAL} in both conditions (Townsend et al., 2017). Bartram et al. (2018) noted that the $W'_{BAL\text{-}ODE}$ model significantly underestimated W'_{REC} (mean difference of ~3.5 kJ)

in a sample of elite cyclists performing high-intensity interval training (3-4 efforts, separated by 20 minute recovery periods, each effort consisting of 2x 30s work intervals, interspersed with 60s recovery, followed by an exhaustive work interval). Subsequently, in Caen et al. (2019) W'_{REC} was assessed after 2, 4 and 6 minutes of recovery from exhaustive constant work rate severe-intensity exercise at POs predicted to elicit exhaustion in either 4 or 8 minutes (P4 and P8 respectively). The $W'_{BAL\text{-}INT}$ model significantly underestimated the magnitude of W'_{REC} following P4 exercise (predicted W'_{REC} 30 and 18% lower vs actual W'_{REC} for 2 and 4 minutes of recovery respectively) and after 2 minutes of recovery from P8 exercise [predicted W'_{REC} 18% lower vs actual W'_{REC}] (Caen et al., 2019). Following 6 minutes of recovery from P4 exercise, and both 4 and 6 minutes of recovery following P8 exercise, there were no significant differences between actual and $W'_{BAL\text{-}INT}$ model-predicted W'_{REC}. Thus, it was concluded that the $W'_{BAL\text{-}INT}$ model underestimated W'_{REC} when shorter recovery intervals were used. In Chorley et al. (2019), the $W'_{BAL\text{-}INT}$ model significantly underestimated W'_{REC} (up to ~ 2kJ) following repeated bouts of exhaustive ramp-incremental exercise. Given the equivocal findings of previous studies, it would be prudent to investigate factors which may have contributed to the poor predictive validity of the $W'_{BAL\text{-}INT}$ and $W'_{BAL\text{-}ODE}$ models. In addition, it is important to note that whilst the $W'_{BAL\text{-}INT}$ and $W'_{BAL\text{-}ODE}$ models theoretically have superior predictive accuracy in comparison to the $W'_{BAL\text{-}MORTON}$ model due to accounting for the curvilinear nature of W' recovery kinetics (Ferguson et al., 2010; Skiba et al., 2012; Skiba et al., 2014b), it has yet to be established whether either model can characterise W'_{BAL} with increased accuracy versus the $W'_{BAL\text{-}MORTON}$ model.

A recent review identified two key limitations of both the $W'_{BAL\text{-}INT}$ and $W'_{BAL\text{-}ODE}$ models (Skiba and Clarke., 2021). Firstly, both models rely upon accurate estimates of CP and W′: Both parameters are subject to measurement error and day-to-day variability due to physiological factors e.g., fatigue level (Skiba and Clarke., 2021; Skiba et al., 2012; Skiba et al., 2014b). Secondly, both models assume that CP and W'_0 remain constant during exercise (Skiba et al., 2012; Skiba et al., 2014b). Previous studies have demonstrated that exercise can elicit dynamic changes in both parameters (Clark et al., 2018; Clark et al., 2019b). Both limitations are discussed in detail below.

Inherent variability in CP and W′

Accurate estimates of CP and W′ are of critical importance in W'_{BAL} modelling (Skiba and Clarke., 2021). In both the $W'_{BAL\text{-}INT}$ and $W'_{BAL\text{-}ODE}$ models, W′ depletion and recovery are calculated as functions of the difference between PO and CP (Skiba et al., 2012; Skiba et al., 2014b). Therefore, an inaccurate estimate of CP could result in inaccurate estimates of W′ expenditure and W′ recovery, thereby negatively affecting the ability of the $W'_{BAL\text{-}MODELS}$ to characterise the behaviour of W'_{BAL} during exercise. W'_0 is used to calculate the W′ recovery time constant in the case of the $W'_{BAL\text{-}ODE}$ model (Equation 7), and sets the starting value of W'_{BAL} for both W'_{BAL} models (Equations 4, and 6a,b) and, therefore, the point at which W'_{BAL} reaches 0 i.e., predicted T_{lim} (Skiba et al., 2012; Skiba et al., 2014b).

Both parameters of the power-duration relationship are subject to a degree of measurement error: The error associated with CP is typically ~ 5 % (Black et al., 2015; Black at al., 2016b; Caen et al., 2019; Lievens et al., 2020), with the error associated with W′ being ~7 - 20% (Skiba and Clarke., 2021). It is also important to consider that there is likely to be physiological variability associated with both parameters (Burnley et al., 2011; Pethick et al., 2020; Shearman et al., 2016; Skiba and Clarke., 2021; Townsend et al., 2017). In Shearman et al. (2016), 3MTs were performed under both normoxic and hypoxic conditions. CP decreased by 9% in the hypoxic relative to the normoxic condition, with no significant change in W′ (Shearman et al., 2016). Townsend et al. (2017) noted that both CP and W′ decreased at altitude. In Burnley et al. (2011), heavy-intensity priming exercise was demonstrated to significantly increase time to exhaustion in subsequent severe-intensity exercise (~52s increase vs a non-primed condition. The improvement in performance was attributed to a significant increase in W′ elicited by the heavy-intensity priming exercise alongside a significant increase in the speed of $\dot{V}O_2$ kinetics (Burnley et al., 2011). It was concluded that the observed increase in W′ may have been due to the rapid $\dot{V}O_2$ response, more specifically, the latter would have resulted in increased aerobic contribution during the early part of the exercise bout, thus 'sparing' the W′ (Burnley et al., 2011). Thus, it is possible that physiological variability in W′ is partially attributable to variation in the amount of W′ being expended in response to initial increases in PO (Burnley et al., 2011), something which could conceivably vary between individuals (Chorley & Lamb., 2020). Recently, Pethick et al. (2020) measured muscle oxygen uptake (m$\dot{V}O_2$; measured indirectly using near infrared spectroscopy [NIRS]), EMG and maximal voluntary contraction (MVC) at work rates below but within the 95% confidence interval of critical torque (CT; analogous to CP) and at a work rate corresponding to 107% of CT. Non-steady-state i.e., severe-intensity behaviour of m$\dot{V}O_2$, EMG and MVC was observed at sub-CP work rates (Pethick et al., 2020). Additionally, at a work rate of 107% of CT, severe-intensity behaviour of m$\dot{V}O_2$, EMG and MVC was not consistently observed (Pethick et al., 2020). Thus, it was suggested that CP may represent a narrow 'bandwidth' of work rates, encompassing a gradual transition from heavy to severe-intensity behaviour, rather than single point value (Pethick et al., 2020). In summary, it is likely that the considerable variability associated with the power-duration parameters is attributable to both measurement error and physiological factors (Burnley et al., 2011; Black et al., 2015; Black et al., 2016b; Caen et al., 2019; Lievens et al., 2020; Pethick et al., 2020; Shearman et al., 2016; Skiba and Clarke., 2021; Townsend et al., 2017). It is highly likely that the inherent variability in CP and W′ will significantly affect the accuracy of the W'_{BAL} models, however, it has yet to be experimentally verified.

Dynamic changes in the power-duration relationship

The current iterations of the $W'_{BAL\text{-}INT}$ and $W'_{BAL\text{-}ODE}$ models assume that (i) CP remains constant throughout an exercise bout, and (ii) that the speed of W′ recovery does not decrease during exercise (Skiba et al., 2012; Skiba et al., 2014b). However, there is evidence to suggest that dynamic changes in the power-duration relationship may occur during exercise (Clark et al., 2019b). In Clark et al. (2019b), subjects performed 3MTs on 4 separate occasions. Firstly, participants undertook a 3MT in a rested condition i.e., with no prior exercise (Clark et al., 2019b). Subsequently, participants completed 3MTs following 40, 80, and 120 minutes of heavy-intensity constant work rate exercise at a work rate corresponding to PO at GET + 50% of the difference between PO at GET and power at $\dot{V}O_{2Peak}$ (25% Δ) [Clark et al., 2019b]. Following 40 minutes of exercise, there were no significant differences in CP and W′ in comparision to the unfatigued consition (Clark et al., 2019b). W′ decreased significantly by 18 and 23% relative to baseline following 80 and 120 minutes of exercise respectively. CP did not significantly decline following 80 minutes of exercise, but was 9% lower in comparison to baseline following 120 minutes of exercise (Clark et al., 2019b). The findings of Clark et al. (2019b) demonstrate that exercise can elicit dynamic changes in the power-duration parameters. It is unknown whether the magnitude of such changes will vary according to the type and/or intensity of exercise being performed.

It is important to note that the mechanisms resulting in the development of fatigue and thereby contribute to exercise intolerance differ between heavy and severe-intensity exercise (Burnley et al., 2012). Central fatigue is defined as a reduction in central nervous system (CNS) drive to motor neurons (Amann., 2011). The contribution of central fatigue to overall fatigue development is greater in heavy and moderate-intensity exercise in comparison to severe-intensity exercise (Pethick et al., 2016). In supra-CP exercise, in which W′ is depleted, the metabolic and ionic perturbations that occur, such as extracellular K^+ accumulation, increase in muscle pH and decrease in muscle phosphocreatine [PCr], result in a reduced muscle response to neural stimulation, termed peripheral fatigue (Amann, 2011; Francaux et al., 2000; Hostrup & Bangsbo., 2017). Bouts of high-intensity intermittent exercise will encompass both sub-CP i.e., heavy or moderate-intensity and supra-CP i.e., severe-intensity efforts. Due to the difference in fatigue mechanisms, it is currently unclear whether high-intensity intermittent exercise will elicit dynamic changes in the parameters of the power-duration relationship, as observed in response to heavy-intensity constant work rate exercise such as that used in Clark et al. (2019b).

The presence of dynamic changes in the parameters of the power-duration relationship during intermittent high-intensity exercise would have important implications for W'_{BAL} modelling. A time dependent reduction in CP would result in the W'_{BAL} models underestimating and overestimating W′ expenditure and W'_{REC} respectively (Skiba et al., 2012; Skiba et al., 2014b). Likewise, a decrease in the speed of W′ recovery kinetics throughout an exercise bout would result in the current W'_{BAL} models underestimating W'_{REC}. Thus it is likely that, in order for their predictive accuracy to be improved, the W'_{BAL} models would require modification in order to accommodate time-dependent changes in the power-duration parameters. Therefore, it would be prudent to investigate the effect of intermittent high-intensity exercise on CP, W′, and W′ recovery kinetics.

Summary

Two key parameters can be derived from the hyperbolic power-duration relationship, namely, CP and W′ (Jones et al., 2010; Poole et al., 2016). The former is defined as the work rate that can be sustained without incurring a progressive loss of systemic and intramuscular homeostasis, and the latter as a fixed amount of work that can be performed above CP (Jones et al., 2008a; Jones et al., 2010). Using the two-parameter CP model, severe-intensity exercise tolerance can be predicted with a reasonable degree of accuracy (Jones et al., 2010; Poole et al., 2016). However, the two-parameter CP model is limited, as it can only be applied to CWR exercise when in reality, in both endurance-based and team sports, the work rate is likely to fluctuate above and below CP (Brickley et al., 2007; Jones & Vanhatalo., 2017). Mathematical models that account for both the expenditure and recovery of W′ have since been developed, the most prominent of which are the $W'_{BAL\text{-}INT}$ and $W'_{BAL\text{-}ODE}$ models (Skiba et al., 2012; Skiba et al., 2014b). The accuracy with which the $W'_{BAL\text{-}INT}$ and $W'_{BAL\text{-}ODE}$ models can characterise W'_{BAL} and predict exercise tolerance has been found to be equivocal (Bartram et al., 2018; Caen et al., 2019; Chorley et al., 2019; Townsend et al., 2017). Day-to-day variability in CP and W′, due to both measurement error and physiological factors may effect the accuracy of the W'_{BAL} models (Skiba and Clarke., 2021), but this has yet to be fully investigated. Additionally, dynamic changes may occur in the parameters of the power-duration relationship during intermittent high-intensity exercise. If present, any such changes in CP, W′ or W′ recovery kinetics would have significant implications for W'_{BAL} modelling.

Aims & Hypotheses

The purpose of the current thesis was to investigate: (i) the effect of day-to-day variability in the parameters of the power-duration relationship on the accuracy with which the $W'_{BAL\text{-}INT}$ and $W'_{BAL\text{-}ODE}$ models characterise W'_{BAL} and predict exercise tolerance, and; (ii) the effect of intermittent high-intensity exercise on CP, W′ and the speed of W′ recovery kinetics.

The following hypotheses will be tested:

1A) That the behaviour of W'_{BAL} during intermittent high-intensity exercise will not be accurately characterised by the $W'_{BAL\text{-}INT}$ and $W'_{BAL\text{-}ODE}$ models, resulting in an inaccurate prediction of exercise tolerance and will be impaired when using parameter estimates within the 95% confidence intervals for CP and W′.

1B) The $W'_{BAL\text{-}ODE}$ and $W'_{BAL\text{-}INT}$ models will provide a more accurate characterisation of W'_{BAL} and prediction of exercise tolerance in intermittent high-intensity exercise vs the $W'_{BAL\text{-}MORTON}$ model.

2A) CP and W′ will significantly decline following prolonged high-intensity intermittent exercise.

2B) There will be a significant time-dependent reduction in the speed at which W′ recovers during high-intensity intermittent exercise.

Chapter 3: General Methods

General experimental procedures

Ethical considerations, and participant consent

The two studies included in the current thesis were approved by the Sport and Health Sciences Ethics Committee of the University of Exeter. In both studies, participants provided written informed consent, having read the participant information sheet (PIS) beforehand which provided a detailed description of the experimental protocol and what participation would involve. Participants had the opportunity to ask questions about the study, which were answered prior to them providing written informed consent.

Health and safety

All experimental procedures were conducted in accordance with the Sport and Health Sciences Health and Safety Code of Practice 2012-13 (Chapter 4), and 2020-21 (Chapter 5). Researchers complied with regulations on laboratory cleanliness, and safety and suitability for the exercise testing of human participants. In study 2, additional measures were taken in order to minimize the risk of Covid-19 infection.

Participants

The participants recruited for the study in chapter 4 were 10 male club-level cyclists (mean ± SD: age, 25 ± 7 years, height 1.80 ± 0.05 m, body mass 73.8 ± 6.4 kg, BMI 22.6 ± 2.29 $kg.m^2$. For the study in chapter 5, participants were nine male (mean ± SD: age, 24 ± 5 years; height, 1.78 ± 0.05 m; body mass, 74 ± 8.8 kg, BMI 23.6 ± 3.65 $kg.m^2$) and four female (mean ± SD: age, 23 ± 3 years; height, 1.67 ± 0.06 m; body mass, 55 ± 3.4 kg, BMI 1.97 ± 1.12 $kg.m^2$) recreationally active team-sport players. All participants were non-smokers, and free from any conditions that would make maximal exercise testing unsafe. In both studies, participants were instructed to report to the laboratory in a rested and fully hydrated state. Participants were told to avoid alcohol and to not perform strenuous exercise in the 24 h prior to the start of laboratory visits. In addition, participants were instructed to avoid caffeine prior to visits (3 h before in chapter 4, and 12 h before in chapter 5). For each participant, testing was performed at the same time of day (± 90 min in chapter 4, and ± 120 min in chapter 5).

Measurement procedures

Descriptive data

Prior to the start of experimental testing, participants height and body mass were recorded using a Seca Stadiometer SEC-225 (Seca, Hamburg, Germany) and Seca Digital Column Scale SEC-170 (Seca, Hamburg, Germany), respectively.

Exercise testing

Cycle ergometry

All laboratory-based cycling, with the exception of the self-paced prediction trials used to determine the power-duration relationship in chapter 4 (see below) was performed on an electronically braked cycle ergometer (Lode Excalibur Sport, Groningen, The Netherlands). The ergometer seat and handlebar position were adjusted for the comfort of each participant during their first visit to the laboratory, with the settings recorded and replicated for all subsequent tests.

In the current thesis, three of the available ergometer modes were used:

1) Ramp mode: Permits a continuous increase in work rate at a predetermined ramp-rate (i.e 30 W/min^{-1}) for a predetermined duration. The work rate is independent of the participant's cadence from 25 to 180 RPM.
2) Step mode: Permits instantaneous changes in a step-wise manner, from one constant work rate to another. As with ramp mode, the work rate is independent of cadence.
3) Linear mode: Work rate is set according to the participant's cadence, based upon the equation below.

$$Linear\ factor = \frac{PO}{Cadence^2} \qquad \textbf{(8)}$$

Pulmonary gas exchange

During all laboratory-based sessions, pulmonary gas exchange was measured on breath-by-breath basis. Gases were analysed using commercially available metabolic cart systems, specifically, a Mobile Jaeger Oxycon Pro (Jaeger, Hoechbergy, Germany) in chapter 4, and a

Cosmed Quark CPET analyser (Cosmed, Rome, Italy) in chapter 5. Participants wore a face mask (Hans Rudolph Inc., Shawnee, KS, USA) and breathed through a turbine assembly (Triple V, Jaeger, Viasys Healthcare GmbH, Hoechberg, Germany). Inspired and expired gas volume and concentration signals were continuously analysed via a capillary line connected to the face mask, with the latter using paramagnetic (O_2) and infrared (CO_2) sensors. Before each test, the analyser was calibrated using gases of a known concentration (15% O_2 and 5% CO_2) and ambient air. The impeller turbine assembly (Jaeger Triple V in chapter 4 and Cosmed Turbine 2,000 in chapter 5) was fitted with a volume transducer and was calibrated prior to each test, using a 3-L syringe (Hans Rudolph Inc., Shawnee, KS, USA). The volume and concentration signals were time-aligned, to account for transit delay between the volume and concentration sensors. Following each test, the data files were exported into Microsoft Excel format for later analysis.

Ramp-Incremental testing

In chapter 4, participants performed a ramp-incremental test on cycle ergometer, for the determination of gas exchange threshold (GET) and $\dot{V}O_{2Peak}$. The test began with 4 minutes of cycling at 20 W, followed by an increase in power of 30 $W.min^{-1}$. Subjects were instructed to maintain their preferred cadence throughout the test, and to remain seated. The test was terminated when cadence decreased by > 10 rpm below the preferred cadence for 5 s, despite strong verbal encouragement. The GET was determined as: (i) the first disproportionate increase in carbon dioxide output ($\dot{V}CO_2$) vs $\dot{V}O_2$; (ii) an increase in minute ventilation ($\dot{V}_E$) relative to $\dot{V}O_2$ with no corresponding increase in $\dot{V}_E$/ $\dot{V}CO_2$, and; (iii) the first increase in end-tidal O_2

tension with no fall in end-tidal CO_2 tension. $\dot{V}O_{2Peak}$ was determined as the highest 15-s average value of $\dot{V}O_2$ recorded during the test.

