

***W'* reconstitution modelling during intermittent exercise performed to task failure**

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Running head:

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Abstract

Purpose

W' balance (W'_{BAL}) modelling is becoming an important tool to monitor intermittent cycling performance. This study assessed the ability of different time constant ($\tau_{W'}$) equations for W' reconstitution (W'_{rec}) to predict exhaustion during intermittent exercise and the relationship between parameters of W'_{rec} with established determinants of endurance performance.

Methods

Thirteen cyclists performed cycling performance tests to determine: lactate threshold (LT), critical power (CP), W' , $\dot{V}O_{2\text{max}}$, maximal aerobic power (MAP) and maximal sprint power (P_{max}). Participants subsequently performed three intermittent W' depletion trials to volitional exhaustion involving different work and recovery periods: 20:10; 3 x 20 s intervals separated by 10 s recoveries before a final continuous effort, 60:30; 3 x 60 s intervals separated by 30 s recoveries before a final continuous effort, 20:10_{TE}; repeated 20 s intervals each separated by 10 s recoveries. W'_{BAL} was determined via five different $\tau_{W'}$ equations and an individualised equation ($\tau_{W'\text{INDV}}$) calculated from the 20:10_{TE} under the assumption that the point of task failure represents 0 kJ.

Results

Current $\tau_{W'}$ equations failed to predict exhaustion during intermittent exercise protocols to exhaustion. Total work done above CP for the 20:10_{TE} ($W'_{\text{total20:10TE}}$) was positively correlated with absolute and relative LT, CP, $\dot{V}O_{2\text{max}}$, MAP, and P_{max} ($r=0.64 - 0.80$; $P<0.05$). The $\tau_{W'\text{INDV}}$ was negatively correlated with relative CP ($r=-0.69$), and LT₁ ($r=-0.58$), and $W'_{\text{total20:10TE}}$ ($r=-0.63$).

Conclusion

Individualised $\tau_{W'}$ should be utilised for accurate prediction of W'_{BAL} . W'_{rec} is influenced primarily by aerobic performance parameters including LT₁ and CP.

Keywords

Intermittent exercise; Cycling performance; Critical power; W' reconstitution W'_{BAL}

Introduction

The two parameters of the power-duration relationship during sustained severe-intensity exercise have become key performance markers within applied cycling performance science. The asymptote, critical power (CP), demarcates the heavy and severe exercise intensity domains (Jones et al., 2008; Poole et al., 1988, 2016), and is considered to reflect the greatest sustainable rate of oxidative metabolism in the absence of a progressive loss of muscle metabolic homeostasis. (Jones et al., 2010) The curvature constant, W' , represents a finite work capacity that can be continuously performed above CP (Jones & Vanhatalo, 2017; Morton, 2006; Poole et al., 1988). Both CP and W' can be assessed in the laboratory and field (Leo et al., 2022; Moritani et al., 1981; Poole et al., 1988; Spragg et al., 2022) which has allowed the CP model to become a versatile performance tool for athletes and coaches.

The CP model can reliably predict time to task failure during sustained severe-intensity exercise however, it is unable to account for the recovery periods during intermittent exercise such that when power $>$ CP there is a proposed linear utilisation of W' and when power $<$ CP, there is a reconstitution of W' . To address this, a model was developed to incorporate W' reconstitution (W'_{rec}) using the CP model as parameter inputs (Skiba et al., 2012; Skiba & Clarke, 2021). The balance between utilisation and reconstitution allows estimation of a W' value at a given time point during the intermittent exercise (W'_{BAL}). Furthermore, as intermittent exercise continues, with inadequate recovery it is assumed exhaustion will occur or that the individual will no longer be able to perform work above CP when W' eventually reaches 0 kJ. The ability to reconstitute W' is therefore key to performance observed through the ability to repeated high intensity efforts that can be crucial to overall cycling performance and training quality (Abbiss et al., 2013; Menaspà et al., 2017).

The early work of Skiba et al. (2012) developed an integral model, which allows the prediction of W'_{rec} using a curvilinear time constant, $\tau_{W'}$. This original time constant was derived from untrained individuals. Later work by Skiba et al. (2015) developed a differential model which uses a $\tau_{W'}$ derived from W' and the recovery work rate below CP (D_{CP}). However, this variation is unable to be individualised in its current format, as only CP and W' are used. Subsequent work has indicated that W'_{rec} is faster in well-trained individuals (Bartram et al., 2018; Caen et al., 2021; Chorley et al., 2019). This may be attributable to differences in aerobic capacity, for example, individuals with higher $\dot{V}O_{2\text{peak}}$ and CP demonstrate faster rates of W'_{rec} (Bartram et al., 2018, 2022; Caen, Bourgois, Dauwe, et al., 2021). There are now multiple $\tau_{W'}$ variations (Bartram et al., 2018, 2022; Pugh et al., 2022) that provide generalised models to allow W'_{BAL} to be predicted in athletes. These are based on a power function with values fixed to the D_{CP} , indicating that differences in CP between participants would lead to differences in W'_{rec} . There appears to be a consensus that to further improve the accuracy of predicting W'_{BAL} , $\tau_{W'}$ should be individualised (Bartram et al., 2022; Skiba et al., 2014), although there is limited insight on best practice.

While the physiological determinants of CP are well established (Goulding & Marwood, 2023; Mitchell et al., 2018; Peden et al., 2024; Poole et al., 2016), the physiological determinants underpinning W' , W'_{rec} and W'_{BAL} remain somewhat elusive. W' correlates with muscle volume in elite track cyclists (Kordi et al., 2021), and whilst no relationships have been observed with skeletal muscle fibre composition (Vanhatalo et al., 2016; Mitchell et al., 2018, Caswell et al., 2024), or capillarity (Mitchell et al., 2018), some facets of mitochondrial respiration may influence W' (Peden et al., 2024). Nevertheless, it appears that depletion of W' is related to the reduction of metabolic substrates (phosphocreatine, PCr), and the accumulation of fatigue related metabolites (H^+ , P_i , ADP) to levels that can limit skeletal muscle function

(Chidnok, Fulford, Bailey, Dimenna, et al., 2013; Ferguson et al., 2010; Fukuba et al., 2003; Poole et al., 1988) . These contribute to the muscle fatigue process and subsequent task failure (Hostrup & Bangsbo, 2017; Sundberg & Fitts, 2019). Furthermore, the underpinning determinants of W'_{rec} have yet to be fully established with the main observations being correlations between parameters of W'_{rec} and CP (absolute, $r=0.52$; relative, $r=0.57$) and $\dot{V}O_{2\text{max}}$ (absolute, $r=0.8$; relative, $r=0.62$) (Caen et al., 2021; Chorley et al., 2020). Gaining a further insight into the association between established determinants of endurance performance with W'_{rec} and $\tau_{W'}$ will help guide further mechanistic exploration of the W'_{BAL} model.

Research investigating W'_{BAL} models has employed various protocols to determine CP and W' , creating methodological inconsistencies that affect model accuracy. Estimations from training data (Bartram et al., 2018) have been used to derive fixed duration mean maximal powers (MMP). These require careful interpretation, as Spragg & Leo) 2020) have reported a 3 kJ bias in W' values between formal testing and training-derived data. The choice of testing protocol also influences parameter estimation. For example, the 3-minute all-out test to establish CP and W' (Vanhatalo et al., 2007) was used by Skiba et al. (2012), but demonstrates questionable validity for trained athletes (Bartram et al., 2017). Moreover, the work rates used in the intermittent W'_{BAL} testing protocols vary considerably and may affect the rate of W'_{rec} (Caen et al., 2019). For instance, male elite team pursuit cyclists generate work rates exceeding 600W, (Bartram et al., 2018) which likely surpass the work rate required to achieve $\dot{V}O_{2\text{max}}$. Such intensities fall outside the validated range of the 2-parameter CP model (Ozkaya, Jones, Burnley, As, Balci, 2023), potentially compromising prediction accuracy. These methodological variations emphasise the need for a comprehensive understanding of how different W'_{BAL} models behave, where they converge or diverge, and what their inherent limitations are. Such understanding would establish clear boundaries for each model's

predictive capabilities and enable researchers to select appropriate W'_{BAL} models based on predetermined performance characteristics. This approach could inform the development of individualised testing protocols and guide future advances in W'_{BAL} modelling.

The aim of this study was two-fold: 1) assess different equations of $\tau_{W'}$ in the W'_{BAL} model to understand and identify which $\tau_{W'}$ value reflects a W'_{BAL} of 0 kJ at the point of exhaustion during three intermittent exercise protocols; 2) assess the relationship between cycling performance parameters with W'_{rec} parameters. It was hypothesised that; 1) there will be differences in W'_{BAL} at the point of task failure between the different $\tau_{W'}$ equations; 2) endurance performance parameters would correlate with the ability to complete more work during intermittent exercise and subsequently related to the ability to reconstitute W' .

