Crank length alters kinematics and kinetics, yet not the economy of recumbent handcyclists at constant handgrip speeds

Barry S. Mason,[1] Benjamin Stone,[1] Martin B. Warner,[2,3] Victoria L. Goosey-Tolfrey[1]

[1] Peter Harrison Centre for Disability Sport, School for Sport, Exercise & Health Sciences, NCSEM, Loughborough University, Loughborough, UK.

[2] School of Health Sciences, University of Southampton, UK.

[3] Arthritis Research UK Centre for Sport, Exercise and Osteoarthritis.

Corresponding author:

Dr Barry Mason, Peter Harrison Centre for Disability Sport, School for Sport, Exercise & Health Sciences, NCSEM, Loughborough University, Loughborough, UK.

Email: b.mason@lboro.ac.uk

Footnote

Mason and Stone should be considered joint first authors

Abstract

Handcycling performance is dependent on the physiological economy of the athlete, however handbike configuration and the biomechanical interaction between the two is also vital. The purpose of this study was to examine the effect of crank length manipulations on physiological and biomechanical aspects of recumbent handcycling performance in highly trained recumbent handcyclists at a constant linear handgrip speed and sport-specific intensity. Nine competitive handcyclists completed a 3-min trial in an adjustable recumbent handbike in four crank length settings (150, 160, 170 & 180 mm) at 70% peak power output. Handgrip speed was controlled (1.6 m·s^{-1}) across trials with cadences ranging from 102 to 85 rpm. Physiological economy, heart rate and ratings of perceived exertion were monitored in all trials. Handcycling kinetics were quantified using an SRM (Schoberer Rad Messtechnik) power meter and upper limb kinematics were determined using a 10-camera VICON motion capture system. Physiological responses were not significantly affected by crank length. However, greater torque was generated ($p < 0.0005$) and peak torque occurred earlier during the push and pull phase ($p \leq 0.001$) in longer cranks. Statistical parametric mapping revealed that the timing and orientation of shoulder flexion, shoulder abduction and elbow extension was significantly altered in different crank lengths. Despite the biomechanical adaptations, these findings suggest that at constant handgrip speeds (and varying cadence) highly trained handcyclists may select crank lengths between 150 – 180 mm without affecting their physiological performance. Until further research, factors such as anthropometrics, comfort and self-selected cadence should be used to facilitate crank length selection in recumbent handcyclists.

Keywords:

Paralympic sport, handcycling, biomechanics, physiology, handbike configuration

Introduction

Recumbent handcycling is a Paralympic sport for athletes with a physical lower limb impairment. Handcycling performance is determined by a triad of the athlete, handbike and the handbike-user interface. However, previous research has largely focused on the physiological characteristics of the athlete,[1-5] rather than the configuration of the handbike and how athletes interact with their equipment.[6] Although there are numerous components to a handbike, the length of the crank arms was recently identified by handcycling experts as an area of configuration that could have a substantial bearing on performance.[6] Crank arms connect the handgrips, where force is applied by the user, to the crank axis which drives the chain and the handbike forward.[7] Crank lengths typically range between 160 – 175 mm in handbikes,[8] with elite handcyclists often selecting between 170 – 175 mm.[9] These crank lengths mimic those observed in leg-powered cycling.[10] Since the arm is approximately 30% shorter than the leg,[11] it seems unlikely that settings taken from leg-powered cycling would also be optimal for handcycling. However, the effect of crank length on handcycling performance has received limited empirical research.[12,-14]

Of the limited previous research, a higher power output was observed in able-bodied participants during maximal effort sprinting in longer (~ 190 mm) compared to shorter cranks (~ 139 & ~ 164 mm).[13] Whereas wheelchair users were more mechanically efficient in shorter cranks (180 mm) than longer cranks (220 mm) during submaximal handcycling (90 W) at fixed cadences.[12] Finally, no meaningful changes in muscular activity were noted between 160 mm to 175 mm crank lengths in a single sample case study with a highly trained handcyclist, where multiple other adjustments to handbike configuration were made concurrently.[14] Unfortunately, the application of these previous findings to highly trained recumbent handcyclists are limited by several factors. Firstly, the ergometer-based handbike[13] and touring handbike[12] used differ distinctly to the recumbent handbikes used by elite handcyclists.

72 Secondly, the limited use of handcyclists as participants in addition to the non-sport specific

73 range of crank lengths investigated further limits the application of these findings.[12,13] From a

74 methodological perspective, the fixed cadences adopted by Goosey-Tolfrey et al.[12] could

75 confound performance when investigating crank length. At fixed cadences (angular handgrip

76 speeds), participants must move the handgrips at a higher linear speed in a longer crank to

77 match the cadence of a shorter crank and likely accounts for the physiological differences

78 observed with respect to crank length.[12] Finally, performance in different crank length settings

79 have only been described according to power output, physiological cost or muscle activation

80 patterns. No previous studies have considered the kinetic or kinematic implications of crank

81 length adjustments.

