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COMPARISON OF INTER-TRIAL RECOVERY TIMES FOR THE DETERMINATION OF CRITICAL POWER AND W' IN CYCLING

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Manuscripts

1 **COMPARISON OF INTER-TRIAL RECOVERY TIMES FOR THE**

2 **DETERMINATION OF CRITICAL POWER AND W' IN CYCLING**

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4 **Running Head: Determination of Critical Power in a single session**

5

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25 **Abstract**

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27 Critical Power (CP) and W' are often determined using multi-day testing protocols. To

28 investigate this cumbersome testing method, the purpose of this study was to compare the

29 differences between the conventional use of a 24 h inter-trial recovery time with those of 3 h

30 and 30 min for the determination of CP and W'. Methods: Nine moderately trained cyclists

31 performed an incremental test to exhaustion to establish the power output associated with the

32 maximum oxygen uptake (p$\dot{V}O_{2\,max}$), and three protocols requiring time-to-exhaustion trials

33 at a constant work-rate performed at 80%, 100% and 105% of p$\dot{V}O_{2\,max.}$ Design: Protocol A

34 utilised 24 h inter-trial recovery (CP_{24}/W'_{24}), protocol B utilised 3 h inter-trial recovery

35 (CP_3/W'_3), and protocol C used 30 min inter-trial recovery period ($CP_{0.5}/W'_{0.5}$). CP and W'

36 were calculated using the inverse time (1/t) versus power (P) relation ($P = W'(1/t) + CP$).

37 Results: 95% Limits of Agreement between protocol A and B were -9 to 15 W; -7.4 to 7.8 kJ

38 (CP/W') and between protocol A and protocol C they were -27 to 22 W; -7.2 to 15.1 kJ

39 (CP/W'). Compared to criterion protocol A, the average prediction error of protocol B was

40 2.5% (CP) and 25.6% (W'), whilst for protocol C it was 3.7% (CP) and 32.9% (W').

41 Conclusion: 3 h and 30 min inter-trial recovery time protocols provide valid methods of

42 determining CP but not W' in cycling.

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49 **INTRODUCTION**

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51 Critical Power (CP), the maximum power that can be sustained without a progressive loss of

52 homeostasis, demarcates the heavy and the severe exercise domains (Jones, Vanhatalo,

53 Burnley, Morton, & Poole, 2010). CP is sensitive to changes in aerobic metabolism and is

54 therefore predictive of future performance (Jenkins & Quigley, 1990; Stickland, Petersen, &

55 Dressendorfer, 2000). Exceeding CP results in the utilisation of its related finite anaerobic

56 energy source, W', with the depletion rate of W' being proportional to the degree to which

57 power output (PO) exceeds CP. The determination of CP and W' has traditionally required an

58 incremental maximal exercise test to determine the power output associated with the

59 maximum oxygen uptake (p$\dot{V}O_{2\,max}$), followed by fixed intensity time to exhaustion (TTE)

60 trials at three or more predetermined work-rates. These trials generally require one or more

61 24 h inter-trial recovery period. Critical Power testing is therefore a multi-day process.

62

63 The time consuming and resource intensive process of CP testing would be more easily

64 incorporated into an athlete's training schedule if testing could be completed within one day.

65 A number of authors have therefore examined alternatives to multi-day methods by

66 employing inter-trial recovery periods from 30 min to 4 h (Barker, Bond, Toman, Williams, &

67 Armstrong, 2012; Brickley et al., 2007; Carter et al., 2005; Dekerle et al., 2009; Housh &

68 Terry, 1989). However, most of these investigations have failed to report direct comparisons

69 of their findings with the traditional 24 h recovery protocol. In running, Galbraith, Hopker, &

70 Lelliott (2014) recently demonstrated that a recovery period of 30 min in between exhaustive

71 trials is sufficient to determine Critical Velocity (analogous of CP) but not the Anaerobic

72 Running Distance (analogue of W') when compared against the conventional 24 h recovery

73 testing method. In cycling only, Bishop and Jenkins (1995) also directly compared protocols

3

74 utilising 24 h and 3 h recovery periods in untrained participants, and reported no significant

75 differences between estimates of CP and *W'* derived from each.