Methods

Participants

Thirteen healthy individuals (10 males, 3 females, Table 1), volunteered to participate in the study. Participants were competitive cyclists training between 10-20 hours per week, competing at regional and national level. All completed health screening questionnaires prior to participation to mitigate for contraindications to maximal exercise. Participants did not have a history of cardiovascular, haematological, neuromuscular, or musculoskeletal abnormalities. Participants were fully informed of the risks and discomforts associated with all experimental trials before providing written, informed consent. All experimental procedures were approved by the Loughborough University Ethics Approvals Human Participants Sub-Committee (2021-6426-5519), and conformed to the Declaration of Helsinki, except for registration in a database.

Experimental protocol

Participants attended the laboratory on seven occasions over a four-week period for the determination of; lactate thresholds, $\dot{V}O_{2\max}$ and maximal aerobic power (MAP), CP and W' using 3- and 12-minute fixed duration time-trial (TT) efforts, assessment of peak lactate $[Bla^-]_{\text{peak}}$ and lactate clearance rate $[BLa^-]_{\text{clr}}$ after the 3-minute fixed duration TT, maximal sprint power ($P_{\max}$), and three intermittent W' depletion trials performed to volitional exhaustion. Each visit was separated by at least 48 hours.

All exercise tests were performed on the participants own racing bicycle attached to a commercially available cycle trainer (Kickr, Wahoo Fitness, Georgia, USA) which was calibrated prior to each use according to manufactures guidelines. Power data was recorded at 1 Hz and downloaded into WKO5™ (Training Peaks™, Louisville, USA) and processed in

Microsoft Excel. All performance trials were conducted at the participants freely chosen pedal cadence. Prior to each performance trial (except the lactate threshold, and $\dot{V}O_{2\max}$ tests), participants performed a standardised warm up involving 5-min at 50 W and 100 W, 3 min at 55% and 65% of MAP, before a final 5 min at 50 W. Participants were instructed to maintain a normal diet during the testing period and refrain from consuming alcohol and caffeine during the 24 h preceding testing. All tests were conducted in constant laboratory ambient conditions (19-21°C, 40-50% humidity).

Test procedures

Lactate thresholds, $\dot{V}O_{2\max}$ and MAP

Participants performed a step incremental test to determine the first (LT₁) and second (LT₂) lactate thresholds. The test commenced at 100 W for males and 70 W for females with power output being increased by 30 W every 4 min until 90% of age predicted max heart rate ($220 \text{ beats} \cdot \text{min}^{-1} - \text{age}$) was achieved. Capillary blood samples (20 μL) were collected from the fingertip at rest (baseline) and during the final 30 s of each stage and analysed for lactate concentration within three hours (Biosen C-line analyser, EKF Diagnostics, UK). A lactate-power curve was produced for each participant and fitted with a 3rd order polynomial, with lactate threshold parameters defined as: LT₁, baseline + 0.4 mMol·L⁻¹ (Bourdon, 2013) and LT₂, fixed lactate concentration of 4 mMol·L⁻¹ (Kindermann et al., 1979).

After 30 minutes of rest, participants completed an incremental step test to determine $\dot{V}O_{2\max}$ and MAP. Following a warm-up for 5 min at 50 W, the test began at 150 W for males and 100 W for females for 1 min after which power increased 25 W every 60 s, in a step wise manner, until volitional exhaustion or when pedal cadence fell 10% below the chosen cadence

for ~5 s. **Breath-by-breath** pulmonary gas exchange was measured continuously throughout exercise (Vyntus-CPX; CareFusion, Hoechberg, Germany). The system had been calibrated with known O₂ and CO₂ concentrations and a 3-L volume syringe. $\dot{V}O_{2\max}$ and MAP were defined as the highest $\dot{V}O_2$ and power output for a 30-s and 60-s period during the test, respectively.

CP and W'

CP and W' were estimated using two fixed duration TT efforts to achieve the highest average the power possible (Parker-Simpson & Kordi, 2017, Coakley and Passfield 2018). Participants completed two rolling-start TT for 3 and 12 min, where gear-ratio and cadence was self-selected. Participants were instructed and encouraged to complete each TT with the greatest average power output possible and to ensure they were completely exhausted at the end of each effort. This method was performed twice over three separate visits. On one visit participants performed both the 3- and 12-min test protocols (same day procedure), and on the other two visits the 3- and 12-min tests were performed on separate days (separate day procedure).

Same day procedure: Following the standardised warm up, participants performed the 3-min TT. Immediately after the effort participants recovered passively for approximately 1-2 minutes, before cycling at 50 W for 30 min (resulting in a total recovery period of 32 minutes). Capillary blood samples (20uL) were collected at 1, 2, 3, 4, 6, 8, 10, 15, 20, 25, 30 minutes following the TT. After the final blood sample was obtained the 12-min test commenced. Blood samples were analysed for blood lactate concentration and peak lactate ($[Bla^-]_{\text{peak}}$) and lowest lactate ($[Bla^-]_{\text{min}}$) determined as the highest and lowest concentrations recorded, respectively, and lactate clearance rate $[BLa^-]_{\text{clr}}$ was calculated as $([BLa^-]_{\text{peak}} - [BLa^-]_{\text{min}}) / \text{duration from peak}$

to lowest value). Separate day procedure: Participants attended the laboratory on two occasions separated by 48 hours. On each of the two occasions, after the warm-up was completed, participants first performed a 6 s maximal sprint to determine $P_{\max}$ (peak 1 s power). Participants chose their own resistance via gear choice with the ergometer in resistance mode with the sprint starting from rolling start ($<40 \text{ rev} \cdot \text{min}^{-1}$). Participants recovered by cycling for 20 min at 50 W before performing either the 3- or 12-min TT as described above. The highest value from either of the two 6 s maximal sprints was used for $P_{\max}$.

The parameters of the power-duration relationship, CP and W' , were calculated using the linear inverse-time-model (Eq.1)

$$P = W' \cdot \frac{1}{t} + CP$$

(Eq.1)

where P is the given power output above CP, and t is the time to task failure (s) and W' is the total work (J) completed above CP.

Intermittent W' depletion trials

Three intermittent trials were completed, on separate occasions in a randomised order. Each trial consisted of different work and recovery periods performed until volitional exhaustion or when pedal cadence fell 10% below the chosen cadence for ~ 5 s. Power output for the work periods (P_{work}) was determined using Eq.2.

$$P_{\text{work}} = P_6 + 0.5 * \Delta CP$$

$$P_6 = (W'/360s) + CP$$

(Eq.2)

Where P_6 is the time to exhaustion in 6 minutes, and ΔCP represents the difference between CP and P_6 . The highest CP and W' values obtained through the same day and separate CP assessments were selected for each participant and used to calculate P_{work} . Specifically, in two participants values were used from the separate day trials and in 11 participants values were used from the same day procedure. The recovery power output was set at 50% of LT_1 (P_{rec}).

Intermittent W' depletion trial 1 (20:10_{TE}). This consisted of repeated 20 s intervals at P_{work} , each separated by 10 s recovery periods at P_{rec} and performed continuously until exhaustion.

Intermittent W' depletion trial 2 (20:10). This consisted of 3 x 20 s intervals at P_{work} , each separated by 10 s recovery periods at P_{rec} before a final continuous effort at P_{work} .

Intermittent W' depletion trial 3 (60:30). This consisted of 3 x 60 s intervals at P_{work} , each separated by 30 s recovery periods at P_{rec} before a final continuous effort at P_{work} . During these trials, participants were permitted to view duration, power, and cadence during the initial 3 efforts of the 60:30 and 20:10, however, during the final exhaustive effort (and throughout the 20:10_{TE}) no feedback other than cadence was provided.

