The relationship between neuromuscular function and the W' in elite cyclists

Original article

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Abstract

Purpose: The aim of the study was to assess the association between the (W prime) W′ and measures of neuromuscular function relating to the capacity of skeletal muscle to produce force in a group of elite cyclists. Methods: Twenty-two athletes specialising in a range of disciplines and competing internationally volunteered to participate. Athletes completed assessments of maximum voluntary torque (MVT), voluntary activation (VA), and isometric maximum voluntary contraction (MVC) to measure rate of torque development (RTD). This was followed by assessment of peak power output (PPO), and 3-, 5- and 12-minute time trials to determine critical power (CP). Pearson's correlation was used to examine associations with CP and W'. Goodness-of-fit was calculated, and significant relationships were included in a linear step-wise regression model. Results: Significant positive relationships were evident between W′ and MVT ($r = 0.82$), and PPO ($r = 0.70$), and RTD_{200} ($r = 0.59$), but not with RTD_{50} and VA. Correlations were also observed between CP and RTD_{200} and MVT ($r = 0.54$, and $r = 0.51$, respectively), but not with PPO, VA or RTD_{50}. The regression analysis found 87% of the variability in W′ ($F_{1, 18} = 68.75$; $p < 0.001$) was explained by two variables: MVT (81%) and PPO (6%). Conclusions: It is likely that muscle size and strength, as opposed to neural factors, contribute meaningfully to W'. These data can be used to establish training methods to enhance W' in order to improve cycling performance in well trained athletes.

Key words. Elite athletes, power-duration, muscle strength, critical power, neuromuscular

Introduction

The duration of elite level cycling events can range from <10 s (200 m time-trial [TT] on the track) whilst mountain bike events last ~90 min and grand tour stages as long as 6 hours. In addition, the intensity and duration of the majority of competitive TT cycling events align closely with the extreme- and severe-intensity domains of the power-duration (P-D) relationship. [1] The P-D relationship describes how the tolerable duration of an event is related to its intensity in a hyperbolic manner; the asymptote represents the critical power (CP), and the curvature constant is termed (W prime) W′. [1–3] The CP represents the upper limit for exercise supported by aerobic metabolism, and the W' quantifies the finite amount of work that the athlete could complete above CP. As W' is finite, it contributes relatively more to the work done, and thus performance, as the event duration shortens. [3] Indeed, when W′ is compromised, even in the face of an elevated CP, exercise performance at the 'top-end' of the severe-intensity domain is lowered. [4] Understanding the determinants of W′ is therefore of importance to the performance of elite track cyclists, as the short duration of such events means the W′ could be decisive.

While the mechanisms relating to CP are increasingly well understood [3,4] and relate to multiple aspects of oxidative physiology, the physiology underpinning W′ is not as well elucidated. [5,6] The W′ was historically considered an anaerobic energy store comprising of phosphocreatine (PCr), muscle glycogen and myoglobin-bond O_2. [3,7] However, a number of observations do not support this premise. For example, the W' is altered with manipulations in oxygen availability; being increased in hypoxia [8] and under blood flow occlusion. [9] Furthermore, there is an association between the oxygen uptake ($\dot{V}O_2$) slow component amplitude and the magnitude of the W′ [10] suggesting the W′ is not simply 'anaerobic', but rather, along with CP, is part of a complex, integrated bioenergetic system. [3] Once considered as an energy store to be 'used up' when exercising above CP, this viewpoint has been reconsidered, whereby W′ is considered to be a reservoir that might be 'filled up' with fatigue-implicated metabolites. [11] This viewpoint is partly supported by observation that the W′ relates closely to a specific limit to metabolite accumulation (e.g. ADP, P_i & H^+) within the exercising muscle, [4,11] and that a greater degree of peripheral disturbance is associated with a higher W′. [12]

Recent work in the determinants of W′ indicates the size and function of the involved skeletal muscle are potentially influential. [5,6,13] Quadricep muscle cross sectional area, [6] mineral-free thigh mass [13] and thigh muscle volume [5] have all shown positive associations with the magnitude of W′, though there is partly contrasting evidence demonstrating no association between type-II fibre proportion and W′. [4,14] More recently, the W′ of elite track cyclists has been associated with maximal voluntary force, [5] and there is evidence suggesting that strength training can elicit positive improvements in W′. [15–17] These findings could suggest that indices of neuromuscular function could be positively related to the W′, [18,19] but the neuromuscular determinants of the W′ are not well-understood.