In chapter 5, participants also performed a ramp-incremental test to determine GET and $\dot{V}O_{2Peak}$. The ramp-incremental test was performed as previously described for chapter 4, with 2 minor differences: (i) the test was preceded by 3 min of unloaded cycling, rather than 4 min of cycling at 20 W, and; (ii). $\dot{V}O_{2Peak}$ was determined as the highest 10s, rather than the highest 15s average value of $\dot{V}O_2$ recorded during the test.

Determination of the power-duration relationship

In chapter 4, following the completion of 3-5 self-paced prediction trials (see above), CP and W′ were estimated using 3 models: the hyperbolic power-time (P-T_{lim}) model (equation 1); the linear work-time (W-T_{lim}) model (equation 2); and the linear inverse of time (1/T_{lim}) model (equation 3).

$$\mathrm{T_{lim}} = \mathrm{W'/(P - CP)} \qquad (1)$$

$$W = CP * T_{lim} + W' \qquad (2)$$

$$P = \mathrm{W'} * \left(\frac{1}{\mathrm{T_{lim}}}\right) + \mathrm{CP} \qquad (3)$$

The standard errors of the estimate (SEE) associated with CP and W′ were expressed as coefficient of variation (CV%). The “total error” associated with the modelling of the power-duration parameters was calculated as the sum of the CV% associated with the CP and W′. *A priori* criteria were set for the standard errors associated with CP and W′, as a quality control measure of the mathematical modelling of both parameters. If the standard errors of CP and W′ exceeded 5 and 10% respectively, after the completion of 4 prediction trials, additional trials were performed until the standard error of estimate (SEE) fell within the acceptable range. The model associated with the smallest sum of the CV% was used to produce the “best individual fit” (BIF) parameter estimates. Note that use of the three models and subsequent selection of that providing the best fit, i.e., smallest SEE for each individual participant is currently considered to be best practice when estimating the parameters of the power-duration relationship using the protocol described above (Chorley and Lamb., 2020). Likewise, the 5 and 10% acceptable standard error margins used for CP W′ respectively are commonly used, such that their application can be considered as standard practice, e.g., Black et al. (2015), Black et al. (2016b), Nixon et al. (2021), Morgan et al. (2018).

In chapter 5, end power (EP) considered equivalent to CP (Vanhatalo et al., 2007) was estimated as the mean power for the last 30s of the 3-AOT. Work done above EP (WEP), considered equivalent to W′ (Vanhatalo et al., 2007) was calculated as the power-time integral above EP during the 3-AOT. W′ recovery (W'_{REC}) was calculated as the amount of work performed above EP during the 2-AOT, subtracted from WEP.

Statistical methods

All statistical analyses were performed using SPSS version 25 (SPSS Inc, Chicago, Illinois, USA). Specific statistical tests are discussed in chapters 4 and 5. Statistical significance was accepted at the $P < 0.05$ level. All data are presented as mean ±SD, unless otherwise specified in chapters 3 and 4.

Chapter 4: Modelling W'_{BAL} during a 16.1-km road cycling TT: effect of W'_{BAL} model and variability in the parameter estimates of the power-duration relationship.

Abstract

Introduction: The accuracy of mathematical models designed to model the dynamic balance of W' (W'_{BAL}) during exercise in which PO fluctuates above and below critical power, CP, is equivocal. We tested the hypotheses that the W'_{BAL} models would not accurately characterise W'_{BAL} during a 16.1 km road time trial (TT) and that the accuracy of the models would be significantly affected by day-to-day variability in CP and W'. **Methods:** 10 male subjects completed a series of 3-5 maximal self-paced TT's on a cycle ergometer in order to determine CP and W', prior to performing a 16.1 km road TT. W'_{BAL} was modelled for the 16.1 km TT using the $W'_{BAL\text{-}MORTON}$, $W'_{BAL\text{-}INT}$, and $W'_{BAL\text{-}ODE}$ models, using the upper and lower 95% confidence intervals of the point estimates of CP and W'**. Results**: Upon completion of the 16.1 km TT, predicted end W'_{BAL} was -14.7 ± 26.4, -0.82 ± 5.52, and -14.2 ± 20.0 kJ for the $W'_{BAL\text{-}MORTON}$, $W'_{BAL\text{-}INT}$ and $W'_{BAL\text{-}ODE}$ models respectively, with no significant differences ($P > 0.05$) between models. When accounting for the 95% CIs of CP and W', the 'bandwidth' in predicted end W'_{BAL} was equivalent to 278, 134 and 292% of starting W' (W'_0) for the $W'_{BAL\text{-}MORTON}$, $W'_{BAL\text{-}INT}$ and $W'_{BAL\text{-}ODE}$ models respectively. **Conclusions**: The above results suggest that the 3 W'_{BAL} models did not accurately characterise W'_{BAL} during the 16.1 km road TT and that the accuracy of the W'_{BAL} models is significantly influenced by inherent variability in the power-duration parameters.

Introduction

The decrease in exercise tolerance that occurs alongside an increase in work rate, is hyperbolic (Jones et al., 2010; Poole et al., 2016). Critical power (CP), can be defined as the asymptote of the power-duration relationship, and is functionally representative of the highest work rate that can be sustained without incurring a progressive loss of intramuscular and systemic homeostasis (Black et al., 2016; Poole et al., 1988; Vanhatalo et al., 2016). The curvature constant of the power-duration relationship is known as W′, and is defined as a fixed amount of work i.e the magnitude is constant, regardless of the rate of expenditure that can be performed above CP (Jones et al., 2010; Jones & Vanhatalo., 2017). Exercise tolerance (T_{lim}) at a given power output (PO) in the severe-intensity domain, above CP, can be accurately predicted using the parameters of the power-duration relationship, with the following equation (Jones et al., 2010):

$$T_{lim} = W' / P\text{-}CP \qquad (1)$$

The two-parameter CP model (Equation 1) is limited in that it only accounts for the expenditure of W′ and can therefore only be applied to exercise in which PO is above CP for the entire duration of a bout. However, during endurance exercise in the field, exercise work rate is likely to fluctuate with periods both above and below CP (Brickley et al., 2007). Given that W′ will recover following supra-CP exercise i.e if PO falls below CP (Chidnok et al., 2013a; Ferguson et al., 2010), mathematical models of energy expenditure, accounting for both the expenditure and recovery of W′ have been developed (Morton & Billat., 2004; Skiba et al., 2012; Skiba et al., 2014b). Due to the development of mobile power meters, cycling PO can be accurately measured in a field setting (Bertucci et al., 2005). Therefore, it is theoretically possible to model energy expenditure for field-based cycling events, which can be useful in the optimisation of performance therein (Skiba et al., 2012; Sreedhara et al., 2019).

The development of mathematical models of energy expenditure during intermittent-intensity exercise has been reviewed in detail elsewhere (Jones & Vanhatalo., 2017; Sreedhara et al., 2019). In brief, Morton & Billat. (2004) were the first to develop a model for intermittent-high-intensity exercise, based on the two-parameter CP model, assuming linear kinetics for both expenditure and recovery of W′. For intermittent-intensity exercise where the durations and POs of work (P > CP) and recovery (P < CP) intervals are not pre-defined, the dynamic balance of W′ (W'_{BAL}) can be modelled using a rearranged bi-conditional form of Morton's model ($W'_{BAL\text{-}MORTON}$), Ferguson et al. (2010) demonstrated that the recovery of W′ was curvilinear. Two novel models have since been developed, both acknowledging the apparent non-linear nature of W′ recovery kinetics (Skiba et al., 2012; Skiba et al., 2015). The first is known as the integral W'_{BAL} model ($W'_{BAL\text{-}INT}$), and assumes that both W′ recovery and W′ expenditure follow an exponential time course, and that the rate of W′ recovery is constant throughout the exercise bout, i.e., not dependent on the intensity of an individual recovery interval (Skiba et al., 2012). The second model, termed the differential W'_{BAL} model ($W'_{BAL\text{-}ODE}$), is bi-conditional, with W′ expenditure following linear kinetics, whilst the recovery of W′ is assumed to be exponential, the latter is calculated using a differential equation which can be continuously solved throughout an exercise bout (Skiba et al., 2015).

Whilst the $W'_{BAL\text{-}INT}$ and $W'_{BAL\text{-}ODE}$ models are considered to have superior ability to predict exercise tolerance vs the $W'_{BAL\text{-}MORTON}$ model, due to acknowledging the non-linear nature of W′ recovery kinetics (Ferguson et al., 2010; Skiba et al., 2012; Skiba et al., 2015), it has yet to be established whether either model predicts cycling performance with increased accuracy, versus the $W'_{BALMORTON}$ model. In addition, the accuracy with which the $W'_{BAL-INT}$ and $W'_{BAL-ODE}$ models are able to characterise W'_{BAL} during cycling exercise and thereby predict cycling performance remains equivocal, with both models having subsequently been found to overestimate and underestimate W′ recovery in cycling exercise (Bartram et al., 2018; Caen et al., 2019; Caen et al., 2021; Chorley et al., 2019; Lievens et al., 2020; Sreedhara et al., 2020; Townsend et al., 2017).Therefore, at present, caution is advised regarding use of the $W'_{BAL-INT}$ and $W'_{BAL-ODE}$ models in training and/or racing situations (Caen et al., 2019; Skiba and Clarke., 2021).

Both CP and W′ exhibit considerable variability. For a given individual, the error associated with CP is typically ~ 5 % e.g Black et al. (2015), Black at al. (2016b), Caen et al. (2019), Lievens et al. (2020), with the error associated with W′ between 7 and 20% of the point estimate (Skiba and Clarke., 2021). In addition, it has recently been suggested that the boundary between heavy and severe-intensity exercise may be represented by a phase transition, encompassing a narrow ‘bandwidth’ of work rates, rather than by a discrete threshold (Pethick et al., 2020). Thus, it is possible that the observed variability in CP may be partly physiological in nature (Pethick et al., 2020). It is probable that the inherent variability in CP and W′ may account for some of the observed inaccuracy in the $W'_{BAL-INT}$ and $W'_{BAL-ODE}$ models. Given that the position of CP dictates whether W′ is expended or recovered at a given work rate, variability in CP could result in overestimation or underestimation of both W′ expenditure and W′ recovery. Likewise, variability in W′ may result in full W′ depletion occurring prematurely, according to the $W'_{BAL-ODE}$, $W'_{BAL-INT}$ and $W'_{BAL-MORTON}$ models, thereby underestimating performance, or W'_{BAL} remaining positive at T_{lim}, resulting in an overestimation of performance. No study to date has sought to examine the effect of inherent variability in CP and W′, on the ability of the $W'_{BAL\text{-}INT}$ and $W'_{BAL\text{-}ODE}$ models to characterise W'_{BAL} and predict exercise performance.

The purpose of the current study was to: (1) Compare the predictive accuracy of the $W'_{BAL\text{-}ODE}$, $W'_{BAL\text{-}INT}$, and $W'_{BAL\text{-}MORTON}$ models, and; (2) Examine the effect of variability in the parameter estimates of the power-duration relationship on the accuracy with which the W'_{BAL} models characterize W'_{BAL}, and predict 16.1-km cycling TT performance. Our hypothesis was two-fold. Firstly, that the work performed above CP (W > CP), the amount of W′ recovered (W'_{REC}), and end W'_{BAL} during a 16.1-km road cycling TT would not be accurately estimated by the W'_{BAL} models, and would be impaired when using parameter estimates within the 95% confidence intervals for CP and W′. Secondly, that the $W'_{BAL\text{-}ODE}$ and $W'_{BAL\text{-}INT}$ models would provide a more accurate characterisation of W'_{BAL} and thereby a superior prediction of performance in a 16.1 km road TT, vs the $W'_{BAL\text{-}MORTON}$ model.

Methods

The datasets used for this study were collected in a previous investigation conducted by our research group (Morgan et al., 2018). Briefly, for this previous investigation, 12 participants performed a ramp-incremental test, a series of maximal self-paced time trials (T_{lim} ranging: ~ 2-15 min) for determination of CP and W′, a 20-min maximal self-paced time trial for determination of functional threshold power, and a 16.1-km road cycling time trial. To be included in the present study, participants were required to have performed maximally during: (1) the series of self-paced TT’s, such that end exercise $\dot{V}O_2$ was >95% of ramp test $\dot{V}O_{2Peak}$, thus providing a valid estimate for CP and W′, and; (2) the 16.1-km road TT, with a mean PO greater than CP. It was also required that power output was recorded frequently throughout the 16.1-km road TT, with no recording gaps of ≥ 20 s.

In total, data from 10 participants (Mean ± SD: age 22 ± 7.2 years, height 1.8 ± 0.6 m, body mass 74 ± 6.4 kg, BMI 23 ± 2.3 kg.m^{-2}) was included in the present study. Testing was performed at the same time of day (± 90 min) for each participant, and each test was separated by a minimum of 24 h. For all tests, participants were instructed to be adequately hydrated and fed so as to produce a maximal performance. Participants were also instructed to avoid strenuous exercise and caffeine consumption for 24 h and 3 h respectively, prior to testing sessions. All procedures were approved by the University of Exeter Research Ethics committee, and conformed to the declaration of Helsinki.

Laboratory based tests

The ramp incremental test, and the series of self-paced TT's were performed in the same air conditioned laboratory in similar environmental conditions (temperature 18-20°C, relative humidity 45-55 %). During these tests, $\dot{V}O_2$ was measured continuously using a Mobile Jaeger Oxycon Pro online gas analyser (Hoechburg, Germany). Prior to each test, the gas analyser was calibrated with gases of known concentration, and a calibration syringe of known volume (3 L; Hans Rudolph, KS).

Ramp incremental cycling test

Participants performed a ramp incremental cycling test on an electronically braked cycling ergometer (Lode Excalibur Sport, Groningen, The Netherlands) for determination of $\dot{V}O_{2peak}$ and gas exchange threshold (GET). The ramp-incremental test consisted of 4 min of cycling at 20 W followed by a continuous increase in PO of 30 $W \cdot min^{-1}$. Participants were instructed to maintain their self-selected cadence for as long as possible. The test was terminated when pedal rate decreased by ≥ 10 rpm below the self-selected cadence for >5 s despite verbal encouragement. The gas exchange threshold (GET) was established according to: (i) the first disproportionate increase in carbon dioxide output ($\dot{V}CO_2$) vs $\dot{V}O_2$; (ii) an increase in minute ventilation ($\dot{V}_E$), without an increase in $\dot{V}_E$ / $\dot{V}CO_2$, and; (iii) the first increase in end-tidal O_2 tension, without a fall in end-tidal CO_2 tension. $\dot{V}O_{2peak}$ was defined as the highest 15-s rolling mean $\dot{V}O_2$ value recorded during the test. $\dot{V}O_{2peak}$ was used as a criterion for maximal effort during the series of self-paced TT's (see below).

Self-paced prediction trials

The parameter estimates of the power-duration relationship (i.e., CP and W′) were estimated from 3-5 (3 trials, n=1; 4 trials, n = 7; 5 trials, n = 2) self-paced, maximal TT's that were performed on the participants own road-bike, which had been loaded on to a static trainer (Elite Volare Trainer Mag Alu, Fontana, Italy) and fitted with a power meter (PowerTap G3 Hub, CycleOps, Madison USA). The power meter was wirelessly connected to a data logger (Garmin Edge 500, Garmin, Chicago, USA) to display and record PO and work done, and these data were used to provide verbal and visual feedback to the participants during each trial. The static trainer resistance was set at maximum (arbitrary unit of '5'), and tyres were inflated to a pressure of 110 psi. The power meter was calibrated prior to each trial according to the manufacturer's instructions. Participants were instructed to complete a target amount of work as quickly as possible, with the shortest trial completed in ~2-3 min and the longest trial lasting ~12-15 min with 2 or 3 trials spaced approximately equally between. This range in duration was selected to ensure that participants were exercising within the severe-intensity domain, in accordance with current best practice (Muniz-Pumares et al., 2019). Any trials in which participants did not attain ≥95% of ramp test determined $\dot{V}O_{2peak}$ were repeated. Prior to each trial, participants performed a self-selected warm up during which PO was kept below GET in order to ensure that the warm up would not significantly enhance subsequent exercise performance by means of a priming effect (Gerbino et al., 1996). The warn up was followed by 5 min of stretching or passive rest. Participants then completed a further 3 min of pedalling (20 W) at their preferred cadence that was immediately followed by a maximal self-paced effort. To familiarise participants with the self-paced TTs, each participant performed a minimum of 2 TTs, with a set amount of work requiring ~5-7 minutes to complete, until the difference in the repeated TT duration was <1.3%, corresponding to the test-retest variability for laboratory based TT's, observed in (Sparks et al., 2016). These familiarisation trials were not included in the subsequent data analysis. In accordance with previous studies, e.g., Black et al. (2015), Black et al. (2016b), Nixon et al. (2021), Morgan et al. (2018), as a quality control measure of the mathematical modelling of the power-duration parameters, *a priori* criteria were set for the standard errors associated with CP and W′, such that if the standard errors exceeded 5% and 10%, respectively, after 4 prediction trials had been completed, additional trials were performed until the standard error of estimate (SEE) was acceptable.

16.1-km road TT

The TT was performed in Exeter (Devon, UK), on a dry day with minimal wind, and an ambient air temperature of ~14°C. The 16.1-km TT course was familiar to all participants, being used routinely in club training sessions, and benefited from minimal road traffic, and a good, consistent road surface. The course consisted of an ‘outward’ leg of ~7-km, at the end of which participants made a U-turn and covered part of the same course in the opposite direction. Changes in elevation (net change of 74-m, ~ 22% of altitude at time t = 0) and gradient were minimal (Figure 1).

Prior to the TT, participants performed their normal pre-competition warm-up, and were instructed to complete the TT is the shortest time possible and not to draft. All participants performed the TT on the same day within 1-h. To reduce the possibility of drafting, start times were separated by a 1-min interval and assigned based on previous TT performance, with the fastest cyclist starting first. All participants performed the TT on their own road-bikes, which were all of a similar high-standard, fitted with the same power meter and data logger that had been used in the series of self-paced TTs used for determination of the power-duration relationship. Time to completion was recorded to within the nearest second, and PO and total work done during the TT were provided by the data logger.