Power data from the three intermittent exercise trials along with CP and W' were used to calculate W'_{BAL} using the ordinary differential equation (ODE) (Pugh et al., 2022; Skiba & Clarke, 2021) (Eq.3).

$$W'_{BAL} = \begin{cases} W'_{bal,i-1} - ([P_i - CP] \cdot \Delta\mu_i), P_i > CP \\ W'_0 - W'_{expended} \cdot \left(e^{-\frac{\Delta\mu_i}{\tau W'}}\right), P_i < CP \end{cases}$$

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$$(Eq.3)$$

where i = the i^{th} segment of the total time subdivided into n segments at 1 Hz, $(\Delta\mu)$, P_i = mean power output for the segment i . W'_{BAL} is calculated sequentially and $W'_{BAL,i-1}$ represents the preceding estimation of W'_{BAL} . $W'_{expended}$ is the quantity of the depleted W' at $i - 1$ and is calculated (Eq.4).

$$W'_{expended} = W'_0 - W'_{bal,i-1}$$

$$(Eq.4)$$

The reconstitution time constant ($\tau_{W'}$) for the W'_{BAL} was calculated via five different equations. The first used Eq.5 (Skiba et al., 2012), an exponential regression obtained from the integral model, referred to as Skiba₁.

$$Skiba_1[\tau_{W'}] = 546e^{(-0.01DCP)} + 316$$

$$(Eq.5)$$

The second used Eq.6 (Skiba et al., 2015) from the differential model, which is scaled against the size of W' to D_{CP} , referred to as Skiba₂.

$$Skiba_2[\tau_{W'}] = W'/D_{CP}$$

$$(Eq.6)$$

The next were calculated using the power function of $D_{CP} - \tau_{W'}$ (Eq.7)

$$\tau_{W'} = A \cdot D_{CP}^{-B}$$

$$(Eq.7)$$

where A represents the scaling factor, and B represents the rate of decay.

The **third** used Eq.8 (Bartram et al. 2018).

$$\text{Bart}[\tau_{W'}] = 2287.2 \cdot D_{CP}^{-0.688} \quad (\text{Eq.8})$$

The **fourth and fifth** used Eq.9 and Eq.10 (Pugh et al., 2022), respectively.

$$\text{Nat}[\tau_{W'}] = 1883 \cdot D_{CP}^{-0.487} \quad (\text{Eq.9})$$

$$\text{Reg}[\tau_{W'}] = 5184 \cdot D_{CP}^{-0.700} \quad (\text{Eq.10})$$

An individualised $\tau_{W'}$ ($\tau_{W'INDV}$) was calculated from the 20:10_{TE} where a single $\tau_{W'}$ was calculated for each participant with the **average** D_{CP} of **across all recovery periods** under the assumption that at the point of task failure represents a W'_{BAL} of 0 kJ. **Time-to-exhaustion (TTE), and total work done above CP for the 20:10_{TE} ($W'_{total20:10TE}$) were calculated for the 20:10_{TE} trial.**

Statistical analysis

Data were normally distributed as assessed by Shapiro-Wilk's test ($P \leq 0.05$). An initial 2-way ANOVA was performed to assess differences in W'_{BAL} with trial and $\tau_{W'}$ as the independent variables. One way ANOVA were subsequently used to assess differences in W'_{BAL} between the **five** $\tau_{W'}$ equations for each trial. Where significant effects were observed, Bonferroni corrected post-hoc *t-tests* were used to locate differences. When Mauchly's test of

sphericity indicated that the assumptions of sphericity had been violated, Greenhouse-Geisser correction was used. Relationships between W' , $W'_{\text{total20:10TE}}$, and $\tau_{W'INDV}$ with physiological and performance measures were analysed using Pearson's product-moment correlation coefficient. Significance was accepted at $P \leq 0.05$. Data are presented as mean $\pm$ standard deviation (SD), unless otherwise stated.

Results

Participant characteristics and performance parameters are shown in Table 1.

Table 1. Participant characteristics and performance parameters.

	Mean $\pm$ SD	Range
Participant Characteristics		
Age (y)	24 $\pm$ 8	19 - 50
Height (m)	1.77 $\pm$ 0.07	1.64 - 1.86
Body mass (kg)	69.2 $\pm$ 6.6	57.2 - 81.0
Performance Parameters		
$\dot{V}O_{2\max}$ (mL $\cdot$ min $^{-1}\cdot$ kg $^{-1}$)	58.2 $\pm$ 8.9	38.6 - 71.3
$\dot{V}O_{2\max}$ (L $\cdot$ min $^{-1}$)	4.0 $\pm$ 0.6	2.8 - 4.9
MAP (W)	371 $\pm$ 70	232 - 435
MAP (W $\cdot$ kg $^{-1}$)	5.3 $\pm$ 0.8	3.7 - 6.7
CP (W)	269 $\pm$ 49	187 - 325
CP (W $\cdot$ kg $^{-1}$)	3.9 $\pm$ 0.7	2.7 - 4.7
W' (kJ)	20.9 $\pm$ 6.3	8.6 - 28.6
W' (kJ $\cdot$ kg $^{-1}$)	0.29 $\pm$ 0.08	0.14 - 0.40
LT ₁ (W)	193 $\pm$ 37	130 - 240
LT ₁ (W $\cdot$ kg $^{-1}$)	2.8 $\pm$ 0.5	1.9 - 3.5
LT ₂ (W)	256 $\pm$ 42	185 - 305
LT ₂ (W $\cdot$ kg $^{-1}$)	3.7 $\pm$ 0.6	2.7 - 4.4
P _{max} (W)	1215 $\pm$ 307	627 - 1723
P _{max} (W $\cdot$ kg $^{-1}$)	17.5 $\pm$ 4.4	9.1 - 24.9
[Bla $^{-}$] _{peak} mmol $\cdot$ L $^{-1}$	14.7 $\pm$ 3.1	6.7 - 18.3
[BLa $^{-}$] _{min} mmol $\cdot$ L $^{-1}$	2.1 $\pm$ 0.8	0.5 - 3.3
[BLa $^{-}$] _{clr} mmol $\cdot$ L $^{-1}$ min $^{-1}$	0.48 $\pm$ 0.10	0.24 - 0.59
Abbreviations: [Bla $^{-}$] _{peak} & [Bla $^{-}$] _{min} highest and lowest value obtained 3 and 12 minute testing; [BLa $^{-}$] _{clr} (peak – min)/time between those two values from 3 and 12 testing; CP, critical power; LT ₁ first lactate threshold (baseline + 0.4 mmol $\cdot$ L $^{-1}$); LT ₂ , second lactate threshold (fixed blood lactate concentration of 4 mmol $\cdot$ L $^{-1}$); MAP, maximal aerobic power; P _{max} , maximal sprint power; $\dot{V}O_{2\max}$, maximal oxygen uptake; W' , curvature constant.		

W'_{BAL} modelling

W'_{BAL} at the point of task failure for each intermittent depletion trial, using each $\tau_{W'}$ modelling method are shown in Fig. 1. There was **no** main effect for trial ($F_{(2,24)} = 1.121$, $P = 0.342$, $\eta_p^2 = 0.085$), however there was a main effect for $\tau_{W'}$ ($F_{(1.507,18.080)} = 64.956$, $P < 0.001$, $\eta_p^2 = 0.844$) and an interaction between trial $\times \tau_{W'}$ ($F_{(1.419,17.032)} = 42.497$, $P < 0.001$, $\eta_p^2 = 0.780$)

When combining the three intermittent trials for analysis, there were significant differences ($P < 0.001$) between: Skiba₁[$\tau_{W'}$] and Skiba₂[$\tau_{W'}$] (7.2 ± 1.4 kJ); Skiba₁[$\tau_{W'}$] and Bart[$\tau_{W'}$] (11.5 ± 2.1 kJ); Skiba₁[$\tau_{W'}$] and Nat[$\tau_{W'}$] (6.2 ± 1.3 kJ); Skiba₁[$\tau_{W'}$] and Reg[$\tau_{W'}$] (6.5 ± 0.4); Skiba₂[$\tau_{W'}$] and Bart[$\tau_{W'}$] (4.3 ± 0.8 kJ); Skiba₂[$\tau_{W'}$] and Nat[$\tau_{W'}$] (-1.0 ± 0.3 kJ); Bart[$\tau_{W'}$] and Nat[$\tau_{W'}$] (-5.3 ± 0.9 kJ); Bart[$\tau_{W'}$] and Reg[$\tau_{W'}$] (-4.9 ± 0.8 kJ).