Accordingly, we hypothesised that W′ would be strongly correlated with indices of maximal muscle performance, such as MVT and PPO; therefore, the aim of the study was to assess the association between the W′ and measures of neuromuscular function relating to the capacity of skeletal muscle to produce force. A better understanding of the association between W′ and a range of neuromuscular function measures could provide new information for future work that aims to increase W′, and inform training practices of athletes, such as track sprint cyclists, where the magnitude of W′ could be a determining factor of athletic success.,

Methods

Participants

Following institutional ethical approval from Northumbria University Research Ethics Committee, 22 elite cyclists (17 men, 5 women, age, 23 ± 3 yr; mass 72.3 ± 9.2 kg, stature 169.8 ± 10.0 cm) gave written informed consent to participate in this study. The cyclists specialised in a range of disciplines (4 tandem sprinters: 2 men and 2 women; 13 track endurance: 10 men and 3 women; 4 mountain bikers: 2 men and 2 women: 1 men's road rider) and, with the exception of the road rider (who competed as an elite category domestic road rider), each participant was competing internationally at either under-23 level and/or senior level at the time of participation. At the time of data collection, the cohort included three current Olympic gold medallists and world record holders from the team pursuit, four current world record holders and world champions in the tandem 200 and 1,000 m TT, and numerous medallists at World Championship, European, and World Cup level events.

Experimental Protocol

Participants visited the National Cycling Centre (Manchester, UK) on three separate occasions where all parts of the assessment were performed. All were asked to refrain from strenuous exercise in the preceding 24 h. The first occasion was an in-depth familiarisation session to allow the participants to become accustomed to the different isometric knee extension procedures (i.e. maximal voluntary torque [MVT], rate of torque development [RTD] and voluntary activation [VA]). The two subsequent visits were experimental sessions, completed in successive days 2 – 7 days after familiarisation. The first experimental session was split into two parts: the AM and PM session. In the AM session, the following neuromuscular assessments were performed on the knee extensors of each leg (quadriceps femoris): (a) isometric maximal voluntary contractions (MVCs) to measure MVT (b) VA and (c) explosive isometric MVCs to measure RTD. The subsequent PM session and the visit in the following day solely entailed of the "on-bike" assessments. In the PM session, the assessments were (d) two peak power output (PPO) efforts (e) a 3-min fixed-duration time trial (TT) and (f) a 12-min TT. The final experimental session took place the following day and consisted of only (g) a 5-min fixed duration TT. Participants were already fully familiarised with all the on-bike measures, having completed all fixed-duration time trials at least twice previously. The effect of familiarisation on the power–duration parameter when using this testing protocol has been published previously. [20] All experimental procedures were conducted by experienced doctoral-level researchers and practitioners (MK, LPS, CM, TMW) that were well-versed in the specific techniques.

Isometric Dynamometry

The use of a custom-built isometric dynamometer and the specific protocol used to measure MVT, RTD and VA during knee extension is detailed elsewhere. [21] Briefly, the riders were positioned in a custom-built dynamometer with hip and knee joint angles at 125° and 115°, respectively. A calibrated S-beam strain gauge (Force Logic, Swallowfield, UK) attached securely to the lower leg (~15% of tibial length above the medial malleolus) was used to measure knee extension force. The analogue force signal from the strain gauge was amplified (×370) and sampled (2,000 Hz) using an external analogue-to-digital converter (Micro 1401; CED, Cambridge, UK) and recorded with Spike2 computer software (v7, CED, Cambridge, UK). Force data were gravity corrected and then torque was calculated by multiplying by distance between the knee joint space and the location of the strain gauge.

Maximum Voluntary Torque (MVT)

Following a brief warm-up (three, 3 s contractions at 50, 75 and 90% (×1) of perceived maximum), participants performed 3-4 MVCs and were instructed to ‘push as hard as possible’ (knee extension) interspersed with ≥60 s rest. Torque was presented on a computer screen placed in front of participants and a horizontal cursor indicating the greatest torque obtained within the session was displayed for biofeedback purposes; strong verbal encouragement was provided during all MVCs. The highest instantaneous torque recorded was defined as MVT.

