Accounting for dynamic changes in the power-duration relationship improves the accuracy of W′ balance modeling

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Abstract

Purpose This study aimed to: 1) examine the accuracy with which W′ reconstitution (W'_{REC}) is estimated by the W′ balance (W'_{BAL}) models following a 3-min all-out test (3MT); 2) determine the effects of a 3MT on the power-duration relationship, and; 3) assess whether accounting for changes in the power-duration relationship during exercise improved estimates of W'_{REC}. **Methods** The power-duration relationship and the actual and estimated W'_{REC} was determined for 12 datasets extracted from our laboratory database where participants had completed two 3MT separated by 1-min recovery (i.e., control, C-3MT and fatigued, F-3MT). **Results** Actual W'_{REC} (6.3±1.4 kJ) was significantly overestimated by the $W'_{BAL\cdot ODE}$ (9.8±1.3 kJ; $P<0.001$) and the $W'_{BAL\cdot MORTON}$ (16.9±2.6 kJ; $P<0.001$) models, but was not significantly different to the estimate provided by the $W'_{BAL\cdot INT}$ (7.5±1.5 kJ; $P>0.05$) model. End power (EP) was 7% lower in the F-3MT (263 ± 40 W) compared to the C-3MT (282±44 W; $P<0.001$), and work done above EP (WEP) was 61% lower in the F-3MT (6.3±1.4 kJ) compared to the C-3MT (16.9±3.2 kJ). The size of the error in the estimated W'_{REC} was correlated with the reduction in WEP for the $W'_{BAL\cdot INT}$ and $W'_{BAL\cdot ODE}$ models (both $r>-0.74$, $P<0.01$) but not the $W'_{BAL\cdot MORTON}$ model ($r=-0.18$, $P>0.05$). Accounting for the changes in the power-duration relationship improved the accuracy of the $W'_{BAL\cdot ODE}$ and $W'_{BAL\cdot MORTON}$, but they remained significantly different to actual W'_{REC}. **Conclusion** These findings demonstrate that the power-duration relationship is altered following a 3MT, and accounting for these changes improves the accuracy of the $W'_{BAL\cdot ODE}$ and the $W'_{BAL\cdot MORTON}$, but not $W'_{BAL\cdot INT}$ models. These results have important implications for the design and use of mathematical models describing the energetics of exercise performance.

Key words: Critical Power; W′; Reconstitution; Recovery; Cycling; Exercise Performance

Introduction

Endurance exercise performance is well described by the parameters of the hyperbolic power-duration relationship, the critical power (CP) and the curvature constant (W′) (1, 2). CP is considered to be a metabolic or fatigue threshold that separates the "heavy" and "severe" exercise intensity domains, whilst the W′ represents a fixed work capacity above CP which is intrinsically linked to loss of skeletal muscle efficiency during fatiguing severe-intensity exercise (3). In the heavy-intensity domain (<CP), intramuscular homeostasis is maintained and pulmonary oxygen uptake ($\dot{V}O_2$) attains a delayed steady state (4-6). In contrast, in the severe-intensity domain (>CP), physiological steady states are not achieved, and there is a concomitant loss of intramuscular homeostasis and rise in $\dot{V}O_2$ until the attainment of a critical local metabolic environment and maximal O_2 uptake ($\dot{V}O_{2max}$) at the limit of tolerance (T_{lim}) which coincides with the complete utilization of W′ (3-6). During severe-intensity exercise (>CP), T_{lim} is therefore predictable according to the power output above CP and the W′ (1-3).

The power-duration concept has been applied to intermittent exercise (i.e., "work" intervals >CP separated by "recovery" intervals <CP) using equations that assume linear discharge and reconstitution kinetics for W′ ($W'_{BAL \cdot MORTON}$; (7)), or which appreciate the curvilinear recovery of W′ (W'_{REC}) and use either an integral convolution equation ($W'_{BAL \cdot INT}$; (8)) that implies some W'_{REC} even when a net W′ depletion is observed, or an ordinary differential equation ($W'_{BAL \cdot ODE}$; (9)), that considers mutually exclusive W′ depletion and recovery during exercise above and below CP, respectively. However, the accuracy of these models for describing W′ balance (W'_{BAL}) and thus predicting exercise performance is equivocal (10-12; *cf.* 13-16). Studies that support the application of these models utilized no greater than ~10% of the total W′ during each period of work (10-12), whereas those highlighting inaccuracies employed protocols which either completely (14, 15) or substantially (~50%) (13, 16) utilized

W′ during the first work interval, suggesting that the amount of W′ utilized during each work bout influences its recovery. Furthermore, the rate of W′ utilisation may also be an important factor in the accuracy of the W'_{BAL} models, with W'_{REC} reported to be slower following an 8-min compared to a 4-min severe-intensity exercise bout (14). No study has evaluated the ability of the W'_{BAL} models to predict W'_{REC} following exercise which completely utilizes W′ at its fastest possible rate, by employing an 'all-out' exercise model.