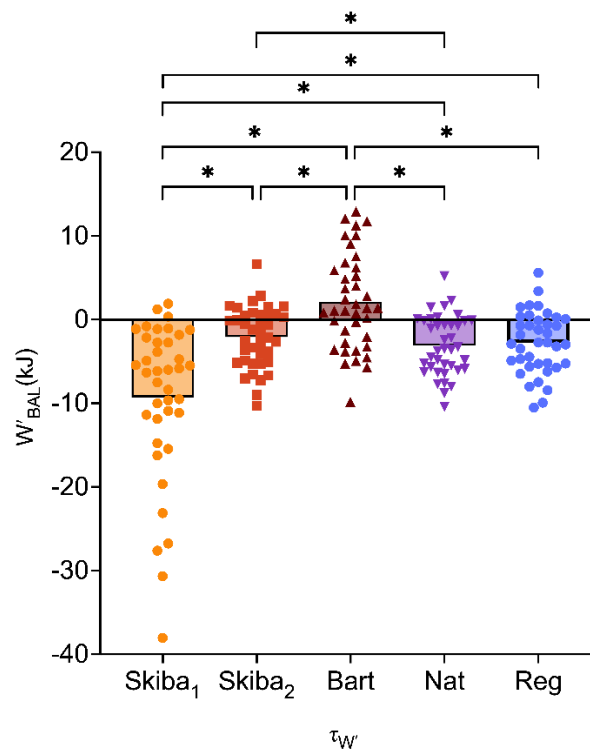


Figure 1: W'_{BAL} at the point of task failure for all intermittent depletion trials calculated using each $\tau_{W'}$ model. Mean and individual data are shown. * $P \leq 0.05$

During the 20:10_{TE} trial (Fig. 2), W'_{BAL} calculated using Skiba₁[$\tau_{W'}$] was lower compared to Skiba₂[$\tau_{W'}$] (-17.4 ± 3.4 kJ, $P < 0.001$); Bart[$\tau_{W'}$] (-26.6 ± 3.4 kJ, $P < 0.001$); Nat[$\tau_{W'}$] (-15.1 ± 2.2 , $P < 0.001$) and Reg[$\tau_{W'}$] (-16.3 ± 2.5 , $P < 0.001$). When calculated using Skiba₂[$\tau_{W'}$], W'_{BAL} was lower compared to Bart[$\tau_{W'}$] (-9.0 ± 1.5 kJ, $P < 0.001$). When calculated using Bart[$\tau_{W'}$], W'_{BAL} was higher compared to Nat[$\tau_{W'}$] (11.4 ± 1.3 kJ, $P < 0.001$) and Reg[$\tau_{W'}$] (10.2 ± 1.2 kJ, $P < 0.001$). There was no difference between Nat[$\tau_{W'}$] and Reg[$\tau_{W'}$].

During the 20:10 trial (Fig. 2), W'_{BAL} calculated using Skiba₁[$\tau_{W'}$] was lower compared to Skiba₂[$\tau_{W'}$] (-0.6 ± 0.1 kJ, $P < 0.001$); Bart[$\tau_{W'}$] (-1.1 ± 0.2 kJ, $P < 0.001$) and Nat[$\tau_{W'}$] (-0.5 ± 0.1 kJ, $P < 0.001$). When calculated using Bart[$\tau_{W'}$], W'_{BAL} was higher compared to Nat[$\tau_{W'}$] (0.6 ± 0.01 kJ, $P < 0.001$) and Reg[$\tau_{W'}$] (0.7 ± 0.2 kJ, $P = 0.007$); There was no difference between Nat[$\tau_{W'}$] and Reg[$\tau_{W'}$].

During the 60:30 trial (Fig. 2), W'_{BAL} calculated using Skiba₁[$\tau_{W'}$] was lower compared to Skiba₂[$\tau_{W'}$] (-3.4 ± 0.2 kJ, $P < 0.001$); Bart[$\tau_{W'}$] (-16.7 ± 0.6 kJ, $P < 0.001$), Nat[$\tau_{W'}$] (-2.9 ± 0.3 kJ, $p < 0.001$) and Reg[$\tau_{W'}$] (-2.9 ± 0.4 kJ, $p < 0.001$). When calculated using Skiba₂[$\tau_{W'}$], W'_{BAL} was lower compared to Bart[$\tau_{W'}$] (-3.3 ± 0.5 kJ, $P < 0.001$). When calculated using Bart[$\tau_{W'}$], W'_{BAL} was higher compared to Nat[$\tau_{W'}$] (3.8 ± 0.4 kJ, $P < 0.001$) and Reg[$\tau_{W'}$] (3.8 ± 0.4 kJ, $P < 0.001$). There was no difference between Nat[$\tau_{W'}$] and Reg[$\tau_{W'}$].

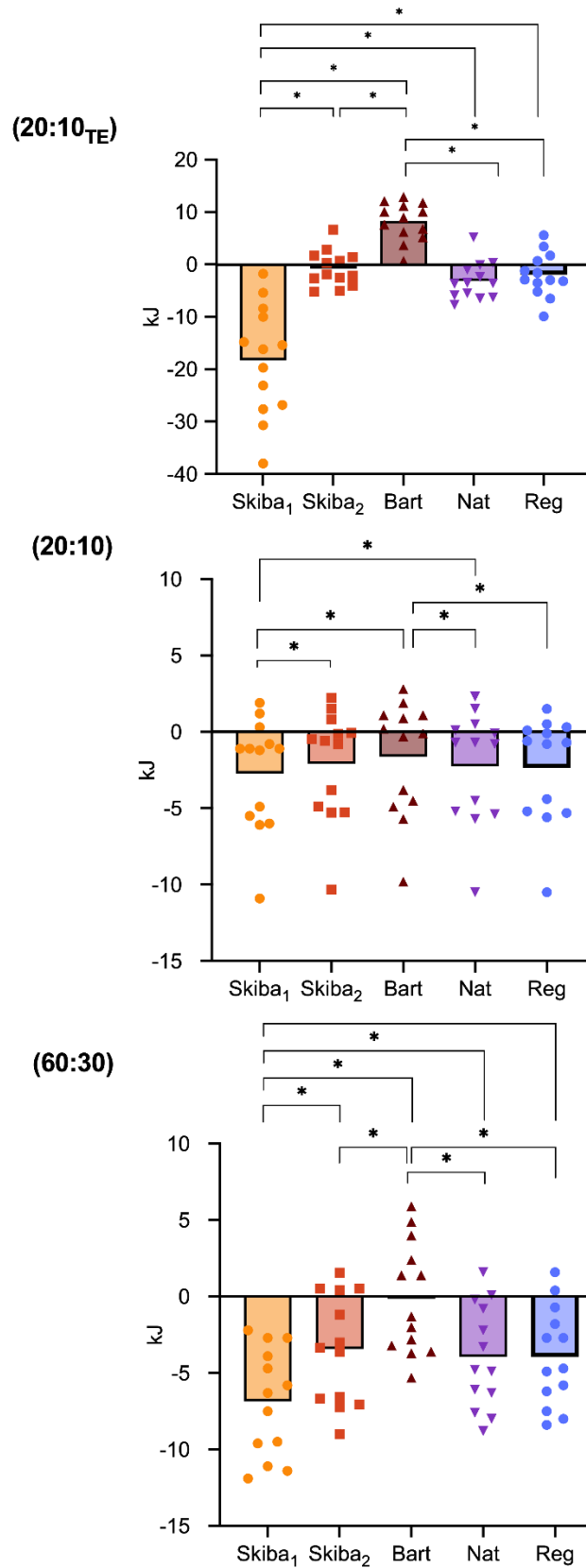


Figure 2. W'_{BAL} at the point of task failure for each intermittent depletion trial (20:10_{TE}; 60:30; 20:10), calculated using each τ_W . Mean and individual data are shown. $*P \leq 0.05$

Individualised $\tau_{W'}$

$\tau_{W'INDV}$ were calculated from the 20:10_{TE} trials under the assumption that the point of task failure represents a W'_{BAL} of 0 kJ. Figure 3 demonstrates, in two participants with contrasting CP values, real time W'_{BAL} modelling during the 20:10_{TE} trials using the five $\tau_{W'}$ models as well as the $\tau_{W'INDV}$. $\tau_{W'INDV}$ calculated for all participants are shown in Table 2.