82   Differences in upper limb kinematics such as greater thorax flexion and shoulder

83 extension have recently been associated with performance during recumbent handcycling.[9]

84 Further changes to kinematics have also been observed when manipulating the horizontal crank

85 position of trained handcyclists.[15] Therefore, motion analysis of upper limb kinematics could

86 provide further insight into the optimisation of handbike, and crank length configuration.

87 Furthermore, recent studies have frequently instrumented recumbent handbikes with Schoberer

88 Rad Messtechnik (SRM) power meters to quantify cycle kinetics during handcycling.[16,17]

89 Whilst this research has largely explored able-bodied participants, the technology offers

90 valuable information to further understand the effects of crank length manipulations. Although

91 previous research has included a combination of kinematic and kinetic measures to examine

92 the effects of different handbike configurations,[18-21] no study has combined all these measures

93 to investigate trained handcyclists, cycling at sport-specific intensities in a recumbent

94 handbike. Subsequently the aim of the current study was to explore the impact of crank length

95 on physiological and biomechanical aspects of recumbent handcycling at fixed linear handgrip

96 speeds and sport-specific intensities in highly trained handcyclists.

Materials and Methods

Participants

Nine handcyclists (8 male; 1 female; age: 33.2 ± 8.6 yrs; body mass: 68.5 ± 11.6 kg; arm length: 67.3 ± 2.5 cm; classification: 4 H3 and 5 H4; injury description: 4 spinal cord injury (SCI) complete (T4 – T11), 1 SCI incomplete (T8), 2 lower limb amputees, 2 cerebral palsy) participated in the study. None of the participants had an upper limb impairment and all competed at national or international level in handcycling or paratriathlon (handcycling experience: 4 ± 2 yrs; training load: 4 ± 2 sessions totalling 9 ± 4 h·wk^{-1} with a weekly self-reported distance of 153 ± 76 km·wk^{-1}). The local ethics advisory committee approved the study. Prior to participation, all participants provided their written, informed consent.

Experimental Design

Participants completed a maximal exercise test followed by four crank length experimental trials (150, 160, 170 & 180 mm) on a power controlled handcycling ergometer (Cyclus II, RBM electronic-automation GmbH, Leipzig, Germany) fixed in the highest gear ratio (50/10), on the same day. The maximal exercise test was performed in participants own customised recumbent handbikes, with their self-selected crank lengths (range: 165 to 175 mm) to determine their peak power output (PO$_{Peak}$). Crank length trials were then performed in a bespoke adjustable recumbent handbike (Schmicking Reha Technik GmbH, Holzwickede, Germany) at 70% PO$_{Peak}$ to replicate handcycling time trial intensity.[5]

i) Maximal Exercise Test

Following a 10-minute warm-up at a self-selected power and cadence, participants performed 4-minute blocks of submaximal handcycling starting at 20 W (15 W for females), increasing by 20 W (15 W for females) every 4 minutes based on a previous protocol.[9] Cadence was still selected, although upper limits existed during some of the early stages. At the end of each 4-minute block, a capillary blood sample was taken from the ear lobe and analysed using a Biosen C-line monitor (EKF Diagnostics, Barleben, Germany) to measure blood lactate (BLa) concentration. Submaximal tests were terminated when BLa exceeded $4 mmol \cdot L^{-1}$. Throughout testing, breath-by-breath expired air was collected and analysed (Cortex Metalyzer 3B, Cortex, Leipzig, Germany), to calculate peak oxygen uptake ($\dot{V}O_2$), determined as the highest value over a 15 s period. On completion of the submaximal test, participants aerobic threshold was calculated via the log-log transformation method.[9] Following 30 minutes rest, a maximal incremental test to exhaustion commenced at a power output equivalent to their aerobic threshold for two minutes. Power increased at a rate of $20 W \cdot min^{-1}$ for males (5 W every 15 s) and $15 W \cdot min^{-1}$ for females (5 W every 20 s), until volitional exhaustion, defined as a failure to maintain a cadence ≥ 50 rpm and an overall rating of perceived exertion (RPE) between 19-20.[9]

ii) Crank Length Experimental Trials

After two hours rest the adjustable handbike was configured to replicate participants recumbent handbike, using anthropometric, handbike configuration and handbike-user interface measurements.[9] To achieve a standardised crank position at each crank length, crank height (2 cm clearance between handgrip and abdomen) and crank fore-aft position (97% arm-length) were adjusted based on previous findings.[14] Crank width (33 cm) and handgrip angle (15°) was also constant.

