1 **Manuscript has been accepted but not published:**

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5

6 **Abstract**

7 **Purpose:** The aim of this study was to investigate the relationship between selected

8 anthropometric, physiological, and upper body strength measures and 15-km handcycling time trial

9 performance.

10

11 **Methods:**

12 Thirteen, trained H3/H4 male handcyclists performed a 15-km time trial, graded exercise test, 15-s

13 all-out sprint and one repetition maximum assessment of bench press and prone bench pull strength.

14 Relationship between all variables were assessed using a Pearson's correlation coefficient matrix

15 with mean time trial velocity representing the principal performance outcome.

16

17 **Results:**

18 Power at a fixed blood lactate concentration of 4 mmol·l^{-1} (r = .927; p <0.01) showed an extremely

19 large correlation to TT performance, whilst relative $\dot{V}O_{2peak}$ (r = .879; p <0.01), power-to-mass ratio

20 (*r* = .879; *p* < 0.01), peak aerobic power (r = .851; p <0.01), gross mechanical efficiency (*r* = 733;

21 *p* <0.01), relative prone bench pull strength (*r* = .770; *p* = 0.03) relative bench press strength (*r*

22 = .703, *p* = 0.11), and maximum anaerobic power (*r* = .678; *p* = 0.15) all demonstrated a very large

23 correlation with performance outcomes.

24
25

26 **Conclusion:** Findings of the present study indicate that power at a fixed blood lactate concentration

of 4 mmol·l^{-1}, relative $\dot{V}O_{2peak}$, power-to-mass ratio, peak aerobic power, gross mechanical

efficiency, relative upper body strength, and maximum anaerobic power are all significant

determinants of 15-km TT performance in H3/H4 handcyclists.

Introduction

Since its formal recognition as a sport by the International Paralympic Committee in 1999, the popularity of handcycling as both a recreational and competitive sport has grown substantially.[3] The sport was first included in the summer 2004 Paralympic Games in Athens and is now also incorporated within the wheelchair classifications of Para-triathlon, a sport that debuted at the summer 2016 Paralympic Games in Rio de Janeiro. Handcyclists are classified into one of five categories (H1 - H5) according to the nature of their physical impairment, with H1 athletes typically having the greatest physical impairment and lowest physical function.[33] Handcycling can be viewed as an endurance sport whereby athletes typically compete in road-races and/or individual time trials (TT) over distances ranging from 37 to 80-km and 10 to 35-km, respectively.[33] Due to varying race formats, terrain, tactics and speeds, handcyclists often use variable pacing strategies, such as frequent short accelerations to push opponents, or drafting behind other riders during road races to reduce overall energy cost.[1,3] Arguably, a TT represents the most pure challenge to a cyclist as, in this format, athletes ride alone, against the clock. Thus, racing tactics briefly mentioned above become irrelevant and a cyclist's ability is laid bare.

As with many other Paralympic sports, the performance level of handcycling at the elite level has increased considerably, which underlines the importance of optimising training in order to achieve success.[23] Handcycling performance is ultimately dependent upon the physical capabilities of the individual, the design of the handbike, and the interaction between the rider and their equipment, typically referred to as the handbike-user interface.[31] Whilst the biomechanics,[20,27,31] handbike-user interface[4,5,6,22,29,32,34] and physiological characteristics of handcycling performance, namely peak oxygen uptake ($\dot{V}O_{2peak}$), peak aerobic power output (PO_{peak}) and gross mechanical efficiency (GME) have been extensively investigated.[1,9,13,19,21,25] To date, only a handful of studies have examined the relationship between the aforementioned physiological characteristics and handcycling race

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52   performance. Janssen et al,[19] investigated how the physical capacity of sixteen male handcyclists with

53   either spinal cord injury, spina bifida or lower limb amputation related to performance during a 10-

54   km handcycling race. Relative $\dot{V}O_{2peak}$ ($r = .90$, $p <0.01$), PO_{peak} ($r = .91$, $p =< 0.01$), and power-to-

55   mass ratio ($r = .89$, $p <0.01$) were all demonstrated to be significant predictor of 10-km race

56   performance. Lovell et al,[21] studied the aerobic performance of ten trained and ten untrained male

57   handcyclists with spinal cord injury. They reported that PO_{peak} ($r = .87$, $p <0.01$), $\dot{V}O_{2peak}$ ($r = .67$, p

58    $= 0.03$), and GME ($r = .50$ $p = 0.04$) were the best predictors of handcycling performance during a

59   laboratory-based, 20-km TT. More recently, Fischer et al,[13] examined the physiological determinants

60   of handcycling performance of seven, male, H2 handcyclists and found that $\dot{V}O_{2peak}$ ($r = .89$, $p <0.01$),

61    $\dot{V}O_{2VT1}$ ($r = .96$, $p <0.01$), $\dot{V}O_{2VT2}$ ($r = .92$, $p = 0.03$) and PO_{peak} ($r = .85$, $p = 0.02$) were all

62   significantly correlated with performance during a simulated 22-km TT.