Further to the potential effects of the work rate and duration of the work interval on W'_{REC}, dynamic changes in CP (reduced by ~9%) and W′ (reduced by ~20%) have been reported following 2 h heavy-intensity exercise (17). Whilst the performance of severe-intensity constant work rate (CWR) exercise has no effect on CP (18), the physiological responses to CWR exercise differ considerably to those elicited during all-out sprint exercise (i.e., exercise that requires the individual to produce as much power as possible throughout the bout). Instead of the progressive activation of motor units (19, 20) and recruitment of additional type II muscle fibers with time that occurs during CWR exercise (21), the muscle activation pattern during all-out sprint exercise is "reversed" with all available (task-specific) motor units recruited at exercise onset (19, 20). The disparity between power profiles results in a much greater utilization of W′ during all-out exercise at a given time compared to a work-matched CWR test of the same duration (22). Furthermore, the utilization of all motor units from the onset of all-out exercise results in substantial fatigue of type II motor units (23, 24) Given that type II muscle fibers recover more slowly than type I muscle fibers (23, 25, 26) W'_{REC} may be significantly slowed following all-out exercise. The impact of all-out exercise on the parameters of the power-duration relationship, and the ability of the W'_{BAL} models to accurately estimate W'_{REC} following all-out exercise, has yet to be examined.

The 3-min all-out cycling test (3MT) permits valid and reliable determination of CP and W′ (27, 28). During this test external power output declines with time to attain a nadir during the final 30 s of the test (end test power, EP) that approximates CP, with the work completed above EP (WEP) being equivalent to W′ (27, 28). Performing two 3MTs, separated by a brief recovery interval (1-min), provides the opportunity to: 1) assess the accuracy of the W'_{BAL} models to predict W'_{REC} following exercise which completely utilises W′ at its fastest possible rate; 2) determine the effect of a 3MT on the power-duration relationship; and thus 3) incorporate any changes to CP and W′ in the W'_{BAL} models and, subsequently, re-evaluate the accuracy of W'_{REC} estimates. Based on the differences in motor unit recruitment patterns between CWR and all-out exercise, and likely differences in the rates of recovery between muscle fiber types, we hypothesized that the existing W'_{BAL} models would overestimate W'_{REC}. We also hypothesized that WEP, but not EP, would be significantly reduced during the second, fatigued, 3MT (F-3MT) compared to the first, control, 3MT (C-3MT). Finally, we hypothesized that estimates of W'_{REC} would be improved by incorporating any changes in the parameters of the power-duration relationship into the W'_{BAL} models.

Methods

Datasets

The datasets for this study were extracted from our laboratory database. We included data from participants who had completed a ramp incremental test, a familiarization 3MT and an experimental "repeated 3MT" (described below), where tests were completed within a 4-wk period and had not included any intervention (e.g., dietary supplementation). Subsequently, the experimental repeated 3MTs were assessed to ensure that all efforts were maximal using the following criteria: 1) the ramp incremental test $\dot{V}O_{2peak}$ was attained and then maintained (≥95% ramp incremental $\dot{V}O_{2peak}$) in both the C-3MT and F-3MT; and 2) the power profiles were devoid of any evidence of a submaximal effort (i.e., a decrease(s) and subsequent increase(s) in power output). In total, datasets from 12 participants (sex: males *n*=11, female *n*=1; age: 23 ± 4 y; body mass 82.2 ± 15.1 kg; height: 1.81 ± 0.12 m) were included in this study. Testing was performed at the same time of day within each dataset. All participants had been instructed to be adequately hydrated and not to have consumed alcohol for 24 h and food or caffeine for 3 h before each test. Each participant had been informed of the protocol and possible risks/benefits involved according to the study from which the dataset originated and had provided written informed consent to participate. All procedures were approved by the local Research Ethics Committee and were conducted in accordance with the Declaration of Helsinki.

Exercise tests

Ramp incremental cycling test

All tests were performed on the same electronically-braked cycle ergometer (Lode Excalibur Sport, Groningen, The Netherlands). The ergometer seat and handlebars were adjusted for comfort, and these settings were recorded and replicated for all tests. The ramp incremental test consisted of a baseline of 3 min of pedaling at 20 W 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 for >5 s despite strong verbal encouragement. $\dot{V}O_{2peak}$ was determined as the highest 30-s mean value recorded during the test and GET was determined as previously described (29). Account was taken of the mean response time (MRT) for $\dot{V}O_2$ during ramp exercise, i.e., two-thirds of the ramp rate was deducted from the work rate at GET and $\dot{V}O_{2peak}$ (30).

