

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

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

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3   **Original article**

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38 **Abstract**

39 Purpose: The aim of the study was to assess the association between the (W prime) W' and  
40 measures of neuromuscular function relating to the capacity of skeletal muscle to produce force  
41 in a group of elite cyclists. Methods: Twenty-two athletes specialising in a range of disciplines  
42 and competing internationally volunteered to participate. Athletes completed assessments of  
43 maximum voluntary torque (MVT), voluntary activation (VA), and isometric maximum  
44 voluntary contraction (MVC) to measure rate of torque development (RTD). This was  
45 followed by assessment of peak power output (PPO), and 3-, 5- and 12-minute time trials to  
46 determine critical power (CP). Pearson's correlation was used to examine associations with  
47 CP and W'. Goodness-of-fit was calculated, and significant relationships were included in a  
48 linear step-wise regression model. Results: Significant positive relationships were evident  
49 between W' and MVT ( $r = 0.82$ ), and PPO ( $r = 0.70$ ), and RTD<sub>200</sub> ( $r = 0.59$ ), but not with RTD<sub>50</sub>  
50 and VA. Correlations were also observed between CP and RTD<sub>200</sub> and MVT ( $r = 0.54$ , and  $r$   
51  $= 0.51$ , respectively), but not with PPO, VA or RTD<sub>50</sub>. The regression analysis found 87% of  
52 the variability in W' ( $F_{1, 18} = 68.75$ ;  $p < 0.001$ ) was explained by two variables: MVT (81%)  
53 and PPO (6%). Conclusions: It is likely that muscle size and strength, as opposed to neural  
54 factors, contribute meaningfully to W'. These data can be used to establish training methods to  
55 enhance W' in order to improve cycling performance in well trained athletes.

56

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

58

59 **Introduction**

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

74  
75 While the mechanisms relating to CP are increasingly well understood <sup>3,4</sup> and relate to multiple  
76 aspects of oxidative physiology, the physiology underpinning W' is not as well elucidated. <sup>5,6</sup>  
77 The W' was historically considered an anaerobic energy store comprising of phosphocreatine  
78 (PCr), muscle glycogen and myoglobin-bound O<sub>2</sub>. <sup>3,7</sup> However, a number of observations do not  
79 support this premise. For example, the W' is altered with manipulations in oxygen availability;  
80 being increased in hypoxia <sup>8</sup> and under blood flow occlusion. <sup>9</sup> Furthermore, there is an  
81 association between the oxygen uptake ( $\dot{V}O_2$ ) slow component amplitude and the magnitude  
82 of the W' <sup>10</sup> suggesting the W' is not simply 'anaerobic', but rather, along with CP, is part of a  
83 complex, integrated bioenergetic system. <sup>3</sup> Once considered as an energy store to be 'used up'  
84 when exercising above CP, this viewpoint has been reconsidered, whereby W' is considered to  
85 be a reservoir that might be 'filled up' with fatigue-implicated metabolites. <sup>11</sup> This viewpoint  
86 is partly supported by observation that the W' relates closely to a specific limit to metabolite  
87 accumulation (e.g. ADP, P<sub>i</sub> & H<sup>+</sup>) within the exercising muscle, <sup>4,11</sup> and that a greater degree  
88 of peripheral disturbance is associated with a higher W'. <sup>12</sup>

89  
90 Recent work in the determinants of W' indicates the size and function of the involved skeletal  
91 muscle are potentially influential. <sup>5,6,13</sup> Quadriceps muscle cross sectional area, <sup>6</sup> mineral-free  
92 thigh mass <sup>13</sup> and thigh muscle volume <sup>5</sup> have all shown positive associations with the  
93 magnitude of W', though there is partly contrasting evidence demonstrating no association  
94 between type-II fibre proportion and W'. <sup>4,14</sup> More recently, the W' of elite track cyclists has  
95 been associated with maximal voluntary force, <sup>5</sup> and there is evidence suggesting that strength  
96 training can elicit positive improvements in W'. <sup>15-17</sup> These findings could suggest that indices  
97 of neuromuscular function could be positively related to the W', <sup>18,19</sup> but the neuromuscular  
98 determinants of the W' are not well-understood.