144   Due to the trade-off between cadence and handgrip speed when handcycling at different

145   crank lengths, handgrip speed was controlled (1.6 m·s^{-1}). This led to fixed cadences of 102, 96,

146   90 and 85 rpm at 150, 160, 170 and 180 mm crank lengths respectively. 3-minute trials were

147   performed at 70% PO$_{Peak}$ in a randomised order, with 15 minutes passive recovery between

148   each crank length setting.

149

150   Measures

151   *Physiology*

152   During the last minute of each crank length trial $\dot{V}O_2$ was averaged and used to quantify

153   handcycling economy, defined as $\dot{V}O_2$ relative to power (mL·min^{-1}·W^{-1}) as documented

154   previously.[9] Heart rate (HR) was collected continuously at 1-s intervals and was averaged over

155   the final minute (Polar RS400, Polar, Kempele, Finland). At the end of each trial participants

156   reported their local (RPE – L), central (RPE – C) and overall (RPE – O) ratings of perceived

157   exertion using Borg's 6-20 scale.[22]

158

159   *Kinetics*

160   The adjustable handbike was equipped with an SRM Science Power meter and SRM Torque

161   Analysis system (Jülich, Germany), which enabled cycle torque to be measured at 200 Hz.

162   Between each trial, the SRM was calibrated according to the manufacturer's instructions. Cycle

163   torque was collected throughout the last minute of each trial and averaged across the recorded

164   cycles. Based on previous handcycling literature,[23] peak torque and the angle at which peak

165   torque occurred during both the push and pull phase were determined for each crank length.

166

167   *Kinematics*

168   Upper body kinematics were captured using a 10-camera motion capture system (Vicon T40S;

169   Vicon Motion Systems, Oxford, UK), sampling at 200 Hz. Based on a previous study,[9]

170   retroreflective markers were attached to anatomical locations on the thorax, upper arm, forearm

171   and hand. Acromion marker clusters were attached bilaterally to the acromions to determine

172   scapular kinematics, according to previous guidelines.[24,25] Two further markers were attached

173   bilaterally to the crank arms of the handbike. With participants seated in the anatomical

174   position, a series of static trials were captured with the tip of a calibration wand used to

175   determine the anatomical landmarks from marker clusters.[9,25] A 10 s shoulder circumduction

176   trial was then captured to functionally determine the glenohumeral joint centre.[26] For the

177   experimental trials, the final 20 s of each 3-minute bout was captured to allow at least 10

178   complete and consecutive cycles in each crank length configuration.

179   The Optimal Common Shape Technique was used to minimise soft-tissue artefact

180   within the kinematic data.[27] The Symmetrical Centre of Rotation Estimation technique was

181   used to calculate the glenohumeral joint centres from the circumduction trials.[28] The global

182   coordinate system was defined such that the Y-axis pointed anteriorly, the X-axis aligned with

183   the rotation axis of the crank, and the Z-axis pointed vertically following the right-hand rule.

184   Anatomical local coordinate systems were then constructed and rotation sequences for the

185   thorax, clavicle, scapula, humerus, forearm, and hand segments followed International Society

186   of Biomechanics' recommendations.[29] Three-dimensional bilateral upper body kinematics

187   were analysed for the thorax, clavicle, scapular, shoulder, elbow, and wrist over 10 cycles. A

188   cycle was defined as one rotation of the crank, starting with the cranks in a vertical position

189   pointing upwards (0° or 0%). Crank angle was determined using Euler angles (ZXY sequence)

190   and upper body kinematics were normalized to cycle duration (0%‑100%) and then averaged

191 across the 10 cycles.[9] Since no kinematic differences between left and right sides were

192 identified during previous handcycling ergometry,[9] only data from the right side was presented.

193

194 <u>Statistical Analysis</u>

195 Statistical analyses were conducted using the Statistical Package for Social Sciences (SPSS

196 version 24, IBM Statistics, Chicago, IL). All data were checked for normality using Shapiro-

197 Wilk tests. Repeated measures analysis of variance was conducted on all physiological, kinetic

198 and joint range of movement (RoM) kinematic data when normality was assumed. When

199 assumptions of normality had been violated, the non-parametric Friedman test was performed.

200 Statistical significance was accepted as $p < 0.05$. Pairwise comparisons with a Bonferroni

201 correction were conducted as a post-hoc test when a significant main effect had been identified.

202 Statistical parametric mapping (SPM) was used to further explore upper body joint

203 kinematics using a repeated measures SPM ANOVA.[30] Where significant differences were

204 established, SPM t-tests were conducted as a post-hoc measure to identify the time points

205 throughout the kinematic waveform where a significant difference existed. All SPM analyses

206 were conducted in Matlab (R2016a, 8.3.0.532, The Mathworks Inc., Natick, MA) using the

207 open-source spm1d.code (v.M0.1, www.spm1d.org).