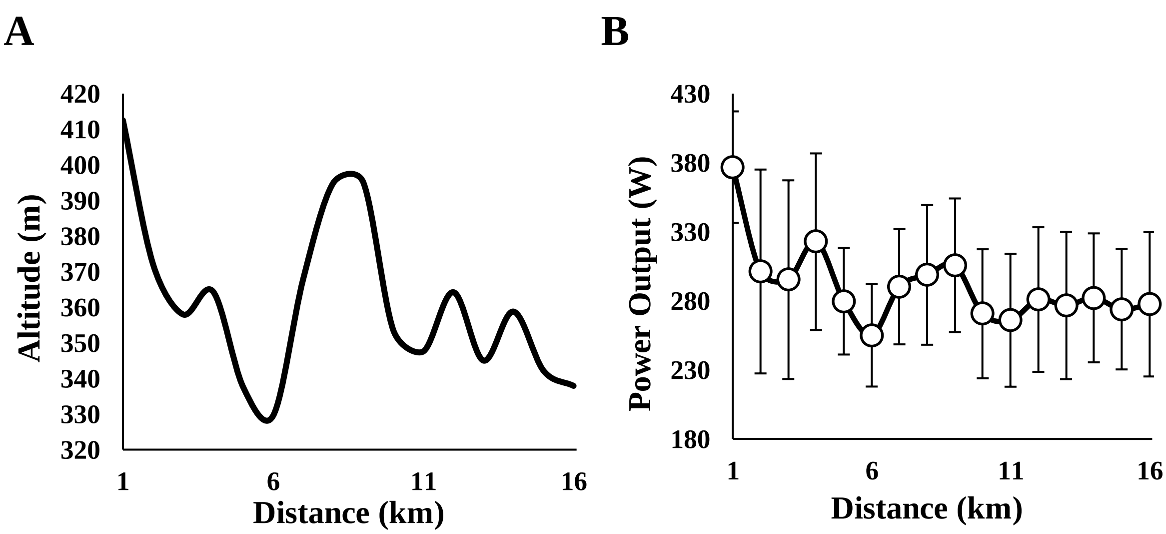


Figure 1. Course profile (A) and group mean pacing strategy (B) for the 16.1 km road TT.

Data analysis

The parameter estimates of the power-duration relationship were estimated using 3 models: the hyperbolic power-time (P-T_{lim}) model (equation 1); the linear work-time (W-T_{lim}) model (equation 2); and the linear inverse of time (1/T_{lim}) model (equation 3).

$$\mathrm{T_{lim}} = \mathrm{W'}/(\mathrm{P} - \mathrm{CP}) \qquad (1)$$

$$W = CP * T_{lim} + W' \qquad (2)$$

$$P = \mathrm{W'} * \left(\frac{1}{\mathrm{T_{lim}}}\right) + \mathrm{CP} \qquad (3)$$

The standard errors of the estimate (SEE) associated with CP and W′ were expressed as coefficient of variation (CV%). The “total error” associated with the modelling of the power-duration parameters was calculated as the sum of the CV% associated with the CP and W′. The model associated with the smallest sum of the CV% was used to produce the “best individual fit” (BIF) parameter estimates. The upper and lower 95% confidence intervals (CI) for the parameter estimates of the BIF were used to examine the effects of day-to-day variability in CP and W′, due to measurement error or physiological difference (Pethick et al., 2020), on the predictive capability of the W'_{BAL} models. Thus, the upper and lower 95% confidence intervals for the parameter estimates derived for the BIF were combined with the BIF single-point estimates for CP and W′, resulting in a total of 9 inputs for the W'_{BAL} models.

The PO data recorded during the 16.1-km TT was uploaded to Golden Cheetah version 3.4 (https://www.goldencheetah.org), converted to second-by-second data, and exported to CSV format. Total work done during the TT (TWD_{TT}) was calculated as the product of PO and time.

Work done above CP (W > CP), equivalent to total W′ expended, was the difference between TWD_{TT} and the amount of work performed above CP-time integral, calculated as the product of CP and time to complete (TTC) the TT (equation 4). The amount of W′ recovered (W'_{REC}) was calculated (Equation 5) as the difference between the amount of work done at PO below CP ($W_{P<CP}$), and the amount of work that would have been performed during this time had PO been equal to CP ($T_{P<CP}$).

$$W > CP = TWD_{TT} - (CP * TTC) \qquad (4)$$

$$W'_{REC} = (CP * T_{P<CP}) - (W_{P<CP}) \qquad (5)$$

W'_{BAL} was modelled for the 16.1-km road TT using 3 models. The bi-conditional $W'_{BAL\text{-}MORTON}$ model, for which the expenditure and recovery of W′ are assumed to be linear, was adapted to provide second-by-second values, and is expressed as follows:

$$If\ P > CP,\ W'_{BAL} = W'_{exp} - [(P_w - CP)t_w] \qquad (6a)$$

$$If\ P < CP,\ W'_{BAL} = W'_{exp} + [(CP - P_r)t_r] \qquad (6b)$$

Where W'_{EXP} is the W'_{BAL} prior to the work/recovery interval, P_w and T_w, and P_r and T_r are the PO and duration of the work (w) and recovery (r) intervals, respectively (Morton and Billat. 2004). In the present study, W'_{BAL} as calculated by the $W'_{BAL\text{-}MORTON}$ model was capped, such that it could not exceed W'_{BAL} at time t = 0 (W'_0).

The $W'_{BAL\text{-}INT}$ model assumes exponential expenditure and recovery of W′, as shown in equation 7:

$$W'_{BAL} = W' - \int_0^t W'_{exp}.e^{\frac{-(t-u)}{\tau_{W'}}} du \qquad (7)$$

Where W'_{EXP} is equal to the expended W′, *-(t-u)* is equal to time between segments in which W′ is expended, *du* denotes that integration has been performed with respect to *u* (initial time), and $\tau_{W'}$ is the time constant of W′ recovery, given by equation 6 [derived from group-averaged data in Skiba et al. (2012)]:

$$\tau_{W'} = 546.e^{(-0.01D_{CP})} + 316 \qquad (8)$$

Where D_{CP} is equal to the difference between mean recovery PO for the bout, and CP (Skiba et al. (2012).

The $W'_{BAL\text{-}ODE}$ model is bi-conditional, assuming linear W′ expenditure and exponential W′ recovery:

$$If\ P \geq CP,\ W'_{BAL} = W'_0 - [(P - CP)t] \qquad (9a)$$

$$If\ P < CP,\ W'_{BAL} = W'_0 - W'_{exp}e^{\frac{-t}{\tau}} \qquad (9b)$$

Where t is the duration of the work or recovery interval, W'_{EXP} is the amount of W′ expended before the recovery interval, and τ is the time constant of W′ recovery given by equation 8:

$$\tau = W'_0 / D_{CP} \qquad (10)$$

Where D_{CP} is the difference between instantaneous recovery interval PO and CP (Skiba et al. 2015).

Using the W'_{BAL} models, $W > CP$, the amount of W'_{REC} and W_{BAL} at T_{lim} were predicted for the 16.1-km road TT. $W > CP$ was calculated as the sum of the negative changes in W'_{BAL} when P was above CP, and total W'_{REC} was determined according to the sum of the positive changes in W'_{BAL}. Predicted end W'_{BAL} was calculated for each model as the sum of predicted W'_{REC} and W'_0, subtracted from predicted $W > CP$. Finally, the ‘bandwidth’ of W'_{BAL} was calculated as the range in predicted end W'_{BAL} i.e., the difference between the permutation that produced the smallest value of end W'_{BAL} and that which produced the largest, for each model

Statistical analysis

Paired samples *t*-tests were used to assess for differences in $\dot{V}O_{2peak}$ between the ramp-incremental test and the self-paced prediction TT’s used to characterise the power-duration relationship. Separate one-way analysis of variance (ANOVA) with repeated measures (RM) was used to examine differences in the: (1) parameter estimates of the power-duration relationship determined by the W-T_{lim}, 1/T_{lim}, P-T_{lim} and BIF models; (2) $W > CP$, and W'_{REC} (actual vs $W'_{BAL\text{-}ODE}$ vs $W'_{BAL\text{-}INT}$ vs $W'_{BAL\text{-}MORTON}$); (3) predicted end W'_{BAL} between the 3 W'_{BAL} models, and; (4) The bandwidth of W'_{BAL} between the three models. Bonferroni post-hoc tests were used to identify the location of any significant differences. Pearson’s product moment correlation coefficients and Bland-Altman analyses were used to assess relationships between actual and predicted $W > CP$ and W'_{REC}. Statistical analyses were performed in SPSS version 25 (SPSS Inc, Chicago, Illinois, USA), with significance set at $P < 0.05$. All data are presented as mean ± SD.

Results

Ramp-incremental test

During the ramp incremental test, participants attained a peak PO of 424 ± 37 W and a $\dot{V}O_{2peak}$ of 4.45 ± 3.70 $L{\cdot}min^{-1}$ (631.1 ± 5.87 $ml{\cdot}kg^{-1}{\cdot}min^{-1}$). The GET occurred at 2.13 ± 0.33 $L{\cdot}min^{-1}$ and 151 ± 28 W. The $\dot{V}O_{2peak}$ measured during the ramp-incremental test was not significantly different from the $\dot{V}O_{2peak}$ measured during the self-paced prediction trials (4.44 ± 0.41 $L{\cdot}min^{-1}$, P =0.14). $\dot{V}O_{2peak}$ (r = -0.67; P = 0.03) and peak PO (r = -0.81; P = 0.004) measured 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 = -0.38; P = 0.28).

Self-paced prediction trials

During the maximal, self-paced prediction trials, mean work done for the shortest and longest trial ranged from 63.3 ± 7.0 kJ to 178 ± 28.9 kJ, which resulted in mean completion times of 166 ± 35 to 597 ± 71s. Importantly, a minimum of 95% of ramp-incremental test $\dot{V}O_{2peak}$ was achieved during all trials, confirming that each trial was performed within the severe-intensity domain and could therefore be used to establish the power-duration relationship. Group mean CP and W′ estimated for the W-T_{lim}, 1/T_{lim}, P-T_{lim} were not significantly different from the BIF model (all P > 0.05; Table 1). However, as expected, there were significant differences in group mean CP and W′ between the BIF model and the models derived from the BIF upper and lower 95% confidence intervals, designed to capture the variability in the CP and W′ (P < 0.05; Table 1).

Table 1. Power-duration parameter estimates, derived from equations 1, 2 and 3, and the BIF model.

	R^2	CP (W)	Lower (W)	Upper (W)	SEE (W)	CV %	W′ (kJ)	Lower (kJ)	Upper (kJ)	SEE (kJ)	CV%	Total Error
W-T_{lim} Model	0.995 – 1.000	264 ± 36	242 ± 36	286 ± 39	5.6 ± 2.8	2.1 ± 1.2	21.3 ± 7.0	12.5 ± 5.9	30.2 ± 10.2	2.3 ± 1.4	10.7 ± 4.7	9.9 ± 3.7
1/T_{lim} Model	0.928 – 0.997	268 ± 38	238 ± 39	298 ± 44	7.6 ± 4.1	2.9 ± 1.6	19.9 ± 5.3	12.5 ± 5.1	27.2 ± 7.5	1.9 ± 0.9	9.5 ± 3.7	12.9 ± 5.6
P-T_{lim} Model	0.896 – 0.994	261 ± 40	233 ± 46	288 ± 37	7.1 ± 3.6	2.9 ± 1.6	22.9 ± 8.7	8.8 ± 7.2	37.0 ± 14.2	3.7 ± 2.1	16 ± 7.1	12.4 ± 5.1
BIF	0.977 – 1.000	266 ± 39[ac]	247 ± 38[bc]	286 ± 42[ab]	5.0 ± 2.2	1.9 ± 0.9	20.9 ± 6.6[ac]	14.2 ± 5.5[bc]	27.6 ± 9.4[ab]	1.7 ± 0.9	8.0 ± 3.1	18.9 ± 8.4

Data are mean ± SD. SEE, standard error of the estimate; W-T_{lim}, linear work-time model;1/T_{lim}, linear inverse of time model P-T_{lim}, hyperbolic power-time model, and; BIF, best individual fit model; Lower, lower 95% CI; Upper, upper 95% CI; a, significantly different from lower bound estimate; b, significantly different from BIF estimate; c, significantly different from upper bound estimate.

16.1-km road TT performance

Participants completed the 16.1-km road TT in 1595 ± 145 s (26:36 ± 2:25 min:ss), performing 459 ± 43.3 kJ of work. The mean PO was ~108% CP (288 ± 41 W), and participants cycled at 93 ± 6.0 rpm. The group mean pacing strategy and course profile is displayed in Figure 1.

Focusing on the BIF model, the group mean W > CP was 64.2 ± 20.8 kJ, ~ 3-fold greater than the group mean W′. W > CP was significantly underestimated by the $W'_{BAL\text{-}ODE}$ (63.8 ± 20.7 kJ), $W'_{BAL\text{-}INT}$ (40.7 ± 10.5 kJ), and $W'_{BAL\text{-}MORTON}$ (63.8 ± 20.7 kJ) models (all $P < 0.01$) with a mean bias of 0.4, 23.5, and 0.4 kJ, respectively (Figure 2). Additionally, W > CP was significantly higher ($P < 0.01$) for the $W'_{BAL\text{-}ODE}$ and $W'_{BAL\text{-}MORTON}$ models vs the $W'_{BAL\text{-}INT}$ model. Actual W > CP was significantly correlated ($P < 0.01$; Figure 2) with W > CP as predicted by the $W'_{BAL\text{-}ODE}$, $W'_{BAL\text{-}INT}$, and $W'_{BAL\text{-}MORTON}$ models. Estimates for the amount of W'_{REC} during the 16.1-km road TT for the $W'_{BAL\text{-}ODE}$ (28.5 ± 9.2 kJ) and $W'_{BAL\text{-}INT}$ (19.0 ± 7.0 kJ) models were not significantly different ($P > 0.05$) from actual W'_{REC} (25.3 ± 13.9 kJ) with a mean bias of 3.2 and 6.3 kJ, respectively (Figure 3). However, W'_{REC} was significantly overestimated by the $W'_{BAL\text{-}MORTON}$ (28.1 ± 13.6 kJ) model ($P < 0.05$) with a mean bias of 2.8 kJ (Figure 3). In addition, predicted W'_{REC} was significantly higher ($P < 0.01$) for the $W'_{BAL\text{-}ODE}$ model vs the $W'_{BAL\text{-}INT}$ model. Actual W'_{REC} was significantly correlated with estimates derived from the $W'_{BAL\text{-}ODE}$ and $W'_{BAL\text{-}MORTON}$ models ($P < 0.01$; Figure 3), but not the $W'_{BAL\text{-}INT}$ model ($P > 0.05$; Figure 3). At completion of the 16.1-km TT, the predicted end W'_{BAL} was -14.3 ± 20.0 kJ for the $W'_{BAL\text{-}ODE}$ model, -0.8 ± 5.52 kJ for the $W'_{BAL\text{-}INT}$ model and -14.7 ± 26.4 kJ for the $W'_{BAL\text{-}MORTON}$ model. Predicted end W'_{BAL} was not significantly different between the $W'_{BAL\text{-}ODE}$ and $W'_{BAL\text{-}INT}$ model ($P = 0.98$), the $W'_{BAL\text{-}ODE}$ and $W'_{BAL\text{-}MORTON}$ model ($P = 0.99$), or the $'_{BAL\text{-}INT}$ and $W'_{BAL\text{-}MORTON}$

model ($P = 0.26$). W'_{BAL} fell below 0 kJ during the course of the TT for the majority of participants, using the $W'_{BAL\text{-}ODE}$ (n = 10), $W'_{BAL\text{-}INT}$ (n = 7) and $W'_{BAL\text{-}MORTON}$ (n = 7) models, first attaining negative values with an average of 62, 58 and 67% of the TT remaining respectively.

The group mean 95% CI's derived from the BIF were 15% and 31% of the CP and W′ respectively, equivalent to the actual CP being within a range of ~39 W and W′ occurring within ~6.9 kJ (Table 1). The upper and lower 95% CI's for the BIF CP and W′ are provided in Table 1, and the combinations of the W'_{BAL} model inputs are provided in appendix 1. The estimated W > CP (Figure 4A) ranged from 43.7 – 85.3 kJ for the $W'_{BAL\text{-}ODE}$, 31.5 – 49.3 kJ for the $W'_{BAL\text{-}INT}$, and 43.7 – 85.3 for the $W'_{BAL\text{-}MORTON}$ model. The estimated W'_{REC} (Figure 4B) ranged from 22.7 – 37.2 kJ for the $W'_{BAL\text{-}ODE}$, 16.9 – 19.9 kJ for the $W'_{BAL\text{-}INT}$, and 28.1 – 33.8 kJ for the $W'_{BAL\text{-}MORTON}$ model. The combinations that resulted in the two extremes in end W'_{BAL} and thus captured the bandwidth or error in W'_{BAL} differed according to the W'_{BAL} model (Figure 4C). Specifically, the combination of the lower 95% CI for CP and the lower 95% CI for W′, and the upper 95% CI for CP and the upper 95% CI for W′ provided the range in W'_{BAL} for the $W'_{BAL\text{-}MORTON}$ and $W'_{BAL\text{-}INT}$ models. The lower 95% CI for CP and the upper 95% CI for W′, and the upper 95% CI of CP and the lower 95% CI of W′ provided the range for the $W'_{BAL\text{-}ODE}$ model. The bandwidth in end W'_{BAL} was significantly smaller ($P < 0.05$) for the $W'_{BAL\text{-}INT}$ model (28.0 ± 15.1 kJ) vs the $W'_{BAL\text{-}ODE}$ (61.4 ± 39.5 kJ) and $W'_{BAL\text{-}MORTON}$ (58.4 ± 29.3 kJ) models, with no significant difference ($P > 0.05$) between the latter 2 models.