Repeated 3-min all-out cycling test

The repeated 3MT protocol began with 3 min of pedalling at 20 W, at the same self-selected cadence chosen during the ramp incremental test, followed by two 3MTs (a single 3MT is described in refs. 27, 28) separated by 1-min passive recovery. The first 3MT served as a rested-control condition (C-3MT), whereas the second 3MT was performed in a fatigued state (F-3MT). Participants were instructed to accelerate to 110-120 rpm over the final 5 s of the baseline period, and for the final 5 s of the active recovery period that preceded the C-3MT and F-3MT, respectively. The resistance on the pedals during the 3MT was set using the linear mode of the ergometer such that, on reaching 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, subjects were instructed and strongly encouraged to attain their peak power as quickly as possible, and to maintain their cadence as high as possible until instructed to stop. EP was defined as the mean power output during the final 30 s for both the C-3MT and F-3MT. The work performed above EP (WEP) was calculated as the work done above EP for the C-3MT and F-3MT. End test $\dot{V}O_2$ was determined as the final 30-s mean value in each of the 3MTs. The end-exercise $\dot{V}O_2$ gain for C-3MT and F-3MT was calculated by dividing the mean $\dot{V}O_2$ by the mean power output during the final 30 s of the C-3MT and F-3MT.

Pulmonary gas exchange

Breath-by-breath pulmonary gas exchange data were collected continuously during all cycling tests. Participants wore a nose clip and breathed through a mouthpiece and impeller turbine assembly (Jaeger Triple V, Hoechberg, Germany). The inspired and expired gas volume and concentration signals were sampled continuously at 100 Hz, the latter using paramagnetic (O_2) and infrared (CO_2) analyzers (Jaeger Oxycon Pro, Hoechberg, Germany) via a capillary line connected to the mouthpiece. These analyzers were calibrated before each test with gases of known concentration, and the turbine volume transducer was calibrated using a 3-L syringe (Hans Rudolph, KS). The volume and concentration signals were time-aligned, accounting for the transit delay in capillary gas and analyzer rise time relative to the volume signal.

W'_{BAL} Modeling

The amount of W′ available at the start of F-3MT, which is assumed to be equal to the measured WEP during F-3MT, was estimated using three different equations, namely $W'_{BAL \cdot MORTON}$,, $W'_{BAL.INT}$ and $W'_{BAL \cdot ODE}$.

Morton and Billat (8) described W'_{REC} according to Equation 1 ($W'_{BAL \cdot MORTON}$):

$$W'_{BAL} = ((CP\text{-}P_r) * Tr) \quad [1]$$

where P_r and T_r are indicative of the power output and the duration of the recovery (<CP) period, respectively.

According to the $W'_{BAL.INT}$ model, the reconstitution of W'_{BAL} occurs exponentially, as given by the convolution integral in Equation 2 (31):

$$W'_{BAL-INT}(t) = W'_o - \int_0^t \left[e^{\frac{-(t-u)}{\tau_{W'}}} \right] W'_{EXP}(u)\, du \quad [2]$$

where,

$$W'_{EXP}(u) = \begin{cases} 0, \ P(u) \leq CP \\ \int (P(u) - CP) du, \quad P(u) > CP \end{cases} \quad [3]$$

where $W'_{BAL \cdot INT}(t)$ is the amount of W′ remaining at any given time (t), W'_o is the individual's known W′ as determined from C-3MT, W'_{EXP} represents the expended *W′, t* and *u* is the time in s spent recovering <CP, and $\tau_{W'}$ is the time constant of the reconstitution of the W′. $\tau_{W'}$ is calculated according to Equation 4 (8):

$$\tau_{W'} = 546 \cdot e^{(-0.01 D_{CP})} + 316 \quad [4]$$

The $W'_{BAL·ODE}$ model is bi-conditional, assuming linear kinetics for W′ expenditure, and exponential W′ recovery. W′ is expended at a rate equal to the difference between CP and P when P>CP. When P<CP, the model specifies that the rate of W′ reconstitution is proportional to the amount of W′ expended relative to W'_o and the difference in P between CP and P (9, 31).

$$\frac{dW'_{BAL.ODE}}{du} = \begin{cases} -(P(u) - CP), & P(u) > CP \\ \left(1 - \frac{W'_{BAL-ODE}}{W'_o}\right)(CP - P(u)), & CP > P(u) \end{cases} \quad [5]$$

The equation is solved piecewise for segments of the ergometer file where *P(u)* is constant. We then express the solutions to the equations as definite integrals from $u = t_a$ to $u = t_b$, where t_a and t_b are time points that bound the periods of constant P.