99  
100 Accordingly, we hypothesised that W' would be strongly correlated with indices of maximal  
101 muscle performance, such as MVT and PPO; therefore, the aim of the study was to assess the  
102 association between the W' and measures of neuromuscular function relating to the capacity  
103 of skeletal muscle to produce force. A better understanding of the association between W'  
104 and a range of neuromuscular function measures could provide new information for future  
105 work that aims to increase W', and inform training practices of athletes, such as track sprint  
106 cyclists, where the magnitude of W' could be a determining factor of athletic success.,

107 **Methods**

108 *Participants*

109 Following institutional ethical approval from Northumbria University Research Ethics  
110 Committee, 22 elite cyclists (17 men, 5 women, age,  $23 \pm 3$  yr; mass  $72.3 \pm 9.2$  kg, stature  
111  $169.8 \pm 10.0$  cm) gave written informed consent to participate in this study. The cyclists  
112 specialised in a range of disciplines (4 tandem sprinters: 2 men and 2 women; 13 track  
113 endurance: 10 men and 3 women; 4 mountain bikers: 2 men and 2 women: 1 men's road rider)  
114 and, with the exception of the road rider (who competed as an elite category domestic road  
115 rider), each participant was competing internationally at either under-23 level and/or senior  
116 level at the time of participation. At the time of data collection, the cohort included three current  
117 Olympic gold medallists and world record holders from the team pursuit, four current world  
118 record holders and world champions in the tandem 200 and 1,000 m TT, and numerous  
119 medallists at World Championship, European, and World Cup level events.

120

121 *Experimental Protocol*

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

142

143 *Isometric Dynamometry*

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

154

155

156

157 *Maximum Voluntary Torque (MVT)*

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

164

165 *Voluntary Activation (VA)*

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

181

182 **Voluntary activation =  $100 * (1 - t/T)$  [Eq. 1]**

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

185

186 *Rate of Torque Development (RTD)*

187 Following familiarisation, participants performed a series of 10 contractions, each separated  
188 by 15 s, with instructions to extend their knee ‘as fast and as hard as possible’ for 1 s from a  
189 relaxed state upon hearing an auditory signal. Contractions involving a visible  
190 countermovement or pre-tension were discarded and another attempt was made. To indicate if  
191 a countermovement or pre-tension had occurred, resting torque was displayed using a sensitive  
192 scale in the preceding 300 ms. During each contraction participants were required to exceed  
193 80% MVT, which was depicted by an on-screen marker. To provide performance feedback and  
194 encourage participants to develop torque as fast as possible, the time taken to reach 80% MVT  
195 was shown after each contraction and the slope of the rising torque-time curve (10 ms time  
196 constant) was displayed throughout, with the peak slope of their best attempt indicated on-  
197 screen. The three best contractions were used for data analysis. Contraction onset, during both  
198 voluntary and single twitch contractions, was defined as the last trough before the torque signal  
199 permanently deflected away from the envelope of the baseline noise; identified via manual  
200 inspection using a systematic standard method by the same trained investigator, in accordance  
201 with previously published methods.<sup>23</sup> Manual onset detection is considered to provide greater  
202 accuracy and reliability than an automatic approach.<sup>24</sup> Absolute voluntary torque (averaged  
203 across the three best contractions) was quantified at 50 ms (RTD<sub>50</sub>) and 200 ms (RTD<sub>200</sub>) from  
204 contraction onset, as indicators of RTD.

205

206

207

### 208 *Peak Power Output (PPO) and Power-Duration Assessment*

209 Participants performed all the on-bike measures using their own racing bikes which were fitted  
210 with a power meter (Infocrank, Verve Cycling Pty, Australia) and attached to a stationary air-  
211 resistance direct drive trainer (LeMond Revolution 1.1, Minnesota, USA). The protocol and  
212 efforts were identical to those previously described.<sup>20</sup> Briefly, each “on bike” session  
213 commenced with a 20-min self-prescribed warm-up. Cyclists performed two to three, short ( $\leq$   
214 6 sec), maximal efforts from a starting cadence of approximately 60 RPM to achieve a measure  
215 of PPO. Upon a countdown from the investigator they performed a maximal sprint with the  
216 instructed objective to achieve a cadence “as high as possible, as quickly as possible”. Passive  
217 and/or active rest (3 min) was allowed between each ‘PPO effort’. Participants had the  
218 opportunity to change gears between PPO efforts, but not during the efforts. Once the PPO  
219 efforts was complete, 5-min of active and/or passive rest elapsed before a 3-min positively  
220 paced fixed-duration TT was performed. Subsequently, at least 40-min of passive and/or active  
221 rest was prescribed before the 12-min, fixed-duration TT effort was performed. The following  
222 day, the participants performed the same warm-up routine as the previous session and  
223 subsequently a 5-min fixed-duration TT effort was performed.