208

209 **Results**

210 Participants achieved a PO_{Peak} of 232 ± 44 W, subsequently, crank length experimental trials

211 were performed at 163 ± 33 W to reflect 70% PO_{Peak}. Results revealed that crank length had

212 no significant effect on any physiological measure (Table 1).

213 ***TABLE 1 HERE***

214   Mean torque traces of each crank length are displayed in Figure 1. Peak torque

215   increased significantly with increased crank length between all settings except between 160

216   mm and 170 mm ($p = 0.107$) during the push phase, and 150 mm and 160 mm ($p = 0.080$)

217   during the pull phase (Table 2). Crank length also significantly affected the angle at which peak

218   torque occurred during the cycle ($p \leq 0.001$). Peak torque occurred earlier into the push phase

219   in a longer crank and occurred closer to top dead centre as crank length reduced, although the

220   difference was only statistically significant between 150 and 180 mm ($p = 0.034$). Peak torque

221   also occurred earlier during the pull phase in longer cranks and later as crank length decreased.

222   Differences were statistically significant ($p \leq 0.017$) between all crank lengths during the pull

223   phase (Table 2).

FIGURE 1 & TABLE 2 HERE

225   Crank length had a significant effect on numerous kinematic parameters during

226   handcycling. Joint RoM significantly increased from the shortest (150 mm) to the longest (180

227   mm) cranks for many joint actions (Table 3). SPM ANOVA indicated that crank length also

228   significantly affected the internal / external rotation at the scapular and shoulder, flexion /

229   extension at the shoulder, elbow and wrist and adduction / abduction at the shoulder. (Table 4).

230   However, significant post-hoc differences were only revealed for shoulder flexion / extension,

231   abduction / adduction and elbow flexion / extension. Figure 2 illustrates these differences

232   between the two extreme crank length settings (150 vs. 180 mm). Shoulder flexion was

233   significantly greater during 0 – 26% and 73 – 100% of the cycle and less flexed during 48 –

234   63% of the cycle in longer crank lengths. Shoulder abduction significantly increased between

235   68 – 74% of the cycle in the longer crank lengths. Elbow extension was greater during 12 –

236   18% of the cycle, with more flexion observed between 42 – 78% of the cycle in longer cranks

237   (Figure 2).

238   ***TABLE 3 & 4 & FIGURE 2 HERE***

239

240 **Discussion**

241   The current study was the first to provide a comprehensive insight into the effect of

242 crank length on the physiological, kinetic and kinematic responses of trained handcyclists,

243 whilst exercising at sport-specific intensities in a highly standardised recumbent handbike.

244 Competitive handcyclists typically select crank lengths between 170 – 175 mm,[9] and this study

245 has revealed that although biomechanical adaptations exist, no physiological gains (or

246 decrements) were experienced in settings either side of this range when handgrip speed is

247 controlled.

248   The lack of physiological differences contrasts the only previous study in the area,[12]

249 and is likely the result of different protocols employed and the complex relationship that exists

250 between crank length, handgrip speed and cadence.[31] Unlike the current study Goosey-Tolfrey

251 et al.[12] manipulated crank length at fixed cadences. Consequently, the reduced mechanical

252 efficiency observed in longer (220 mm) compared to shorter (180 mm) cranks was likely due

253 to increased muscle shortening velocity required to maintain the same cadence in a longer

254 crank.[32] In cyclic sports such as handcycling, changing crank length concurrently affects

255 cadence and handgrip speed and ultimately performance.[31] However, under no additional

256 constraints it was perceived that athletes would automatically adjust their cadence across

257 different crank length settings rather than maintain a fixed cadence. Subsequently, although

258 cadence can alter the physiological demand of handcycling,[33,34] it was deemed more

259 ecologically valid to control handgrip speed in the current study.

260   Under such experimental conditions, the absence of any physiological and perceptual

261 differences between crank lengths suggest that other factors must be considered to establish

262 optimal crank length configurations, of which aerodymanics could be one. The current study

11

was conducted in laboratory settings on a handycling ergometer. However, given the high speeds handcyclists reach during training and competition,[2,35] air resistance can have a bearing on performance outside of a laboratory environment. Mannion et al.[36] reported that the frontal area of a Paralympic handcyclist is greatest when the cranks are positioned at top dead centre and the arms are elevated away from the torso. Therefore, in the same position it is highly likely that a reduced frontal area and subsequently reduced air resistance would be experienced in shorter crank lengths, which could make these settings physiologically advantageous during overground handcycling, if athletes adjust their cadence accordingly.