For the "adjusted" W'_{BAL} models (i.e., ADJ·$W'_{BAL·ODE}$; ADJ·$W'_{BAL·INT}$; ADJ·$W'_{BAL·MORTON}$), the F-3MT EP and F-3MT WEP were entered into the above equations, replacing the C-3MT EP and C-3MT WEP, at the completion of the C-3MT (i.e., T=181 s). Thus, the adjusted W'_{BAL} models accounted for the effect of fatigue on the parameter estimates of the power-duration relationship induced during C-3MT in their estimates of W'_{REC}.

Statistical Analyses

Differences in actual and predicted W'_{REC} derived with each model (i.e., $W'_{BAL·MORTON}$, $W'_{BAL·INT}$, $W'_{BAL·ODE}$) were assessed using analysis of variance (ANOVA) with repeated measures (RM), with significant differences examined used Bonferroni corrected post hoc *t*-tests. Paired samples *t*-tests and Bland-Altman analyses were used to assess differences and agreement between the actual and predicted W'_{REC}, respectively. Further paired samples *t*-tests were used to evaluate differences in peak power output, EP, WEP, total work done (TWD) and end-exercise $\dot{V}O_2$ gain between the C-3MT and F-3MT. These analyses were repeated for the adjusted W'_{BAL} models. Subsequently, separate RM ANOVAs were performed to assess for differences in actual W'_{REC} and the estimates of W'_{REC} provided by the conventional and adjusted W'_{BAL} models. Pearson's product moment correlation coefficients were used to assess relationships between the physiological and performance based parameters derived during the ramp incremental cycling test and C-3MT, and the changes in F-3MT relative to C-3MT (i.e., % decrease). All data are presented as mean ± SD. Statistical analyses were performed using SPSS version 22 (SPSS Inc., Chicago, Illinois, USA) with significance set at $P<0.05$.

Results

The $\dot{V}O_{2peak}$ measured in the ramp incremental test was 4.28 ± 0.57 $L\cdot min^{-1}$, with GET occurring at 1.96 ± 0.18 $L\cdot min^{-1}$. These values corresponded to work rates of 383 ± 48 W and 133 ± 16 W, respectively.

The group mean power output profiles for the C-3MT and F-3MT are displayed in Figure 1. The peak power output in the C-3MT, which was attained within 4.5 ± 0.8 s of the start of the test, was 989 ± 186 W (at 162 ± 10 rpm), and represented 257 ± 28% of the peak power output attained in the ramp incremental test. C-3MT EP was 282 ± 44 W (3.5 ± 0.4 $W\cdot kg^{-1}$). C-3MT WEP was 16.9 ± 3.2 kJ, and participants completed 67.7 ± 8.9 kJ of work in total. Following 60 s recovery, the peak power output during F-3MT (793 ± 178 W; 144 ± 13 rpm) was significantly lower than C-3MT ($P<0.001$; Figure 2A), but tended to be attained in a shorter period of time from the start of the test (3.6 ± 1.4 s; $P=0.07$). F-3MT EP was ~19 W lower (7%; 263 ± 40 W; $P<0.001$; Figure 2B) than C-3MT EP. F-3MT WEP (6.3 ± 1.4 kJ) was 61 ± 11% lower than in C-3MT ($P<0.001$; Figure 2C), thus participants recovered ~39% of their C-3MT WEP during the 60 s recovery period. The total work done during the F-3MT

(53.6 ± 7.6 kJ) was significantly lower than C-3MT (P<0.001; Figure 2D). The end-exercise $\dot{V}O_2$ gain was greater in the F-3MT (16.8 ± 1.7 ml·min^{-1}·W^{-1}) than the C-3MT (15.2 ± 1.1 ml·min^{-1}·W^{-1}, *P*<0.001).

The W'_{REC} (6.3 ± 1.4 kJ) was significantly overestimated by the $W'_{BAL \cdot ODE}$ (9.8 ± 1.3 kJ; *P*<0.001) and the $W'_{BAL \cdot MORTON}$ (16.9 ± 2.6 kJ; *P*<0.001) models, but was not significantly different to the estimate provided by the $W'_{BAL \cdot INT}$ model (7.5 ± 1.5 kJ; *P*>0.05). The estimates provided by each model were significantly different from one another (all *P*<0.001). W'_{REC} was not correlated with the values predicted by $W'_{BAL \cdot INT}$ (*r* = 0.10, Figure 3A), $W'_{BAL \cdot ODE}$ (*r* = 0.28, Figure 3B) or $W'_{BAL \cdot MORTON}$ (*r* = 0.36, Figure 3C), with a mean bias of -1.2 kJ (Figure 3D), -3.5 kJ (Figure 3E) and -10.6 kJ (Figure 3F), respectively.