76

77 It is questionable whether a reduced recovery time allows for full *W'* restoration (Ferguson et

78 al., 2010), whilst shorter intra-trial times can result in 'primed' $\dot{V}O_2$ kinetics and

79 performance enhancements (Bailey et al., 2009). Providing a 20-min intra-trial recovery,

80 Bailey et al. (2009) demonstrated a significant increase in exercise tolerance during a

81 subsequent 2nd bout of severe exercise due to a priming of the kinetic response. However, this

82 shorter recovery between repeated bouts of heavy intensity exercise to exhaustion are

83 associated with elevated fatigue-related muscle metabolites, such as inorganic phosphate

84 molecules, hydrogen and potassium ions (Westerblad, Allen, & Lännergren, 2002).

85 Therefore, deciding on a shortest possible inter-trial recovery period, which allows a full

86 recovery of *W'* whilst avoiding either a detrimental or a performance enhancing effect, is

87 challenging.

88

89 Whilst previous work has made some progress in investigating brief CP testing, the variety of

90 modes of exercise, level of participant and recovery periods leave several questions

91 unanswered. Arguably therefore, further research is warranted. The purpose of the present

92 study was to directly compare estimates of CP and *W'* derived using inter-trial recovery

93 periods of 24 h, 3 h, and 30 min using trained cyclists. We hypothesised an acceptable level

94 of agreement (i.e. mean difference ± 1.96 SD) between CP derived from the three different

95 protocols (with 24 h serving as the criterion measurement). In relation to *W'* we hypothesised

96 an acceptable level of agreement with the criterion measure in the 3 h recovery method only.

97

98 **DESIGN**

99 Participants were nine moderately trained recreational road cyclists [age 33 ± 8 yr, body mass

100 78 ± 10 kg, maximal oxygen consumption ($\dot{V}O_{2\,max}$) 3.9 ± 0.4 L·min^{-1}, power associated with

101 $\dot{V}O_2 max$ (p$\dot{V}O_{2\,max}$) 358 ± 35 W]. The study was approved by the institutional Ethics

102 Committee in accordance with the Declaration of Helsinki. Prior to providing written

103 informed consent, cyclists were fully informed of the nature and risks of the study.

104

105 **Protocol.** In visit 1, values for $\dot{V}O_{2\,max}$ and p$\dot{V}O_{2\,max}$ were established. In randomised order,

106 each cyclist then completed three CP protocols. Protocol A used a traditional 24 h inter-trial

107 recovery (3 visits to laboratory), protocol B a 3 h inter-trial recovery (1 visit to laboratory),

108 and protocol C a 30 min inter-trial recovery (1 visit to laboratory). For each protocol fluid

109 intake was permitted ad libitum. During all tests, participants were blinded to power and

110 elapsed time. Participants were required to refrain from heavy exercise and from food and

111 caffeine intake for 24 h and 3 h prior to testing, respectively. To minimise training effects, all

112 visits were separated by a minimum of 24 h and were completed within a maximum period of

113 14 days. Each cyclist completed each of their six visits at the same time of day.

114

115 A road bicycle equipped with a PowerTap Elite wheel (CycleOps, Madison, USA) and a

116 magnet for direct cadence measurement was used in this study. The road bike was attached to

117 a Computrainer system (RacerMate, Seattle, USA). The saddle and handlebar were adjusted

118 to suit each participant and settings were replicated exactly during subsequent tests. The

119 PowerTap device was zero offset prior to each test according to the manufacturer's

120 instructions.