Voluntary Activation (VA)

The capacity to activate the knee extensor muscles during isometric contractions was assessed using the interpolated twitch technique. [22] The procedure was fully explained, and the participants were slowly accustomed to the electrical stimulation. Single electrical stimuli (200 μs duration) were delivered to the femoral nerve via 100 mm disposable self-adhesive surface electrodes (CF5000, Digitimer Ltd., Welwyn Garden City, Hertfordshire, UK), connected to a constant-current stimulator (DS7AH, Digitimer Ltd., Welwyn Garden City, Hertfordshire, UK). The anode was placed midway between the iliac crest and the greater trochanter, and the cathode was placed high in the femoral triangle, over the femoral nerve. Stimulations commenced at a current of 50 mA and were incremented by 25 mA until a plateau in twitch force was observed; to ensure the stimulus was supramaximal the resulting current intensity was increased by 30% for all subsequent stimulations (mean intensity 344 ± 35 mA). Participants were asked to complete a further 2 MVCs during which electrical stimuli were delivered at the plateau in maximum force for assessment of the superimposed twitch force, and 2 s post to the relaxed muscle for assessment of quadriceps potentiated twitch force ($Q_{tw.pot}$). Subsequently, voluntary activation (%, VA) was calculated as:

$$\textbf{Voluntary activation} = 100 * (1 - t/T) \quad \text{[Eq. 1]}$$

Where t is the amplitude of the superimposed twitch (i.e. the size of the additional peak) and T the value of the resting twitch.

Rate of Torque Development (RTD)

Following familiarisation, participants performed a series of 10 contractions, each separated by 15 s, with instructions to extend their knee ‘as fast and as hard as possible’ for 1 s from a relaxed state upon hearing an auditory signal. Contractions involving a visible countermovement or pre-tension were discarded and another attempt was made. To indicate if a countermovement or pre-tension had occurred, resting torque was displayed using a sensitive scale in the preceding 300 ms. During each contraction participants were required to exceed 80% MVT, which was depicted by an on-screen marker. To provide performance feedback and encourage participants to develop torque as fast as possible, the time taken to reach 80% MVT was shown after each contraction and the slope of the rising torque-time curve (10 ms time constant) was displayed throughout, with the peak slope of their best attempt indicated on-screen. The three best contractions were used for data analysis. Contraction onset, during both voluntary and single twitch contractions, was defined as the last trough before the torque signal permanently deflected away from the envelope of the baseline noise; identified via manual inspection using a systematic standard method by the same trained investigator, in accordance with previously published methods. [23] Manual onset detection is considered to provide greater accuracy and reliability than an automatic approach. [24] Absolute voluntary torque (averaged across the three best contractions) was quantified at 50 ms (RTD_{50}) and 200 ms (RTD_{200}) from contraction onset, as indicators of RTD.

Peak Power Output (PPO) and Power-Duration Assessment

Participants performed all the on-bike measures using their own racing bikes which were fitted with a power meter (Infocrank, Verve Cycling Pty, Australia) and attached to a stationary air-resistance direct drive trainer (LeMond Revolution 1.1, Minnesota, USA). The protocol and efforts were identical to those previously described. [20] Briefly, each "on bike" session commenced with a 20-min self-prescribed warm-up. Cyclists performed two to three, short (≤ 6 sec), maximal efforts from a starting cadence of approximately 60 RPM to achieve a measure of PPO. Upon a countdown from the investigator they performed a maximal sprint with the instructed objective to achieve a cadence "as high as possible, as quickly as possible". Passive and/or active rest (3 min) was allowed between each 'PPO effort'. Participants had the opportunity to change gears between PPO efforts, but not during the efforts. Once the PPO efforts was complete, 5-min of active and/or passive rest elapsed before a 3-min positively paced fixed-duration TT was performed. Subsequently, at least 40-min of passive and/or active rest was prescribed before the 12-min, fixed-duration TT effort was performed. The following day, the participants performed the same warm-up routine as the previous session and subsequently a 5-min fixed-duration TT effort was performed.