Physiological indices indicative of aerobic performance determined during the ramp incremental test ($\dot{V}O_{2peak}$, peak power output, and work rate at GET) were significantly correlated with EP, TWD, and peak power output during the C-3MT and F-3MT (all *P*<0.05; Table 1). However, no significant correlations existed between any variables measured during the ramp incremental test and C-3MT WEP or F-3MT WEP (*P*>0.05; Table 1). No significant relationships were observed between the decrease in EP (absolute, W; relative, %) between the C-3MT and F-3MT and variables assessed during the ramp incremental test or the C-3MT (all *P*>0.05; Table 2). The decrease in peak power output (absolute, W) between the C-3MT and F-3MT was ~~inversely~~ related to C-3MT WEP (r=~~-~~0.66, *P*=0.02). The absolute (i.e., kJ) reduction in WEP between the C-3MT and F-3MT was ~~inversely~~ related to C-3MT WEP (r=~~-~~0.92; *P*<0.001). The error in the $W'_{BAL \cdot INT}$ and $W'_{BAL \cdot ODE}$ models was significantly correlated with the change in WEP between the C-3MT and F-3MT (Figure 4), i.e., a greater reduction in WEP between C-3MT and F-3MT was associated with a greater degree of predictive error when using the $W'_{BAL \cdot INT}$ and $W'_{BAL \cdot ODE}$ models. No significant relationships were observed between the error in the W'_{BAL} models and the reduction in EP (Figure 4).

The W'_{BAL} models were adjusted to account for the significant decrease observed in EP and WEP following the C-3MT. Following these adjustments, actual W'_{REC} was not significantly different to the ADJ·$W'_{BAL·INT}$ (7.5 ± 1.5 kJ) model, and these estimates were not different to the original $W'_{BAL·INT}$ (7.4 ± 1.5 kJ; $P>0.05$) model. The ADJ·$W'_{BAL·ODE}$ (5.3 ± 1.3 kJ) model significantly underestimated actual W'_{REC} ($P<0.001$), and the ADJ·$W'_{BAL·MORTON}$ (15.8 ± 2.4 kJ) model significantly overestimated actual W'_{REC} ($P<0.001$). W'_{REC} was significantly correlated with the predictions provided by ADJ·$W'_{BAL·ODE}$ ($r = 0.94$, Figure 5B) but not ADJ·$W'_{BAL·INT}$ ($r = 0.13$, Figure 5A) and ADJ·$W'_{BAL·MORTON}$ ($r = 0.20$, Figure 5C), with a mean bias of 1.0 kJ (Figure 5E), -1.2 kJ (Figure 5D), and -9.4 kJ (Figure 5F), respectively. The mean bias was significantly improved for the adjusted compared to the original (unadjusted) $W'_{BAL·ODE}$ and $W'_{BAL·MORTON}$ models (both $P<0.001$).

Discussion

The present study aimed to: 1) assess the accuracy with which the existing W'_{BAL} models estimate W'_{REC} following prior all-out sprint exercise that results in the complete utilization of W′; 2) determine the effects of prior all-out sprint exercise on the power-duration relationship; and thus 3) incorporate any changes to CP and W′ in the W'_{BAL} models and, subsequently evaluate the accuracy of W'_{REC} estimates. We therefore used a repeated 3MT protocol (2 x 3MT interspersed with 1-min recovery) to determine the actual W'_{REC} between work intervals based on the assumption that both the first (i.e., control, C-3MT) and second (i.e., fatigued, F-3MT) 3MT would result in the complete utilization of the available W′. This approach also enabled the appraisal of the power-duration relationship performed in a fresh state (i.e., C-3MT) and in the presence of fatigue (F-3MT), and enabled the EP and WEP values from the F-3MT to be entered into the W'_{BAL} models. The principal novel findings of this study were that: 1) W'_{REC} was significantly overestimated by the original (unadjusted) $W'_{BAL\cdot ODE}$ and $W'_{BAL\cdot MORTON}$ models, but not $W'_{BAL\cdot INT}$ model; 2) both EP and WEP were significantly reduced after prior all-out sprint exercise; and 3) accounting for the decrease in EP and WEP between the first and second tests significantly improved accuracy for the ADJ·$W'_{BAL\cdot ODE}$ and ADJ·$W'_{BAL\cdot MORTON}$ models, but not ADJ·$W'_{BAL\cdot INT}$ model.

