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Horizontal crank position affects economy and upper limb kinematics of recumbent handcyclists

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1 **Title: Horizontal crank position affects economy and upper limb kinematics of**
2 **recumbent handcyclists**

3

4 **Authors:** Benjamin Stone¹, Barry S. Mason¹, Martin B. Warner^{2,3}, Vicky L. Goosey-Tolfrey¹

5

6 **Affiliations:**

7 ¹Peter Harrison Centre for Disability Sport, School of Sport, Exercise and Health Sciences,
8 Loughborough University, Loughborough, United Kingdom.

9 ² School of Health Sciences, University of Southampton, United Kingdom.

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

11

12 Corresponding Author: V. L. Goosey-Tolfrey

13 Address: NCSEM 1.26, Loughborough University Campus, Loughborough, LE11 3TU

14 E-mail: V.L.Tolfrey@lboro.ac.uk Telephone Number: +44 (0)1509 226386

15 **Abstract (275 Words)**

16 **Purpose:** To determine the effects of horizontal crank position on economy and upper limb
17 kinematics in recumbent handcycling. **Methods:** Fifteen trained handcyclists performed trials
18 at 50% and 70% of their peak aerobic power output (PO_{Peak}), determined during a maximal
19 ramp test, in each horizontal crank position. Four horizontal crank positions, 94%, 97%, 100%
20 and 103% of arm length, were investigated. Horizontal crank positions were defined as the
21 distance between the acromion angle to the centre of the handgrip, while the crank arm was
22 parallel to the floor and pointing away from the participant. Economy and upper limb
23 kinematics were calculated during the final minute of each three-minute trial. **Results:**
24 Horizontal crank position significantly affected handcycling economy at 70% PO_{Peak} ($P < 0.01$)
25 but not at 50% PO_{Peak} ($P = 0.44$). The 97% horizontal crank position ($16.0 (1.5) \text{ mL} \cdot \text{min}^{-1} \cdot \text{W}^{-1}$)
26 ¹) was significantly more economical than the 94% ($16.7 (1.9) \text{ mL} \cdot \text{min}^{-1} \cdot \text{W}^{-1}$) ($P = 0.04$) and
27 103% ($16.6 (1.7) \text{ mL} \cdot \text{min}^{-1} \cdot \text{W}^{-1}$) ($P < 0.01$) positions. The 100 % horizontal crank position
28 ($16.2 (1.7) \text{ mL} \cdot \text{min}^{-1} \cdot \text{W}^{-1}$) was significantly more economical than the 103% position ($P <$
29 0.01). Statistical parametric mapping indicated that an increase in horizontal crank position,
30 from 94% to 103%, caused a significant increase in elbow extension, shoulder flexion,
31 adduction, internal rotation, scapular internal rotation, wrist flexion, clavicle depression and
32 clavicle protraction between 0 – 50 % ($0^\circ - 180^\circ$) of the cycle ($P < 0.05$). **Conclusion:**
33 Positioning the cranks at 97% to 100% of the athletes' arm length improved handcycling
34 economy at 70% PO_{Peak} as, potentially, the musculature surrounding the joints of the upper
35 limb were in a more favourable position to produce force economically.

36 **Key Words: Handcycling, Statistical Parametric Mapping, Paralympic, Sports**
37 **Ergonomics**

38 **Introduction**

39 Recumbent handcycling is a recreational and sporting exercise modality for individuals
40 with lower limb impairments (1). At a Paralympic level, the sport has become increasingly
41 competitive with medals in the 20 km handcycling time trial at the Rio Paralympic Games
42 being decided by 0.5% differences between competitors (2). Improvements in performance
43 have originated from both improved athletic preparation and handbike design (1,2), yet little is
44 known about the optimal configuration of the recumbent handbike from a performance
45 perspective (3,4). Currently, the International Cycling Union (UCI) regulations primarily
46 concern athlete safety, regulating factors such as handbike geometry and wheel diameter (5)
47 This provides athletes with the freedom to configure their handbike (horizontal crank position,
48 crank width, crank length, backrest position and handgrip angle/shape) to meet their own needs
49 and preferences (6,7), with the only stipulation stating that the top of the crank housing must
50 be lower than the athlete's eye-line (5). The interaction between the athlete and the handbike
51 is critical for handcycling performance (7,8). Manipulating the configuration of the interface
52 between the athlete and the handbike has been found to effect mechanical efficiency, economy
53 and sprint power in handcycling (9–11).