A novel feature of the current study was the inclusion of biomechanical measures, never previously explored with regards to crank length. The only previous kinetic examinations of recumbent handcycling have been with able-bodied participants, where it has been revealed that greater torque was produced during the pull phase.[21] Whereas the current study identified that independent of crank length, trained handcyclists produced greater torque during the push phase, which highlights why results from able-bodied studies cannot be translated to trained handcyclists. As anticipated, greater mean torque was generated in longer crank lengths. Since handgrip speed and power output was controlled, force application was likely to be similar across crank lengths and, therefore, a longer crank would result in the greater mean torque. However, the current study revealed that the peak torque also increased during both the push and pull phases as a result of increased crank length. In addition, the change in crank length also affected the timing of peak torque during both phases. Increasing crank length from the shortest (150 mm) to the longest (180 mm) setting resulted in the peak torque being generated ~ 11° (3%) earlier during the push phase and ~ 13° (4%) earlier during the pull phase. Such changes will likely affect the length-tension relationship[37] and muscle activation-deactivation dynamics[31] of key muscles involved.

287   Consequently, it was no surprise that upper body kinematics were also significantly

288   altered when handcycling with different crank lengths. During the push phase, the shoulder

289   was significantly more flexed and the elbow more extended to lift up and drive forward the

290   longer (180 mm) cranks compared to the shorter (150 mm) cranks. The shoulder was also

291   shown to be significantly more abducted at the onset of the push phase in the longest cranks.

292   This kinematic change was likely associated to the standardised horizontal crank position

293   maintained across settings. Subsequently, a longer crank will pass closer to the thorax of a

294   handcyclist, who likely compensates by abducting the shoulders to help drive the cranks up

295   and forward, which could again make the athlete less aerodynamic in longer cranks outside of

296   a laboratory. Conversely, during the pull phase the shoulder was significantly more extended

297   and the elbow more flexed to pull the longer cranks down and back towards participants.

298   Consequently, joint RoM increased for all these motions in the longest crank setting. Whether

299   or not these biomechanical adaptations associated with different crank lengths are positive or

300   negative remains to be seen and future research should explore the implications for injury risk

301   in different crank length settings owing to the lack of physiological changes in performance

302   currently observed. Such future research could investigate internal joint forces to better

303   understand the impact of handbike configuration on upper limb loading and injury risk.

304   Research into the effects of cadence alongside crank length and handgrip speed are

305   required in future to understand the interrelationships between these phenomena and to better

306   inform athletes about optimal crank lengths. Lower cadences (50 – 60 rpm) have been shown

307   to be more mechanically efficient at low handcycling intensities (15 – 70 W).[33,34] At a slightly

308   higher intensity (90 W), no differences in efficiency were observed between moderate cadences

309   (70 – 85 rpm).[12] Whereas during maximal sprinting, peak power output increased up until 114

310   rpm, before steadily decreasing.[13] Subsequently different crank lengths could be more

311   favourable depending on the intensity, but also the preferred cadence of an athlete. This has

been confirmed to an extent during sprinting, whereby a crank length ~ 190 mm was more effective at 108 rpm, yet a shorter crank length ~ 139 mm was more effective at a higher 125 rpm.[13] However, to test a range of crank lengths at different cadences and handgrip speeds would result in many conditions, trials and even visits, which may not be feasible especially when examining highly trained handcyclists. Therefore, musculoskeletal modelling and computer simulation could be a more viable, alternative method for future research in this area.

To individualise findings to athletes and potentially make the findings applicable to handcyclists outside of those currently investigated, future research could benefit from making crank length adjustments relative to the physical characteristics of the user, such as arm length. This approach was previously adopted by Kramer et al.[13] who manipulated crank length from 19 – 26% of participants arm length, which resulted in crank length setting ranging from 126 – 208 mm. Given the likely differences in arm length between athletes it would not have been possible to test a broad range of relative crank lengths that would cater for all in the current study, without compromising the strict standardisation protocol in a recumbent handbike. However, reporting results relative to anthropometrics could provide a different insight and is worth investigating further.

Perspectives

The current study was the first to explore the effect of crank length on the physiological and biomechanical performance of trained recumbent handcyclists under highly standardised handbike settings and at fixed handgrip speeds. The findings demonstrated that crank length manipulations alter the kinetics and kinematics of recumbent handcyclists without influencing their physiological economy. Consequently, handcyclists could select any crank length between 150 – 180 mm without inhibiting their physiological responses, which are often the key determinants of performance.[1-5] Therefore, until further research, factors such as comfort,

337 aerodynamics and preferred cadence could be used to inform crank length selection and is of

338 relevance to handcyclists, coaches, practitioners and also handbike manufacturers in particular.