63

64   Whilst extensively examined in able-bodied cycling,[10,11] few studies have investigated the impact of

65   anaerobic threshold, anaerobic capacity and upper-body strength upon handcycling performance. The

66   attainment of high-power output during an all-out sprint is frequently used as a measure of anaerobic

67   performance in able-bodied cycling[10,11] and Quittman et al,[26] recently suggested that an understanding

68   of a handcyclists physiological profile should be augmented by testing maximal anaerobic power

69   ($PO_{max,AO15}$). In cycling, anaerobic capacity can be defined as the difference between $PO_{max,AO15}$ and

70   PO_{peak} commonly known as the anaerobic power reserve (APR). Several authors have demonstrated

71   that decrements observed in all-out cycling performance seems to conform to a general relationship

72   with a single exponential decay model, which describes a decrement in power versus increasing

73   duration.[28,35] Therefore, the determination of APR can be viewed as a potentially valid measure of

74   anaerobic capacity in handcyclists. In regard to upper body strength Nevin et al,[25] demonstrated that

75   8-weeks of concurrent strength and endurance training enhanced handcycling performance to a

76   greater degree than endurance training alone, suggesting that enhanced upper body strength may also

77   be an important determinant of handcycling performance.

78

79   Given the current paucity of research relating to the impact of anaerobic threshold, anaerobic capacity

80   and upper-body strength upon handcycling performance the aim of the present study was to build

81   upon the existing literature and investigate how relative $\dot{V}O_{2peak}$, PO_{peak}, GME, power at a fixed blood

82   lactate concentration of 4 mmol·l^{-1} (PO$_4$), $PO_{max,AO15}$, and measures of upper-body strength influence

83   performance of an ecologically valid (field-based), 15-km TT in a group of trained H3/H4 male

84   handcyclists. It was hypothesized that relative $\dot{V}O_{2peak}$, PO_{peak}, GME, PO_4, $PO_{max,AO15}$, and relative

85   upper-body strength would all demonstrate a significant correlation with 15-km TT velocity.

86

87   **Methods**

88   **Participants**

89   Thirteen male handcyclists with at least one year's recreational handcycling experience provided

90   written informed consent to take part in this study. All participants were classified as either an H3 or

91   H4 arm-powered handcyclist in accordance with current UCI Paracycling regulations.[33] Six

92   participants were bi-lateral, above knee amputees (H4); one was a triple amputee (H3); and five were

93   paraplegic with impairments corresponding to a spinal lesion been levels T1 to T10 (H3). In all

94   aspects of physiological testing and TT performance, each participant used their own, customised

95   handbike. Mean ($\pm$ *SD*) participant characteristics were age 37 $\pm$ 11 yrs; body mass; 76.6 $\pm$10.1 kg;

96   and 4-site skinfold summation 50.0 $\pm$ 7.2 mm. No medical conditions or upper-body musculoskeletal

97   injuries were reported prior to the study. Finally, the study was conducted in accordance with the

98   declaration of Helsinki with approval granted by the Research Ethics Committee of Buckinghamshire

99   New University, High Wycombe, United Kingdom.

100

Design

This was a single-cohort, cross sectional research study to examine the influence of body mass, body composition, relative $\dot{V}O_{2peak}$, PO_{peak}, PO_4, GME, $PO_{max,AO15,}$ APR and upper-body strength on 15-km TT performance using thirteen experienced H3/H4 male handcyclists. Testing was completed over three consecutive days: 15-km TT (day 1), anthropometric assessment, graded exercise test (GTX), and 15-s all-out sprint test (day 2); and 1 repetition maximum (1RM) strength testing (day 3). A period of 24 hours separated testing sessions in order to limit the impact of fatigue. Before testing, participants were asked to abstain from strenuous exercise and refrain from consuming alcohol for at least 48 hours. Outdoor TT testing was conducted in dry and stable meteorological conditions ($19 \pm 2°$ C, <10 km·h^{-1} wind speed) whilst, laboratory testing was performed indoors, under controlled environmental conditions ($18°$ C, $50 – 60\%$ relative humidity).

Individual 15-km Time Trial

In order to assess real world, ecologically valid handcycling performance, a 15-km individual TT was completed at a closed, cycling racing circuit (Odd Down, Bath, England). This location provided an undulating 1.5-km, smooth tarmac circuit with a total elevation loss and gain of 9 m per lap. Following two familiarisation laps, each participant was required to complete ten laps of the 1.5-km circuit as quickly as possible. Participants were monitored by means of a GPS receiver (Garmin Edge 1000, Garmin Ltd, USA), and data were used to establish TT performance in the form of mean velocity (km·h^{-1}).

Anthropometry

Body mass was measured to the nearest 0.1 kg using a calibrated scale (Seca 714, Hamburg, Germany); whilst skinfold thicknesses were measured to the nearest mm using a pair of skinfold

126   callipers (accurate to 0.2 mm) from the Harpenden range of anthropometric instruments (Holtain, Ltd,

127   UK). All anthropometric measurements including body mass and four-site skinfold thickness

128   summation (chest, triceps, subscapular, and iliac crest), were performed in accordance with

129   International Society for the Advancement of Kinanthropometry guidelines.[17] Percentage body fat

130   was not calculated as no validated four-site skinfold predication equations currently exists in the

131   literature for disabled population groups with substantial body asymmetry as a result of amputation

132   or lower body muscular atrophy due to spinal cord injury.[15]

133

134   **Graded Exercise Test**

135   For both the GTX and 15-s all-out sprint tests, each participant's bike was fitted to a standard, indoor

136   cycling turbo trainer (Fluid 2, CycleOps, USA). Mechanical power output was measured using an

137   instrumented front wheel hub (Powertap, G3, CycleOps. USA, 1.5% accuracy between 0 and 1999