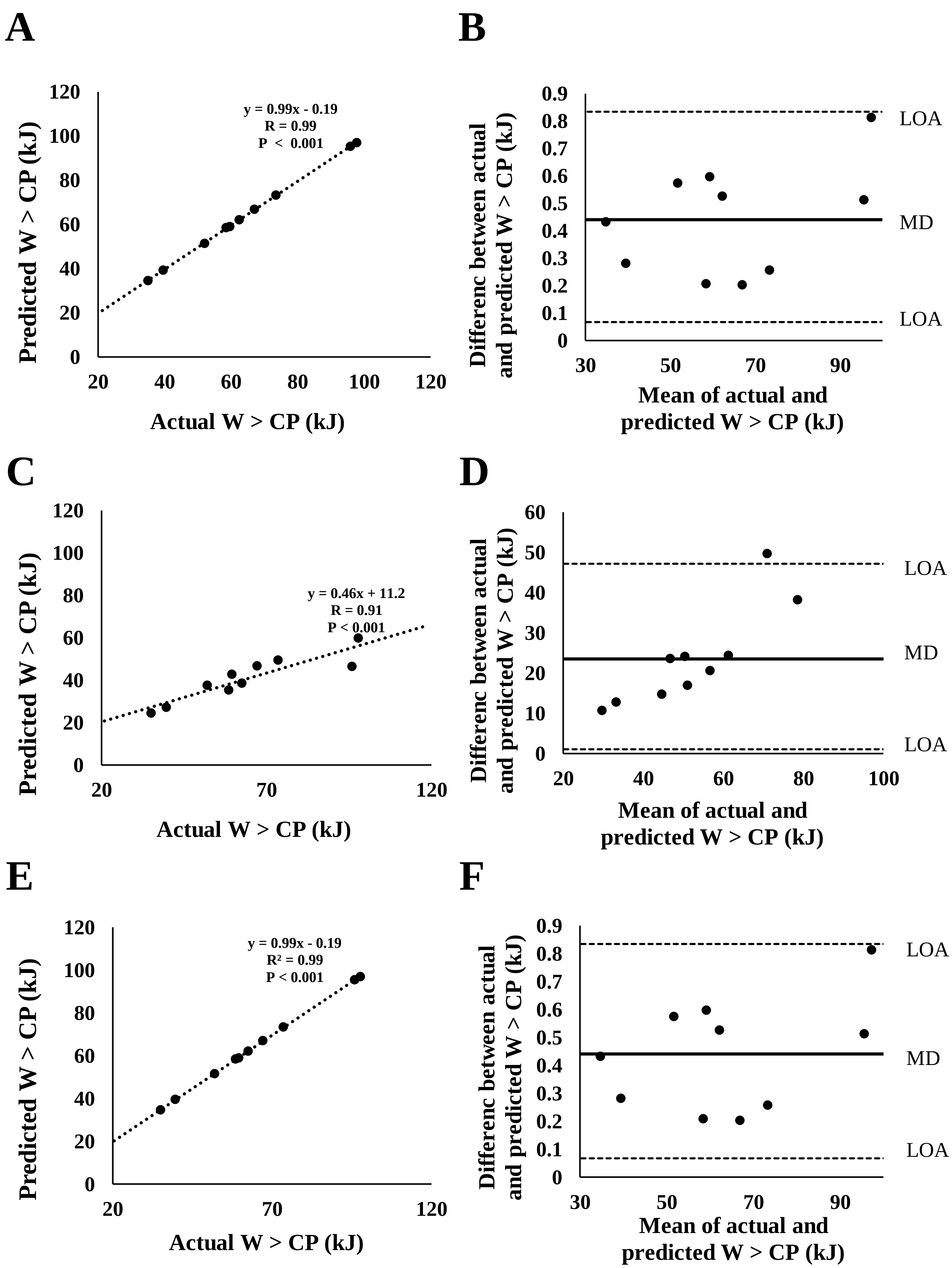


Figure 2. Correlation (A,C, and E) and Bland-Altman (B, D and F) analyses for predicted and actual W > CP, for the $W'_{BAL\text{-}ODE}$ (A and B), $W'_{BAL\text{-}INT}$ (C and D), and $W'_{BAL\text{-}MORTON}$ (E and F) models. In panels B, D and F, the dashed horizontal lines represent the 95% limits of agreement (LOA) and the solid black line represents the mean difference (MD) between the two measures.

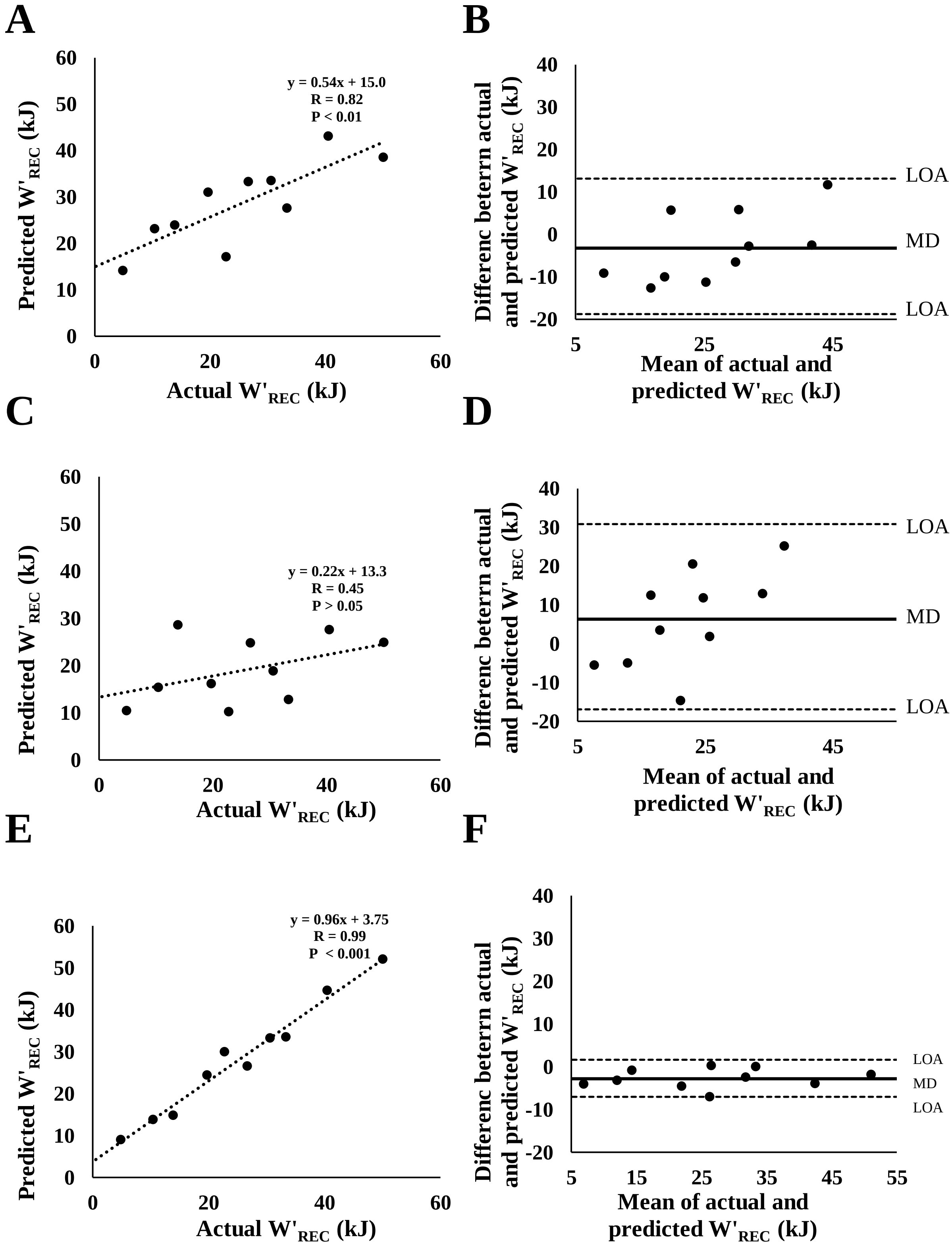


Figure 3. Correlation (A,C, and E) and Bland-Altman (B, D and F) analyses for predicted and actual W'_{REC} , for the $W'_{BAL\text{-}ODE}$ (A and B), $W'_{BAL\text{-}INT}$ (C and D), and $W'_{BAL\text{-}MORTON}$ (E and F) models. In panels B, D and F, the dashed horizontal lines represent the 95% limits of agreement (LOA) and the solid black line represents the mean difference between the two measures.

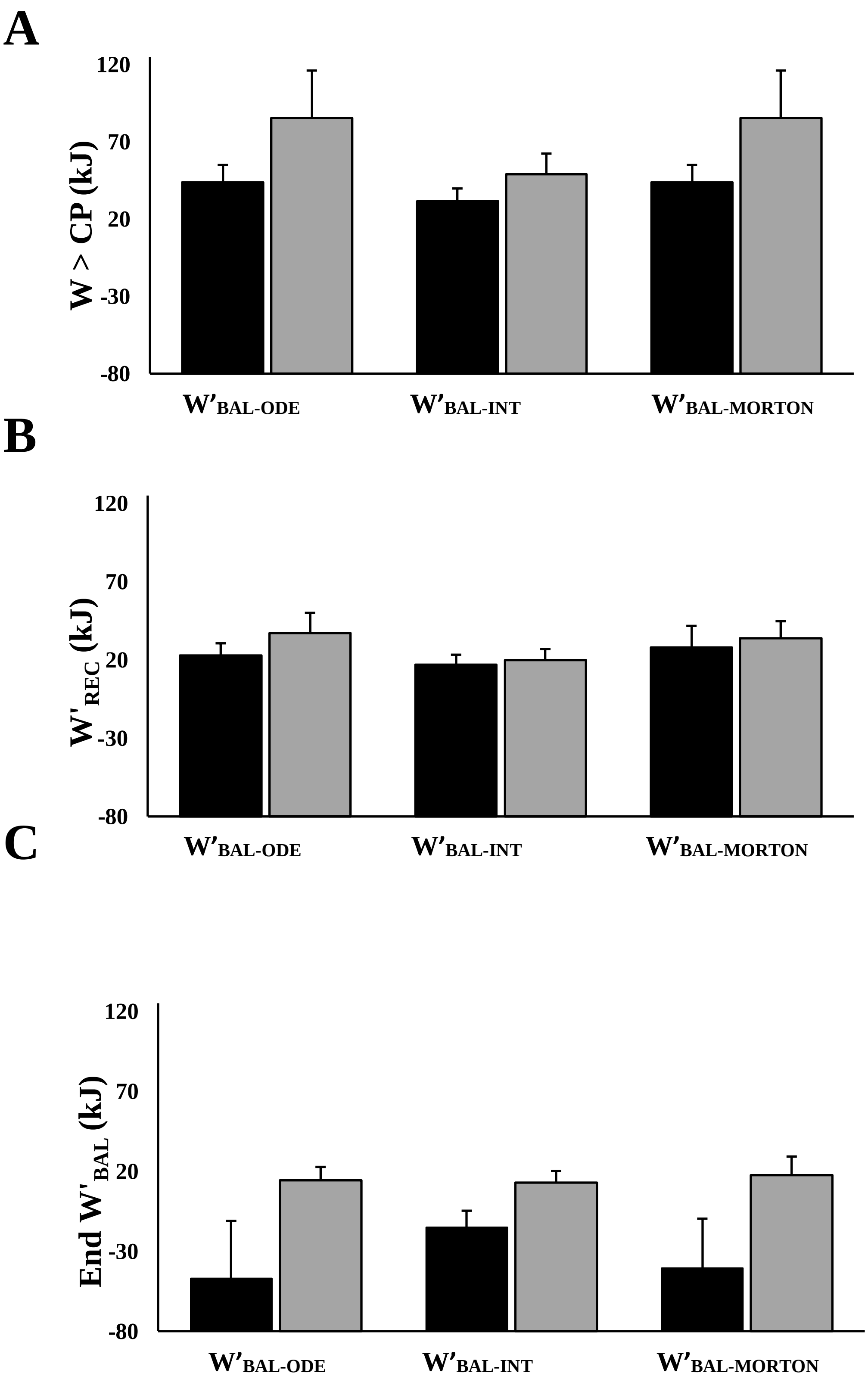


Figure 4. Bandwidth of predicted W > CP (A), W'_{REC} (B), and end W'_{BAL} (C), for the $W'_{BAL\text{-}INT}$, $W'_{BAL\text{-}ODE}$, and $W'_{BAL\text{-}MORTON}$ models. Permutations that yielded the lowest values are represented by black bars, and permutations that yielded the highest values by grey bars. Data are mean ± SD.

Discussion

In the present study, W'_{BAL} was modelled for a 16.1 km road TT using current iterations of the $W'_{BAL\text{-}ODE}$, $W'_{BAL\text{-}INT}$, and $W'_{BAL\text{-}MORTON}$ models using a range of permutations of CP and W′, such that the effect of day-to-day variability in both parameters on the characterisation of W'_{BAL} could be assessed. The study aimed to assess: (1) The accuracy with which the 3 W'_{BAL} models characterised W'_{BAL} and predicted field-based cycling performance, and; (2) the effect of inherent variability in CP and W′ on the predictive accuracy of the W'_{BAL} models. The primary novel findings were that: (1) the $W'_{BAL\text{-}ODE}$, $W'_{BAL\text{-}INT}$, and $W'_{BAL\text{-}MORTON}$ models failed to provide an accurate characterisation of W'_{BAL}, and therefore did not accurately predict field-based cycling performance and; (2) That the inherent variability in estimates of CP in W′ produced a significant 'bandwidth' of error in W'_{BAL} in the case of all 3 current W'_{BAL} models, further demonstrating their lack of predictive accuracy.

None of the 3 W'_{BAL} models used in the current study provided an accurate characterisation of W'_{BAL} or prediction of performance during the 16.1 km road TT. Theoretically, T_{lim} will occur upon full depletion of W′ (e.g. Jones et al., 2010; Moritani et al., 1981; Poole et al., 1988). In practice, it is acknowledged that T_{lim} may not precisely coincide with the point at which W'_{BAL} reaches 0 kJ, indeed athletes may be-able to continue exercising if PO is reduced to a lower supra-CP value, therefore, W'_{BAL} may briefly oscillate around the 0 kJ mark prior to attainment of T_{lim} (Skiba and Clarke., 2021). In the present study, when BIF estimates of CP and W′ were used W'_{BAL} attained negative values, for the majority of participants, with > 50% of the TT remaining, resulting in a highly negative predicted end W'_{BAL} in the case of all three W'_{BAL}

models. Therefore, it can be argued that the current iterations of the W'_{BAL} models tended to mischaracterise the behaviour of W'_{BAL} throughout the TT. Additionally, the group mean predicted end W'_{BAL} values for $W'_{BAL\text{-}ODE}$ and $W'_{BAL\text{-}MORTON}$ models were equivalent to -68 and -70% of W'_0 respectively, demonstrating that both models significantly underestimated 16.1 km TT performance. Whilst predicted end W'_{BAL} was not significantly different between the three models, group mean predicted end W'_{BAL} for the $W'_{BAL\text{-}INT}$ model was closest to 0 kJ (-3.9 % of W'_0), suggesting that the $W'_{BAL\text{-}INT}$ model provided the most accurate characterisation of W'_{BAL} throughout the 16.1 km TT. Note, however, that the standard deviation of predicted end W'_{BAL} was for the $W'_{BAL\text{-}INT}$ model was still equivalent to ± 28% of W'_0, indicating that the model failed to accurately predict performance in the majority of cases. Therefore, the results of the present study indicate that, whilst it could be argued the $W'_{BAL\text{-}INT}$ model provided a marginally more accurate characterisation of W'_{BAL} and prediction of 16.1 km TT performance in comparison to the $W'_{BAL\text{-}ODE}$, and $W'_{BAL\text{-}MORTON}$ models, ultimately, all three models failed to accurately characterise W'_{BAL} and predict 16.1 km TT performance.

Various factors contributed to the observed differences between the 3 W'_{BAL} models. Regardless of permutation, total work done during periods where PO was greater than CP, equivalent to total W' expenditure ($W > CP$) was the same for $W'_{BAL\text{-}ODE}$ and $W'_{BAL\text{-}MORTON}$ models, this was expected, given that both models use the same equation for W' expenditure (Skiba et al., 2012; Skiba et al., 2014b: Equation 6a, 9a), identical to the linear P-T_{lim} model (Equation 1). Likewise, it was anticipated that, as observed, predicted $W > CP$ for $W'_{BAL\text{-}ODE}$ and $W'_{BAL\text{-}MORTON}$ models would closely agree with 'actual' $W > CP$ given that the latter was effectively calculated using the W-T_{lim} model (Equation 2,4). $W'_{BAL\text{-}INT}$ model predicted $W > CP$ was significantly lower vs the other 2 W'_{BAL} models, this is likely due to the $W'_{BAL\text{-}INT}$ model assuming that some recovery of W′ takes place at supra-CP work rates, resulting in a slower non-linear W′ discharge (Skiba et al., 2012; Skiba and Clarke., 2021). Given that the linear CP models (Equations 1-3) can accurately predict T_{lim} during constant work rate supra-CP exercise (Jones et al., 2010; Poole et al., 2016), it is generally acknowledged that W′ expenditure is linear, and that there is no recovery of W′ at severe-intensity work rates, though this has been questioned (Broxterman et al., 2016). Thus, the assumption of exponential discharge of W′ can be considered a limitation of the $W'_{BAL\text{-}INT}$ model. Additionally, it can be argued that the $W'_{BAL\text{-}INT}$ model is limited in its ability to characterise W'_{REC}, as the rate of W'_{REC} is assumed to be the same regardless of the PO of individual recovery intervals (Equation 7; Skiba et al., 2012; Skiba and Clarke., 2021) Whilst W'_{REC}, as predicted by the $W'_{BAL\text{-}INT}$ model, was not significantly different from actual W'_{REC}, it was significantly higher vs $W'_{BAL\text{-}ODE}$ model predicted W'_{REC} – likely due to the latter taking the intensity of individual recovery intervals into account (Skiba et al., 2012; Skiba et al., 2014b; Skiba and Clarke., 2021). Likewise, the $W'_{BAL\text{-}MORTON}$ model is limited in that it fails to acknowledge the curvilinear kinetics of W'_{REC} (Morton and Billat., 2004), this is reflected in the results of the present study, given that the $W'_{BAL\text{-}MORTON}$ significantly overestimated W'_{REC}. It could be argued that the $W'_{BAL\text{-}ODE}$ model would be likely to provide the most accurate characterisation of W'_{BAL}, given that it assumes linear discharge of W′ and exponential recovery of W′, with the time constant of W'_{REC} varying according to the intensity of individual recovery intervals (Skiba et al., 2014b). However, as previously discussed, the $W'_{BAL\text{-}ODE}$ model did not perform better than the $W'_{BAL\text{-}INT}$ or $W'_{BAL\text{-}MORTON}$ model. It has been suggested that the assumption of simple monoexponential recovery of W′, as included $W'_{BAL\text{-}ODE}$ model may be an oversimplification (Caen et al., 2021; Skiba and Clarke., 2021). Caen et al. (2021) found that

W'_{REC} was better described using a biexponential vs a monoexponential equation, with the former assuming a rapid initial phase of W'_{REC}, followed by a slow W'_{REC} component. Caen et al. (2021) concluded that the rapid initial phase of W'_{REC} could be attributable to rapid recovery of intramuscular [PCr], as it has previously been demonstrated that recovery of intramuscular [PCr] is curvilinear and significantly more rapid in comparison to the recovery of W′ (Skiba et al., 2014b). Ultimately, given that none of the models were capable of accurately characterising W'_{BAL} in the present study, it is clear that further work is required in order to better understand the behaviour of W′ during intermittent high-intensity exercise.

In the present study, W'_{BAL} was modelled for the 16.1 km road TT using 9 different permutations of CP and W′ (Appendix 1), reflecting the 95% CI's around the point estimates of both parameters so as to capture the effect of inherent variability therein on the characterisation of W'_{BAL} in the 16.1 km TT. Accurate estimates of both CP and W′ are required, in order for the W'_{BAL} models to accurately characterise W'_{BAL} during exercise (Skiba and Clarke., 2021). For the 3 W'_{BAL} models used in the current study, W'_0 dictates the starting position of W'_{BAL} (Morton & Billat., 2004; Skiba et al., 2012; Skiba et al., 2014b). CP dictates whether W′ is being discharged or recovered at a given PO, and both W > CP and W'_{REC} are calculated as functions of the difference between PO and CP, in all 3 W'_{BAL} models (Morton & Billat., 2004; Skiba et al., 2012; Skiba et al., 2014b). Thus, error in either W′ or CP can result in late or premature attainment of negative W'_{BAL} values – negatively impacting the ability of the W'_{BAL} models to predict exercise tolerance (Skiba et al,, 2012; Skiba et al., 2014b; Skiba and Clarke., 2021).