339

340 **References**

341 1. Janssen TWJ, Dallmeijer AJ, van der Woude LHV. Physical capacity and race

342 performance of handcycle users. J Rehabil Res Dev 2001;38:33-40.

343 2. Abel T, Schneider S, Platen P, Struder HK. Performance diagnostics in handbiking

344 during competition. Spinal Cord 2006;44:211-216.

345 3. de Groot S, Postma K, van Vliet L, Timmermans R, Valent L. Mountain time trial in

346 handcycling: exercise intensity and predictors of race time in people with a spinal cord

347 injury. Spinal Cord 2014;52:455-461.

348 4. Fischer G, Figueiredo P, Ardigo LP. Physiological performance determinants of a 22

349 km handbiking time trial. Int J Sports Physiol Perform 2015;10:965-971.

350 5. Stone B, Mason BS, Stephenson BT, Goosey-Tolfrey VL. Physiological responses

351 during simulated 16 km recumbent handcycling time trial and determinants of

352 performance in trained handcyclists. Eur J Appl Physiol 2020;120:1621-1628.

353 6. Stone B, Mason BS, Bundon A, Goosey-Tolfrey VL. Elite handcycling: a qualitative

354 analysis of recumbent handbike configuration for optimal sports performance.

355 Ergonomics 2019;62:449-458.

356 7. Zipfel E, Olson J, Puhlman J, Cooper RA. Design of a custom racing hand-cycle:

357 review and analysis. Disabil Rehabil Assist Technol 2009;4:119-128.

358 8. Litzenberger S, Mally F, Sabo A. Biomechanics of elite recumbent handcycling: a case

359 study. Sports Eng 2016;19:1-11.

360   9. Stone B, Mason BS, Warner MB, Goosey-Tolfrey VL. Shoulder and thorax kinematics

361   contribute to increased power output of competitive handcyclists. Scand J Med Sci

362   Sports 2019;29:843-853.

363   10. Ferrer-Roca V, Rivero-Palomo V, Ogueta-Alday A, Rodriguez-Marroyo JA, Garcia-

364   Lopez J. Acute effects of small changes in crank length on gross efficiency and

365   pedalling technique during submaximal cycling. J Sports Sci 2017;35:1328-1335.

366   11. Gordon CC, Churchill T, Clauser CE, et al. 1988 Anthropometric Survey of U.S. Army

367   Personnel: Summary Staistics: Interim Report. Natick Labs, Yellow Springs, OH. 1989.

368   12. Goosey-Tolfrey VL, Alfano H, Fowler N. The influence of crank length and cadence

369   on mechanical efficiency in hand cycling. Eur J Appl Physiol 2008;102:189-194.

370   13. Kramer C, Hilker L, Bohm H. Influence of crank length and crank width on maximal

371   hand cycling power and cadence. Eur J Appl Physiol 2009;106:749-757.

372   14. Litzenberger S, Mally F, Sabo A. Biomechanics of elite recumbent handcycling: a case

373   study. Sports Biomech 2016;19:201-211.

374   15. Stone B, Mason BS, Warner MB, Goosey-Tolfrey VL. Horizontal crank position

375   affects economy and upper limb kinematics of recumbent handcyclists. Med Sci Sports

376   Exerc 2019;51:2265-2273.

377   16. Quittman OJ, Abel T, Albracht K, Meskemper J, Foitschik T, Strueder HK.

378   Biomechanics of handcycling propulsion in a 30-min continuous load test at lactate

379   threshold: kinetics, kinematics and muscular activity in able-bodied participants. Eur J

380   Appl Physiol 2020;120:1403-1415.

381   17. Quittmann OJ, Abel T, Albracht K, Strueder HK. Biomechanics of all-out handcycling

382   exercise: kinetics, kinematics and muscular activity of a 15-s sprint test in able-bodied

383   participants.   Sports   Biomech   2020;Epub   ahead   of   print:7   May   2020

384   https://doi.org/10.1080/14763141.2020.1745266

385   18. Faupin A, Gorce P, Meyer C, Thevenon A. Effects of backrest positioning and gear
386   ratio on nondisabled subjects handcycling sprinting performance and kinematics. J
387   Rehabil Res Dev 2008;45:109-116.

388   19. Kramer C, Schneider G, Bohm H, Klopfer-Kramer I, Senner V. Effect of different
389   handgrip angles on work distribution during hand cycling at submaximal power levels.
390   Ergonomics 2009;52:1276-1286.

391   20. Arnet U, van Drongelen S, Schlussel M, Lay V, van der Woude LHV. The effect of
392   crank position and backrest inclination on shoulder load and mechanical efficiency
393   during handcycling. Scand J Med Sci Sport 2014;24:386-394.