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122 **Maximal oxygen uptake test protocol**. Following a standardised warm-up, cyclists

123 completed a progressive, incremental exercise test to exhaustion. The maximal test

124 commenced at a work rate of 150 W. Thereafter, intensity increased at a step rate of 20

125 $W \cdot min^{-1}$. Cyclists were allowed to self-select cadence and were instructed to maintain this

126 cadence throughout all tests. The test was terminated when cadence dropped by more than 10

127 $rev \cdot min^{-1}$ for more than 10 seconds. Expired gases were collected breath-by-breath

128 throughout the test using a Cortex MetaLyzer 3B gas analyser (Cortex Biophysik, Leipzig,

129 Germany). Fingertip blood lactate was analysed using the Biosen C_line analyser (EFK

130 Diagnostics, Barleben, Germany), and heart rate (HR) was continuously observed using the

131 monitor built in the Cortex gas analyser. $p\dot{V}O_{2\,max}$ was calculated as the highest 30-s mean

132 PO value (W). $\dot{V}O_{2\,max}$ was calculated as the highest mean oxygen consumption over the

133 same period.

134

135 **Critical Power tests**. Each protocol required cyclists to complete three TTE trials at work-

136 rates equivalent to 80%, 100% and 105% $p\dot{V}O_{2\,max}$. Protocol A used a randomised TTE trial

137 order, with protocol B and C requiring participants to perform trials in the order lowest work

138 rate (i.e., 80% $p\dot{V}O_{2\,max}$) to highest work rate (i.e., 105% $p\dot{V}O_{2\,max}$). After a 5-min

139 standardised warm-up, the test resistance was set and participants were instructed to maintain

140 their preferred cadence for as long as possible. At TTE termination participants continued

141 with a 5 minute unloaded cycling phase before dismounting the bike. HR ($b \cdot min^{-1}$), PO (W)

142 and cadence ($rev \cdot min^{-1}$) were recorded continuously via the PowerTap, and expired gases

143 were continuously sampled. Tests were terminated when cadence dropped by 10 $rev \cdot min^{-1}$

144 below preferred cadence for more than 10 seconds. Fingertip capillary blood samples were

145 collected prior to and post TTE trials. All cyclists reached their individual $\dot{V}O_2 max$ value ($\pm$

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146   0.08 L·min^{-1}), a post-test blood [lactate] of $\geq$ 8 mM and a HR within $\pm$ 5 beats of their

147   maximal HR values established during the $\dot{V}O_2$max test.

148

149   **Calculation of Critical Power and *W'***. Linear regression was used to calculate CP and *W'*

150   using the power-1/time (P = *W'*(1/t) + CP) model. Results using protocol A were termed

151   CP$_{24}$/*W'*$_{24}$ and for protocol B and protocol C they were termed CP$_3$/*W'*$_3$ and CP$_{0.5}$/*W'*$_{0.5}$

152   respectively.

153

154   **Statistical Methods**. Data were examined using the Shapiro-Wilk normality test. Pearson

155   product moment correlation analysis was used to provide an indication of the strength of

156   relationship between the different inter-trial protocols for CP or *W'*. Agreement between

157   different testing protocols for CP$_{24}$/*W'*$_{24}$, CP$_3$/*W'*$_3$ and CP$_{0.5}$/*W'*$_{0.5}$ was assessed using a

158   repeated measures ANOVA and Limits of Agreement (LOA; Atkinson & Nevill, 1998; Bland

159   & Altman, 1986). A repeated measures ANOVA was also used to assess differences between

160   the protocol specific durations of TTE trials and resting and in-exercise blood [lactate]

161   between and within different protocols. Linear regression was used to calculate the Standard

162   Error of Estimates (SEE) to determine the error associated with predicting experimental CP

163   and *W'* values. Partial eta squared (η_p^2) values are reported to provide an estimate of

164   standardised effect size (small η_p^2=0.01; moderate η_p^2=0.06; and large η_p^2=0.14). *Greenhouse-*

165   *Geisser* correction was used to correct the violation of *sphericity*. Statistical significance was

166   accepted at *P* < 0.05. Results are reported as mean and standard deviation (SD) unless

167   otherwise stated.