Data Capture and Analysis for Cycling assessments

Data was collected using ANT+ wireless cycling computers (Garmin International, Olathe, KS, USA). Once the warm-up was complete and prior to starting experimental data collection, the zero-offset of the power was set. All ANT+ data were recorded at a resolution of 1 Hz. Data were downloaded and viewed using desktop software (Golden Cheetah Training Software, goldencheetah.org) where the highest 1-s, 3-, 5-, and 12-min power output windows were identified. These data were extracted and CP and W′ were calculated using 3 different models; (1) the 2-parameter hyperbolic model [Eq. 2], (2) the linear work-time model [Eq. 3] and (3) the linear inverse time model [Eq. 4]. The model pertaining to the lowest total error (sum of CV for CP and W'), and therefore 'best individual fit' (BIF); [25] was selected for each participant.

$$t = W' / (P - CP) \quad [Eq. 2]$$

$$W = CP\,t + W' \quad [Eq. 3]$$

$$P = W' (1/t) + CP \quad [Eq. 4]$$

Where t is the duration of the TT (sec), P is the power output achieved (W) and W′ is the Work Done (kJ).

Statistical Analysis

All data were analysed using SPSS statistical software (IBM SPSS Inc., Chicago, IL.) or GraphPad Prism (v8, GraphPad Software, San Diego California, USA). Pearson's correlation was first used to examine the relationship between all measured neuromuscular parameters that were associated with both (1) CP and (2) W′. The following criteria were adopted to interpret the magnitude of the relationship between measures: <0.3 small, 0.3 to 0.5 moderate, >0.5 to 0.7 large, >0.7 to 0.9 very large, and >0.9 to 1.0 almost perfect. In addition, goodness-of-fit R^2 was also calculated to examine the proportion (percentage) of variance in the dependent variables explained by the independent variables. Significance was accepted as $p \leq 0.05$. All significant relationships were included in a linear step-wise regression model to examine whether any independent variables can significantly predict CP or W′.

Results

The mean (± SD) power-duration parameter estimates (CP & W′) are provided in Table 1, with a representative participant’s power-duration relationship summarised in Figure 1. Of the 22 participants, 7 declined to participate in, or did not complete, the femoral twitch protocol (contractions were completed, but no twitch responses were administered/recorded for these athletes). Therefore, electrical stimulation parameters are reported for 15 participants. Correlation coefficient and coefficient of determination values for all neuromuscular measures in relation to CP and W′ are shown in Table 2 and Figure 2. Significant positive relationships were evident between W′ and MVT ($r = 0.82$; $p < 0.001$, $R^2 = 0.67$), PPO ($r = 0.70$; $p < 0.001$, $R^2 = 0.49$), and RTD_{200} ($r = 0.59$, $p = 0.004$, $R^2 = 0.35$), but not with RTD_{50} and VA. In addition, significant positive corelation were also found between CP and RTD_{200} and MVT ($r = 0.54$, $p = 0.009$, $R^2 = 0.29$ and $r = 0.51$; $p = 0.015$, $R^2 = 0.26$, respectively), but not with PPO, VA or RTD_{50}.

Subsequently, step-wise multiple regression analyses were performed using the three significant predictors from the bivariate correlations (MVT, PPO and RTD_{200}) to examine their combined relationship with W′. The regression analysis found 87% of the variability in W′ ($F_{1,18} = 68.75$; $p < 0.001$) was explained by two variables: MVT (81%) and PPO (6%).

Discussion

The aim of this study was to assess the relationship between measures of neuromuscular function and W’ in a population of elite cyclists. For the first time we demonstrate that W’ was strongly associated with both MVT and PPO in elite cyclists, which collectively explained 87% of the variance in W’. In contrast there was no association between VA and RTD_{50} with W′. In line with our hypothesis, this study and suggested that the strength of the knee extensors, and the capacity to produce high external mechanical power output, are likely contributors to W’, and possible targets for training interventions to improve this parameter.