394   21. Vegter RJK, Mason BS, Sporrel B, van der Woude LHV, Goosey-Tolfrey VL. Crank
395   fore-aft position alters the distribution of work over the push and pull phase during
396   synchronous recumbent handcycling in able-bodied participants. PLoS One
397   2019;14:e0220943.

398   22. Borg G. Borg's perceived exertion and pain scales. Human Kinetics, Champaign, IL.
399   1998.

400   23. Verellen J, Janssens L, Meyer C, Vanlandewijck Y. Development and application of a
401   handbike ergometer to measure 3D force generation pattern during arm crank
402   propulsion in realistic handcycling conditions. Sport Technol 2012;5:65-73.

403   24. Shaheen AF, Alexander CM, Bull A. Effects of attachment position and shoulder
404   orientation during calibration on the accuracy of the acromial tracker. J Biomech
405   2011;44:1410-1413.

406   25. Warner MB, Chappell PH, Stokes MJ. Measurement of dynamic scapular kinematics
407   using an acromion marker cluster to minimize skin movement artifact. J Vis Exp
408   2015;96:1-14.

409   26. Monnet T, Desailly E, Begon M, Vallee C, Lacouture P. Comparison of the SCoRE and

410   HA methods for locating in vivo the glenohumeral joint centre. J Biomech

411   2007;40:3487-3492.

412   27. Taylor WR, Ehrig RM, Duda, GN, Schell H, Seebeck P, Heller MO. On the influence

413   of soft tissue coverage in the determination of bone kinematics using skin markers. J

414   Orthop Res 2005;23:726-734.

415   28. Ehrig RM, Taylor WR, Duda GN, Heller MO. A survey of formal methods for

416   determining the centre of rotation of ball joints. J Biomech 2006;39:2798-2809.

417   29. Wu G, van der Helm, Veeger H, et al. ISB recommendation on definitions of joint

418   coordinate systems of various joints for the reporting of human joint motion – part II:

419   shoulder, elbow, wrist and hand. J Biomech 2005;38:981-992.

420   30. Pataky TC, Robinson MA, Vanrenterghem J. Vector field statistical analysis of

421   kinematic and force trajectories. J Biomech 2013;46:2394-2401.

422   31. Martin JC, Spiriduso WW. Determinants of maximal cycling power: crank length,

423   pedalling rate and pedal speed. Eur J Appl Physiol 2001;84:413-418.

424   32. Barratt PR, Martin JC, Elmer SJ, Korrf T. Effects of pedal speed and crank length on

425   pedalling mechanics during submaximal cycling. Med Sci Sports Exerc 2016;48:705-

426   713.

427   33. Verellen J, Theisen D, Vanlandewijck Y. Influence of crank rate in hand cycling. Med

428   Sci Sports Exerc 2004;36:1826-1831.

429   34. Kraaijenbrink C, Vegter RJK, Hensen AHR, Wagner H, van der Woude LHV. Different

430   cadences and resistances in submaximal synchronous handcycling in able-bodied men:

431   effects on efficiency and force application. PLoS One 2017;12:e0183502.

432   35. Zeller S, Abel T, Strueder HK. Monitoring training load in handcycling: a case study.

433   J Strength Cond Res 2017;31:3094-3100.

434   36. Mannion P, Toparlar Y, Clifford E, Hajdukiewicz M, Andrianne T, Blocken B. The

435   impact of arm-crank position on the drag of a Paralympic hand-cyclist. Comput

436   Methods Biomech Biomed Eng 2019;22:386-395.

437   37. Murray WM, Buchanan TS, Delp SL. The isometric functional capacity of muscles that

438   cross the elbow. J Biomech 2000;33:943-952.

439

Table 1. Mean ± SD physiological measures of performance in different crank lengths.

		P	150 mm	160 mm	170 mm	180 mm
Economy	$(\text{mL·min}^{-1}\text{·W}^{-1})$	0.942	16.5 ± 3.0	16.2 ± 2.0	16.3 ± 2.6	16.2 ± 2.2
Heart rate	(beats·min^{-1})	0.065	166 ± 12	164 ± 12	161 ± 14	159 ± 15
RPE – L		0.568	15 ± 2	14 ± 1	15 ± 2	15 ± 1
RPE – C		0.246	15 ± 3	14 ± 2	14 ± 2	14 ± 2
RPE - O		0.697	15 ± 2	14 ± 2	15 ± 2	14 ± 2

Table 2. Mean ± SD cycle kinetics during the push and pull phase in different crank lengths.