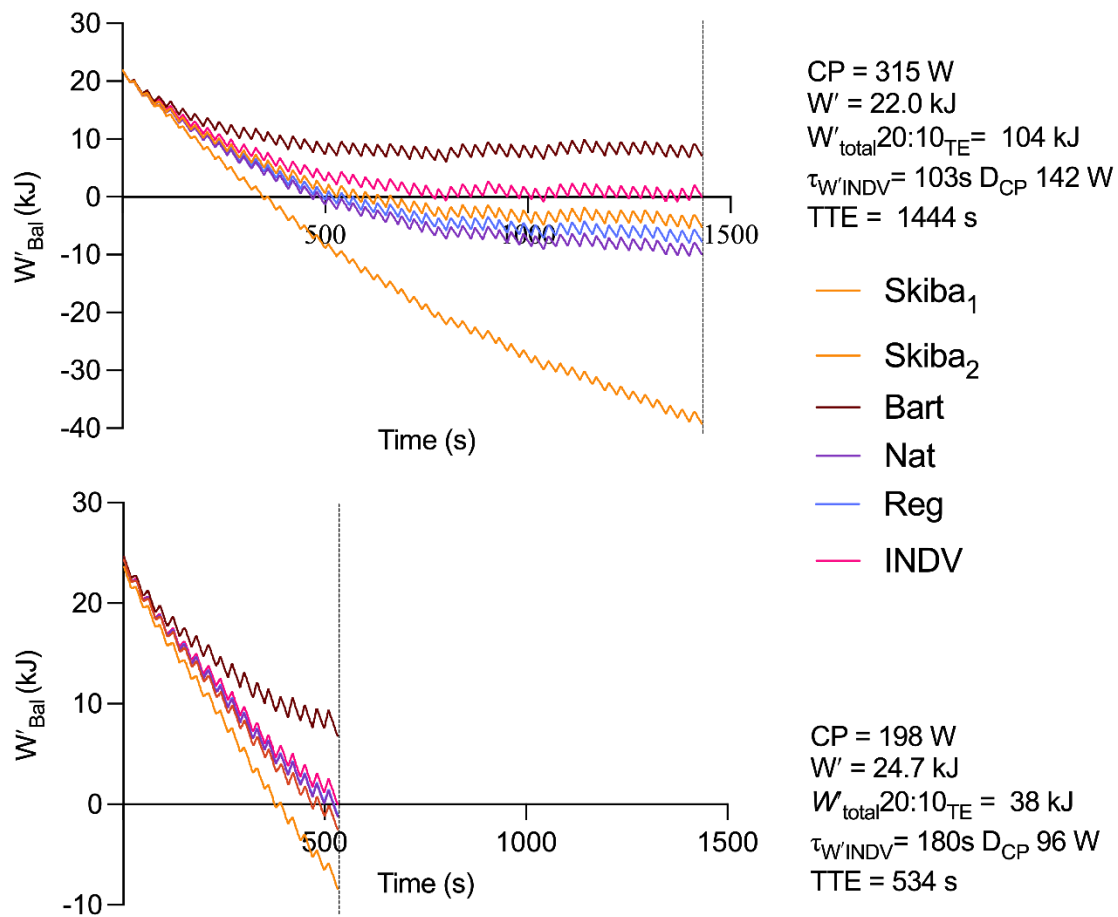


Figure 3. W'_{BAL} in two participants with different CP characteristics throughout the 20:10_{TE} trial calculated using the five $\tau_{W'}$ models and $\tau_{W'INDV}$. Vertical line indicates task failure.

Table 2. Individual performance values, $\tau_{W'INDV}$ and average D_{CP} during intermittent depletion trial 20:10_{TE}

ID	CP (W)	W' (kJ)	$\tau_{W'INDV}$ (s)	D_{CP} (W)	TTE (s)	$W'_{total20:10TE}$ (kJ)	$W'_{total20:10TE}/W'$ (%)
1	306	21.1	***	183	768	49.5	235
2	264	22.6	134	123	740	30.3	134
3	315	22.1	103	142	1444	103.5	468
4	272	28.1	189	154	769	47.6	169
5	298	24.5	115	121	1070	56.0	229
6	317	24.0	115	134	1127	86.5	360
7	325	25.4	149	148	978	58.9	232
8	195	13.7	132	79	1603	41.6	304
9	268	28.6	124	95	697	63.4	222
10	245	12.0	134	127	1274	42.0	350
11	187	8.6	168	123	678	17.3	201
12	301	16.1	108	143	1100	60.8	378
13	198	24.7	180	96	534	38.2	155
Mean	269	20.9	138	128	983	53.5	264
SD	49	6.3	28	28	323	22.7	100

Abbreviations: CP, critical power; D_{CP} , recovery work rate below CP; TTE, time to exhaustion during 20:10_{TE}; $\tau_{W'INDV}$, individualised time constant of W'_{rec} ; W' , curvature constant; $W'_{total20:10TE}$, total work done completed above critical power during 20:10_{TE} until task failure; $W'_{total20:10TE}/W'$, percentage ratio between $W'_{total20:10TE}$ and W' .

In Figure 4, individual $\tau_{W'}$ values obtained from the 20:10_{TE} trial in Table 2 are plotted in relation to D_{CP} . Also plotted are the relationships between $\tau_{W'}$ and D_{CP} for the five $\tau_{W'}$ equations; Skiba₁[$\tau_{W'}$], Skiba₂[$\tau_{W'}$], Bart[$\tau_{W'}$], Nat[$\tau_{W'}$] and Reg[$\tau_{W'}$] (see Methods). At the D_{CP} utilised in the present study (i.e., 50% of LT₁) the $\tau_{W'INDV}$ values calculated for each participant fell between Bart[$\tau_{W'}$], Nat[$\tau_{W'}$] and Reg[$\tau_{W'}$] except participant 4.

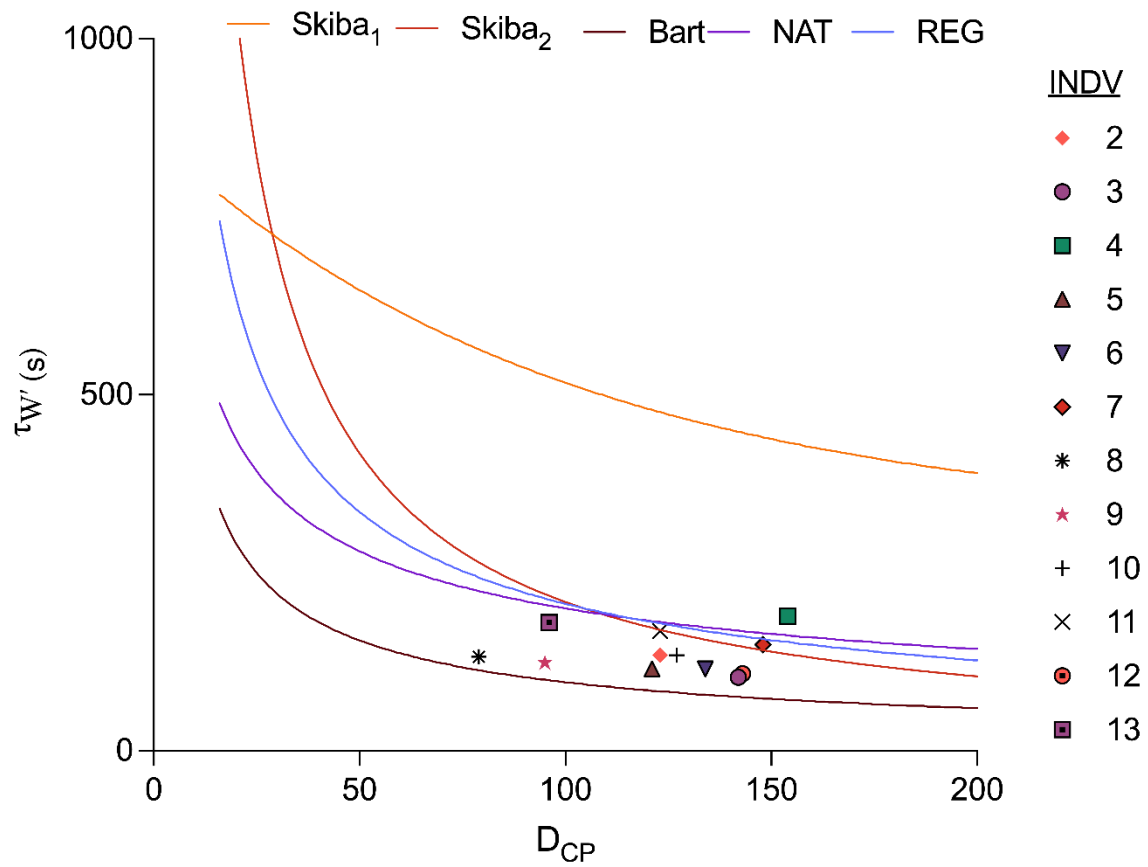


Figure 4. $\tau_{W'INDV}$ obtained from the 20:10_{TE} trial plotted in relation to D_{CP} . Also plotted are the relationships between $\tau_{W'}$ and D_{CP} for the five $\tau_{W'}$ equations; Skiba₁[$\tau_{W'}$], Skiba₂[$\tau_{W'}$] fitted as mean W' (20.8 kJ) / D_{CP} , Bart[$\tau_{W'}$], Nat[$\tau_{W'}$] and Reg[$\tau_{W'}$] (see Methods).