138   W, sample frequency 0.2 Hz). The Powertap has been shown to be a reliable instrument (CV 0.9 –

139   2.9%) for the measurement of power whilst cycling[7] and was calibrated prior to testing, in accordance

140   with the manufacturer's instructions. Oxygen consumption ($\dot{V}O_2$), carbon dioxide production

141   ($\dot{V}CO_2$), minute ventilation ($\dot{V}E$), and respiratory exchange ratio (RER) were continuously monitored

142   using a calibrated, online gas analysis system (Oxycon Pro, Jeager, Warwick, Warwickshire, UK)

143   whist heart rate (HR) was logged using a commercially available receiver (Garmin Edge 1000,

144   Garmin Ltd, USA).

145

146   Following a 10-min warm-up at a self-selected mechanical power output, participants were requested

147   to start the test protocol at a work rate of 40 W with subsequent 20 W increments every 5-mins until

148   the required mechanical power output could no longer be maintained, or until participants reached

149   volitional exhaustion.[2,27,31] $\dot{V}O_{2peak}$ and PO_{peak} were identified as the respective mechanical power

150   output and peak oxygen consumption achieved during the last fully completed 30-s. Throughout the

151   test, participants were free to adjust their gear ratio and/or crank rate as needed in order to maintain

152   the required mechanical power output. Every 5-mins and upon immediate completion of the test,

153   participants were asked to indicate their global rating of perceived exertion (RPE) using a 6 to 20

154   Borg scale.[8] All respiratory parameters were calculated for each breath and averaged at 1-min

155   intervals at rest and every 30-s during each exercise stage.

156

157   At the end of each stage and at the point of volitional exhaustion, a small sample of capillary blood

158   was collected from an earlobe to measure blood lactate concentration. These data were used to

159   identify fixed blood lactate concentrations of 2 and 4 mmol·l^{-1}. Once collected, capillary blood

160   samples were treated, analysed and disposed of immediately using a fully automated analyser (Biosen

161   C-line, EKF Diagostics, Barleban, Germany). GME was calculated as the ratio of external work

162   produced to the amount of energy expended when a fixed blood lactate concentration of 2 mmol·l^{-1}

163   was reached. This metabolic parameter was selected as it represents a consistent, submaximal exercise

164   intensity during which energy production is predominantly achieved via aerobic metabolic pathways.

165   Metabolic energy expenditure was calculated from associated $\dot{V}O_2$ and RER data according to Garby

166   and Astrup[14] and expressed as a percentage value:

167

168   Equation 1: GME = ((external work done / energy expenditure) x 100) (%).

169

170   As an approximation of anaerobic threshold, power output corresponding to the onset of blood lactate

171   accumulation (OBLA) at a fixed blood lactate concentration 4 mmol·l^{-1}was also identified.

172

173   **15-s All-Out Sprint Test**

174   Following the GTX , participants were given a one-hour recovery period prior to completing a 15-s

175   all-out sprint protocol to assess anaerobic performance. Participants were asked to complete a 10-

176 min warm up at a self-selected mechanical power output. Prior to commencement of the test protocol

177 participants were requested to adopt their highest gear ratio (50/11). Once the participant

178 acknowledged that they were ready, the test was initiated. Throughout the test protocol participants

179 were verbally encouraged to exert maximum, physical effort with the greatest mechanical power

180 output subsequently recorded. APR was established using the following formula:[35]

181

182 Equation 2: $APR = PO_{max,AO15} - PO_{peak}$.

183

184

185 **Upper-Body Strength Testing**

186 In order to evaluate upper body strength, maximal and relative values of bench press and prone bench

187 pull 1RM were determined. Strength testing was conducted on a specifically designed, IPC Para-

188 powerlifting bench (Eleiko, Sweden) and a prone-pull bench (Pullum Sports, England) using a 20 kg

189 Olympic barbell, 450 mm diameter barbell plates (25, 20, 15 and 10 kg), 200 mm diameter barbell

190 plates (5, 2.5, 2.0, 1.5, 1.0 and 0.5 kg), two safety locks and two Velcro securing straps (Eleiko,

191 Sweden).

192

193 Both bench press and prone bench pull 1RM testing was conducted in line with the protocols proposed

194 by Haff and Triplett.[16] Participants were instructed to perform a light warm-up with the bar only,

195 performing 5 – 10 repetitions. Following a 1-min recovery period, a second set of 3 – 5 repetitions

196 was performed with an estimated 60% 1RM load. After a 3-min recovery period another set of 2 – 3

197 repetitions, was performed with an estimated 80% 1RM load. Thereafter, an estimated 1RM load

198 was selected and the participant asked to perform a single repetition. If successful, the participant was

199 given a 3-min recovery period prior to performing a further 1RM attempt with an increased load.

200　Participants were allowed, to perform 3 – 5 more 1RM attempts with 3-min recovery between sets

201　until their 1RM had been established within a precision of 1.0 kg.

202

203　**Statistical Analyses**

204　All data are reported as mean (± *SD*) with a level of significance for all statistical analyses set at *p*

205　<0.05. Statistical analyses were performed using SPSS Version 25.0 (SPSS Inc, Chicago, USA).