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171 **RESULTS**

172 CP and W' were normally distributed. Repeated measures ANOVA demonstrated no

173 significant differences for CP, $F(1.4,11.17) = 1.22$, p = 0.31 and W' ($F[1.6,12.89] = 4.03$, p =

174 0.07) between protocols. Where the assumption of sphericity was not met, the Greenhouse-

175 Geisser correction was used. There was a large effect of the protocol for CP and for W' ($\eta_p^2 \geq$

176 0.14). Applying the power-1/time CP model, mean r for protocol A was 0.94 ± 0.12 (SEE

177 10.0 ± 9.0 W) for protocol B it as was 0.97 ± 0.04 (SEE 8 ± 6 W) and for protocol C it was

178 0.99 ± 0.01 (SEE 5 ± 3 W). Table 1 illustrates mean difference and 95% LoA for all results

179 with Table 2 illustrating mean CP/W' values and average prediction errors for the

180 experimental protocols. Figure 1 depicts a graphical presentation of the Bland-Altman

181 analysis, including SEE and r values.

182   ---Fig 1 about here---

183

184 Significant differences ($P < 0.05$) were observed for mean resting [lactate] in protocol C

185 between 80% TTE trials and both 100% and 105% TTE trials but also between protocol C

186 100% and 105% TTE trials and their protocol B and C counterparts. For post [lactate],

187 significant differences were observed between protocol A 80% TTE trials and 105% TTE

188 trials in protocols B and C (Table 3). No significant differences in TTE durations between

189 respective protocol trials were observed (Table 4).

190   ---Table 1 a and 1 b about here---

191   ---Table 2 a and 2 b about here---

192   ---Table 3 about here---

8

193   ---Table 4 about here---

194

195 **DISCUSSION**

196 The present study investigated whether recovery times of 3 h or 30 min are sufficient to

197 derive values of CP and W' equivalent to those derived using the 'standard' 24 h inter-trial

198 recovery method. Mean differences between protocol A (24 h recovery) and protocol B (3 h

199 recovery) and between protocol A and protocol C (30 min recovery) were 3 ± 6 W and $-2 \pm$

200 12 W respectively. This suggests that CP can be determined using either a 3 h or a 30 min

201 inter-trial recovery period. LoA for standard and experimental CP_3 and $CP_{0.5}$ values (Table

202 1a; Fig 1) also suggest an acceptable level of agreement between the 24 h and the shorter

203 recovery duration protocols. Table 2a demonstrates average prediction errors for all

204 experimental CP. Our levels of error are considerably lower than those reported by

205 Nimmerichter, Williams, Bachl, & Eston (2010), who suggested that a field test with a

206 random error of 5% and levels of agreement between -0.4 W and 49 W was valid. CP

207 findings were also consistent with those of Bishop and Jenkins (1995), and of Galbraith et al.

208 (2014) which further suggests that recovery periods as short as 30 min provide good

209 estimates of CP/CV.

210 Although not reaching statistical significance, data for W' indicated an unacceptably low level

211 of agreement (Table 1b), as well as high average prediction errors for both 3 h and 30 min

212 testing protocols (Table 2b). These data allow us to reject our hypothesis that an acceptable

213 level of agreement with the criterion measure would be observed in the 3 h recovery method.

214 Previous research suggests that prior exercise such as a TTE trial can be detrimental to

215 subsequent exercise when it is too intense (Wilkerson, Koppo, Barstow, & Jones, 2004) or

216 when recovery periods are too short (Ferguson et al., 2007). Arguably only minimal

217 detrimental effects are evident in the current study, as indicated by shorter exhaustive trial

218 durations in Table 4. However, these might explain the lack of agreement for W' across

219 protocols. Our results, furthermore, support findings by Galbraith et al. (2014) who also

220 identified differences in values of anaerobic running distances using a 30 min and 60 min

221 inter-trial recovery method. However our results do not explain findings for W' under

222 protocol B, where a 3 h inter-trial recovery period should have been sufficiently long or a full

223 reconstitution of this parameter.