W'_{BAL} correlates

Correlations of W' , $W'_{\text{total}20:10\text{TE}}$, and $\tau_{W'\text{INDV}}$ with physiological and performance parameters are shown in Table 3. W' was positively correlated with body mass, absolute and relative $\dot{V}\text{O}_{2\text{max}}$, absolute MAP, absolute and relative P_{max} , $[\text{BLa}^-]_{\text{peak}}$, and $[\text{BLa}^-]_{\text{min}}$ (Fig. 4). $W'_{\text{total}20:10\text{TE}}$ was positively correlated with absolute and relative $\dot{V}\text{O}_{2\text{max}}$, absolute and relative MAP, absolute and relative CP, absolute and relative LT_1 , absolute and relative LT_2 , absolute and relative P_{max} , and $[\text{BLa}^-]_{\text{peak}}$ (Fig. 5). The $\tau_{W'\text{INDV}}$ was negatively correlated with relative CP, relative LT_1 , and $W'_{\text{total}20:10\text{TE}}$ (Fig. 6).

TABLE 3. Correlations between W' , $W'_{\text{total}20:10\text{TE}}$, and $\tau_{W'\text{INDV}}$ and physiological and performance parameters.

	W' (kJ)	$W'_{\text{total}20:10\text{TE}}$ (kJ)	$\tau_{W'\text{INDV}}$ (s)
Body mass (kg)	$r = 0.658$ $P = 0.015^*$	$r = 0.216$ $P = 0.478$	$r = -0.053$ $P = 0.870$
$\dot{V}O_{2\text{max}}$ (mL·min ⁻¹ ·kg ⁻¹)	$r = 0.582$ $P = 0.037^*$	$r = 0.781$ $P = 0.002^*$	$r = -0.525$ $P = 0.080$
$\dot{V}O_{2\text{max}}$ (L·min ⁻¹)	$r = 0.742$ $P = 0.004^*$	$r = 0.678$ $P = 0.011^*$	$r = -0.393$ $P = 0.207$
MAP (W)	$r = 0.735$ $P = 0.004^*$	$r = 0.693$ $P = 0.009^*$	$r = -0.435$ $P = 0.157$
MAP (W·kg ⁻¹)	$r = 0.543$ $P = 0.055$	$r = 0.766$ $P = 0.002^*$	$r = -0.333$ $P = 0.291$
CP (W)	$r = 0.504$ $P = 0.879$	$r = 0.703$ $P = 0.007^*$	$r = -0.543$ $P = 0.068$
CP (W·kg ⁻¹)	$r = 0.252$ $P = 0.407$	$r = 0.772$ $P = 0.002^*$	$r = -0.699$ $P = 0.011^*$
W' (kJ)	-	$r = 0.478$ $P = 0.09$	$r = -0.060$ $P = 0.852$
W' (W'·kJ ⁻¹)	-	$r = 0.497$ $P = 0.084$	$r = 0.077$ $P = 0.812$
LT ₁ (W)	$r = 0.506$ $P = 0.078$	$r = 0.711$ $P = 0.007^*$	$r = -0.457$ $P = 0.135$
LT ₁ (W·kg ⁻¹)	$r = 0.266$ $P = 0.078$	$r = 0.800$ $P = 0.001^*$	$r = -0.588$ $P = 0.044^*$
LT ₂ (W)	$r = 0.474$ $P = 0.102$	$r = 0.637$ $P = 0.019^*$	$r = -0.441$ $P = 0.151$
LT ₂ (W·kg ⁻¹)	$r = 0.474$ $P = 0.554$	$r = 0.721$ $P = 0.005^*$	$r = -0.575$ $P = 0.151$
P_{max} (W)	$r = 0.823$ $P = 0.001^*$	$r = 0.718$ $P = 0.006^*$	$r = -0.237$ $P = 0.459$
P_{max} (W·kg ⁻¹)	$r = 0.735$ $P = 0.004^*$	$r = 0.792$ $P = 0.001^*$	$r = -0.286$ $P = 0.368$
[BLa] _{peak} mmol·L ⁻¹	$r = 0.647$ $P = 0.017^*$	$r = 0.578$ $P = 0.039^*$	$r = -0.424$ $P = 0.170$
[BLa] _{min} mmol·L ⁻¹	$r = 0.590$ $P = 0.034^*$	$r = 0.140$ $P = 0.647$	$r = -0.115$ $P = 0.722$
[BLa] _{clr} mmol·L ⁻¹	$r = 0.427$ $P = 0.146$	$r = 0.514$ $P = 0.056$	$r = -0.438$ $P = 0.154$
Endurance Ratio	$r = 0.805$ $P = 0.056$	$r = 0.050$ $P = 0.872$	$r = 0.404$ $P = 0.193$
$W'_{\text{total}20:10\text{TE}}$ (kJ)	$r = 0.478$ $P = 0.090$	-	$r = -0.635$ $P = 0.027^*$

Abbreviations: [BLa]_{peak} & [BLa]_{min} highest and lowest value obtained 3 and 12 minute testing; [BLa]_{clr} (peak – min)/time; CP, Critical power; Endurance ratio, curvature constant/critical power; LT₁ first inflection point calculated as baseline + 0.4 mmol·L⁻¹; LT₂, Fixed blood lactate concentration of 4 mmol·L⁻¹; MAP, maximal aerobic power; P_{max} , maximal sprint power; $\dot{V}O_{2\text{max}}$, maximal oxygen uptake; W' , curvature constant; $W'_{\text{total}20:10\text{TE}}$, work done above critical power during 20:10_{TE} until task failure. * $P \leq 0.05$

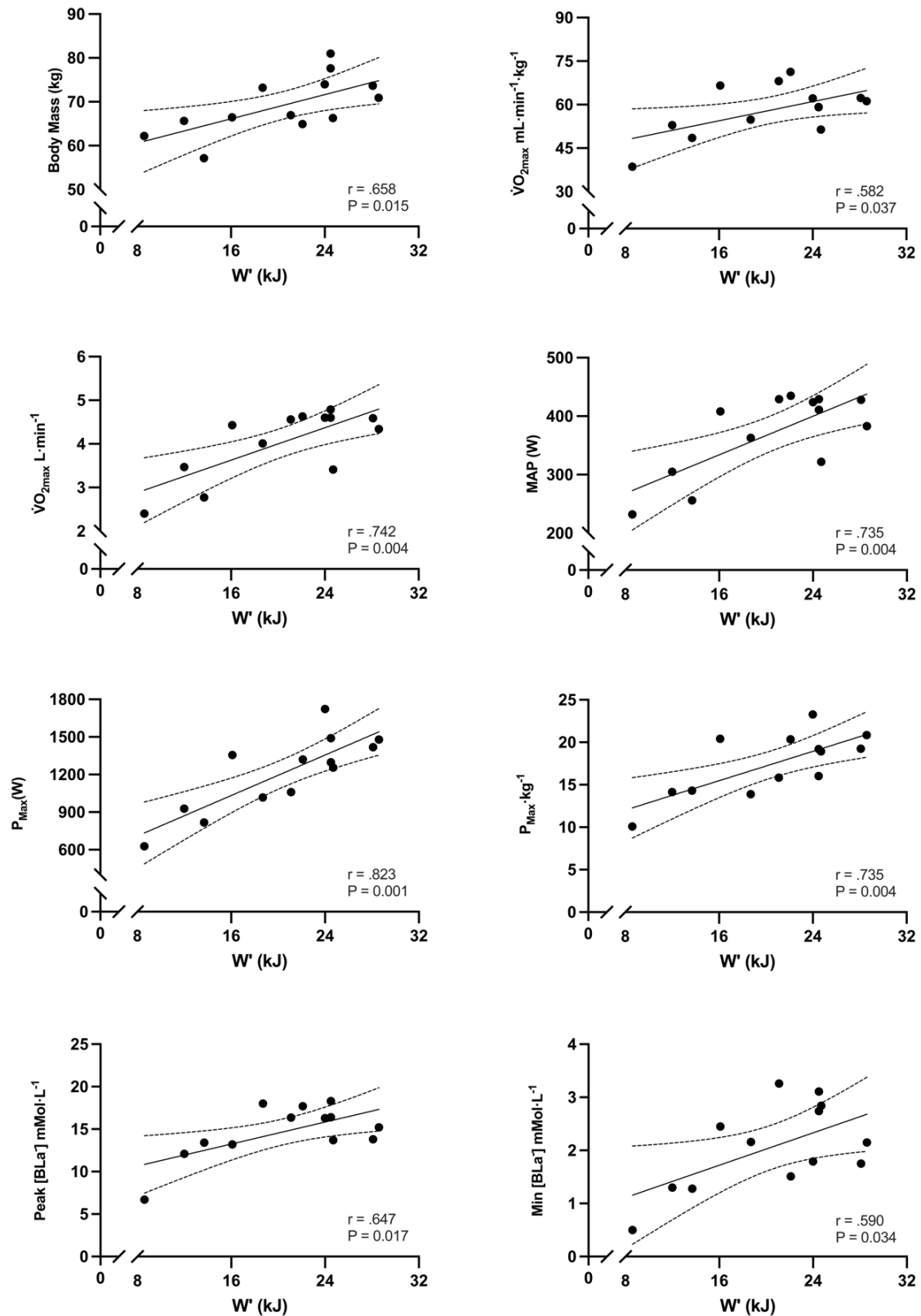


Figure 5. Correlations between W' and physiological and performance parameters (95% CI are also shown)