206　Parameters were checked for normal distribution using the Shapiro-Wilk test with the Spearman's

207　coefficient used in cases of violation. Pearson's product-moment correlation coefficients (*r*) were

208　calculated to establish the relationships between 15-km TT velocity (dependent variable), body mass,

209　4-site skinfold summation, relative $\dot{V}O_{2peak,}$ PO_{peak}, power-to-mass ratio (W·kg^{-1}), PO_4, GME,

210　$PO_{max,AO15}$, APR, and maximal (kg) and relative (kg·kg^{-1} body mass) bench press and prone bench

211　pull 1 RM (independent variables). Correlation coefficients were evaluated as follows >0.1 small,

212　>0.3 moderate, >0.5 large, >0.7 very large, and >0.9 extremely large.[17]

213

214　**Results**

215　Mean (± *SD*) data are summarised in Table 1. Pearson product-moment correlation coefficients were

216　calculated between 15-km TT velocity and all other anthropometric, GTX, 15-s all-out sprint and

217　strength testing variables (Table 2). PO_4 (*r* = .927; *p* <0.01) showed an extremely large correlation

218　whilst relative $\dot{V}O_{2peak}$ (*r* = .879; *p* <0.01), power-to-mass ratio (*r* = .879; *p* < 0.01), PO_{peak} (*r* = .851;

219　*p* <.0.01), body mass (*r* = -.783*; p* <0.01), GME (*r* = .733; *p* <0.01), relative prone bench pull strength

220　(*r* = .770; *p* = 0.03) relative bench press strength (*r* = .703, *p* = 0.11) and $PO_{max,AO15}$ (*r* = .678; *p* =

221　0.15) all demonstrated very large correlation with 15-km TT velocity. APR demonstrated a large

222　correlation (*r* = .548*; p* = 0.65) whilst, body composition (*r* = -.448; *p* = 0.14), bench press 1RM (*r*

223　= .423; *p* = 0.17) and prone bench pull 1RM (*r* = .447; *p* = 0.14) revealed only a moderate correlation

224　with performance outcomes.

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225

226 **##Insert Table 1 Here##**

227

228 **##Insert Table 2 Here##**

229

230 **##Insert Figure 1 Here##**

231 **Discussion**

232 The aim of this study was to investigate the relationship between selected anthropometric,

233 physiological, and upper body strength measures and 15-km handcycling time trial performance. The

234 main findings based upon the data collected were that PO_4, relative $\dot{V}O_{2peak}$, power-to-mass ratio,

235 PO_{peak}, GME, relative upper body strength and $PO_{max,AO15}$ all demonstrated a significant correlation

236 with handcycling performance (Figure 1).

237

238 **Anthropometrics**

239 In agreement with the findings of De Groot et al,[9] the present study demonstrated that body mass

240 displayed a considerable, negative association with 15-km TT velocity. When relative PO_{peak} was

241 examined, another large and meaningful relationship was observed. These finding concur with those

242 of Janssen et al,[19] who demonstrated that power-to-mass ratio was a significant predicator of 10-km

243 handcycling race performance. De Groot et al,[9] reported that a lower waist circumference was a good

244 predictor of handcycling performance, therefore, it can be inferred that a lower fat mass would result

245 in improved 15-km TT performance. However, findings of the current study revealed that body

246 composition, as assessed via 4-site skinfold summation exhibited only a moderate, negative

247 relationship with performance. These findings were somewhat surprising as greater skinfold

248 summation (*e.g.,* higher fat mass) would have been expected to have a larger negative impact upon

249 15-km TT velocity. Goosey-Tolfrey et al,[15] suggested that skinfold estimations may not be a valid

250 assessment tool of body composition in disabled population groups and the findings of the present

251 study support this position. Another point to note is that the combined rider-bike mass is also likely

252 to be important and negatively linked to TT velocity. Thus, where feasible, it is recommended that

253 the combined mass of a handcyclist and their bike be minimised in an attempt to optimise TT

254 performance.

255

Aerobic Performance

Relative $\dot{V}O_{2peak}$ and, to a slightly lesser extent PO_{peak} and GME demonstrated a very large correlation with 15-km TT performance. These finding are in agreement with previous studies that have shown relative $\dot{V}O_{2peak}$, and PO_{peak} to be significant determinants of handcycling performance during TT,[13,18,19] ultra-endurance,[1,2] and mountain climbing,[9] events. GME has also been demonstrated to be a significant determinant of handcycling performance.[19] Participants in the present study achieved a mean GME value of $13.4 \pm 2.7\%$ which is similar to a previous reports of $11.5 \pm 0.8\%$,[19] $14.1 \pm 2.0\%$,[21] and $13.5 \pm 1.4\%$[25] for trained handcyclists. GME is of particular importance to handcyclists as improvements in efficiency will likely translate to a reduction in relative workload at a given mechanical power output. Theoretically, this should enable a rider to produce a higher mechanical power output for an equivalent amount of energy expended (*e.g.*, improved performance) or alternatively result in a longer time to exhaustion at a given rate of work (*e.g.*, improved endurance capacity), with both scenarios holding the potential to enhance an athlete's performance.