Relationship of Neuromuscular Measures & W′

MVT was strongly associated with the W’, as was PPO, though the small amount of additional variance explained by PPO (6%) suggests that MVT and PPO predict a similar variance of W′. MVT could be a target of training programmes aimed at increasing W′, and indeed sprint cyclists commonly commit large portions of their training programmes to resistance exercise. There is evidence that increasing (lower extremity) muscle strength is effective at increasing PPO, in elite cyclists, [21] and resistance exercise has emerged as the only efficacious training methodology that might evoke an increase in the W′ [15] and severe-intensity exercise performance without affecting CP. [15,16] Previous work [26] in an elite population suggested that muscle volume and architecture are potentially important determinants of PPO in elite athletes. However, the biggest detectable determinant of PPO was quadriceps muscle volume, and to a lesser extent, muscle pennation angle. [26] Collectively, it would appear that the ability of the muscle(s) to exert a larger force is beneficial for PPO, W′ and presumably, very short-duration cycling performance.

There are many neural factors that influence maximal strength, including motor unit recruitment, firing frequency, and motor unit synchronisation. [18] Maximal VA, a measure of central and peripheral nervous system function, [27] is thought to represent the proportion of maximal motor unit recruitment and/or sub-optimal firing rates during a maximal contraction. [28] In this investigation, VA exhibited a weak relationship with W’ ($r = 0.09$, $p = 0.746$) suggesting that either VA is not a sensitive measure to ascertain a relationship with W′, or that any neural mechanism that influences W′, is not detectable with VA in this population of elite cyclists. The capacity to produce a high amount of force is clearly a more important determinant of W′ than the ability to activate a large proportion of the available maximum force.

In the absence of fatigue, this study demonstrated an association of CP between RTD_{200} and MVT (Table 2: r = 0.54; r = 0.51, respectively). The lack of an association of RTD_{50} suggests that the early component of RTD, that is thought to be primarily governed by neural factors, is of little importance in the context of CP. However, RTD_{200}, which is heavily influenced by the maximum force generating capacity of the muscle, [19] had a greater association on CP. Previous work examined the response to exhaustive cycling exercise within the severe-intensity domain and showed those who had a higher CP, experienced a smaller decrease in MVT post-exercise; [29]; collectively, this suggests that maximum force capability could be an important factor for determining performance in endurance athletes. Additionally, the current study showed that MVT was positively correlated (r = 0.82) with W′. Previously, research has also showed that individuals with the largest W′, experienced the greatest change in MVT following severe-intensity exercise to the limit of tolerance in a single-muscle (group) exercise. [12] Furthermore, the magnitude of W′ has previously been linked to MVT albeit in a smaller cohort (n = 11); [5] Knee extensor MVT is a strong predictor of cycling W′ and its relationship with CP suggests MVT might also be a determining factor for high level endurance performance.

Power-duration Variation and Error

To the best of the authors’ knowledge, we report the error for CP & W′ parameters (Table 1) for the first time in a large cohort of elite cyclists. Using the best individual fit for each participant [Eq. 2 – 4], CP SEE was 2 ± 2 W (0.7 ± 0.6%) and W′ SEE was 1.51 ± 1.34 kJ (6.1 ± 4.5%). Compared with the typically ‘accepted’ CV of <5 and <10% for CP and W′, respectively, [30] we attribute these very low error values to a group of well-familiarised participants. [20] The cyclists who participated in this work all had undergone power-duration assessments on numerous occasions as part of their routine athlete monitoring, and therefore had extensive prior experience of both what was expected of them, and what to expect of the fixed-time TTs. This is an important aspect to highlight because it suggests these assessments show a high degree of sensitivity in an elite cycling cohort, and hence only small detectable changes are necessary to show meaningful physiological differences.

This investigation is not without limitations; it would have been useful to measure muscle volume and architecture to understand if these factors contribute to W′. Additionally, the study was cross-sectional in nature and whilst strong associations and predictors of W′ were identified, a “cause-effect” relationship cannot be established, and thus any speculation about training-induced changes should be interpreted with caution. Future work could examine changes in these measures (i.e., measures such as muscle size and architecture) and W′, to capture changes across a season or as a result of a specific training intervention. Finally, this research did not aim to investigate sex differences, however the cohort used was a mixed sex group of elite athletes. Amidst a great deal of discussion in the literature regarding sex differences and performance the females in this study were generally less powerful and strong, but W’ was similar to men and did not deviate from the trends in data (Figure 2). Future research could re-explore this work in females or indeed to understand more fully possible sex differences in these performance parameters.