224

225 Nielsen, de Paoli & Overgaard (2001) suggested that acidosis caused by elevated blood

226 [lactate] actually protects the muscle from fatigue. Moreover, an optimal [lactate] of ~2-3

227 mM has been suggested by Jones et al. (2003) as a level at which, through the preservation of

228 muscle K^+, performance can be enhanced. Resting blood [lactate] was significantly elevated

229 for both the 100% and 105% TTE trials in protocol C (Table 3) without indicating such

230 performance enhancement. Protocol C 105% TTE trial durations on average were ~36 s

231 shorter when compared with their protocol A counterparts. Ferguson et al. (2010) suggested

232 that lactate recovery kinetics are slower than those of W', which implies that full recovery

233 was not evident in protocol C, since W' was considerably smaller when compared to protocol

234 A.

235

236 There appears to be a lack of consensus as to the true nature and role of W'. W' defined as a

237 finite amount of energy was believed to result in exhaustion when depleted (Moritani,

238 Nagata, Devries, & Muro, 1981). More recently W' has been suggested to represent the

239 accumulation of fatigue-related metabolites to some critical tolerable limit (Coats et al., 2003;

240 Jones, Wilkerson, DiMenna, Fulford, & Poole, 2008). According to Coats et al. (2003),

241 depletion of W' resulting from a prior bout of severe exercise negatively influences

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242 subsequent performances around CP intensity. This was seen in the present study in that

243 100% and 105% test durations under protocol C conditions were shorter than those of their

244 protocol A counterparts. Challenging a finite capacity-based explanation for tasks to failure,

245 Ferguson et al. (2010) explored the effects of an exhaustive conditioning bout on CP and W'.

246 The study demonstrated that W' reflects an ability to exercise under increasing levels of

247 fatigue caused by its own utilisation. Consequently, Ferguson et al. (2010) found no

248 differences in CP, but a reduction in W' when employing different recovery durations (2 to 15

249 min) after a W' depleting exercise bout followed by TTE trials. In agreement with Ferguson

250 et al. (2010), the results of the present study suggest the reductions in time to exhaustion after

251 prior exhaustive exercise seem to be primarily dependent on the variability of W'. In this

252 regard, Ferguson et al (2010) demonstrated an exponential repletion of W' and not, as is

253 assumed by the 2-parameter CP model, a linear one, and therefore this might suggest that W'

254 is not fully reconstituted by the end of the 3 h and 30 minute recovery period used in Protocol

255 B and C.

256

257 Investigating the influence of moderate hypoxia on high intensity exercise tolerance, Dekerle,

258 Mucci & Carter (2012) found that the ranges of TTE did not differ between normoxic and

259 hypoxic conditions. However CP was significantly affected (mean 13%) under hypoxic

260 conditions with W' not demonstrating a significant difference but exhibiting large intra-

261 individual responses (-36 to + 66%). Dekerle et al. (2012) consequently questioned whether

262 the two parameter model allows a valid estimation of W'. Indeed some recent research

263 attempts have been made to account for some shortcomings in the two-parameter CP model

264 (Chatagnon, Pouilly, Thomas, & Busso, 2005; Heubert et al., 2005) with Gaesser, Carnevale,

265 Garfinkel, Walter, & Womack (1995) highlighting an inherent difficulty in accurately and

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266 reliably determining W'. With an apparent disagreement in the literature about the true

267 constitution of this parameter, we can only suggest that an additional TTE trial would have

268 resulted in an increased accuracy of CP and W' predictions whilst arguably adding to a time

269 consuming and cumbersome testing protocol. It is however unlikely that W' derived through

270 4 TTE trials would have provided acceptable results. The present study was limited in that 3

271 h and 30 min protocols were not repeated on more than one occasion. Therefore, it is difficult

272 to ascertain the level of reliability within these methods to determine CP. Nevertheless, using

273 a similar protocol, Karsten et al. (2015) investigated the reliability of CP in the field with 30

274 min recovery periods in a group of recreational athletes. Over three repeated trials, Karsten et

275 al. (2015) reported mean coefficient of variation values of 2.35%, with intraclass correlation

276 coefficient values of value of 0.99 (CI 0.98–0.99). Therefore, it is not unreasonable to expect

277 that similar levels of reliability could be expected in the current study.