224

### 225 *Data Capture and Analysis for Cycling assessments*

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

236

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

237

$$W = CP t + W' \text{ [Eq. 3]}$$

238

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

239 Where t is the duration of the TT (sec), P is the power output achieved (W) and W' is the Work  
240 Done (kJ).

241

### 242 *Statistical Analysis*

243 All data were analysed using SPSS statistical software (IBM SPSS Inc., Chicago, IL.) or  
244 GraphPad Prism (v8, GraphPad Software, San Diego California, USA). Pearson’s correlation  
245 was first used to examine the relationship between all measured neuromuscular parameters that  
246 were associated with both (1) CP and (2) W'. The following criteria were adopted to interpret  
247 the magnitude of the relationship between measures: <0.3 small, 0.3 to 0.5 moderate, >0.5 to  
248 0.7 large, >0.7 to 0.9 very large, and >0.9 to 1.0 almost perfect. In addition, goodness-of-fit  
249 R<sup>2</sup> was also calculated to examine the proportion (percentage) of variance in the dependent  
250 variables explained by the independent variables. Significance was accepted as  $p \leq 0.05$ . All  
251 significant relationships were included in a linear step-wise regression model to examine  
252 whether any independent variables can significantly predict CP or W'.

253

254

255

## 256 **Results**

257 The mean ( $\pm$  SD) power-duration parameter estimates (CP &  $W'$ ) are provided in Table 1, with  
258 a representative participant's power-duration relationship summarised in Figure 1. Of the 22  
259 participants, 7 declined to participate in, or did not complete, the femoral twitch protocol  
260 (contractions were completed, but no twitch responses were administered/recorded for these  
261 athletes). Therefore, electrical stimulation parameters are reported for 15 participants.  
262 Correlation coefficient and coefficient of determination values for all neuromuscular measures  
263 in relation to CP and  $W'$  are shown in Table 2 and Figure 2. Significant positive relationships  
264 were evident between  $W'$  and MVT ( $r = 0.82$ ;  $p < 0.001$ ,  $R^2 = 0.67$ ), PPO ( $r = 0.70$ ;  $p < 0.001$ ,  
265  $R^2 = 0.49$ ), and  $RTD_{200}$  ( $r = 0.59$ ,  $p = 0.004$ ,  $R^2 = 0.35$ ), but not with  $RTD_{50}$  and VA. In  
266 addition, significant positive correlations were also found between CP and  $RTD_{200}$  and MVT ( $r$   
267  $= 0.54$ ,  $p = 0.009$ ,  $R^2 = 0.29$  and  $r = 0.51$ ;  $p = 0.015$ ,  $R^2 = 0.26$ , respectively), but not with PPO,  
268 VA or  $RTD_{50}$ .

269

270 Subsequently, step-wise multiple regression analyses were performed using the three  
271 significant predictors from the bivariate correlations (MVT, PPO and  $RTD_{200}$ ) to examine their  
272 combined relationship with  $W'$ . The regression analysis found 87% of the variability in  $W'$  ( $F_{1,18}$   
273  $= 68.75$ ;  $p < 0.001$ ) was explained by two variables: MVT (81%) and PPO (6%).

274

## 275 **Discussion**

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

283

### 284 *Relationship of Neuromuscular Measures & $W'$*

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

298

299 There are many neural factors that influence maximal strength, including motor unit  
300 recruitment, firing frequency, and motor unit synchronisation.<sup>18</sup> Maximal VA, a measure of  
301 central and peripheral nervous system function,<sup>27</sup> is thought to represent the proportion of  
302 maximal motor unit recruitment and/or sub-optimal firing rates during a maximal contraction.  
303<sup>28</sup> In this investigation, VA exhibited a weak relationship with  $W'$  ( $r = 0.09$ ,  $p = 0.746$ )  
304 suggesting that either VA is not a sensitive measure to ascertain a relationship with  $W'$ , or that



305 any neural mechanism that influences  $W'$ , is not detectable with VA in this population of elite  
306 cyclists. The capacity to produce a high amount of force is clearly a more important determinant  
307 of  $W'$  than the ability to activate a large proportion of the available maximum force.