Practical Applications

In the first instance, these data describe important physiological components of performance in a cohort of elite cyclists and allows practitioners, coaches and athletes decisions on parameters in their own environments. Importantly, determining CP and hence W′ (an important factor in elite cycling performance across a range of disciplines), can be time consuming and onerous to perform for athletes in applied scenarios. These data show that two simple measures, namely MVT and PPO, collectively contribute to W′ estimations. These data can be used as a platform for practitioners, coaches and athletes wishing to establish training methods to enhance W′ in order to improve cycling performance in well trained athletes.

Conclusion

In conclusion, W′ is predominantly explained by MVT and PPO. We also show a lack of association between W' and RTD_{50} and VA. The fact that MVT and PPO have previously been shown to be highly influenced by muscle morphology (particularly muscle size) and that MVT and PPO are strong predictors of W' it is likely muscle size and strength, as opposed to fibre type and neural factors, contribute meaningfully to W′.

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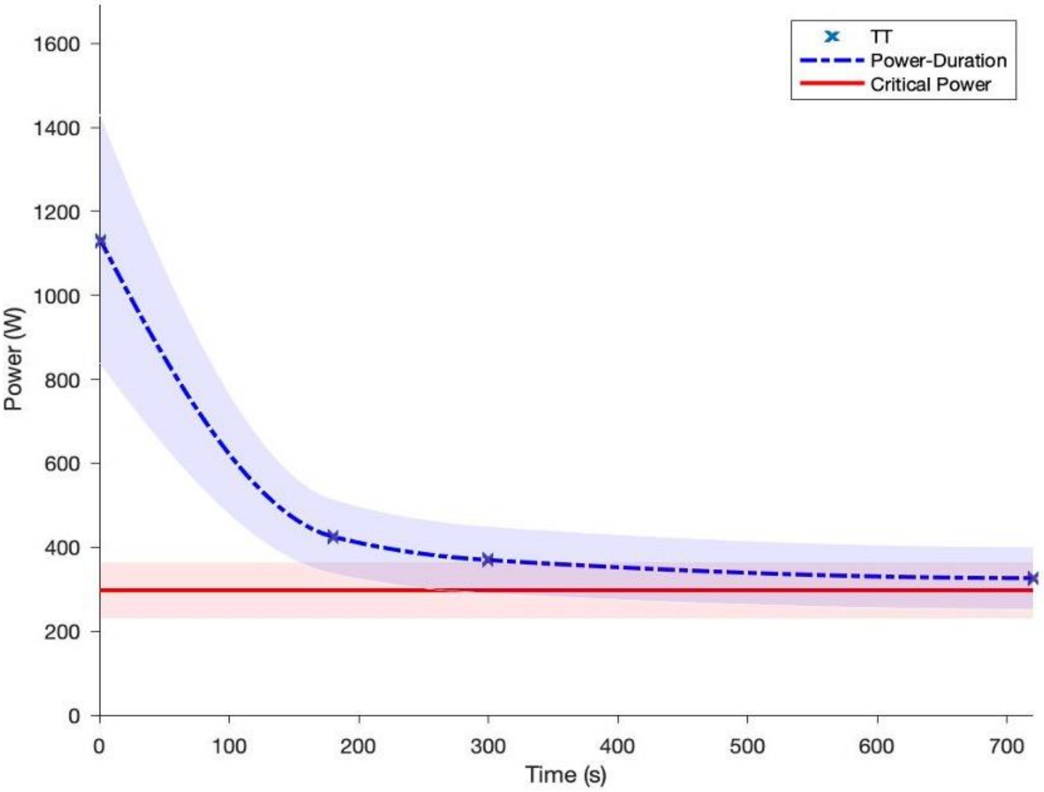

Figure 1: The average power-duration relationship (blue dotted line) in conjunction with the critical power represented by the solid red line of all the riders. The shaded areas of the respective lines represent standard deviation; the crosses denote each measurement point (1, 180, 300 and 720 s). Model parameter values showed mean R^2 was 0.9986 ± 0.0016 with total error of 6.9 ± 5.1%. SEE for CP and W' was 2.3 W and 1,510 J, respectively.