278

279 **CONCLUSION**

280 CP has traditionally been determined using 24 h inter-trial recovery periods. Results of the

281 present study suggest a high agreement and a low prediction error in CP using 3 h and 30 min

282 inter-trial recovery periods. With W' requiring further investigations to fully understand its

283 mechanistic underpinnings, CP appears to be robust to the manipulation of TTE recovery

284 times.

285

286 **PRACTICAL APPLICATIONS**

287 CP can be determined in a single session of 1.5 h. A substantially reduced inter-trial recovery

288 period – as low as 30 min – increases the possibility for CP testing to be incorporated into an

289 athlete's training regimen.

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414 **Figure captions**

415 **Figure 1.** Bland-Altman plots of the relationship (panel A and B) and the limits of agreement

416 (panel C and D) between CP_{24} and CP_3 and between CP_{24} and $CP_{0.5}$ respectively. In panel C

417 and D the horizontal line represent the mean difference between CP_{24} and CP_3 and between

418 CP_{24} and $CP_{0.5}$, and the dashed line represents 95% LoA.
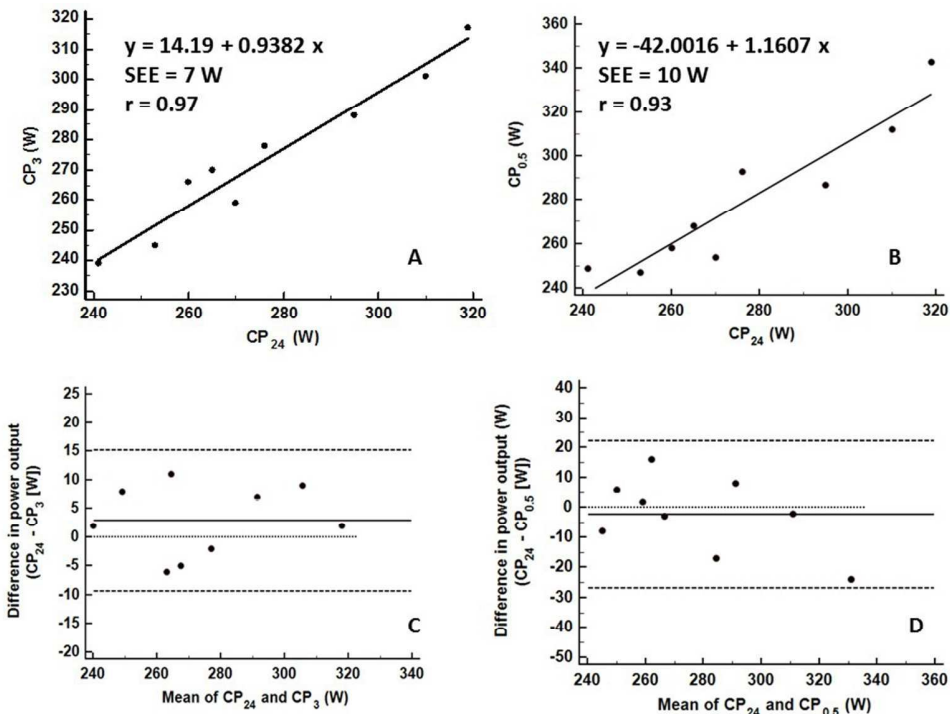
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Figure 1. Bland-Altman plots of the relationship (panel A and B) and the limits of agreement (panel C and D) between CP24 and CP3 and between CP24 and CP0.5 respectively. In panel C and D the horizontal line represent the mean difference between CP24 and CP3 and between CP24 and CP0.5, and the dashed line represents 95% LoA.
254x190mm (96 x 96 DPI)