The group mean actual W'_{REC} between work intervals was overestimated for the $W'_{BAL\cdot ODE}$ and $W'_{BAL\cdot MORTON}$ models by +3.5 kJ and +10.6kJ, respectively. Moreover, whilst the group mean W'_{BAL} estimated from the $W'_{BAL\cdot INT}$ model was not statistically different to actual W'_{REC}, the estimate was not correlated with the actual value with a mean bias of +1.2 kJ. The most accurate prediction for any participant, which was provided by the $W'_{BAL\cdot INT}$ model, overestimated W'_{REC} by ~0.7%. In stark contrast, the least accurate prediction for this individual, provided by the $W'_{BAL\cdot MORTON}$ model, overestimated W'_{REC} by ~126%. In addition to this considerable between-model variability, there was a substantial difference in the within-model accuracy, which ranged from -19% to 94% for the $W'_{BAL\cdot INT}$ model, 24% to 143% for the $W'_{BAL\cdot ODE}$ model, and 93% to 319% for the $W'_{BAL\cdot MORTON}$ model, highlighting concerns in their ability to provide accurate estimates for an individual-athlete. It is important to recognize that we applied the W'_{BAL} models as published (7-9, 31) and did not determine an individualized time constant for W'_{REC} (see “Experimental Considerations”) nor include a decay rate for CP. The considerable within-model variation highlights that the generalized equation used to describe the time constant for W'_{REC} provided a more accurate estimate of performance for some participants compared to others, an observation that is consistent with previous reports (13-15, 32, 33). However, unlike Bartram and colleagues (32) who proposed a modified time constant for W'_{REC} for use in highly trained cyclists, we found no relationships between the error in W'_{BAL} for any of the models and any variable assessed during the incremental test or the C-3MT. It is therefore not likely that the overestimation in

W'_{REC} in the current study was mediated by any effect of fitness on the time constant for W'_{REC}.

The assumed constancy of CP throughout exercise is a key tenet of the W'_{BAL} models, and is essential in defining both W′ expenditure and W'_{REC}. Previous investigations have shown that CP can be altered in line with changes in $\dot{V}O_2$ kinetics (34-40), and that it is also reduced during 2 h of heavy-intensity CWR exercise (17), but not following short-duration exhaustive severe-intensity CWR exercise (18). Despite evidence to demonstrate the plasticity of CP, prior to this study, the effects of prior all-out sprint exercise that exhausts W′ on 3MT performance had not been determined. In the current study, EP, WEP and TWD all declined in F-3MT. Specifically, there was a ~7% reduction in F-EP, which varied considerably between individuals (range: -13% to +1%), and a ~61% reduction (range: -44% to -77%) in F-WEP. Whilst the reduction in WEP in the F-3MT was expected given the complete utilization of W′ during the C-3MT and the short (1-min) recovery between work intervals, the reduction in EP following all-out sprint exercise is an important novel finding which, when viewed in light of our previous research, indicates that EP decreases with time during both continuous endurance exercise (17) and following all-out sprint exercise (current study). These changes in EP question the practice of estimating performance capacity from models which incorporate EP measured in a previously rested state and do not account for changes due to fatigue. Specifically, the observed reduction in EP during repeated all-out sprint exercise might necessitate a progressively greater W′ contribution during each work interval performed above EP, and thus result in the cessation of exercise sooner than predicted by the current W'_{BAL} models.

Several factors may contribute to the left-downward shift in the power-duration relationship following the C-3MT. We have previously reported that the decrease in EP (-9%) during heavy-intensity CWR exercise lasting 2 h is correlated with muscle glycogen depletion and the decrement in EP is ameliorated with carbohydrate feeding (17). However, whilst the reduction in muscle glycogen content may be an important and limiting factor implicated in the fatigue process(es) during prolonged endurance exercise, it is likely of less importance following the 3MT where muscle glycogen stores are not appreciably depleted (22). Instead, the accompanying exercise-induced reductions in muscle PCr and pH, and increases in P_i (22), are more likely responsible for the observed reductions in EP and WEP following C-3MT. The importance of PCr availability to initial and repeated all-out sprint performance is well documented (e.g., 41, 42), and its utilization during C-3MT would be expected to impair subsequent sprint performance and thus contribute to the observed reduction in WEP in the second test. The decrease in muscle pH, due to H^+ accumulation and the concomitant increase in P_i have been shown to impair excitation-contraction coupling (43-47) and would therefore be expected to increase the oxygen cost per watt of power produced. However, in the current study, we observed no relationships between the decreases in EP or WEP between the C-3MT and F-3MT and physiological performance variables assessed during the ramp incremental test or the C-3MT.

In contrast to the findings of the present study, Ferguson et al. (18) reported that exhaustive severe-intensity CWR exercise resulted in a reduction in W′ but no changes in CP. Given that a similar muscle metabolic perturbation is evident following all-out and work-matched CWR exercise performed to T_{lim} (22), it seems plausible that this discrepancy is due to differences in motor unit recruitment profiles. The recruitment of all available (task specific) motor units at the onset of all-out sprint exercise results in a greater muscle metabolic perturbation at a given iso-time compared to work- and time-matched CWR exercise (22), increasing the intensity and duration of muscle afferent feedback, accelerating the rate of central fatigue development and reducing central motor drive (48).