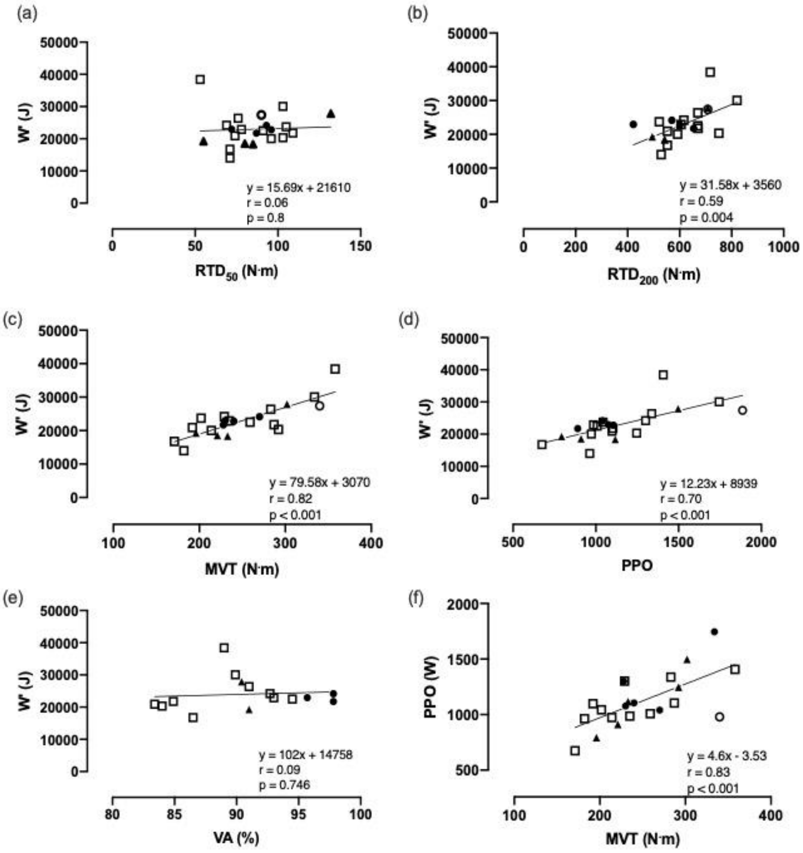

Figure 2: Relationships of W′ with: (a) rate of torque development of knee extensors at 50 ms (RTD$_{50}$); (b) rate of torque development of knee extensors at 200 ms (RTD$_{200}$); (c) maximum voluntary torque of the knee extensors (MVT); (d) peak power output (PPO); and (e) Voluntary activation of knee extensors (VA). In addition, (f) which represents the relationship between PPO and MVT. Closed squares denotes men's track endurance riders; closed circles denotes men's track sprinters; closed triangle denotes men's mountain bikers; closed diamond denotes men's road rider; open squares denotes women's track endurance riders; open circles denotes women's track sprinters; open triangle denotes women's mountain bikers.

Table 1: Mean (±SD) values of CP and W′ accompanied by respective error values which include standard error of estimate (SEE), coefficient of variation (CV) and confidence intervals (CI).

	Mean ± SD	Mean SEE ± SD	Mean CV (%) ± SD	95% CI ± SD
CP (W)	296 ± 72	2 ± 2	0.7 ± 0.6	29 ± 26
W′ (kJ)	22.96 ± 5.09	1.51 ± 1.34	6.1 ± 4.5	19.20 ± 17.03

Table 2: The Pearson's coefficient correlation (r), goodness-of-fit (R^2) and significance (p-value) of all neuromuscular parameters with W' and CP.

Parameter	r	R^2	p-value
W'			
RTD_{50}	0.14	0.02	0.534
RTD_{200}	0.54	0.30	0.009
MVT	0.82	0.67	<0.001
PPO	0.72	0.52	<0.001
VA	0.36	0.13	0.187
CP			
RTD_{50}	0.40	0.16	0.065
RTD_{200}	0.54	0.29	0.009
MVT	0.51	0.26	0.015
PPO	0.38	0.14	0.081
VA	−0.03	0.001	0.915

Critical Power (CP); Rate of Torque Development at 50 ms (RTD_{50}) and 200 ms (RTD_{200}); maximal voluntary torque (MVT); Peak Power Output (PPO); voluntary activation (VA).