Table 1a. Mean Difference (±SD), 95% Limits of Agreement between CP results

	Mean Difference (W)	95% LoA (W)
Prot. A vs. B/CP_{24} vs. CP_3	3 ± 6	-9 to 15
Prot. A vs. C/CP_{24} vs. $CP_{0.5}$	-2 ± 12	-27 to 22

Table 1b. Mean Difference (±SD), 95% Limits of Agreement between W' results

	Mean Difference (kJ)	95% LoA (kJ)
Prot. A vs. B/W'_{24} vs. W'_3	0.2 ± 3.9	-7.4 to 7.8
Prot. A vs. C/W'_{24} vs. $W'_{0.5}$	3.9 ± 5.7	-7.2 to 15.1

Table 2a. Mean CP (±SD), Standard error of estimates (lower and upper confidence limits) and average prediction errors (%)

	Mean (W)	SEE (W)	Lower CL	Upper CL	Average pred. error (%)
Protocol A vs. B: **(CP$_{24}$ vs. CP$_3$)**	277 ± 26 vs. 274 ± 25	7	4.7	12.0	2.5
Protocol A vs. C: **(CP$_{24}$ vs. CP$_{0.5}$)**	277 ± 26 vs. 279 ± 33	10	7.1	18.1	3.7

Table 2b. Mean *W'* (±SD), Standard error of estimates (lower and upper confidence limits) and average prediction errors (%)

	Mean (kJ)	SEE (kJ)	Lower CL	Upper CL	Average pred. error (%)
Protocol A vs. B: **(*W'*$_{24}$ vs. *W'*$_3$)**	15.2 ± 4.7 vs. 15.0 ± 4.2	3.9	2.7	7.0	25.6
Protocol A vs. C: **(*W'*$_{24}$ vs. *W'*$_{0.5}$)**	15.2 ± 4.7 vs. 11.3 ± 3.5	5.0	3.5	9.0	32.9

Applying the power-1/time CP model, mean r for protocol A was 0.94 ± 0.12 (SEE 10 ± 9 W) for protocol B it as was 0.97 ± 0.04 (SEE 8 ± 6 W) and for protocol C it was 0.99 ± 0.01 (SEE 5 ± 3 W).

Table 3. Group mean (±SD) resting and post-TTE trials blood [La] (mM) results

Prior TTE trial	Lactate (mM) 80% TTE trial	Lactate (mM) 100% TTE trial	Lactate (mM) 105% TTE trial
Protocol A	1.5 ± 0.6	1.5 ± 0.7	1.4 ± 0.6
Protocol B	1.5 ± 0.5	1.8 ± 0.8	1.5 ± 0.5
Protocol C	1.2 ± 0.3	3.5 ± 0.8[*]	4.1 ± 1.3[**]
Post TTE trial	**Lactate (mM) 80% TTE trial**	**Lactate (mM) 100% TTE trial**	**Lactate (mM) 105% TTE trial**
Protocol A	12.5 ± 1.5	11.8 ± 3.0	10.5 ± 2.8
Protocol B	13.2 ± 2.7	11.0 ± 2.6	10.1 ± 2.3
Protocol C	11.5 ± 3.1	10.4 ± 2.2	9.2 ± 2.0

[*] Significantly different to protocol A and B TTE trial resting value ($p = 0.000$)
[**] Significantly different to protocol A and B TTE trial resting values ($p = 0.000$)

Table 4. Mean durations (±SD) of set TTE trials for each protocol and p-values of pairwise protocol comparisons

Protocol	80% TTE (s)	100% TTE (s)	105% TTE (s)
A	650 ± 237	251 ± 81	179 ± 59
B	623 ± 213	222 ± 81	169 ± 49
C	578 ± 170	210 ± 79	143 ± 23
TTE trial	Protocol A vs. B p-value	Protocol A vs. C p-value	Protocol B vs. C p-value
80% TTE	0.83	0.75	0.87
100% TTE	0.18	0.10	0.37
105% TTEC	0.84	0.12	0.08