The factors underpinning the overestimation of W'_{REC} for the $W'_{BAL\cdot ODE}$ and $W'_{BAL\cdot MORTON}$ models and poor agreement between $W'_{BAL\cdot INT}$ and W'_{REC} in the present study may also be related to the amount and rate of W′ utilized within each work interval, variables that are not currently considered in the W'_{BAL} models. Indeed, investigations that have employed an intermittent protocol which results in complete (14, 15) or substantial (~50%) (13, 16) utilization of W′ in the first work interval have invariably reported inaccuracies when fitting the W'_{BAL} models to performance data. This is in contrast to studies that have utilized a much smaller proportion of W′ during each work interval (~10%), which have reported a close matching between actual performance and that predicted using the W'_{BAL} models (10-12). In addition, W'_{REC} has been shown to slow with repeated exhaustive intervals (15), and to depend on the rate of W′ utilization (14). Whilst the findings of the aforementioned studies, and those of the current investigation, highlight error in the W'_{BAL} models that appear linked to the magnitude and rate of W′ utilization, the putative mechanisms that underpin this phenomenon are unclear and require further attention.

The reduction in EP and WEP during the F-3MT compared to the C-3MT observed in the current study is not accounted for by the W'_{BAL} models and would therefore be expected to negatively impact their ability to estimate W'_{REC}. Indeed, the predictive accuracy of the $W'_{BAL\cdot INT}$ and $W'_{BAL\cdot ODE}$ models, but not $W'_{BAL\cdot MORTON}$ model, was significantly correlated with the change in WEP between the C-3MT and F-3MT. However, no significant correlations were found between changes in EP and the degree of error in the model predictions. Nevertheless, given that (changes in) EP dictates the power outputs corresponding to W′ expenditure and recovery, we considered it important to incorporate changes in both EP and WEP. Accordingly, we adjusted the W'_{BAL} models to include the F-3MT EP and WEP instead of the C-3MT EP and WEP. This adjustment had a varying influence on the accuracy of the W'_{BAL} models. Specifically, whilst the accuracy of the

ADJ·$W'_{BAL·ODE}$ (~67%) and ADJ·$W'_{BAL·MORTON}$ (~11%) models were significantly improved compared to their original form and, in the case of the ADJ·$W'_{BAL·ODE}$ there was a strong relationship (r=0.98) and a substantial improvement in the agreement between actual and estimated W'_{REC}. However, no improvements were observed for the ADJ·$W'_{BAL·INT}$ model compared to the original $W'_{BAL·INT}$ model. This lack of change for the $W'_{BAL·INT}$ model following adjustment for the changes in EP and WEP is explained in the calculation of the time constant (or tau) for W'_{REC} (see equation 4). Using the mean values for the C-3MT EP and F-3MT EP, the original model provides a tau of ~355 s whilst the tau for the adjusted model is ~364 s. This small change (~ 9 s, ~2.5%) in the tau between the original and adjusted $W'_{BAL·INT}$ model did not appreciably alter the group mean W'_{BAL}. In contrast, the tau for the $W'_{BAL·ODE}$ model was ~62% faster for the adjusted (~26 s) compared to the original (~65 s) model. It should also be noted, that despite a strong relationship between the actual and predicted W'_{REC} for the ADJ·$W'_{BAL·ODE}$ model, it continued to significantly underestimate (~17%) actual W'_{REC}. Similarly, the ADJ·$W'_{BAL·MORTON}$ model significantly overestimated (~259%) actual W'_{REC}. The basis for this observed error was not related to indices of cardiovascular fitness assessed during this study. Further research into the potentially multifactorial physiological underpinnings of W'_{REC}, and mathematical adjustments reflecting such physiological mechanisms to prediction equations, will be required to more accurately describe the plasticity of the power-duration parameters during fatiguing exercise.

Experimental considerations

Our results highlight important considerations in the application of the W'_{BAL} models. It should be appreciated that our findings are specific to the conditions of our study. The exercise protocol was designed to completely utilise W′ ‘all-out’ at its fastest possible rate and, following a brief (1-min) recovery, to again completely utilise W′ as rapidly as possible. This protocol is not typical of a pacing strategy utilised during competition or training but enabled us to test the limits of the W'_{BAL} models. The 1-min recovery duration was selected to ensure that recovery was incomplete but sufficient to enable participants to (re-)perform maximal exercise. Indeed, participants were able to attain and maintain $\dot{V}O_{2max}$ during the F-3MT and, thus, provide valid estimates for F-3MT EP and WEP. This exercise protocol enabled us to answer specific research questions, but our study was not designed to assess the constancy in the predictive error across different recovery durations, or determine how W'_{REC} might differ according to the work-rate forcing function (e.g. all-out vs. constant work rate exercise). How exercise and recovery durations, and/or work rate forcing functions might affect the accuracy of the W'_{BAL} models was beyond the scope of the present investigation.