The bandwidth in W > CP (Figure 4A) was greater for the $W'_{BAL\text{-}ODE}$ and $W'_{BAL\text{-}MORTON}$ models (41.6 kJ), vs the $W'_{BAL\text{-}INT}$ model (17.7 kJ). Likewise, the bandwidth of W'_{REC} (Figure 4B) was smallest for the $W'_{BAL\text{-}INT}$ model (3.00 kJ), with ranges of 14.4 and 5.63 kJ for the $W'_{BAL\text{-}ODE}$ and $W'_{BAL\text{-}MORTON}$ models respectively. The resultant bandwidth in end W'_{BAL} (Figure 4C) was significantly smaller for the $W'_{BAL\text{-}INT}$ model (equating to 134 % of W'_0), vs the $W'_{BAL\text{-}ODE}$ and $W'_{BAL\text{-}MORTON}$ models (292 and 278% of W'_0 respectively). A smaller bandwidth in W'_{BAL} in the $W'_{BAL\text{-}INT}$ model suggests that its functionality is less effected by error in estimates of CP and W′ vs the $W'_{BAL\text{-}ODE}$ and $W'_{BAL\text{-}MORTON}$ models. However, as previously discussed – the $W'_{BAL\text{-}INT}$ model still failed to accurately characterise W'_{BAL} or predict exercise tolerance for the 16.1 km road TT. Given the inherent variability in CP and W′, the bandwidth in predicted end W'_{BAL} can be considered to represent the range of values in which the true end W'_{BAL} value lies. As the 16.1 km TT was maximal, it is reasonable to assume that the true value of end W'_{BAL} at T_{lim} would be at or close to 0 kJ. In the case of all 3 W'_{BAL} models, the magnitude of the bandwidth in predicted end W'_{BAL} demonstrates a severe lack of predictive accuracy. In practical terms, it is likely that the current iterations of the models will not be-able to provide a valid prediction of performance and / or useful retrospective analyses of performance in training or racing settings. Therefore, at present, caution should be observed by athletes and coaches in using the W'_{BAL} models.

A potential limitation of the current $W'_{BAL\text{-}ODE}$, $W'_{BAL\text{-}INT}$ and $W'_{BAL\text{-}MORTON}$ models is the assumption that CP remains fixed throughout an exercise bout (Skiba et al., 2012; Skiba et al., 2014b). There is evidence to suggest that both parameters of the power-duration relationship may decrease during exercise due to the development of fatigue (Clark et al., 2019a; Clark et al., 2019b). Clark et al. (2019b) observed decreases in both in CP and W′ (~ 9 and 22%

respectively) following 2-h of prolonged heavy-intensity constant work rate exercise. In severe-intensity exercise, such as the 16.1 km TT used in the present study, W′ is expended (Monod & Scherrer., 1965; Moritani et al., 1981; Poole et al., 1988; Jones et al., 2010), but it is unknown whether dynamic changes in CP also occur. The current versions of all 3 W'_{BAL} models calculate W′ expenditure and W′ recovery as functions of the difference between PO and CP (Morton & Billat., 2004; Skiba et al., 2012; Skiba et al., 2015). Therefore, theoretically, a progressive decline in CP during exercise would result in: (i) An underestimation of W > CP, as the difference between a given PO above CP and CP would increase, and; (ii) An overestimation of W'_{REC}, as the proximity to CP of a given sub-CP PO would increase. Thus, a progressive decline in CP would result in an overestimation of exercise tolerance. Given that the group mean end W'_{BAL} was negative for the $W'_{BAL\text{-}ODE}$, $W'_{BAL\text{-}INT}$, and $W'_{BAL\text{-}MORTON}$ models in the present study when BIF estimates of the parameters were used to model W'_{BAL} the results do not appear to suggest that CP significantly declined throughout the 16.1 km road TT. However, further investigation into dynamic changes in the power-duration relationship that occur during exercise may still be warranted.

Experimental considerations

Whilst the results of the current study highlight important factors to consider in the application of the current W'_{BAL} models, it is important to emphasise that our findings are specific to the conditions of the study. Firstly, whilst exclusion of two of the 12 participants, as described in the methods section, was deemed necessary in order to ensure that the data used for the present study was of the highest possible quality, it is important to acknowledge that the sample size in the current study was relatively small (n = 10). Accordingly, it is possible that significant differences in the predictive accuracy of the three W'_{BAL} models may have been detected had the sample size been larger, e.g., the accuracy with which the $W'_{BAL-INT}$ model characterised W'_{BAL} during the 16.1-km road TT may have been significantly higher in comparison to the $W'_{BAL-ODE}$ and $W'_{BAL-MORTON}$ models.

Secondly, it is important to acknowledge that the mean maximum duration of the self-paced prediction trials (~09:57 mm:ss) was relatively short. Previous studies have demonstrated that the duration of predictive trials can affect the estimation of CP and W′, specifically, shorter prediction trials can give rise to lower CP and higher W′ estimates (Muniz-Pumares et al., 2019). Thus, it is possible that the short duration of the self-paced prediction trials used in the present study could have affected the estimates of CP & W and, therefore, the predictive capability of the W'_{BAL} models.

Thirdly, we modelled W'_{BAL} for a 16.1 km road TT using estimates of CP and W′ that had been derived from laboratory-based trials. Previous studies have established that there are physiological and mechanical differences when cycling in an upright vs an aerodynamic body position (e.g., Ashe et al., 2003; Welbergen et al., 1990), thus effecting PO. A previous study identified a discrepancy between road and laboratory-based time trial performance when controlling for body position, with PO significantly lower (~6%) in a laboratory-based vs a road TT (Jobson et al., 2008). Importantly, the laboratory-based TT was performed on a cycle ergometer and the road TT on participant’s own bikes. It is reasonable to assume that a there would be a discrepancy between CP as measured on an ergometer in an upright body position, a typical laboratory-based setup and CP measured within a field setting i.e., on the road with participants on their own bikes in an aerodynamic riding position. In addition, factors such as windspeed, bicycle handling skills and equipment used may have affected performance in the 16.1 km road TT. For example, a more aerodynamic bicycle, e.g., one with an aerodynamic frame, wheels and handlebars would likely have provided a performance advantage to a participant, (Jeukendrup & Martin,, 2001), such that a given speed would require a lesser PO, thus sparing W′ and resulting in faster overall completion time. Any effects of the above would not have been present in laboratory-based trials. The protocol used to determine the power-duration relationship in the present study replicated the conditions of the 16.1 km road time trial as closely as possible, as the prediction trials were self-paced and completed on participants own bikes. Accordingly, the estimates of CP and W′ were as accurate and valid as reasonably possible. In addition, as previously mentioned, the participants performed the 16.1 km TT on the same day, with start times separated by 1-minute intervals – in order to minimise the influence of external conditions e.g., windspeed to as greater extent as possible. Therefore, whilst it is not possible to rule out some discrepancy between road and laboratory-based CP in the current study, this was likely to have been minimal. Thus, it is probable that the majority of the observed poor predictive accuracy of the 3 W'_{BAL} models can be attributed to issues with the models themselves, rather than inaccurate estimates of CP and W′.

Finally, a further limitation of the current study was the used of a generalized time constant for W'_{REC}, in the case of the $W'_{BAL\text{-}ODE}$ and $W'_{BAL\text{-}INT}$ models. It has been demonstrated that the speed of W′ recovery kinetics varies with training status (Bartram et al., 2018). Indeed, it is currently recommended that an individualized time constant should be estimated for each athlete for the specific mode of exercise in which they are taking part, in order for the $W'_{BAL\text{-}ODE}$ and/or $W'_{BAL\text{-}INT}$ model to provide a more accurate prediction of performance (Skiba and Clarke., 2021). Though, it has yet to be experimentally verified whether individualised time constants for W'_{REC} significantly increase the predictive accuracy of the $W'_{BAL\text{-}ODE}$ and $W'_{BAL\text{-}INT}$ models. We decided to apply the original published forms of the $W'_{BAL\text{-}ODE}$ and $W'_{BAL\text{-}INT}$ models, given that the majority of athletes and applied practitioners are likely to use this method, due to its comparative simplicity and ease of use. The cohort of participants used in the current study were of comparable training status (good club-level athletes but non-elite) to those for which the formulations of the W'_{REC} time constants used in the published forms of the $W'_{BAL\text{-}ODE}$ and $W'_{BAL\text{-}INT}$ models were determined (Skiba et al., 2012; Skiba et al., 2014b). However, the mode of exercise to which the $W'_{BAL\text{-}ODE}$ and $W'_{BAL\text{-}INT}$ models were applied in the present study i.e., a road TT differs from that which was originally used to determine the time constant of W'_{REC} for both the $W'_{BAL\text{-}ODE}$ (Supine knee extension exercise; Skiba et al., 2014b), and $W'_{BAL\text{-}INT}$ (Intermittent high-intensity exercise, with both work and recovery intervals conducted at a fixed PO; Skiba et al., 2012) models. Therefore, it is possible that the use of generalized time constants for W'_{REC} contributed to the lack of predictive accuracy of the $W'_{BAL\text{-}ODE}$ and $W'_{BAL\text{-}INT}$ models.

Conclusions

The results of the present study demonstrate that the current $W'_{BAL\text{-}ODE}$ and $W'_{BAL\text{-}INT}$ models do not provide an accurate characterization of W'_{BAL} during self-paced severe-intensity field-based cycling exercise. Indeed, neither model can be said to provide a significantly more accurate prediction of exercise tolerance vs the $W'_{BAL\text{-}MORTON}$ model. In addition, our findings indicate that inherent variability in CP and W′ has a significant effect on the predictive accuracy of the W'_{BAL} models. These findings indicate that caution must be taken when applying the $W'_{BAL\text{-}ODE}$ and $W'_{BAL\text{-}INT}$ models to exercise modalities which differ to those used to derive the models, specifically, the time constant of W'_{REC}. Future studies should investigate the effect of: (i) different exercise modalities on CP, W′, and the speed of W′ recovery kinetics, and; (ii) the effect of using recovery time constants specific to individuals and exercise modalities, on the predictive accuracy of the $W'_{BAL\text{-}ODE}$ and $W'_{BAL\text{-}INT}$ models.

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Chapter 5: *Effects of Intermittent Exercise on The Parameters of The Power-Duration Relationship*

Abstract

Introduction: The parameters of the power-duration relationship, namely critical power (CP), W′, and the recovery of W′ (W'_{REC}) are critical to exercise performance prediction. It is unknown whether dynamic changes in the power-duration parameters occur during team sport type exercise. We tested the hypotheses that CP, W′, and W'_{REC} would decline during simulated match play. **Methods:** 9 male and 4 female recreational team sport players performed a repeat all-out test (R-AOT) on a cycle ergometer, consisting of a 3-minute followed by a 2-minute all-out test, interspersed with 90s of recovery, assessing CP, W′ and W'_{REC}. The R-AOT was performed in a fresh condition, and following: (i) one 40 minute block and; (ii) two 40 minute blocks separated by 15 minutes of 'half-time' of simulated match-play, in the form of an intermittent sprint test (IST). **Results**: CP and W'_{REC} did not significantly decline ($P > 0.05$) relative to the fresh condition following either 40 or 80 minutes of the IST. W′ was significantly lower ($P < 0.05$) in comparison to baseline in both the 40 and 80 minute conditions, but was not significantly different ($P > 0.05$) between the 40 and 80 minute conditions indicating that the 15 minute 'half-time' window permitted W′ to recover to its baseline magnitude. **Conclusion:** The results indicate that simulated match-play did not elicit dynamic changes in CP or W'_{REC} but did elicit a reduction in W′.

Introduction

Two parameters can be derived from the hyperbolic power-duration relationship: (i) Critical Power (CP), the asymptote of the power-duration relationship, is defined as a critical metabolic threshold, separating the heavy and severe exercise intensity domains, and; (ii) The curvature constant of the power-duration relationship, termed W′, is representative of a fixed amount of work that can be performed above CP, which will recover at sub-CP work rates (Ferguson et al., 2010; Jones et al., 2016; Poole et al., 1988; Poole et al., 2016). In the heavy-intensity domain, metabolic homeostasis is maintained, and pulmonary oxygen uptake ($\dot{V}O_2$) attains a steady state (Jones et al., 2008a; Vanhatalo et al., 2016). In contrast, in the severe-intensity domain, metabolic homeostasis is not achieved and $\dot{V}O_2$ is driven inexorably toward its maximum (Jones et al., 2008a; Poole et al., 2016). Both CP and W′ are strongly predictive of endurance exercise performance, (Black et al., 2014; Morgan et al., 2018). Importantly, the rate at which W′ recovers (W'_{REC}) can also be considered critical to exercise performance (Jones & Vanhatalo., 2017), as faster recovery of W′ will permit a greater total amount of work to be performed at work rates above CP during an exercise bout.

It has long been established that a single three-minute all-out test (3MT) against a fixed resistance can be used to accurately estimate both CP and W′, with the former calculated as the mean power output during the last 30s of the test (End Power; EP), and the latter as the work done above end power (WEP) during the test (Burnley et al., 2006; Vanhatalo et al., 2007). Indeed, the 3MT has been demonstrated to provide accurate estimates of both parameters in a rested state, and following prolonged exercise i.e., in a fatigued condition (Clark et al., 2018; Clark et al., 2019a; Vanhatalo et al., 2007; Vanhatalo et al., 2008). Performing repeated all-out tests (R-AOT) i.e., two all-out tests separated by a brief recovery period would allows for the assessment of W'_{REC} (Black et al., 2022). Given that a 3MT would completely deplete W′ (Vanhatalo et al., 2007), it is likely not necessary that the second all-out test to also be three minutes in length, such that a shorter bout of two minutes (2MT) would be sufficient to fully deplete W′ again provided that the recovery interval was short. Thus, W'_{REC} could be assessed using an R-AOT consisting of a 3MT followed by a 2MT, separated by a 90s recovery period. Subtracting 2MT-WEP from 3MT-WEP yields the amount of W′ recovered during the 90s rest period, thus allowing the rate of W'_{REC} to be calculated.

In Clark et al. (2019b), both CP and W′ significantly declined following 2h of heavy-intensity constant work rate exercise (~ 9 and 24% respectively) compared to a fresh condition, with the latter also significantly reduced following 80 minutes of heavy-intensity exercise. It is unknown how CP and W′ respond to intermittent high-intensity exercise in which work rate fluctuates above and below CP, as is performed in team-sport scenarios. Additionally, no study to date has examined the effect of prolonged intermittent high-intensity exercise on the W'_{REC}. In a match-play scenario more rapid recovery of W′ will allow players to sprint more frequently and for a longer period of time. Chorley et al. (2019) noted that the recovery of W′ was significantly slowed following repeated exhaustive exercise – suggesting the presence of a fatiguing effect. Thus, it is possible that W'_{REC} may also decline in response to intermittent high-intensity exercise.

Given that CP, W′ and W'_{REC} can be considered indicators of fatigue development (Chorley et al., 2019; Poole et al., 2016; Jones et al., 2010; Jones & Vanhatalo., 2017), it may be prudent to investigate how the 3 parameters change in response to a protocol that simulates the metabolic demands of team sport match-play. No study to date has sought to investigate dynamic changes in the parameters of the power-duration relationship during intermittent high-intensity exercise. Accordingly the purpose of the current study was to investigate the influence of simulated match play on the parameters associated with the power-duration relationship, namely CP, W′, and W'_{REC}. We hypothesised that EP, WEP and W'_{REC} would significantly decline following simulated match play.

Methods

Participants

13 recreational, i.e., non-elite team sport players, 9 male and 4 female (mean ± SD: age, 24 ± 5y; height 1.75 ± 0.07 m; body mass 68.4 ± 12 .0kg; BMI 22.4 ± 3.6 kg.m^2) volunteered to participate in this study.

The participants were free from any musculoskeletal injury at the time of the study and had been following their team-sport training schedule for at least 1 month. Following an explanation of the experimental procedures, associated risks, potential benefits and likely value of possible findings, participants gave their written informed consent to take part. The study was approved by the local institutional Research Ethics Committee and conformed to the code of ethics of the Declaration of Helsinki.

Experimental design

Participants visited the laboratory on five occasions over a 4-8 week period. On day 1, participants completed a ramp incremental cycling test for the determination of $\dot{V}O_{2peak}$, GET, and the linear factors used for the intermittent sprint test (IST) and the R-AOT (see "exercise testing"). During visit 2, participants completed a familiarisation session to the IST. Participants were also familiarised to the R-AOT. During visit 3, participants performed an experimental R-AOT. Subsequently, participants were randomised in a crossover design to perform a 40-min IST (40-IST) and an 80-min IST (80-IST), both of which were immediately followed by a repeated all-out test. The 40-IST and 80-IST protocols were separated by a minimum of 3 days. Exercise visits were scheduled at the same time of day (± 2 h) within-individual and participants were instructed to report to all testing sessions in a rested and well-hydrated state, having avoided strenuous exercise and alcohol consumption for at least 24 h and caffeine for at least 8 h prior to each test.

Exercise testing

All tests were performed on the same electronically-braked cycling ergometer (Lode Excalibur Sport, Groningen, The Netherlands). The ergometer seat and handlebars were adjusted for comfort during visit 1, and settings recorded and replicated for all subsequent visits.

Ramp incremental test

The ramp incremental test consisted of 3 min of unloaded baseline cyling followed by a ramp increase in power output of 30 $W \cdot min^{-1}$ until the limit of tolerance (T_{lim}). Participants were instructed to maintain their self-selected cadence (70-90 rpm) for as long as possible. The test was terminated when the pedal rate fell >10 rpm below the chosen cadence despite strong verbal encouragement. Breath-by-breath pulmonary gas exchange data were collected continuously during the test. $\dot{V}O_{2peak}$ was determined as the highest 10-s mean $\dot{V}O_2$. The GET was established from the gas exchange data averaged in 10-s time bins using the following criteria: 1) the first disproportionate increase in $\dot{V}CO_2$ vs. $\dot{V}O_2$; 2) an increase in minute ventilation ($\dot{V}_E$) relative to $\dot{V}O_2$ with no increase in $\dot{V}_E$/ $\dot{V}CO_2$, and; 3) the first increase in end-tidal O_2 tension with no fall in end-tidal CO_2 tension.