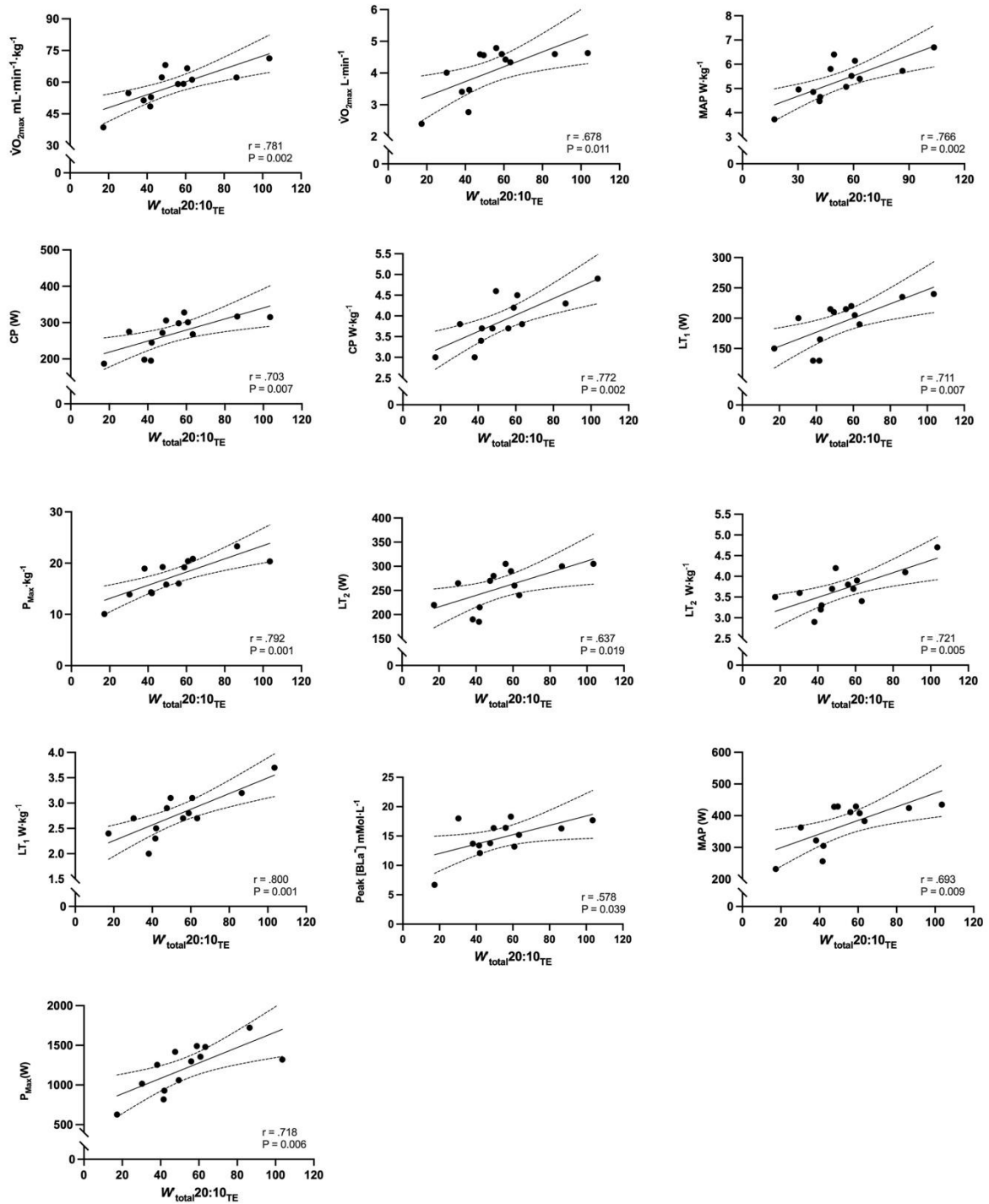


Figure 6. Correlations between $W'_{total20:10TE}$ and physiological and performance parameters (95% CI are also shown)

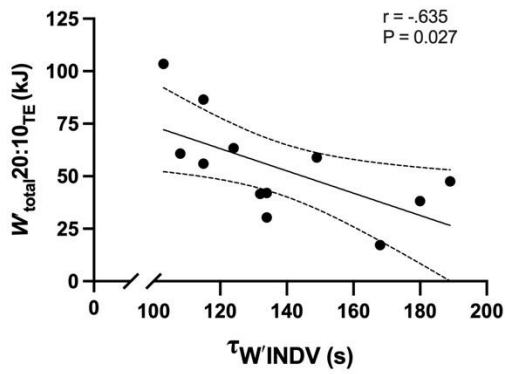
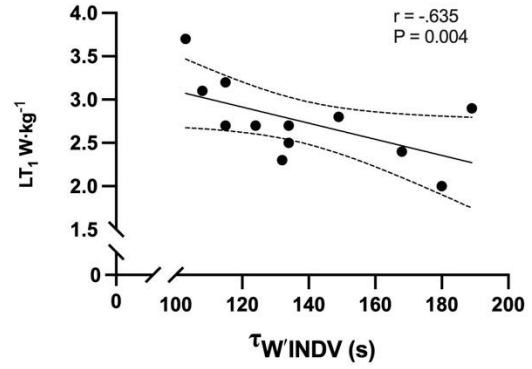
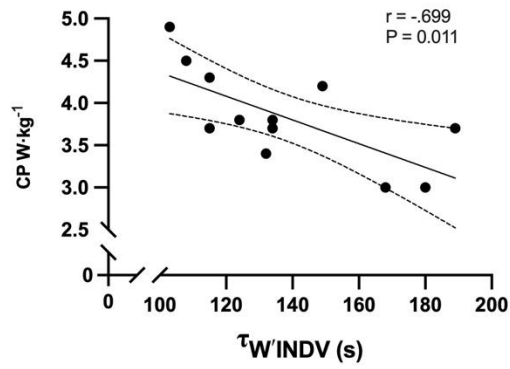


Figure 7. Correlations between $\tau W'INDV$ and physiological and performance parameters (95% CI are also shown)

Discussion

The main findings of this study are as follows: (1) current $\tau_{W'}$ equations used to calculate W'_{rec} failed to predict exhaustion during intermittent exercise protocols to exhaustion; (2) when utilising the W'_{BAL} model $\tau_{W'}$ should be individualised for accurate prediction; (3) multiple physiological performance characteristics including LT_1 , LT_2 , CP, $\dot{V}O_{2\text{max}}$, MAP, P_{max} , and $[BLa]_{\text{peak}}$ were positively correlated with W' and $W'_{\text{total}20:10\text{TE}}$; (4) relative CP, LT_1 , and $W'_{\text{total}20:10\text{TE}}$ were negatively correlated with $\tau_{W'\text{INDV}}$.

According to the W'_{BAL} model it is assumed that when W' is depleted, i.e., 0 kJ, exhaustion will occur, or the individual will no longer be able to perform work above CP (Chorley & Lamb, 2020; Jones et al., 2010; Skiba et al., 2012). However, the five equations of $\tau_{W'}$ used to model W'_{BAL} failed to predict a value of 0 kJ at the point of exhaustion during the intermittent W' depletion trials. The original time constant described by Skiba et al., (2012); $Skiba_1[\tau_{W'}]$ clearly underpredicted the W'_{BAL} at the point of exhaustion, particularly in the 20:10_{TE} and 60:30 trials, with no values above 0 kJ being reported. There was an improvement in the prediction when using $Skiba_2[\tau_{W'}]$ which had the lowest mean value during the 20:10_{TE} trial (Fig 2). $Bart[\tau_{W'}]$, however, often overpredicted W'_{BAL} particularly in the 20:10_{TE}. The time constants described by Pugh et al., (2022) resulted in slight improvements in prediction compared to $Skiba_1[\tau_{W'}]$ and $Bart[\tau_{W'}]$ particularly in the 20:10_{TE} and provided values much closer to 0 kJ.