A limitation of this study was the use of a generalized time constant for W'_{REC} in the $W'_{BAL.INT}$ trials. This approach has been questioned, with reports demonstrating that the W'_{REC} time constant is dependent on training status (32). Nevertheless, we decided to apply the W'_{BAL} models as published (7-9, 31), as we believe that this is the method most likely to be utilized by applied practitioners and athletes due to its comparative simplicity and "readiness" for use. Whilst the published time constant for W'_{REC} was derived from a group of participants of comparable training status to those of the present study (8), it was determined during exercise which utilized W′ to a differing extent and in a contrasting fashion to that of the current study. That we observed no significant relationship between the C-3MT WEP and F-3MT WEP highlights that W'_{REC} differs between individuals and provides further reason to abandon the use of a generalized time constant.

This study demonstrates that the $W'_{BAL\cdot INT}$ model provides estimates that are not different to actual W'_{REC} but displays relatively large limits of agreement. In contrast, the $ADJ\cdot W'_{BAL\cdot ODE}$ model has much better limits of agreement, despite providing estimates that are significantly different from actual W'_{REC}. In light of these findings, and, given that it is not feasible to assess changes in CP and W′ *during* athletic competition or training, we would encourage applied practitioners and athletes to consider employing the $W'_{BAL\cdot INT}$ model to objectively assess performance capabilities, at least following all-out sprint exercise.

Conclusions

The findings of this study demonstrates that the accuracy with which W'_{REC} is estimated following a 3-min all-out sprint cycling test differs according to the W'_{BAL} model. The original $W'_{BAL\cdot INT}$ model provided estimates that were not significantly different to actual W'_{REC}, whilst W'_{REC} was significantly overestimated by the original $W'_{BAL\cdot ODE}$ and.$W'_{BAL\cdot MORTON}$ models. We also report, for the first time, that EP and WEP, surrogates for CP and W′, respectively, are reduced following the C-3MT. Finally, we report that novel W'_{BAL} models that accounted for the observed reductions in EP and WEP improved the accuracy of the $W'_{BAL\cdot ODE}$ and $W'_{BAL\cdot MORTON}$ models, although these remained significantly different to actual W'_{REC}, but did not further enhance the accuracy of the $W'_{BAL\cdot INT}$ model. These results highlight that the $W'_{BAL\cdot INT}$ model provides superior estimates of W'_{REC}, at least following all-out sprint exercise. However, despite a strong relationship between actual and predicted W'_{REC}, the limits of agreement for the original and adjusted $W'_{BAL\cdot INT}$ model may limit its practical utility. These results have important implications for the design and use of mathematical models describing the energetics of exercise performance. Further work is necessary to resolve the factors that determine the durability of CP, and the mechanisms that underpin W'_{REC}.

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American College of Sports Medicine. The results of the study are presented clearly, honestly, and without fabrication, falsification, or inappropriate data manipulation.

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Figure Captions

Figure 1 Group mean power profiles for the 3-min all-out test during the control (i.e., C-3MT; open circles) and fatigued (F-3MT, grey circles) conditions. *SD* is displayed every 10 s and is indicated for the C-3MT and F-3MT using positive and negative error bars, respectively.

Figure 2 Group mean end power (EP; A), work above EP (WEP; B), peak power output, (PPO; C), and total work done (TWD; D), during the 3-min all-out test for the control (i.e., rested, C-3MT) and fatigued (F-3MT) conditions. *Dashed lines* represent individual responses. *Significantly different from C-3MT condition (P<0.001).

Figure 3 Bland-Altman plots of the relationship (A, B, C) and the limits of agreement (D, E, F) between the actual and predicted WEP during F-3MT using the integral (A and D), differential (B and E) and Morton (C and F) models. A, B, C, the line of origin (solid line) is presented. D, E, F the mean difference (solid line) and the limits of agreement (dashed line) are provided.

Figure 4 Scatterplots of the correlation between the change in EP (A, B, C) and WEP (D, E, F) between the control (i.e., rested, C-3MT) and fatigued (F-3MT) 3MT and the accuracy (i.e., actual W'_{REC} minus predicted W'_{REC}) for the $W'_{BAL\cdot INT}$ (A and C), $W'_{BAL\cdot ODE}$ (B and E), $W'_{BAL\cdot MORTON}$ (C and F) models. The correlation coefficient for each W'_{BAL} model is provided in the respective panel. *P<0.001. For clarity, a negative change in EP and WEP is indicative of a reduction (i.e., F-3MT *minus* C-3MT), whilst the size of the predictive error is directionless.

Figure 5 Bland-Altman plots of the relationship (A-C) and the limits of agreement (D-F) between the actual and predicted WEP during F-3MT using the adjusted $W'_{BAL\cdot INT}$ (A and D), adjusted $W'_{BAL\cdot ODE}$ (B and E), $W'_{BAL\cdot MORTON}$ (C and F) models. A-C, the line of origin (solid line) is presented. D-F, the mean difference (solid line) and the limits of agreement (dashed line) are provided.