Intermittent sprint test

The IST (Figure 1) was based on a motion analysis study of international field hockey (Spencer et al., 2004) and mimics the demands of match play. The test was performed on a cycle ergometer. Briefly, the test consisted of a 10-min warm-up followed by either a 40-min half of intermittent exercise or two 40-min halves of intermittent exercise separated by 15 min of passive recovery ("half time"). The warm-up required participants to cycle for 5 min at 50%, and 1-min at 70% ramp incremental test work rate peak, followed by 2 min of passive recovery. A practice 2-min block of intermittent exercise was then performed followed by a 2-min rest period prior to the start of the IST. Each 40-min half of the IST was identical and was divided into 2-min blocks that consisted of a 6-s all-out sprint, 100 s of active recovery, and 14 s of passive recovery. On two occasions during each half, participants performed an intensive sprint-block composed of 5 x 4-s all-out sprints separated by 16 s of active recovery. The fixed resistance for the 6-s and 4-s all-out sprints was determined using the linear function of the Lode ergometer such that at a cadence of 120 rpm, participants would achieve 300% of the ramp incremental test peak power output. The active recovery periods required the participants to cycle at 35% of ramp incremental test peak power output at the same self-selected cadence chosen during the ramp incremental test.

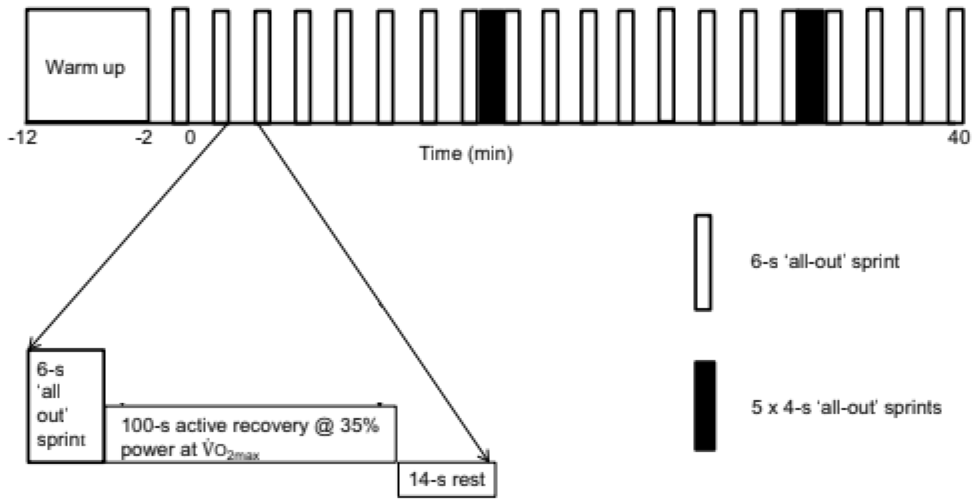


Figure 1 Schematic of one "half" of the intermittent sprint test (IST). Each 40-min half was separated into 2-min blocks (6-s all-out sprint, 100 s of active recovery and 14 s of passive rest). On two occasions during the 40-min half, participants performed an intensified sprint block which consisted of 5x 4-s all-out sprints separated by 16 s of active recovery. For the 80-min IST, each half was separated by a 15-min passive rest period (half-time).

Repeated all-out test

The repeated all-out test consisted of one 3-min all-out test (3MT; see Burnley et al. 2006; Vanhatalo et al. 2007) and a 2-min all-out test (2MT) separated by 90 s of active recovery (unloaded pedalling). The 3MT results in the complete utilisation of W′, enabling the determination of CP and W′ (Burnley et al. 2006; Vanhatalo et al. 2007). W′ is recovered at work rates below CP. Thus the rate of W'_{REC} can be assessed from the subsequent 2MT, which will again fully utilise the available W′. The rate of W'_{REC} was calculated as the W´ measured in the 2MT divided by 90 s (the recovery period between the end of the 3MT and the start of the 2MT). The repeated all-out tests were performed at: (1) baseline, to determine CP, W′ and W'_{REC} with no preceding intermittent exercise, and following; (2) 40-IST and; (3) 80-IST to establish the effects of intermittent exercise on the parameter estimates of the power-duration relationship and

W'_{REC}. Participants were asked to accelerate to 100 rpm in the 5 s preceding the 3MT and 2MT. The resistance on the pedals during the tests was set using the linear mode of the ergometer such that, when cycling at their self-selected cadence, the power output would be equivalent to 50% of the difference between the power output at GET and $\dot{V}O_{2peak}$ (linear factor = power/cadence^2). To ensure an all-out effort, participants were instructed to attain their peak power output as quickly as possible, and to maintain their cadence as high as possible until instructed to stop. Strong verbal encouragement was provided throughout, but participants were not provided with any time-based feedback. End test power (EP) during the final 30 s of the 3MT was used to determine CP. The work performed above EP (WEP) was used to estimate W′ during 3MT and 2MT. W'_{REC} was calculated as the WEP in the 2MT / 90. End test $\dot{V}O_2$ was determined as the final 30-s mean value during the 3MT and 2MT. Participants were required to achieve and maintain >95% of their ramp incremental test $\dot{V}O_{2peak}$ during the 3MTs and were asked to repeat any trials where these criteria were not fulfilled.

Pulmonary Gas Exchange

Breath-by-breath pulmonary gas exchange and ventilation were measured continuously during all tests. Participants wore a face mask and breathed through a turbine assembly (Cosmed Quark Turbine Cosmed, Rome, Italy). The inspired and expired gas volume and concentration signals were continuously sampled, the latter using paramagnetic (O_2) and infrared (CO_2) analysers (Cosmed, Quark CPET, Rome, Italy) via a capillary line connected to the face mask. The analysers were calibrated before each test using a known gas mixture (15% O_2 and 5% CO_2) and ambient air. The turbine volume transducer was calibrated using a 3-L syringe (Hans Rudolph Inc., Shawnee, KS, USA). The volume and concentration signals were time-aligned, accounting for transit delay in capillary gas and analyser rise time relative to the volume signal. Breath-by-breath data were converted to second-by-second data using linear interpolation.

Statistical analyses

One-way repeated measures (RM) analysis of variance (ANOVA) was used to assess for differences in $\dot{V}O_{2peak}$ between the ramp incremental test and the baseline, 40-IST, and 80-IST repeated all-out tests (i.e., 3MT and 2MT). One-way RM ANOVAs were performed to assess differences in CP, W′, peak power output, and TWD for the 3MT performed at baseline, 40-IST, and 80-IST. Further one-way RM ANOVAs were used to assess for differences in W'_{REC} and EP, WEP, peak power output and TWD between the 3MT and 2MT performed at baseline, 40-IST, and 80-IST. Paired samples *t*-tests were used to evaluate differences in mean power, TWD, sprint peak power, sprint mean power, acceleration (defined as change in PO / time to reach sprint peak power), blood [lactate] and $\dot{V}O_2$ between the 40-IST and the first-half of the 80-IST. The data from the 40-IST and first-half of the 80-IST were subsequently averaged for each participant and this mean was used for comparison with the second-half of the 80-IST via one-way ANOVAs and paired samples *t*-tests. Statistical analyses were performed using Statistical Package for the Social Sciences version 28. Statistical significance was set as $P<0.05$. Significant interactions and main effects were examined using LSD *post hoc* tests. Data are presented as mean ± SD.

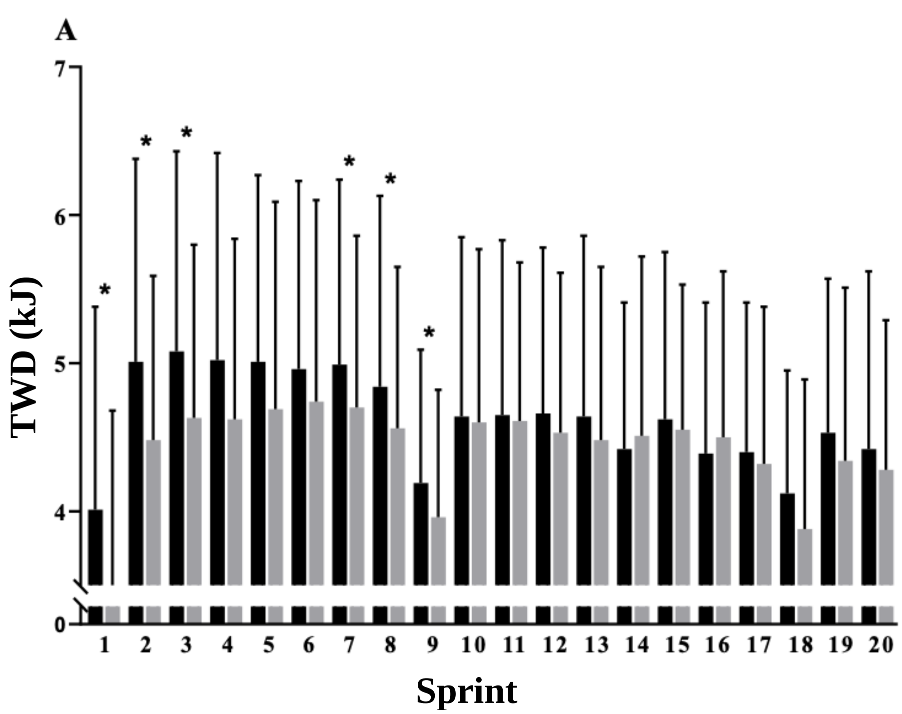
Results

The $\dot{V}O_{2peak}$ measured in the ramp incremental test was 3.4 ± 0.61 $L{\cdot}min^{-1}$ (49.3 ± 6.9 $mL{\cdot}kg^{-1}{\cdot}min^{-1}$) and the peak work rate was 320 ± 50 W. GET occurred at 136 ± 19 W.

Intermittent exercise performance

No significant differences were observed for TWD or work performed in each sprint between the 40-IST and the first-half of the 80-IST ($P > 0.05$), thus data were averaged for further analyses. During the first 40 min, participants performed 343 ± 59 kJ of work, with work done during sprinting accounting for 38 ± 5% of the total work done. The mean power output was 144 ± 26 W and this work rate elicited a mean $\dot{V}O_2$ of 2.4 ± 0.4 $L{\cdot}min^{-1}$ (35.0 ± 3.8 $ml{\cdot}kg^{-1}{\cdot}min^{-1}$). Total work done and peak power output during each sprint is displayed in Figure 2. The sprint work performed during the first (Q1, 4.8 ± 1.3 kJ), second (Q2, 4.7 ± 1.1 kJ), and third (Q3, 4.6 ± 1.1 kJ) quarters of the first-half were significantly greater than that achieved at the end (Q4, 4.4 ± 1.0 kJ; all $P \leq 0.01$). Peak power during the sprints was significantly greater for Q1 (1075 ± 323 W) compared to Q2 (1013 ± 285 W; $P<0.01$), Q3 (1011 ± 277 W; $P<0.05$) and Q4 (944 ± 239 W; $P<0.01$). Acceleration significantly slowed with each preceding quarter from Q1 (790 ± 193 $J{\cdot}s^{-2}$) to Q2 (758 ± 182 $J{\cdot}s^{-2}$; $P<0.01$), Q3 (720 ± 182 $J{\cdot}s^{-2}$; $P \leq 0.001$), and Q4 (506 ± 152 $J{\cdot}s^{-2}$; $P \leq 0.001$).

During the second-half, mean power output was 141 ± 25 W, and was significantly lower compared to the first half ($P < 0.05$). Mean $\dot{V}O_2$ during the second half (34.8 ± 4.3 $ml.min.kg^{-1}$) was not significantly different in comparison to the first half ($P>0.05$). Work completed during the sprints (125.9 ± 32.4 kJ) was significantly less than during the first half (131.1 ± 33.5 kJ; *P*<0.05), thus total work done (-1.4 ± 1.8%; *P*<0.05) and mean power output (-1.5 ± 1.8%; *P*<0.05) during the second half of the protocol were also significantly lower than the first half. The amount of work performed during the first 10 min of the second half (Q1, 4.4 ± 1.2 kJ) was not significantly different to second-half Q2 (4.5 ± 1.1 kJ), Q3 (4.5 ± 1.1 kJ), or Q4 (4.3 ± 1.0 kJ) (all *P*>0.05). Peak power during the sprints was ~6% lower during the second-half compared to the first-half (*P*<0.01). Peak power during the sprints in the final 10 min of the second-half (Q4, 906 ± 245 W) was significantly lower than Q1 (975 ± 274 W; *P*<0.05) and Q3 (964 ± 262 W; *P*<0.01), and tended to be lower than Q2 (948 ± 248 W; *P*=0.053). There was no significant difference in acceleration between the first and second halves of the IST (*P*>0.05), nor were there any significant differences in acceleration between second half Q1 (742 ± 184 J·s^{-2}), Q2 (747 ± 185 J·s^{-2}), Q3 (707 ± 168 J·s^{-2}) or Q4 (705 ± 167 J·s^{-2}; all *P*>0.05).



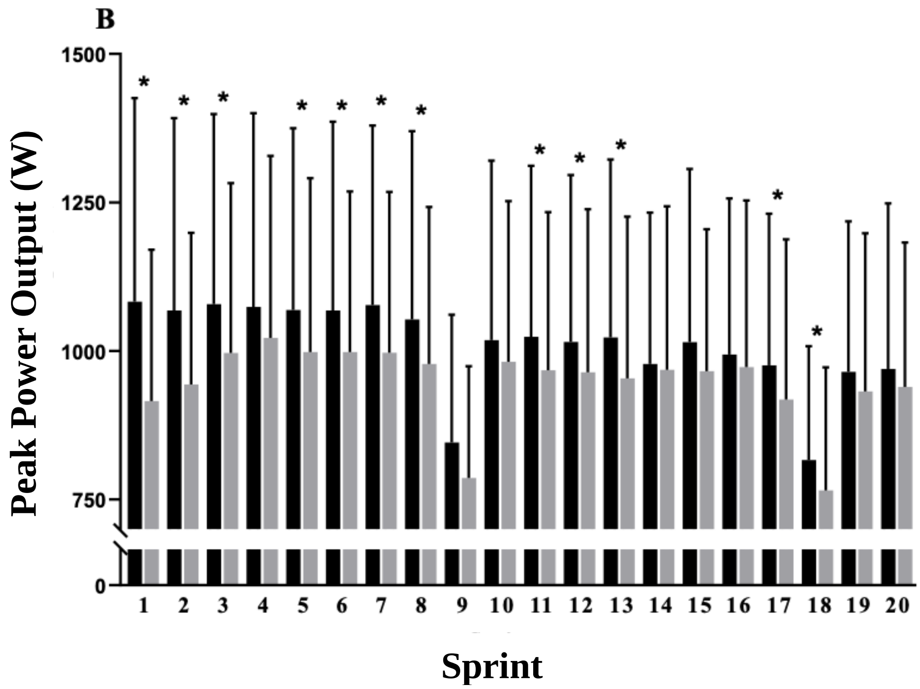


Figure 2. Group mean total work done (TWD, A) and peak power output (B) for each 6s sprint during the 40-minute (black bars) and 80-minute (grey bars) IST.* statistically significant difference between the 40-IST and 80-IST (P<0.05).

Dynamic changes in parameters of the power-duration relationship and W'$_{REC}$ after 40 min, and 80 min of intermittent high-intensity exercise

The group mean power profiles for the baseline, 40-minute and 80-minute 3MTs are displayed in Figure 3. The *a priori* criterion for the attainment and maintenance of >95% ramp incremental test $\dot{V}O_{2peak}$ was achieved by each participant during the C-3MT (104 ± 4% $\dot{V}O_{2peak}$) 40-3MT (106 ± 7% $\dot{V}O_{2peak}$), and 80-3MT (104 ± 6% $\dot{V}O_{2peak}$) (all P>0.05). Whilst this stringent criterion was not set *a priori* for the 2MTs, the majority of participants (n=9) also achieved and maintained >95% ramp incremental test $\dot{V}O_{2peak}$ during the baseline 2MT (104 ± 5% $\dot{V}O_{2peak}$), 40-2MT (104 ± 7% $\dot{V}O_{2peak}$), and 80-2MT (105 ± 7% $\dot{V}O_{2peak}$). One participant achieved ramp incremental test $\dot{V}O_{2peak}$ during the 40-2MT (103%) and 80-2MT (99%), but not during the baseline 2MT (91%). Two participants achieved ramp incremental test $\dot{V}O_{2peak}$ during the baseline 2MT (100 ± 0%) only, whilst one participant was not able to achieve >95% ramp incremental test $\dot{V}O_{2peak}$ during the baseline 2MT (94%), 40-2MT (87%), or 80-2MT (92%).

The group mean and individual responses during the 3MTs and 2MTs are provided in Figure 4. For the 3MTs, total work done was significantly lower during the baseline 3MT (50.1 ± 9.8 kJ) compared to the 40-3MT (53.5 ± 10.2 kJ; $P<0.05$) and the 80-3MT (47.7 ± 10.4 kJ) was significantly lower than both the baseline 3MT ($P<0.001$) and the 40-3MT ($P<0.05$).

There were no differences in CP between the baseline 3MT (222 ± 52 W), 40-3MT (222 ± 57 W; $P>0.05$) and 80-3MT (213 ± 49 W; $P>0.05$). Both W′ and peak power output were significantly lower during the 40-3MT (WEP, 10.1 ± 4.0 kJ; PPO, 665 ± 172 W; both $P<0.01$) and 80-3MT (WEP, 9.1 ± 3.5 kJ; PPO, 662 ± 171 W; both $P<0.001$) compared to the baseline 3MT (WEP, 13.5 ± 4.0 kJ; PPO, 771 ± 186 W). Following 90 s recovery, baseline 2MT-EP (214 ± 49 W), 40-2MT-EP (210 ± 48 W), and 80-2MT-EP (207 ± 44 W) were not significantly different to EP during the preceding 3MT ($P>0.05$) and no significant differences were observed for the change in EP between conditions ($P>0.05$). WEP was significantly lower during C-2MT (7.0 ± 1.8 kJ; $P<0.001$), 40-2MT (6.4 ± 2.0 kJ; $P<0.001$) and 80-2MT (6.4 ± 1.8 kJ; $P = 0.01$) compared to WEP during the preceding 3MT. However, the rate with which W´ was recovered (W'_{REC}) was not significantly different ($P>0.05$) following 40-IST (0.07 ± 0.02 $kJ \cdot s^{-1}$) and 80-IST (0.07 ± 0.02 $kJ \cdot s^{-1}$) compared to control (0.08 ± 0.02 $kJ \cdot s^{-1}$).