308  
309 In the absence of fatigue, this study demonstrated an association of CP between  $RTD_{200}$  and  
310 MVT (Table 2:  $r = 0.54$ ;  $r = 0.51$ , respectively). The lack of an association of  $RTD_{50}$  suggests  
311 that the early component of RTD, that is thought to be primarily governed by neural factors, is  
312 of little importance in the context of CP. However,  $RTD_{200}$ , which is heavily influenced by the  
313 maximum force generating capacity of the muscle,<sup>19</sup> had a greater association on CP. Previous  
314 work examined the response to exhaustive cycling exercise within the severe-intensity domain  
315 and showed those who had a higher CP, experienced a smaller decrease in MVT post-exercise;  
316<sup>29</sup>; collectively, this suggests that maximum force capability could be an important factor for  
317 determining performance in endurance athletes. Additionally, the current study showed that  
318 MVT was positively correlated ( $r = 0.82$ ) with  $W'$ . Previously, research has also showed that  
319 individuals with the largest  $W'$ , experienced the greatest change in MVT following severe-  
320 intensity exercise to the limit of tolerance in a single-muscle (group) exercise.<sup>12</sup> Furthermore,  
321 the magnitude of  $W'$  has previously been linked to MVT albeit in a smaller cohort ( $n = 11$ );<sup>5</sup>  
322 Knee extensor MVT is a strong predictor of cycling  $W'$  and its relationship with CP suggests  
323 MVT might also be a determining factor for high level endurance performance.

#### 324 325 *Power-duration Variation and Error*

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

337  
338 This investigation is not without limitations; it would have been useful to measure muscle  
339 volume and architecture to understand if these factors contribute to  $W'$ . Additionally, the study  
340 was cross-sectional in nature and whilst strong associations and predictors of  $W'$  were  
341 identified, a "cause-effect" relationship cannot be established, and thus any speculation about  
342 training-induced changes should be interpreted with caution. Future work could examine  
343 changes in these measures (i.e., measures such as muscle size and architecture) and  $W'$ , to  
344 capture changes across a season or as a result of a specific training intervention. Finally, this  
345 research did not aim to investigate sex differences, however the cohort used was a mixed sex  
346 group of elite athletes. Amidst a great deal of discussion in the literature regarding sex  
347 differences and performance the females in this study were generally less powerful and strong,  
348 but  $W'$  was similar to men and did not deviate from the trends in data (Figure 2). Future  
349 research could re-explore this work in females or indeed to understand more fully possible sex  
350 differences in these performance parameters.