Anaerobic Threshold

As an approximation of anaerobic threshold, mechanical power output corresponding to OBLA at a fixed blood lactate concentration of 4 mmol·l^{-1} (PO_4) was utilised. Power at this threshold demonstrated an extremely large relationship with 15-km TT velocity. These finding are in agreement with findings of several other studies, demonstrating a strong relationship between PO_4 and performance in both handcyclists[2,23] and able-bodied road cyclists.[10,11] OBLA can be defined as the point at which blood lactate concentration increases exponentially, with the rate of production outstripping removal and leading to acute metabolic acidosis. The validity of using OBLA at a fixed blood lactate concentration of 4 mmol·l^{-1} to identify the shift from predominantly aerobic energy turnover to anaerobic energy production has been questioned previously.[10,11,30] Indeed, the threshold at which anaerobic metabolism starts to predominate is strongly influenced by individual lactate

281 kinetics, which varies depending upon the activity and volume of skeletal muscle mass.[26] Therefore,

282 OBLA at a fixed blood lactate concentration of 4 $mmol \cdot l^{-1}$ may either over- or underestimate

283 anaerobic threshold depending upon the individual athlete, exercise modality and intensity.

284 Nevertheless, findings of the present study demonstrated that anaerobic threshold, as estimated by

285 PO_4 to be a very strong indicator of 15-km handcycling TT performance.

286

Anaerobic Performance

288 Anaerobic performance assessed by the maximum power output generated during a 15-s all-out sprint

289 test produced a large correlation with 15-km TT performance. In order to assess anaerobic capacity,

290 the difference between $PO_{max,AO15}$ and PO_{peak} commonly known as APR was also investigated. The

291 concept of APR has been suggested to be a valid measure of anaerobic capacity in able-bodied road

292 cyclists[28,35] and findings of the current study showed large correlation between handcycling APR and

293 15-km TT velocity. Given the nature of an individual TT, it can be reasoned that riders in the present

294 study maintained a velocity at, or just below their anaerobic threshold and were unlikely to have

295 utilised their APR to a great extent. Despite this, it can be strongly argued that in the context of a road

296 race competitive handcyclists require a high APR to repeatedly generate and recover from the

297 production of high power outputs over short periods of time. This will allow a rider to either close a

298 gap on an opponent, break away from other riders, or win in a sprint finish.

299

Maximal and Relative Upper Body Strength

301 Maximal and relative upper body strength in the present study was determined by assessing bench

302 press and prone bench pull 1RM. These exercises were chosen as they closely mimic the

303 synchronistic, horizontal push/pull force production movement pattern observed during

304 handcycling.[25] Bench press and prone bench pull 1RM demonstrated only a moderate relationship

305 with 15-km TT velocity. However, when relative upper body strength was examined, both bench

13

306 press and prone bench pull displayed a significant influence upon 15-km TT velocity, further

307 confirming the relative importance of body mass to handcycling performance.

308

309 Relative strength is the product of one's ability to generate considerable maximal forces relative to

310 one's body mass. Therefore, it can be inferred that greater maximal upper body strength, at a given

311 body mass or in combination with a reduction in non-functional body mass (*e.g.,* adipose tissue) may

312 result in an improvement in an individual's handcycling performance capabilities. Interestingly,

313 relative upper body pulling strength demonstrated a larger correlation with 15-km TT velocity than

314 relative pushing strength. This is in agreement with previously published studies which have

315 demonstrated that a greater proportion of the work generated during the propulsion cycle of

316 handcycling occurs during the pull phase with an increase in pulling torque and concomitant decrease

317 in pushing torque observed at progressively higher power outputs.[5,27,34] Therefore, based upon these

318 observations it can be inferred that greater relative upper body pulling strength may enhance

319 handcycling performance. Strength training should, therefore, form a central component of any

320 successful handcyclists training programme.

321

322 **Limitations**

323 While these findings provide a novel insight into the determinants of TT performance in trained

324 H3/H4 handcyclists, it must be noted that there are several limitations associated with the study and

325 its design. Firstly, as is usually the case in this area of research, sample size was small and the

326 participant group relatively heterogeneous in terms of age, performance level, and disability which

327 resulted in considerable variance within the group. The small sample size also meant that it was not

328 possible to conduct a multiple regression analysis in order to develop a accurate handcycling

329 performance model. A further limitation was that the 15-km TT was a self-paced time trail, which

330 was conducted in variable climactic conditions. Such an approach represents a less controlled

14

331 environment compared to sterile laboratory conditions; however, this approach does add a degree of

332 ecological validity as it more closely resembles real-world handcycling race conditions. Additionally,

333 whilst the Powertap power measuring device has been shown to be a reliable instrument for the

334 measurement of mechanical power output whilst cycling, its sampling frequency (0.2 Hz) is relatively

335 low for the purpose of measuring $PO_{max,AO15}$. Thus, it is recommended that future studies use a more

336 sensitive instrument for the measurement of mechanical power output such as the Cyclus 2 ergometer

337 (8 Hz, RBM Electronic automation GmbH, Leipzig, Germany). However, it could also be argued

338 that, from a consistency of power measurement perspective and to facilitate meaningful comparison,

339 the same measuring device should be used in a laboratory and field-based environment if possible.

340 Finally, as with all criterion validity studies exploring links between independent variables and, in

341 this case, a (dependent) performance outcome measure, correlational analyses do not necessarily

342 confirm causation, thus additional studies should be conducted to provide further, confirmatory

343 evidence.