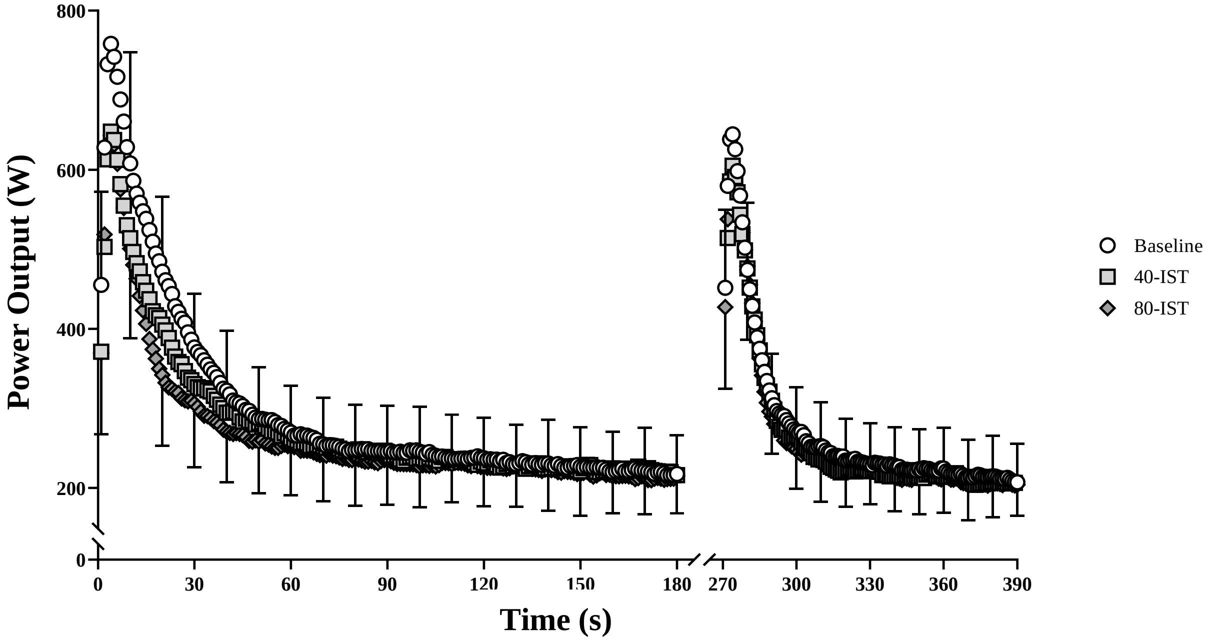


Figure 3. Group mean power profiles for the 3-min all-out test (3MT) and 2-min all-out test (2MT) at baseline (open circles) and following the 40-minute (light grey squares) and 80-minute (dark grey diamonds) IST. For clarity, *SD* is displayed every 10 s and is indicated for the baseline and 80-IST only, using positive and negative error bars, respectively.

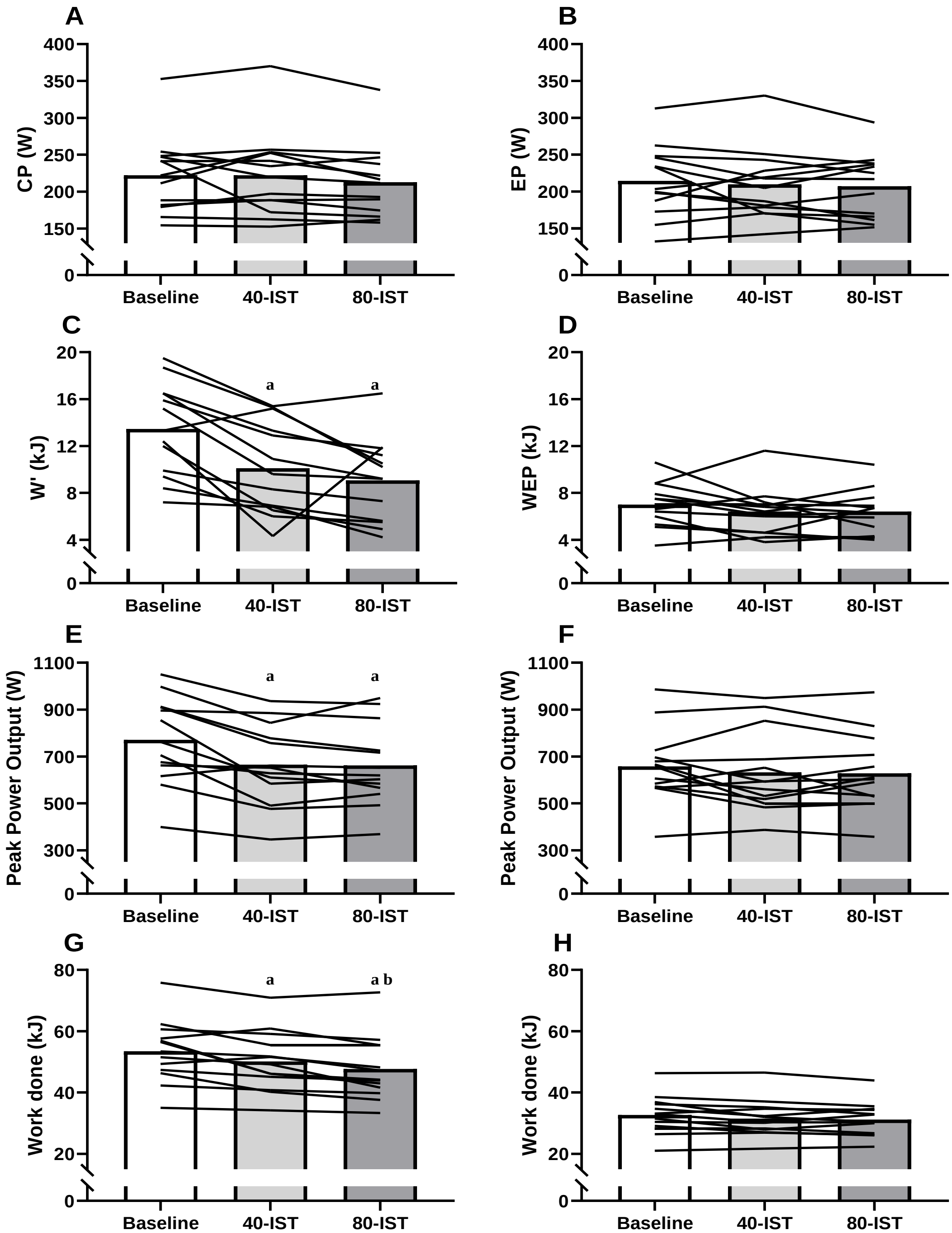


Figure 4. Group mean and individual responses for 3MT-EP (A), 2MT-EP (B), 3MT-WEP (C), 2MT-WEP (D), 3MT-Peak power output (E), 2MT-Peak power output (F), 3MT-TWD (G), 2MT-TWD (H) at baseline (white bars) and following 40-minute IST (40-IST; light grey bars) and 80-minute IST (80-IST; dark grey bars). [a] different from baseline (P<0.05). [b] different from 40-IST (P<0.05).

Discussion

This is the first study to investigate the effect of intermittent high-intensity exercise on the parameters of the power-duration relationship. We used the R-AOT to assess changes in CP, W′ and W'_{REC} following simulated match play. The primary novel finding of this study was that W′ was decreased following intermittent high-intensity exercise with no concurrent reduction in CP or W'_{REC}.

As expected, intermittent exercise performance deteriorated between the first and second half of the IST with TWD, mean sprint power and peak sprint power significantly lower in the second vs the first half. The decline in sprint performance in the first half of the IST was initially rapid, with peak power significantly higher in Q1 of the first half of the IST vs Q2, Q3, and Q4. Additionally, TWD was significantly lower in Q4 in the first half of the IST vs Q1, Q2, and Q3, and acceleration significantly slowed with each preceding quarter. In the second half of the IST there were no significant differences in TWD, mean sprint PO, peak sprint PO, and acceleration between Q1, Q2, Q3 and Q4, suggesting a slowing in the rate at which performance decreased. Performance in sprint exercise is primarily dependent upon ATP produced via PCr breakdown and anaerobic glycolysis (Bishop & Edge 2006; Gaitanos et al., 1993; Glaister., 2005). In the case of repeated sprints, changes in the metabolic environment result in a gradual inhibition of anaerobic glycolysis, specifically, H^+ accumulation results in a decrease in muscle pH, and inhibits glycolytic enzymes (Glaister., 2005; Turner & Stewart., 2013). Thus, the relative contributions of PCR breakdown and anaerobic glycolysis increase and decrease respectively over time, reflecting an increase in the contribution of aerobic metabolism, as the majority of PCR resynthesis occurs via oxidative processes (Bishop & Spencer., 2004; Gaitanos et al., 1993;

Turner & Stewart., 2013; McMahon et al., 2002). Thus, it is possible that inhibition of anaerobic glycolysis coupled with a greater reliance on oxidative phosphorylation, ultimately resulting in a decreased rate of ATP resynthesis, accounts for the initial rapid decline in performance observed in the first half of the IST. It is unknown why a similar phenomenon was not observed during the second half of the IST.

In the present study, 3MT-EP was not significantly different from baseline after either 40 or 80 minutes of the IST, indicating that the IST did not elicit a significant reduction in CP. Additionally, there was no significant difference in 3MT-EP between the 40 and 80-minute conditions. 3MT-WEP was significantly reduced in comparison to baseline following 40 and 80 minutes of the IST (~25 & 32% respectively). Whilst W′ is notoriously difficult to precisely quantify, such that a proportion of any observed dynamic change in WEP may be attributable to measurement error (Clark et al., 2018; Skiba and Clarke., 2021), the magnitude of the decrease in WEP observed in the present study is substantial relative to the likely error in W′ (~ 7-20%; Skiba and Clarke., 2021). However, it is important to note that the 6s and 4s sprints in the IST took place at supra-CP work rates, and thus would have resulted in W′ depletion (Jones et al., 2008a; Jones et al., 2010). Thus, it is likely that W′ would not have been fully recovered by the beginning of the R-AOT, as the 3MT commenced only 114s after the last 6s all-out sprint of the IST. In other words, the observed decrease in 3MT-WEP following 40 and 80 minutes of the IST is likely to be at least partially attributable to W′ depletion prior to the beginning of the 3MT. Given that 3MT-WEP was not significantly different between the 40 and 80-minute conditions, it is indicated that the 15 minute ‘half-time’ break between the first and second halves of the IST allowed W′ to recover to its baseline value i.e., the magnitude of the work capacity above CP in an unfatigued condition (W'_0). In other words, W′ was 'acutely' depleted by the IST, but it is likely that the IST did not elicit a significant reduction in W'_0.

Clark et al., (2019b) demonstrated that, in contrast to the IST used in the present study, constant work rate heavy-intensity exercise elicited a time-dependent reduction in CP in addition to W′. More specifically, 3MT-EP was significantly lower relative to the baseline condition following 120 minutes of exercise. 3MT-WEP was not significantly different to the baseline condition following 40 minutes of constant exercise, however, 3MT-WEP was significantly lower in comparison to baseline following both 80 and 120 minutes of exercise, additionally, 3MT-WEP was significantly lower following 80 minutes in comparison to 40 minutes of exercise. CP is an important threshold in terms of neuromuscular fatigue development (Burnley et al., 2012; Pethick et al., 2016). The contribution of central fatigue, defined as the reduction in central nervous system (CNS) drive to motor neurons (Amann., 2011), to overall fatigue development is greater in the heavy vs the severe-intensity domain (Burnley et al., 2012; Pethick et al., 2016). In the latter, metabolic perturbations contribute to the development of peripheral fatigue (Jones et al., 2008a; Burnley et al., 2012). Specifically, supra-CP exercise elicits an inexorable decrease in muscle [PCr] and pH, and an increase in muscle [lactate], such that levels of metabolites eventually reach a 'critical threshold', resulting in exercise intolerance (Amann., 2011; Horstrup and Bangsbo., 2017). The mean intensity of the exercise used in Clark et al. (2019b) was greater than that of the present study, taking place at a work rate corresponding to power output at GET + 25% of the difference between power output at GET and power output at $\dot{V}O_{2Peak}$ (25% Δ), vs 4.3 and 3.0% Δ for the first and second halves of the IST respectively. Indeed, the majority of the IST (95% of total time) was performed in either the moderate-intensity domain (active recovery intervals; 83%) or at rest (passive recovery intervals; 11%). Therefore, it is possible that the rate of central fatigue development during the IST would have been lower vs that for the heavy-intensity exercise used in Clark et al. (2019b) [Burnley et al., 2012; Poole et al., 2016]. However, the latter would not have elicited 'acute' W′ depletion as the entirety of the bout took place at a sub-CP work rate. In other words, the observed reduction in W′ in Clarke et al. (2019b) was likely due to a fatiguing effect which significantly reduced W'_0. Contrastingly, the 6s and 4s sprints during the IST took place at supra-CP work rates, depleting W′. Therefore, the IST is likely to have elicited a significantly greater rate of peripheral fatigue development in comparison to the protocol of Clark et al. (2019b) [Amann., 2011; Burnley et al., 2012; Chidnok et al., 2013a; Gaitanos et al., 1993; Jones et al., 2008a]. The IST did not elicit a significant reduction in CP. Additionally, in contrast to Clark et al. (2019b), the reduction in W′ relative to baseline was not significantly lower in the 80-minute vs the 40-minute condition indicating that, as previously discussed, the half-time period included within the 80-IST permitted W′ to recover to its baseline magnitude, i.e., the IST did not elicit a reduction in W'_0. Thus, it is probable that the overall, 'global' rate of fatigue development in the IST was lower than that in the constant work-rate heavy-intensity exercise used in Clark et al. (2019).

In the present study, there was no significant difference in the amount of W′ expended in the 2MT following either 40 or 80 minutes of the IST, in comparison to baseline. Indicating that the IST failed to elicit a significant reduction in W'_{REC}. This is the first time that the effect of simulated match play on the recovery of W′ has been investigated. In a match-play scenario, more rapid recovery of W′ offers performance benefits (Jones & Vanhatalo., 2017), allowing players to sprint for a longer period of time and with increased frequency, as a greater amount of work can be performed at supra-CP work rates. The precise physiological determinants of the speed of W′ recovery kinetics remain unclear (Skiba and Clarke., 2021). However, it has been demonstrated that W'_{REC} is curvilinear in nature and is effected by: (i) Work and recovery characteristics of previous exercise bouts; (ii) training status and; iii) the intensity domain in which recovery (sub-CP) intervals take place (Caen et al., 2019; Chorley et al., 2020; Bartram et al., 2018; Ferguson et al., 2010; Lievens et al., 2020). Chorley et al. (2019) noted that the recovery of W′ slowed significantly following a series of consecutive bouts of maximal exercise, each involving complete discharge of W′ (see below for full description), suggesting the presence of a fatiguing effect. It was suggested that the slowing in W'_{REC} may be at least partially attributable to a slowing the speed of phosphocreatine (PCR) recovery kinetics, which have been demonstrated to decrease during intermittent high-intensity exercise (Chidnok et al., 2013). No fatiguing effect on W'_{REC} was observed in the present study, importantly, whilst the IST contained multiple supra-CP efforts in the form of the all-out sprints (20x 6s, and 10x 4s per 40-minute half of the IST), it is likely that W′ would not have been fully depleted at any point throughout the IST. Therefore, it is possible that W'_{REC} is subject to a substantial fatiguing effect only when W′ has been completely discharged. Additionally, the protocol of the current study and that of Chorley et al. (2019) substantially differ, specifically, the latter used a repeated ramp-incremental test (RRT; three exhaustive incremental ramp tests [20 $W.min^{-1}$], interspersed with 2-min recovery intervals) rather than an R-AOT to assess W'_{REC}. Thus, it is also a possibility that the type of exercise i.e., all-out vs constant work rate vs intermittent high-intensity may influence W'_{REC}.

Experimental Considerations

Firstly, it is important to note that averaging the data for the 40-IST and the first half of the 80-IST may have, effectively, increased the accuracy of data for the first half of the IST relative to the second half. Note, however, that as previously described participants were familiarised to the IST prior to performing it in the 40-minute and 80-minute conditions, thus ensuring that all IST data was as accurate as reasonably possible. Secondly, whilst all participants performed the 2MT, such that its results were valid as a means of comparison, it is important to acknowledge that the 2MT has not been formally validated, such that future work should be carried out on order to determine the reliability of the power profile.

Thirdly, it is important to consider that the IST used in the present study may not have fully replicated the demands of match-play. The IST was developed by Spencer at al. (2004), following a time-motion analysis of international field hockey, and is designed to imitate the metabolic demands of team sport, consisting of repeated sprints interspersed with short rest periods. We chose to use a cycling-based IST protocol in order to allow the R-AOT to be performed. In reality, the majority of team sports are running based. Running and cycling have distinct metabolic demands and different muscle activation patterns (De Azevdeo Franke et al., 2021). Specifically, running generates a higher level of mechanical stress on the muscles, due to the repeated impact of the foot making ground contact, thus inducing a greater level of muscle damage in comparison to cycling exercise (Stocchero et al., 2014). Thus, it is possible that a running protocol would have elicited more rapid development of muscle fatigue which may have been reflected by a greater magnitude of change in the power-duration parameters. It may be prudent for future studies to investigate the impact of exercise type e.g. running versus cycling on the power-duration relationship.

Finally, in the current study the parameters of the power-duration relationship were only assessed following 40 and 80 minutes of the IST. In Clark et al. (2019b) the constant work rate heavy-intensity exercise was extended to 120 minutes. Thus, it is not possible to draw a direct comparison between the two different exercise protocols. We chose not to extend the IST because the majority of team sport matches are likely to be < 120 minutes in duration. In Clark et al. (2019b), CP was significantly reduced following 120 but not 40 or 80 minutes of exercise. Therefore, it could be argued that, had the IST been longer, changes in the power-duration parameters may have been observed. However, it is important to note that, as mentioned previously, the magnitude of W′ was not significantly different between the 40-IST and 80-IST. Contrastingly, in Clark et al. (2019b) W′ was significantly lower following 80 minutes of heavy-intensity exercise in comparison to 40 minutes. Therefore, it is still reasonable to conclude that the intermittent high-intensity exercise protocol of the present study elicited a slower rate of fatigue development in comparison to the heavy-intensity exercise used in Clark et al. (2019b).

Conclusions

As expected, intermittent exercise performance gradually decreased throughout the IST, the decline in performance was noticeably more rapid during the first half, in comparison to the second half. There were no significant changes in either CP or W'_{REC} in response to the IST. W′ declined significantly following both 40 and 80 minutes of the IST. However, there was no significant difference in W′ between the 40 and 80-minute conditions, indicating that the 15 minute ‘half-time’ recovery interval in the latter permitted W′ to recover to its baseline value. Thus, it is likely that the majority of the observed reduction in W′ was attributable to the W′ being ‘acutely’ depleted during the sprints within the IST such that it was not fully recovered at the beginning of the R-AOT. In summary, the results of the present study indicate that simulated match play: (i) does not elicit significant dynamic changes in CP or W'_{REC} and; (ii) elicits an ‘acute’ reduction in W′ but does not effect W'_0.

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Chapter 6: General Discussion

The aims of this thesis were to investigate: (i) the effect of day-to-day variability in the parameters of the power-duration relationship on the modelling of W'_{BAL} during intermittent high-intensity exercise and; (ii) whether dynamic changes in the power-duration relationship occur during intermittent high-intensity exercise. In order to achieve this, two studies were performed independently, addressing the following research questions:

1) Does day-to-day variability in the parameters of the power-duration relationship effect the accuracy with which the current W'_{BAL} models are able to characterise W'_{BAL} during intermittent high-intensity exercise, and thereby impact the ability of the models to predict exercise tolerance?