The reasons for the poor predictive capability of current $\tau_{W'}$ equations are complex and multi-faceted. It is likely that the curvilinear responses of W'_{rec} through the mono-exponential $\tau_{W'}$ function during the recovery phase of exercise are either too fast or slow such that W'_{BAL} at

the point of exhaustion is either over or under predicted. This is likely to be a function of the complex processes of skeletal muscle energetics, including PCr utilisation and recovery (Chidnok, DiMenna, et al., 2013; Skiba et al., 2015) and O₂ delivery and utilisation (Korzeniewski & Rossiter, 2020; Lievens et al., 2024) interacting with the key intermittent exercise protocol parameters including interval work rate and duration, recovery power (normalised recovery power relative to CP; D_{CP}) and duration (Caen et al., 2019; Skiba et al., 2014). For example, whilst one of our protocols utilised a 60:30 work:recovery ratio, similar to that used by (Skiba et al., 2014), the D_{CP} values were substantially different e.g., with D_{CP} based on a 20 W recovery power compared to 50% LT₁ (resulting in a D_{CP} of 129 W). $\tau_{W'}$ equations from Pugh et al. (2022) were derived from D_{CP}'s of 25, 50 and 100 W with work:recovery ratio of 30:60. Furthermore, individual participant performance capacities (e.g., LT₁, CP, $\dot{V}O_{2\max}$, P_{max}), and physiology (e.g., muscle fibre composition) are also likely to interact. For example, the average CP in our population was 269 W compared to 240 W for recreational athletes in Skiba et al., (2012), ~380 W for competitive track cyclists in Pugh et al., (2022) and 393 W for elite team pursuit cyclists in Bartram et al., (2018). Consequently, the generalised $\tau_{W'}$ values used were unable to fully capture the intricacies in these protocol and participant performance capacities to accurately predict 0 kJ at the point of exhaustion.

To achieve more accurate predictions additional parameters would be required to input into the W'_{BAL} model. This might include individual participant performance and physiological characteristics that have been shown to correlate with W'_{rec} parameters. Whilst not a W'_{rec} parameter per se, $W'_{total20:10TE}$ reflects how much W' was used during intermittent exercise, indicating a great ability to reconstitute W' and was positively correlated to P_{max}, $\dot{V}O_{2\max}$, MAP, CP, LT₁, LT₂ and [BLa⁻]_{peak}. In addition, the individualised $\tau_{W'}$ values were negatively correlated with LT₁ and CP (when expressed relative to body mass). **Given the close relationships**

between these performance parameters and skeletal muscle morphological and metabolic properties (Mitchell et al., 2018; Peden et al., 2024), it might be suggested that skeletal muscle characteristics such as muscle fibre type distribution, capillarity, and mitochondrial content/function play an important role and permit a faster rate of rate of W'_{rec} . Furthermore, W' was positively correlated to body mass, P_{max} , $\dot{V}O_{2\text{max}}$, MAP, and $[\text{BLa-}]_{\text{peak}}$ supporting previous observations that W' is highly dependent on muscle strength and size parameters (Kordi et al., 2018; Kordi et al., 2021).

The inherent limitations of the 2-parameter model at work rates above the severe domain likely cause W'_{BAL} models to underestimate W' depletion rates, potentially affecting calculated W'_{rec} values. Our observation of positive relationships between performance parameters, including P_{max} , suggests that incorporating a 3-parameter CP model may enhance W'_{BAL} prediction accuracy by improving W' precision in the extreme domain, though this is beyond the scope of the current study. Regardless, adding components to W'_{BAL} models increases complexity, and the mathematisation of physiology remains challenging, particularly given uncertainty about how these components would influence W'_{rec} .

Whilst our focus has been on W'_{rec} during the recovery period, the W'_{BAL} model works on the assumption that W' utilisation is linear when work is being performed above CP which is built on the assumption (Morton, 2006) that mechanical efficiency remains constant during exercise. This is particularly important since it has been established that mechanical efficiency is not constant over time, particularly during intense dynamic exercise (González-Alonso et al., 2000), and repeated intense exercise (Bangsbo et al., 2001; Krstrup et al., 2001, 2003). In fact, mechanical efficiency declines as exercise progresses which is dependent upon ATP production from the different metabolic pathways involved throughout exercise i.e., PCr hydrolysis,

glycolysis, and oxidative phosphorylation. Additionally, there are suggestions that W' is not a fixed work capacity (Chidnok, Dimenna, et al., 2013; Dekerle et al., 2015) rather it may be more of a dynamic work capacity which is influenced by work rate and total W' depletion (Welburn et al., 2024). Collectively, these observations highlight the complexity of modelling W' utilisation and reconstitution, and further investigation is warranted to explore the constraints and boundaries of the W'_{BAL} model.

The present study was not without limitations. Accurate and reliable determination of CP and W' are essential for W'_{BAL} modelling. Large errors in the measurement of these parameters will reduce the confidence in an accurate W'_{BAL} prediction. For example, a larger error with W' will have implications for the prediction of time to failure. CP also influences the D_{CP} value which directly impacts the mathematical function to predict W'_{BAL} at any given point. In the present study, CP and W' were determined using two fixed duration TT efforts (Parker-Simpson & Kordi, 2017). Whilst this method provides a valid and reliable assessment of CP and W' , it is not possible to determine the level of measurement error. However, these highlight the balance between the applicability of W'_{BAL} modelling in the field for elite athletes and more accurate laboratory-based assessment. Finally, more detailed modelling of W'_{rec} has been suggested by Caen et al, (2021) who reported a bi-exponential recovery pattern with separate $\tau_{W'}$ values for fast and slow phases of reconstitution. However, the intermittent protocols in the present study adopted 10 s and 30 s recovery periods, thus the slow phase was unlikely to be captured.

In conclusion, this study suggests the $Reg[\tau_{W'}]$ or $Skiba_2[\tau_{W'}]$ equations could be used in generalised W'_{BAL} modelling during intermittent exercise with short recovery periods. However, the framework for $Skiba_2[\tau_{W'}]$ does not allow for individualisation in its current

format, therefore, an individualised τ_W should be utilised for a more accurate prediction of W'_{BAL} . There were correlations between parameters of W'_{rec} and multiple physiological performance characteristics, including LT_1 and CP, suggesting that W'_{rec} is influenced primarily by aerobic parameters, which could be incorporated into further W'_{BAL} models. From a practical perspective we suggest that the specific needs of the athlete should be considered, and individualised intermittent exercise protocols utilised in which intensity and duration-specific parameters are adopted. Such considerations could enhance the use of W'_{BAL} modelling as a powerful performance metric allowing the quantification of 'recoverability'.

581 **Abbreviations**

582	$[\text{BLa}^-]_{\text{clr}}$ – rate of blood lactate clearance between the 3- and 12-minute effort
583	$[\text{BLa}^-]_{\text{min}}$ – lowest blood lactate concentration obtained after the 3-minute time trial effort
584	$[\text{BLa}^-]_{\text{peak}}$ – highest blood lactate concentration obtained after the 3-minute time trial effort
585	ADP – adenosine diphosphate
586	CP – critical power
587	D_{CP} – recovery work rate below CP
588	H^+ – hydrogen ions
589	LT_1 – first lactate threshold, defined as baseline + 0.4 mmol·L ⁻¹
590	LT_2 – second lactate threshold, defined as fixed blood lactate concentration of 4 mmol·L ⁻¹
591	MAP – maximal aerobic power
592	MMP – mean maximal power
593	ODE – ordinary differential equation
594	PCr – phosphocreatine
595	P_i – inorganic phosphate
596	P_{max} – peak 1 s power
597	P_{work} – work rate intensity during interment exercise
598	TTE – time to exhaustion
599	$\dot{V}\text{O}_{2\text{max}}$ – maximal oxygen uptake
600	W' – curvature constant
601	W'_{BAL} – balance between W' depletion and W' reconstitution during intermittent exercise
602	W'_{rec} – W' reconstitution
603	$W'_{\text{total}20:10_{\text{TE}}}$ – total work done completed above critical power during 20:10 _{TE} until task failure
604	$\tau_{W'}$ – time constant to recover 63% of W'
605	$\tau_{W'\text{INDV}}$ – individualised time constant of W' reconstitution
606	
607	

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Author contributions

All authors contributed to the study conception and design. Material preparation, data collection and analysis were performed by Alex Welburn. The first draft of the manuscript was written by Alex Welburn and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

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Data availability

Data are available upon reasonable request.

Conflict of interest

No conflicts of interest, financial or otherwise, are declared by the authors.

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