344

345 **Practical Applications**

346 In order to better optimise handcycling performance capability, it is recommended that an emphasis

347 be placed upon the development and frequent monitoring of the following parameters: PO_4, relative

348 $\dot{V}O_{2peak}$, power-to-mass ratio, PO_{peak}, GME, relative upper body strength and $PO_{max,AO15}$. Particular

349 attention should be placed upon the development of upper body pulling strength in order to enhance

350 the force production during the pulling phase of the handcycling propulsion cycle. Finally, whilst not

351 confirmed by the findings of this study, riders should aim to reduce their overall body fat summation

352 in order to further improve handcycling performance capabilities. Linked to this point, it follows that

353 it would also be prudent for a competitive handcycle to be as lightweight as possible

354

355

Conclusion

In conclusion, the findings of the present study indicate that PO_4, relative $\dot{V}O_{2peak}$, power-to-mass ratio, PO_{peak}, GME, relative upper body strength, $PO_{max,AO15}$ and APR all have significant impact upon 15-km TT velocity in H3/H4 handcyclists. To the best of the authors' knowledge, this is the first study to investigate the combined impact of anaerobic threshold, anaerobic capacity and upper-body strength upon real-world handcycling TT performance. Based upon our findings it is recommended that future research associated with establishing determinants of handcycling performance use a larger, more homogenous, group of competitive, preferably elite handcyclists. If sufficient data could be collected it would be possible to construct an accurate performance model using multiple regression analysis.

Declaration of Interest

There is no conflict of interest to declare for the present article.

References

1. Abel T, Schneider S, Platen P, & Struder HK. Performance diagnostics in handcycling during competition. *Spinal Cord*. 2006; 44: 211 – 216.

2. Abel T, Burkett B, Schneider S, et al. The exercise profile of an ultra-long handcycling race: The Styrkeproven experience. *Spinal Cord*. 2010; 48: 894 – 898.

3. Abel T, Vanlandewijck Y, & Verellen J. Handcycling, In *Wheelchair Sport*. Champaign, IL: Human Kinetics; 2010.

4. Abel T, Burkett B, Thees B, et al. Effect of three different grip angles on physiological parameters during 2 laboratory handcycling tests in able-bodied participants. *Front Physio*. 2015; 23(6): 331.

380   5.   Arnet U, Van Drongelen S, Van Der Woude LHV, et al. Shoulder load during handcycling at

381   different incline and speed positions. *Clin Biomech*. 2012; 27(1): 1 – 6.

382   6.   Arnet U, Van Drongelen S, Schlussel, et al. The effect of crank position and backrest

383   inclination on shoulder load and mechanical efficiency during handcycling. *Scand J Med Sci*

384   *Sport*. 2014; 24: 386 – 394.

385   7.   Bertucci W, Duc S, Villerius V, et al. Validity and reliability of the Powertap mobile cycling

386   power meter when compared with the SRM device. *Int J Sports Med*. 2015; 26(10): 868 –

387   873.

388   8.   Borg, GA. Psychophysical based of perceived exertion. Med Sci Sports Exerc. 1982; 14: 377

389   – 388.

390   9.   De Groot S, Postma K, Van Vliet L, et al. Mountain time trial time in handcycling: exercise

391   intensity and predictors of race time in people with spinal cord injury. *Spinal Cord*. 2014; 52:

392   455 – 461.

393   10.   Faria EW, Parker DL,& Faria IE. The science of cycling physiology and training – Part 1.

394   *Sports Med*. 2005; 35(4): 313 – 337.

395   11.   Faria, EW, Parker DL, & Faria IE. The science of cycling factors affecting performance – Part

396   2. *Sports Med*. 2005; 35(4): 313 – 337.

397   12.   Faupin A, Gorce P, Watelain E, et al. A biomechanical analysis of handcycling: A case study.

398   *J Appl Biomech.* 2010; 2: 240 – 245.

399   13.   Fischer G, Ardigo L, & Figueiredo P. Physiological performance determinants of a 22-km

400   handbiking time trail. *Int J Sports Physiol Perf*. 2016; 10: 965 – 971.

401   14.   Garby L, & Astrup A. The relationship between the respiratory quotient and the equivalent of

402   oxygen during simultaneous glucose and lipid oxidation and lipogenesis. *Acta Physiol Scandi*.

403   1987; 129(3): 443 – 444.

404 15. Goosey-Tolfrey V, Keil M, Brooke-Wavell K, & De Groot S. A comparison of methods for
405   the estimation of body composition in highly trained wheelchair games players. Int J Sports
406   Med. 2016. 37(10): 799 – 806.

407 16. Haff GG, & Triplett NT. *Essentials of Strength Training and Conditioning* (4th Ed).
408   Champaign, Il: Human Kinetics. 2016.

409 17. Hopkins W, Marshall S, Batterham A, et al. Progressive statistics for studies in sports
410   medicine and exercise science. *Med Sci Sports Exerc*. 2009; 14: 3 – 12.

411 18. International Society for the Advancement of Kinanthropometry. *International Standards for*
412   *Anthropometric Assessment*. 2001.

413 19. Janssen TWJ, Dallmeijer AJ, & Van der Woude LHV. Physical capacity and race
414   performance of handcycle users. *J Rehabil Res Develop*. 2001; 38(1): 33 – 40.

415 20. Litzenberger S, Mally, F, & Sabo, A. Biomechanics of elite recumbent handcycling. A case
416   study. *Sports Eng*. 2016; 19(3), 201 – 211.

417 21. Lovell D, Sheilds D, Beck B, Cuneo R, et al. The aerobic performance of trained and
418   untrained handcyclists with spina cord injury. *Euro J Appl Physiol*. 2012; 112(9): 3431 –
419   3437.