2) What are the effects of prolonged intermittent high-intensity exercise on critical power, W′, and W′ recovery?

Summary of findings

Modelling W'_{BAL} during a 16.1-km road cycling TT: effect of W'_{BAL} model and variability in the parameter estimates of the power-duration relationship.

In chapter 4, the effect of day-to-day variability in critical power (CP) and W′ on the ability of the current W′ balance (W'_{BAL}) models to accurately characterise W'_{BAL} throughout a 16.1-km road TT and predict exercise tolerance was assessed. W'_{BAL} was modelled using the $W'_{BAL\text{-}ODE}$, $W'_{BAL\text{-}INT}$, and $W'_{BAL\text{-}MORTON}$ models, for 9 different permutations of CP and W′, reflective of the 95% confidence intervals associated with both parameters. When the BIF permutation of CP and W′ was used, none of the 3 W'_{BAL} models were able to accurately characterise W'_{BAL} during the 16.1 km road TT. In the majority of participants, W'_{BAL} first attained negative values with > 50% of the TT remaining, with all 3 W'_{BAL} models. Subsequently, participants were still able to perform supra-CP efforts, such that they utilised more W′ than was available according to the W'_{BAL} models. In other words, the W'_{BAL} models underestimated performance. Indeed, the group mean predicted end W'_{BAL} values were equivalent to -168 and -170% of W'_0 for the $W'_{BAL\text{-}ODE}$ and $W'_{BAL\text{-}MORTON}$ models respectively, significantly underestimating TT performance. Group mean predicted end W'_{BAL} was -3.9 % of W'_0 for the $W'_{BAL\text{-}INT}$ model, suggesting an accurate W'_{BAL} characterisation. However, the standard deviation of predicted end W'_{BAL} for the $W'_{BAL\text{-}INT}$ model was equivalent to ± 28% of W'_0, demonstrating that the model failed to accurately characterise W'_{BAL} in the majority of cases. When all 9 permutations of the power-duration parameters were taken into account, the bandwidth in group mean predicted end W'_{BAL} was equivalent to 292, 134, 278 % of W'_0 for the $W'_{BAL\text{-}ODE}$, $W'_{BAL\text{-}INT}$, and $W'_{BAL\text{-}MORTON}$ models respectively. The range in predicted end W'_{BAL} should encompass the true end W'_{BAL} value (theoretically 0 kJ), thus, the magnitude of the ranges in predicted end W'_{BAL} yielded by all 3 models demonstrates poor predictive accuracy.

Effects of Intermittent Exercise on The Parameters of The Power-Duration Relationship

Clark et al. (2019b) demonstrated that constant work rate heavy-intensity exercise elicited decreases in both CP and W′. It is unknown whether dynamic changes in the power-duration parameters occur during other types of exercise. If present, such changes in CP or W′ may partially explain the poor predictive accuracy of the W'_{BAL} models, as observed in the study in Chapter 4. Additionally, as Clark et al. (2019b) only assessed CP and W′ following exercise, it was unknown whether dynamic changes in CP or W′ were accompanied by changes in the speed of at which W′ recovered. Thus, in chapter 5 the effect of prolonged intermittent high-intensity exercise in the form of simulated match-play on CP, W′ and W′ recovery (W'_{REC}) was assessed.

Participants performed a repeat all-out test (R-AOT) on 3 occasions. The R-AOT consisted of of a 3-minute all-out test (3MT) and a 2-minute all-out test (2MT) interspersed with 90s of passive recovery. CP and W′ were assessed via the 3MT, and the 2MT was used to assess W'_{REC}. Specifically, the rate at which W′ recovered between the 3MT and the 2MT was calculated as the difference between 2MT and 3MT end power (EP), divided by recovery time. The R-AOT was first performed in an unfatigued condition and subsequently following either 40 or 80 minutes of an intermittent sprint test (IST) in a counterbalanced order. The IST was designed to replicate the metabolic demands of team sport type exercise i.e., match play. Following the IST, participants performed an R-AOT in order to examine the effect of the IST on the parameters of the power-duration relationship. CP and W'_{REC} were not significantly reduced following either 40 or 80 minutes of the IST in comparison to the baseline condition. W′ was significantly lower in comparison to baseline in both the 40 and 80-minute conditions. However, as there was no significant difference in W′ between the 40 and 80-minute conditions, it was concluded that the observed reduction in W′ was attributable to W′ being ‘acutely’ depleted during the supra-CP sprint efforts within the IST such that it was not fully recovered at the beginning of the R-AOT.

Applications and directions for future research

In chapter 4, the $W'_{BAL\text{-}ODE}$ and $W'_{BAL\text{-}INT}$ models did not accurately characterise W'_{BAL} during the 16.1-km T, yielding predicted end W'_{BAL} values equivalent to -68 ± 95 and -3.9 ± 28% of W'_0 respectively. Indeed, neither the $W'_{BAL\text{-}ODE}$ or $W'_{BAL\text{-}INT}$ model was able to characterise W'_{BAL} with increased accuracy in comparison to the $W'_{BAL\text{-}MORTON}$ model. As discussed extensively in chapter 2, both CP and W′ are subject to a considerable day-to-day variability, attributable to measurement error and physiological factors (Pethick et al., 2020; Skiba & Clarke., 2021). Thus, it is not surprising that modelling W'_{BAL} in chapter 4 using the upper and lower 95% CI's of CP and W′ yielded a significant 'bandwidth' of predicted end W'_{BAL} values. However, the magnitude of the bandwidth of predicted end W'_{BAL} was unexpected (equivalent to 14 and 6.4x W'_0 for the $W'_{BAL\text{-}ODE}$, and $W'_{BAL\text{-}INT}$ models respectively), indicating that even with theoretically accurate estimates of CP and W′, the impact of inherent variability in both parameters on the accuracy of the W'_{BAL} models is highly significant. From a practical perspective, the W'_{BAL} models are unlikely to yield accurate predictions of performance and are, therefore, of limited usefulness as a means of analysing performance in training and/or racing scenarios. Therefore, it can be recommended that the W'_{BAL} models should be used with a high degree of caution by athletes and coaches. If the W'_{BAL} models are used, it is vital that estimates of CP and W′ are as accurate as possible.

In chapter 5, it was concluded that the IST did not elicit a significant reduction in CP, or W'_{REC}. The IST did elicit a significant reduction in W′, however, it is likely that the reduction was due to W′ being depleted by the (supra-CP) sprints during the IST such that it was not fully recovered prior to the beginning of the R-AOT rather than an underlying fatiguing effect of the IST i.e., it is probable that the IST did not significantly reduce W'_0.Thus, it is indicate that team sport match play does not elicit significant dynamic changes in the power-duration relationship. The mean work rate in the first half of the IST was equivalent to power output (PO) at GET +4.3% of the difference between PO at GET and PO at $\dot{V}O_{2Peak}$ (4.3% Δ), and the intensity of the second half was equivalent to 3% Δ. In Clark et al. (2019b), constant work rate heavy-intensity exercise was performed at a work rate corresponding to 25% Δ, amounting to significantly higher mean intensity in comparison to the IST. The exercise protocol in Clark et al. (2019b) elicited time-dependent reductions in both W′ and CP, with significant decreases observed following 80 and 120 minutes of exercise respectively. Thus, it is indicated that dynamic changes in the power-duration relationship do not occur in all forms of exercise, and that they may be related to the intensity of exercise performed.

Additionally, it is important to consider that the extent to which W′ is depleted in the supra-CP efforts during a bout of high-intensity intermittent exercise may have a significant effect on the power-duration relationship (Chorley et al., 2019). W'_{REC} has been demonstrated to decrease significantly following multiple exhaustive bouts in which W′ is fully depleted (Chorley et al., 2019). Crucially, the 6 s and 4 s sprints performed during the IST in chapter 5 would have only resulted in partial W′ depletion. In chapter 4, given that all-out tests were not performed following the road TT, it was not possible to draw conclusions regarding the effect of such exercise on CP, W′ and W'_{REC}. It is possible that intermittent high-intensity exercise performed at a higher average intensity and/or in which a greater proportion of W′ is depleted during the supra-CP sections of the bout, such as the 16.1-km road TT in chapter 4 (performed at 50% Δ) may elicit significant dynamic changes in the power-duration relationship. Therefore, it may be prudent for further studies to be carried out in order to fully ascertain the effects of both exercise modality and exercise intensity on CP, W′ and ultimately W'_{REC}.

A number of previous studies have shown that W′ recovery kinetics are affected by factors which are not currently accounted for in the $W'_{BAL\text{-}ODE}$ or $W'_{BAL\text{-}INT}$ models, including: (i) training status i.e., trained individuals are able to recover W′ more rapidly (Bartram et al., 2018); (ii) characteristics of previous work (> CP) bouts (Caen et al., 2019; Chorley et al., 2019), and; (iii) whether recovery takes place in the heavy or moderate-intensity domain (Lievens et al., 2020). Additionally, it has been suggested that the recovery of W′ may be a biexponential process (Caen et al., 2021), rather than monoexponential as assumed in the current $W'_{BAL\text{-}ODE}$ and $W'_{BAL\text{-}INT}$ models (Skiba et al., 2012; Skiba et al., 2014b). The findings of the studies within the current thesis introduce additional considerations. In the chapter 4 study, the predictive accuracy of the $W'_{BAL\text{-}ODE}$ and $W'_{BAL\text{-}INT}$ models was poor when the models were applied to field-based cycling exercise. Indicating that both models in their current forms are of limited practical usefulness i.e., as a tool for athletes and coaches. In addition, the findings of the study in Chapter 5, taken together with those of Clark et al. (2019b) demonstrate that dynamic changes in the power-duration relationship which would likely have a significant impact on the accuracy of the W'_{BAL} models can occur during exercise and that the magnitude of the changes may be dependent upon the intensity and the modality of exercise. It is notable that few studies have attempted to either modify the existing W'_{BAL} models or design novel models, accounting for the findings of the studies outlined above, such that the poor predictive accuracy of the current $W'_{BAL\text{-}INT}$ and $W'_{BAL\text{-}ODE}$ models can be rectified. Whilst novel W'_{BAL} models have been proposed, e.g., a multicomponent $W'_{BAL\text{-}INT}$ model to account for biexponential W′ recovery (Skiba et al., 2012; Skiba and Clarke., 2021), these models have not been experimentally tested. Thus, further work could be carried out in order to develop and test novel W'_{BAL} model formulations, such that the accuracy and validity of the models can be improved upon.

Conclusion

From the results of the study in chapter 4 it can be concluded that: (i) the current $W'_{BAL\text{-}INT}$ and $W'_{BAL\text{-}ODE}$, and $W'_{BAL\text{-}MORTON}$ models do not accurately characterise W'_{BAL} or predict exercise tolerance in endurance-based intermittent high-intensity exercise, and; (ii) inherent variability in CP and W′ has a significant effect on the accuracy of W'_{BAL} modelling. The findings of the study in chapter 5 demonstrate that significant dynamic changes in CP, and W'_{REC} do not occur during intermittent-high intensity exercise of the type performed in team sports and that, whilst W′ is acutely depleted by such exercise, it is probable that W'_0 is not significantly reduced therein. Taken collectively, the findings of the current thesis serve to highlight novel sources of error, namely inherent variability in CP and W′ and dynamic changes in the power-duration relationship that can occur during some but not all types of exercise, that can impact the accuracy of the current W'_{BAL} models. Thus, it is indicated that the W'_{BAL} models require extensive development in order to make them more useful to athletes and coaches.

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Appendices

Appendix 4.1

Certificate of ethical approval for study 1

College of Life and Environmental Sciences
SPORT HEALTH SCIENCES

St Luke's Campus
University of Exeter
Heavitree Road
Exeter
EX1 2LU
United Kingdom

CERTIFICATE OF ETHICAL APPROVAL

Proposal Ref No: 2013/657 *Date Commencing:* XX XXX 20XX

TITLE
Practical Application of the 3-min All-out Critical Power Cycling Test with Elite Athletes

Applicants **Paul Morgan**

The proposal was reviewed by a Representative on the Committee

Decision: The proposal has been approved until XX/XX/20XX

Your attention is drawn to the attached paper that reminds the researcher of information which needs to be observed when Ethics Committee approval is given.

Appendix 4.2

W > CP (1.1), W'_{REC} (1.2), and end W'_{BAL}(1.3) for the $W'_{BAL\text{-}ODE}$, $W'_{BAL\text{-}INT}$, and $W'_{BAL\text{-}MORTON}$ models, for each permutation of CP and W′. LCP-LW′, lower bound CP and lower bound W′; LCP-BW′, lower bound CP and BIF W′; LCP-UW′; lower bound CP and upper bound W′; BCP-LW′, BIF CP and lower bound W′; BCP-BW′, BIF CP and BIF W′; BCP-UW′; BIF CP and upper bound W′; UCP-LW′, upper bound CP and lower bound W′; UCP-BW′, upper bound CP and BIF W′; UCP-UW′; upper bound CP and upper bound W′.

1.1

W > CP, for the 3 W'_{BAL} models, for each permutation

Permutation		**W > CP (kJ)**	
	$W'_{BAL\text{-}ODE}$	**$W'_{BAL\text{-}INT}$**	**$W'_{BAL\text{-}MORTON}$**
LCP-LW′	85 ± 31	49 ± 13	85 ± 31
LCP-BW′	85 ± 31	49 ± 13	85 ± 31
LCP-UW′	85 ± 31	49 ± 13	85 ± 31
BCP-LW′	64 ± 21	41 ± 11	64 ± 21
BIF	64 ± 21	41 ± 11	64 ± 21
BCP-UW′	64 ± 21	41 ± 11	64 ± 21
UCP-LW′	44 ± 11	32 ± 8.3	44 ± 11
UCP-BW′	44 ± 11	32 ± 8.3	44 ± 11
UCP-UW′	44 ± 11	32 ± 8.3	44 ± 11

Data are mean ± SD.

1.2

W'_{REC} for the 3 W'_{BAL} models, for each permutation

Permutation		**W'_{REC} (kJ)**	
	$W'_{BAL-ODE}$	**$W'_{BAL-INT}$**	**$W'_{BAL-MORTON}$**
LCP-LW′	37 ± 13	20 ± 7.0	30 ± 31
LCP-BW′	28 ± 11	20 ± 7.0	30 ± 31
LCP-UW′	24 ± 10	20 ± 7.0	30 ± 31
BCP-LW′	36 ± 11	19 ± 7.0	28 ± 14
BIF	28 ± 9.2	19 ± 7.0	28 ± 14
BCP-UW′	24 ±8.6	19 ± 7.0	28 ± 14
UCP-LW′	30 ± 9.4	17 ± 6.4	34 ± 11
UCP-BW′	25 ± 8.4	17 ± 6.4	34 ± 11
UCP-UW′	23 ± 7.9	17 ± 6.4	34 ± 11

Data are mean ± SD

1.3

Predicted end W'_{BAL}, for the 3 W'_{BAL} models, for each permutation.

Permutation		**End W'_{BAL} (kJ)**	
	$W'_{BAL\text{-}ODE}$	**$W'_{BAL\text{-}INT}$**	**$W'_{BAL\text{-}MORTON}$**
LCP-LW′	34 ± 33	15 ± 10	40.7 ± 31
LCP-BW′	43 ± 36	15 ± 10	40.7 ± 31
LCP-UW′	47 ± 36	15 ± 10	40.7 ± 31
BCP-LW′	6.8 ± 17	0.5 ± 4.9	14.4 ± 26
BIF	14 ± 19	0.5 ± 4.9	14.4 ± 26
BCP-UW′	18 ± 20	0.5 ± 4.9	14.4 ± 26
UCP-LW′	-14 ± 8.4	-13 ± 7.2	-18 ± 12
UCP-BW′	-9.7 ± 7.3	-13 ± 7.2	-18 ± 12
UCP-UW′	-6.6 ± 6.7	-13 ± 7.2	-18 ± 12

Data are mean ± SD.

Appendix 5.1

Certificate of Ethical Approval for Study 2

College of Life and Environmental Sciences
SPORT HEALTH SCIENCES

St Luke's Campus
University of Exeter
Heavitree Road
Exeter
EX1 2LU
United Kingdom

CERTIFICATE OF ETHICAL APPROVAL

Proposal Ref No: 2210324-A-04 *Date Commencing:* 26 Mar 2021

TITLE

Effects of intermittent exercise on critical power, W' and W' reconstitution kinetics.

Applicants: **Professor Andrew Jones,** Anni Vanhatalo, James Lewis, Matthew Black, Chris Thompson, Jon Fulford

The proposal was reviewed by a Representative on the Committee

Decision: The proposal has been approved until 01/010/2021

Signature: Gjeymaur Date: 26/03/2021

Name of Ethics Committee Reviewer: Richard Pulsford

Your attention is drawn to the attached paper that reminds the researcher of information which needs to be observed when Ethics Committee approval is given.

Appendix 5.2

Approved Ethics Amendment Form for Study 2

Notification of Minor Amendment(s)

This template **must only** be used to notify of amendments which are **NOT** categorised as Substantial Amendments.
If you need to notify a Substantial Amendment to your study then you MUST use the appropriate Substantial Amendment form.

For guidance on amendments refer to https://www.hra.nhs.uk/approvals-amendments/amending-approval/examples-of-substantial-and-non-substantial-amendments/

1. Study Information

Details of lead applicant: Name: e-mail	Professor Andrew M. Jones A.M.Jones@exeter.ac.uk
Full title of study:	Effects of intermittent exercise on critical power, W' and W' reconstitution kinetics.
SHS ethics application reference number:	*210324-A-04*
SHS admin amendment number:	AM 21-10-20-08
HTA application to store in date?	n/a

2. Summary of amendment(s)

No.	**Brief description of amendment** *(please enter each separate amendment in a new row)*	**List relevant supporting document(s), including version numbers** *(please ensure all referenced supporting documents are submitted with this form)*	
		Document	**Version**
1	It was calculated that thirteen participants would be required, in order to detect the anticipated effect of the testing protocol, with 80% statistical power. Two participants who had yet to complete the testing protocol were unable to continue with testing, due to injury, shortly before the original data collection end date (01/10/2021). It will not be possible to recruit replacement participants, and have them complete the testing protocol, by the original end date. Therefore, the data collection window needs to be extended by two months, finishing on 01/12/2021.	*2210324-A-04*	Version: 8.1 Date: 25/03/2021

3. Declaration

Declaration by Chief Investigator (lead applicant)

- I confirm that the information in this form is accurate to the best of my knowledge and I take full responsibility for it.

- I consider that it would be reasonable for the proposed amendment(s) to be implemented.

Signature of Lead Applicant:

Print name: Andrew M...........

Date: Jones 22/09/2021....

Approved 27/9/21