54 The horizontal crank position has been identified, through a series of interviews of
55 participants with expert views and/or experience of recumbent handcycling, as having a
56 substantial impact on power production, handcycling efficiency and endurance performance
57 (7). Previous literature has defined horizontal crank position, often referred to as crank fore-aft
58 position, as the distance between the user's shoulder and the handgrip while the handgrips are
59 in a horizontal position pointing away from the participant (3,11). Horizontal crank position
60 varies substantially in trained recumbent handcyclists, ranging by 110 mm, which equated to a
61 13 % difference relative to the handcyclist's arm length (12). Previous research has shown that
62 horizontal crank position affects handcycling technique (6,13) and that positioning the cranks

63 closer to the shoulder (30° of elbow flexion) improved handcycling economy and mechanical
64 efficiency (11,14). Conversely, Arnet et al. (3) found horizontal crank position not to affect
65 mechanical efficiency. However, these findings must be interpreted with caution since
66 participants varied in level of experience (e.g. able-bodied, novice through to moderately
67 trained handcyclists), but more importantly exercising at arbitrarily selected low intensities (\leq
68 60 W) in upright attachable or touring handbikes, which does not reflect competitive recumbent
69 handcycling. Additionally, these studies manipulated horizontal crank position by measuring
70 elbow extension angle (0°, 15° and 30°) statically with a goniometer, which can be inaccurate
71 and unreliable (15,16). Furthermore, the maximal elbow angles selected in previous research
72 (0° to 30°) differ to those measured in dynamic recumbent handcycling (20° to 50°) (6,12). In
73 leg-cycling, a percentage (%) of inseam length and knee angle have been widely used in the
74 literature to determine saddle height (17,18). The equivalent in handcycling would be to use a
75 % of arm length or elbow angle to determine horizontal crank position. Measuring solely the
76 elbow angle does not consider the position and orientation of the wrist, humerus and shoulder
77 girdle. An advantage of standardising horizontal crank position to a % of arm length is that it
78 is simplistic to determine, it is easily transferable and specific to the anthropometry of the
79 athlete.

80 Therefore, the current study aimed to determine the effects of horizontal crank position,
81 relative to arm length, on handcycling economy and upper limb kinematics (thorax, clavicle,
82 scapula, humerus, forearm, hand) in trained handcyclists. It was hypothesised that the closest
83 and furthest horizontal crank positions would be the least economical, as these configurations
84 differ most from what has been observed in our laboratory.

85

86 **Methods**

87 **Participants**

88 Thirteen male and two female trained handcyclists (age 35.6 (12.0) years; body mass
89 67.8 (10.5) kg; classification: 6 H3 and 9 H4; injury description: 5 spinal lesion complete (T6
90 – T11), 4 spinal lesion incomplete (T5 - L1), 3 lower limb amputees, 2 cerebral palsy, 1
91 fibromyalgia; arm length: 0.65 (0.04) m) volunteered to participate in the study. An a priori
92 power analysis revealed that a sample size = 8 was required to detect a small effect (0.2), based
93 on the effect sizes (ES) and variability observed in previous research (10,14), and achieve a
94 minimum statistical power of 90% ($P = 0.05$) (G*Power 3.1.9.2). All participants had competed
95 at a national or international level in recumbent handcycling or paratriathlon (handcycling
96 experience: 3.6 (2.4) yrs; training load: 4 (1) sessions totalling 7 (3) $\text{h}\cdot\text{wk}^{-1}$ with weekly self-
97 reported distance of 113 (67) $\text{km}\cdot\text{wk}^{-1}$). The study was approved by the Ethics Committee, for
98 research involving human participants, at Loughborough University. Before participation, all
99 athletes provided their written, informed consent.

100 **Experimental Protocol**

101 Participants completed two bouts of exercise on a single day. Firstly, participants
102 performed a maximal incremental exercise test to determine their peak aerobic power output
103 (PO_{Peak}) in their recumbent sports handbike attached to an ergometer (Cyclus 2, Richter,
104 Germany). Following a warm-up, the test began at 50 W for males and 40 W for females for
105 two minutes. Load then increased by 20 $\text{W}\cdot\text{min}^{-1}$ or 15 $\text{W}\cdot\text{min}^{-1}$ for males and females
106 respectively until the participants reached volitional exhaustion (10.2 (2.0) min) or cadence
107 dropped below 60 rpm for 5 s (19).