420 22. Mannion P, Toparlar Y. Clifford E, Hajdukiewicz M, Andrainne T, & Blocken B. The impact
421   of arm-crank position on the drag of a Paralympic hand-cyclist. *Comp Methods in Biomech*
422   *and Biomech Engr*. 2019; 22(4): 386 – 395.

423 23. Perrett, C. Elite-adapted wheelchair sports performance: a systematic review. *Disabil Rehabil*.
424   2017; 39(2): 164 – 172.

425 24. Mason BS, Van der Woude LHV, & Goosey-Tolfrey VL. The ergonomics of the wheelchair
426   configuration for optimal performance in the wheelchair court sports. *Sports Med*. 2013;
427   43(1): 164 – 172.

428   25.   Nevin JP, Smith P, Waldron M, et al. Efficacy of an 8-week concurrent strength and

429   endurance training programme on hand cycling performance. *J Strength Cond Res*. 2018;

430   32(7): 1861 – 1868.

431   26.   Quittman OJ, Abel T, Zeller S, et al. Lactate kinetics in handcycling under various exercise

432   modalities and their relationship to performance measures of able-bodied participants. *Eur J*

433   *Appl Physiol*. 2018; 118(7): 1493 – 1505.

434   27.   Quittman OJ, Meskemper, J, Abel, T et al. Kinematics and kinetics of handcycling propulsion

435   at increasing workloads in able-bodied subjects. *Sports Eng*. 2018; 21(4): 283 – 294.

436   28.   Sanders D, & Heijboer, M. The anaerobic power reserve and its applicability in professional

437   road cycling. *J Sports Sci*. 2019; 37(6): 621 – 629.

438   29.   Smith P, Chapman M, Hazelhurst K, et al. The influence of crank configuration on muscle

439   activity and torque production during arm crank ergometry. *J Electro Kinesio*. 2008; 18(4): 598

440   – 605.

441   30.   Stangier C, Abel T, Zeller S, Quittman OJ, Perret C, & Struder HK. Comparison of different

442   blood lactate threshold concepts for constant load performance in spinal cord injury

443   handcyclists. *Front Physio*. 2019; 10 (1054): doi: 10.3389/fphys.2019.01054.

444   31.   Stone B, Mason BS, Warner MB, et al. Shoulder and thorax kinematics contribute to increased

445   power output of competitive handcyclists. *Scand J Med Sci Sport*. 2019; 29(6): 843 - 853.

446   32.   Stone B. Mason BS, Warner, MB & Goosey-Tolfrey VL. Horizontal crank position affects

447   economy and upper limb kinematics of recumbent handcyclists. *Med Sci Sports Exerc.* 2019;

448   51(11), 2265 – 2273.

449   33.   Union Cycliste Internationale, *Cycling Regulations*, Part 16 Para-Cycling. 2019.

450   34.   Vegter RJK, Mason, BS, Sporrel B, Stone B, Van Der Woude, LHV & Goosey-Tolfrey VL.

451   Crank fore-aft position alters the distribution of work over the push and pull phase during

452   synchronous recumbent handcycling in able-bodied participants. *PloS one.* 2019; 14(8): doi:

453   10.1371/journal.pone.0220943.

454 35. Weyand, PG, Line JE, & Bundle MW. Sprint performance duration relationships are set by the

455   fractional duration of external force application. *Am J Physio.* 2006; 290(3): 758 – 765.

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Table 1. Mean ($\pm$ *SD*) values of participant testing data

15 km Time Trial Velocity (km·h^{-1})	28.6 ± 6.3
Peak Heart Rate (bpm)	174 ± 12
Peak Blood Lactate (mmol·l^{-1})	11.9 ± 1.8
$\dot{V}O_{2peak}$ (l·min^{-1})	2.8 ± 0.5
Relative $\dot{V}O_{2peak}$ (ml·kg^{-1}min^{-1})	36.8 ± 10
PO_{peak} (W)	160 ± 26.7
Relative PO_{peak} (W·kg^{-1})	2.2 ± 0.7
GME (%)	13.4 ± 2.7
PO_4 (W)	119 ± 26
$PO_{max,AO15}$ (W)	547 ± 120
APR (W)	387 ± 107
Bench Press 1RM (kg)	90.2 ± 16.7
Relative Bench Press Strength (kg·kg^{-1} body mass)	1.2 ± 0.3
Prone Bench Pull 1RM (kg)	77.8 ± 13.2
Relative Prone Bench Pull Strength (kg·kg^{-1} body mass)	1.0 ± 0.3