		p	150 mm	160 mm	170 mm	180 mm
Push						
Peak Torque	N·m^{-1}	<0.0005	32.8 ± 6.6	35.2 ± 6.4*	37.6 ± 7.3*	41.8 ± 8.9*#^
Peak torque angle	Degrees (°)	0.001	358.2 ± 10.2	356.9 ± 9.9	352.8 ± 13.3	347.4 ± 13.2*
	% cycle		99.5 ± 2.8	99.1 ± 2.8	98.0 ± 3.7	96.5 ± 3.7
Pull						
Peak Torque	N·m^{-1}	<0.0005	28.6 ± 5.8	30.9 ± 7.4	33.6 ± 8.4*#	36.3 ± 8.7*#^
Peak torque angle	Degrees (°)	<0.0005	152.3 ± 8.1	148.6 ± 8.4*	144.1 ± 8.9*#	138.8 ± 8.7*#^
	% cycle		42.3 ± 2.3	41.3 ± 2.3	40.0 ± 2.5	38.6 ± 2.4

Significant difference to: * 150 mm, # 160 mm, ^ 170 mm

Table 3. Mean ± SD joint range of movements (°) of handcyclists in different crank lengths.

	p	150	160	170	180
Thorax					
Flexion/extension	0.530	4.0 ± 1.4	3.7 ± 1.3	4.2 ± 1.4	4.0 ± 1.4
Clavicle					
Protraction/retraction	0.479	9.6 ± 1.6	9.9 ± 2.1	10.2 ± 2.1	10.4 ± 1.8
Elevation/depression	0.242	7.0 ± 2.3	7.1 ± 2.9	7.5 ± 2.2	7.6 ± 3.0
Scapular					
Internal/external rotation	<0.0005	17.5 ± 4.1	18.3 ± 5.2	19.3 ± 4.5*	20.6 ± 5.6*#
Upward/downward rotation	0.045	11.3 ± 3.0	12.0 ± 3.2	13.1 ± 3.5	12.9 ± 3.8
Anterior/posterior tilt	0.004	15.2 ± 3.2	15.0 ± 3.3	16.9 ± 5.2	18.0 ± 5.1*
Shoulder					
Flexion/extension	<0.0005	54.6 ± 4.9	58.9 ± 5.2*	62.3 ± 4.7*#	66.0 ± 5.0*#^
Abduction/adduction	0.001	19.8 ± 3.8	22.5 ± 3.9*	23.1 ± 4.4*	24.7 ± 4.4*^
Internal/external rotation	<0.0005	41.2 ± 8.2	44.0 ± 8.7*	44.4 ± 8.7*	47.3 ± 8.6*#
Elbow					
Flexion/extension	<0.0005	73.6 ± 8.3	77.8 ± 9.4*	81.8 ± 10.0*#	86.0 ± 9.4*#^
Pronation/supination	0.053	23.9 ± 6.7	24.7 ± 7.7	26.9 ± 8.6	28.0 ± 9.4
Wrist					
Flexion/extension	0.414	15.6 ± 6.6	15.3 ± 7.2	17.4 ± 6.1	16.9 ± 5.4
Radial/ulnar deviation	0.001	25.8 ± 7.4	27.7 ± 8.2	29.1 ± 7.5	30.1 ± 6.9*

Significant difference to: * 150 mm, # 160 mm, ^ 170 mm

Table 4. Statistical Parametric Mapping ANOVA and post-hoc comparisons of handcycling kinematics in different crank lengths.

	p	150 v. 160	150 v. 170	150 v. 180	160 v.170	160 v. 180	170 v. 180
Thorax							
Flexion/extension	ns	-	-	-	-	-	-
Clavicle							
Protraction/retraction	ns	-	-	-	-	-	-
Elevation/depression	ns	-	-	-	-	-	-
Scapular							
Internal/external rotation	0.048	ns	ns	ns	ns	ns	ns
Upward/downward rotation	ns	-	-	-	-	-	-
Anterior/posterior tilt	ns	-	-	-	-	-	-
Shoulder							
Flexion/extension	0.020	<0.001	<0.001	<0.001	<0.001	<0.010	<0.010
Abduction/adduction	<0.001	ns	ns	0.005	ns	ns	ns
Internal/external rotation	0.047	ns	ns	ns	ns	ns	ns
Elbow							
Flexion/extension	<0.001	<0.005	<0.005	<0.005	ns	<0.001	<0.001
Pronation/supination	ns	-	-	-	-	-	-
Wrist							
Flexion/extension	0.047	ns	ns	ns	ns	ns	ns
Radial/ulnar deviation	ns	-	-	-	-	-	-

ns = non significant

Figure Legends

Figure 1 – Mean torque ($N·m^{-1}$) trace throughout the cycle in different crank lengths

Figure 2 – Comparison of mean kinematic trajectories (± SD cloud) of handcyclists in 150 mm (black lines) vs. 180 mm (green lines) crank lengths. Line represents the mean of all cycles (n = 90). Grey shaded regions identify significant differences between settings. P values are provided for each supra-threshold cluster