108 Following two hours passive rest, participants were fitted into a custom made adjustable
109 recumbent handbike (Schmicking, Germany), which was then attached to the ergometer
110 (Figure 1a). The adjustable handbike was configured to match the configurations of the
111 participant's handbike (backrest height, seat position), allowing a comfortable position to be
112 created. Crank width (330 mm), crank length (170 mm), crank height (20 mm clearance

113 between pedal and abdomen) and handgrip angle (15° pronated) were controlled. Crank fore-
114 aft positions were defined as the distance between the acromion angle to the centre of the
115 handgrip, while the crank arm was parallel to the floor and pointing away from the participant
116 (Figure 1a). Arm length was measured from the acromion angle to the distal end of the fifth
117 metacarpal, in a seated position, while the participant's extended their elbow, with the palms
118 facing towards their side (Figure 1b). Following pilot testing, 94% and 103% were found to be
119 the minimum and maximum horizontal crank positions that could be tested while ensuring that
120 the handgrips did not touch the participant's abdomen (in four instances crank height had to be
121 increased by 10 mm in the 94% condition to prevent an abdominal abrasion) and the back
122 remained in contact with the backrest. Four different horizontal crank positions were tested,
123 94%, 97%, 100% and 103% of the participant's dominant arm length. Whilst horizontal crank
124 positions were being configured the participant was asked to relax and place their hands on
125 their thighs (Figure 1b). The participants self-selected horizontal crank position was also
126 measured in their recumbent handbike.

127 *** Insert Figure 1 ***

128 Participants performed two 3-minute bouts of exercise, at 50% and 70% PO_{Peak} , in all
129 four conditions: eight bouts in total. Unpublished data from our laboratory have shown that
130 exercise intensities equivalent to 50% and 70% PO_{Peak} equate to training and 16 km time trial
131 intensities, respectively. Between each bout, a minimum of three minutes of recovery, or until
132 heart rate dropped below 80 bpm, was provided. For all conditions, participants were asked to
133 cycle at a fixed cadence, within a range of 90 (10) rpm, to replicate the cadences noted during
134 16 km time-trials on an ergometer in our laboratory, since variations in cadence can influence
135 oxygen consumption (10). Conditions were performed in a randomised counterbalanced order,
136 with exercise intensity alternated between 50% and 70% PO_{Peak} to reduce the effect of fatigue.
137 Breath-by-breath gas analysis (Cortex Metalyzer 3B, Cortex, Leipzig, Germany) and heart rate

138 (Polar RS400, Kempele, Finland) were averaged over the last minute of each bout. Following
139 each bout, local, central and overall rating of perceived exertions (RPE) were collected on a
140 Borg scale (6 - 20) (20). Handcycling economy was defined as oxygen uptake per Watt ($\dot{V}O_2$
141 $\text{mL} \cdot \text{min}^{-1} \cdot \text{W}^{-1}$) (21).

142 **Kinematic Analysis**

143 Upper limb kinematics were captured utilising the methodology described previously
144 by Stone et al. (8). Briefly, the method consisted of using a ten camera, passive marker, motion
145 capture system (Vicon T40S, Vicon Motion Systems, Oxford, UK), sampling at 200 Hz.
146 Retroreflective markers were attached to the thorax with marker clusters attached bilaterally to
147 the acromions, to determine scapular kinematics (22,23), the upper arm, forearm and hand.
148 Two markers were also attached bilaterally to the crank arms.

149 The Optimal Common Shape Technique (24) was utilised to reduce soft-tissue artefact
150 and the Symmetrical Centre of Rotation Estimation (25) technique was used to calculate the
151 glenohumeral joint centres. The global coordinate system was defined such that the Y-axis
152 pointed anteriorly, the X-axis aligned with the rotation axis of the crank, and the Z-axis pointed
153 vertically following the right-hand rule. Anatomical local coordinate systems were then
154 constructed and rotation sequences for the thorax, clavicle, scapula, humerus, forearm and hand
155 were followed according to International Society of Biomechanics' recommendations (26).

156 Three-dimensional bilateral upper limb kinematics (thorax, clavicle, scapular, shoulder,
157 elbow and wrist) were captured for the last 20 s of each bout and analysed over ten complete
158 consecutive cycles. A cycle was defined as one rotation of the crank, starting with the cranks
159 in a vertical position pointing up (0% or 0°). Crank angle was determined and upper limb
160 kinematics were normalised to cycle duration (0 – 100 %) and then averaged across the ten
161 cycles (12).