351  
352  
353

354 **Practical Applications**

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

363

364 **Conclusion**

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

370

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374

375 **References**

376

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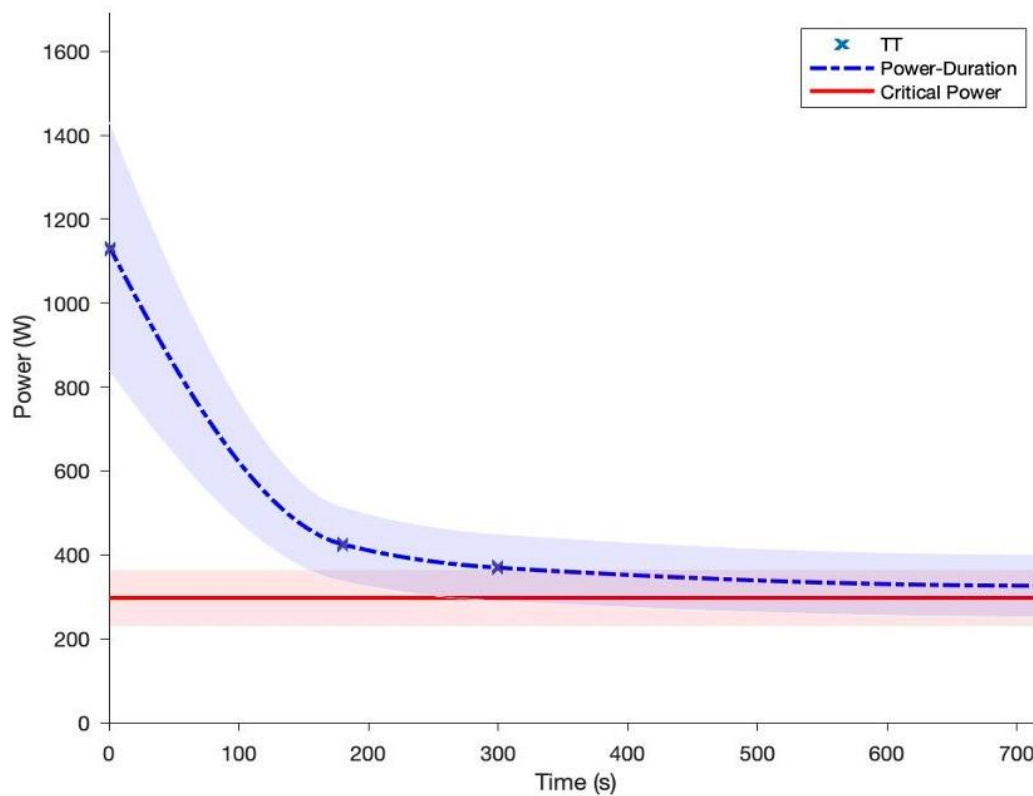
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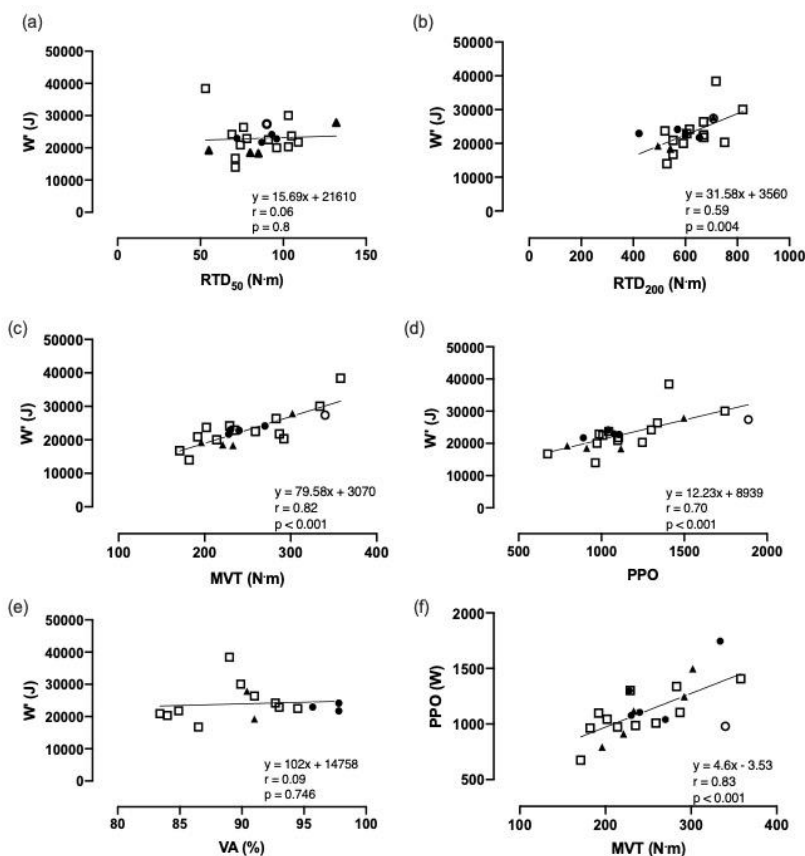
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 468 Figure 1: The average power-duration relationship (blue dotted line) in conjunction with the  
 469 critical power represented by the solid red line of all the riders. The shaded areas of the  
 470 respective lines represent standard deviation; the crosses denote each measurement point (1,  
 471 180, 300 and 720 s). Model parameter values showed mean  $R^2$  was  $0.9986 \pm 0.0016$  with total  
 472 error of  $6.9 \pm 5.1\%$ . SEE for CP and  $W'$  was 2.3 W and 1,510 J, respectively.  
 473



475  
 476 Figure 2: Relationships of  $W'$  with: (a) rate of torque development of knee extensors at 50 ms  
 477 ( $RTD_{50}$ ); (b) rate of torque development of knee extensors at 200 ms ( $RTD_{200}$ ); (c) maximum  
 478 voluntary torque of the knee extensors (MVT); (d) peak power output (PPO); and (e) Voluntary  
 479 activation of knee extensors (VA). In addition, (f) which represents the relationship between  
 480 PPO and MVT. Closed squares denotes men's track endurance riders; closed circles denotes  
 481 men's track sprinters; closed triangle denotes men's mountain bikers; closed diamond denotes  
 482 men's road rider; open squares denotes women's track endurance riders; open circles denotes  
 483 women's track sprinters; open triangle denotes women's mountain bikers.  
 484

485 Table 1: Mean ( $\pm$ SD) values of CP and W' accompanied by respective error values which  
 486 include standard error of estimate (SEE), coefficient of variation (CV) and confidence  
 487 intervals (CI).

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

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

Parameter	r	$R^2$	p-value
<b>W'</b>			
RTD <sub>50</sub>	0.14	0.02	0.534
RTD <sub>200</sub>	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
<b>CP</b>			
RTD <sub>50</sub>	0.40	0.16	0.065
RTD <sub>200</sub>	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

494 Critical Power (CP); Rate of Torque Development at 50 ms (RTD<sub>50</sub>) and 200 ms (RTD<sub>200</sub>);  
 495 maximal voluntary torque (MVT); Peak Power Output (PPO); voluntary activation (VA).  
 496