Table 2. Correlations among parameters of 15-km TT performance

	Velocity (km·h⁻¹)	Body Mass (kg)	4-Site Skin Fold Summation (mm)	Relative $\dot{V}O_{2peak}$ (ml·kg⁻¹·min⁻¹)	PO_{peak} (W)	Power-to-Mass Ratio (W·kg⁻¹)	GME (%)	PO_4 (W)	$PO_{max,AO15}$ (W)	APR (W)	Bench Press 1RM (kg)	Relative Bench Press Strength (kg·kg⁻¹ body mass)	Prone Bench Pull 1RM (kg)	Relative Prone Bench Pull Strength (kg·kg⁻¹ body mass)
Velocity (km·h⁻¹)	-													
Body Mass (kg)	-.783**	-												
4-Site Skin Fold Summation (mm)	-.448	.151	-											
Relative $\dot{V}O_{2peak}$ (ml·kg⁻¹·min⁻¹)	.879**	-.835*	-.510*	-										
PO_{peak} (W)	.851**	-.825**	-.494	.774**	-									
Power-to-Mass Ratio (W·kg⁻¹)	.879**	-.921**	-.391	.831**	.964**	-								
GME (%)	.733**	-.821**	-.528	.853**	.717**	.798**	-							
PO_4 (W)	.927**	-.668*	-.637	.861**	.842**	.827**	.709**	-						
$PO_{max,AO15}$ (W)	.678*	-.571	-.383	.775**	.572	.563	.641*	.595*	-					
APR (W)	.548	-.435	-.306	.676*	.392	.392	.540	.457	.979**	-				
Bench Press 1RM (kg)	.423	-.505	-.271	.603*	.310	.379	.686*	.346	.684*	.690*	-			
Relative Bench Press Strength (kg·kg⁻¹ body mass)	.703*	-.814**	-.313	.822**	.647*	.735**	.871**	.615*	.734**	.662*	.899**	-		
Prone Bench Pull 1RM (kg)	.447	-.363	-.331	.506	.275	.285	.498	.358	.566	.657	.865**	.728**	-	
Relative Prone Bench Pull Strength (kg·kg⁻¹ body mass)	.770**	-.793**	-.356	.819**	.671**	.734**	.811**	.661*	.701*	.619*	.852**	.949**	.843**	-

**Correlation is significant at the <0.01 level (2-tailed)
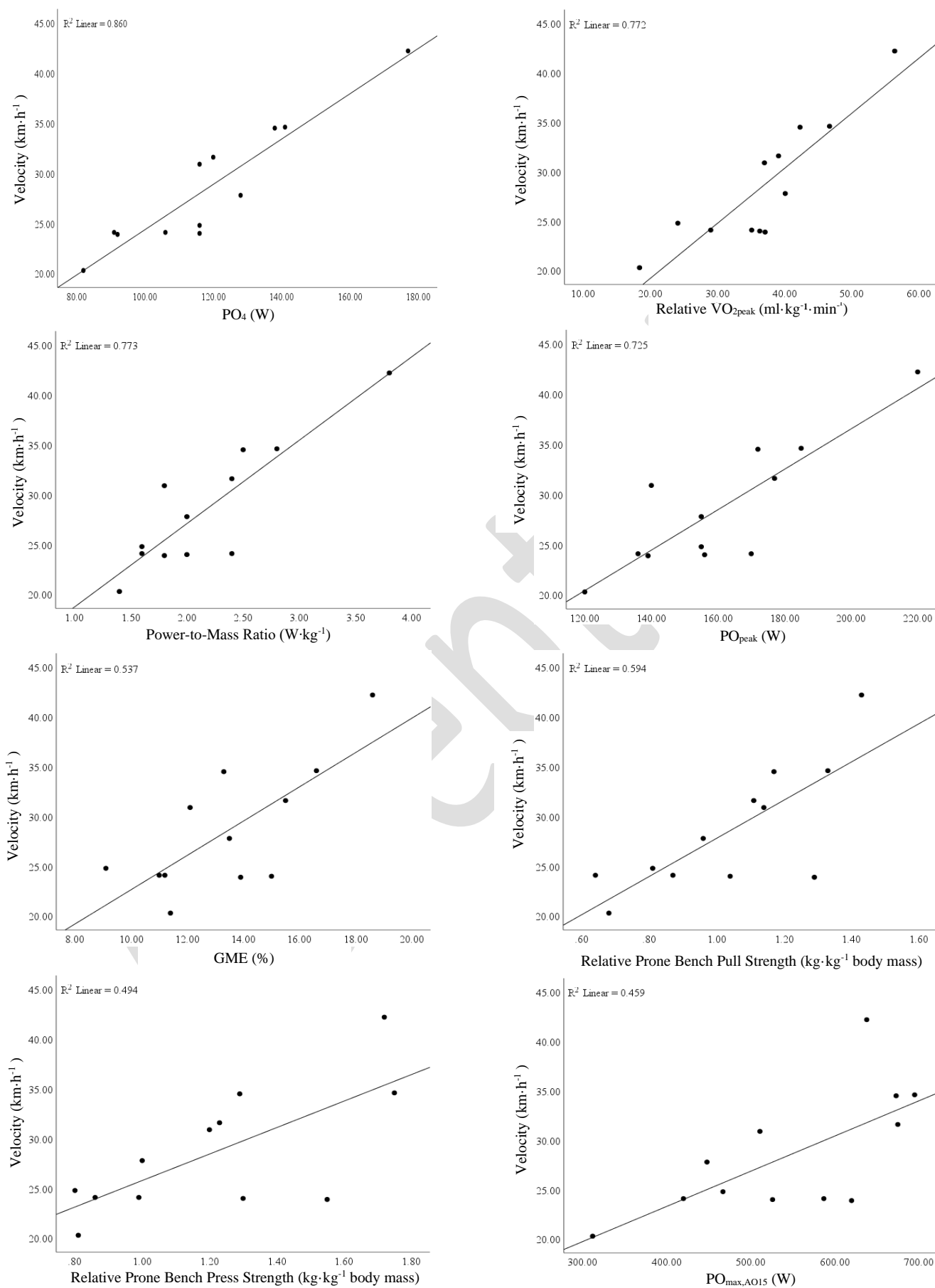* Correlation is significant at the < 0.05 level (2-tailed)

Fig 1. Correlation plots between 15-km TT velocity and parameters of exercise testing