162 **Statistical Analysis**

163 Means, standard deviations (SD) and Shapiro-Wilk normality tests were calculated for
164 economy, heart rate, cadence and RPE data. One-way analysis of variance (ANOVA; crank
165 configuration as within factors) with repeated measures (horizontal crank positions) were
166 conducted on the economy, cadence, heart rate and RPE data at both 50% PO_{Peak} and 70%
167 PO_{Peak} (IBM SPSS Statistics 24, Chicago, IL). Sphericity was assessed and, in one instance, a
168 Huynh-Feldt correction was applied (Greenhouse–Geisser epsilon > 0.75) to the calculated P-
169 value as the data was aspherical (27). If a significant difference was identified, post-hoc paired
170 t-tests with Bonferroni corrections were calculated to determine if there were any differences
171 between the horizontal crank positions. Pairwise effect sizes (ES), calculated using Cohen’s d
172 statistic (28), were calculated for the economy data and categorised as trivial ($ES < 0.2$), small
173 ($0.2 \leq ES < 0.6$), moderate ($0.6 \leq ES < 1.2$), large ($1.2 \leq ES < 2.0$) and very large ($2.0 \leq ES$)
174 (29).

175 A statistical parametric mapping (SPM) repeated measures ANOVA (30) was used to
176 compare upper limb kinematics between crank configurations. If the SPM ANOVA identified
177 a significant difference, post-hoc paired SPM t-test with Bonferroni corrections were applied.
178 The SPM paired t-test identifies regions within the cycle where significant differences in the
179 kinematic trajectories occur. Detailed examples, explanations and theoretical background of
180 SPM are outlined in more detail elsewhere (31–33). All SPM analyses were conducted using
181 the open-source `spm1d` code (v.M0.1, www.spm1d.org) in Matlab (R2016a, 8.3.0.532, The
182 Mathworks Inc, Natick, MA). Peak joint angles and range of motion were calculated for
183 descriptive purposes.

184

185 **Results**

186 The maximal incremental exercise test resulted in a PO_{Peak} 207 (42) W, which equated
187 to 103 (20) W at 50% PO_{Peak} and 144 (28) W at 70% PO_{Peak} . The participants configured their

188 self-selected horizontal crank position in their recumbent handbikes within a range of 95.5%
189 to 106.7% relative in arm length, averaging 100.1 (3.1)%.

190 **Physiology**

191 Handcycling economy was significantly affected by horizontal crank position at 70%
192 PO_{Peak} ($F = 7.452$, $P < 0.01$) but not at 50% PO_{Peak} . At 70% PO_{Peak} , the 97% horizontal crank
193 position was more economical than 94% ($P = 0.04$, $ES = 0.83$), and the 103% positions ($P <$
194 0.01 , $ES = 1.18$), with moderate ESs being calculated. Furthermore, the 100% position was
195 more economical than the 103% position ($P < 0.01$, $ES = 1.30$) indicating a large effect. At
196 50% PO_{Peak} , although no significant differences in economy were identified, the 97% and 100%
197 horizontal crank positions were more economical than the 94% ($ES > 0.32$) indicating a small
198 effect. No other significant differences in economy, heart rate, cadence or central, peripheral
199 and overall RPE were identified between the horizontal crank positions at 50% or 70% PO_{Peak}
200 (Table 1).

201 Only three participants had the horizontal crank position on their handbike configured
202 optimally. The horizontal crank position of the participants own recumbent handbike differed
203 by 3.0 (2.8)% from their optimal configuration identified in this study. Six participants had
204 configured their recumbent handbikes between 97% and 100% of their arm length.

205 *** Insert Table 1 ***

206 **Kinematics**

207 Since no difference in upper limb kinematics were identified between the left and right
208 sides ($P > 0.05$), only the kinematics of the right side, at 70% PO_{Peak} , were used for statistical
209 analysis.

210 Repeated measures ANOVA analysis revealed that horizontal crank position
211 significantly affected clavicle protraction/retraction and elevation/depression, scapular
212 internal/external rotation, shoulder flexion/extension, shoulder abduction/adduction, shoulder

213 internal/external rotation, elbow flexion/extension and wrist flexion/extension ($P < 0.05$)
214 (Table 2). Horizontal crank position had no significant effects on thorax kinematics
215 (flexion/extension, lateral rotation and axial rotation), scapular kinematics (anterior/posterior
216 tilt and upward/downward rotation) and wrist radial/ulnar deviation.

217 *** Insert Table 2 ***

218 Post-hoc SPM t-tests identified that across each incremental increase in horizontal
219 crank position, from 94% to 103%, there was an increase in elbow extension, shoulder flexion,
220 shoulder adduction, shoulder internal rotation, scapular internal rotation and clavicle
221 protraction. Maximal elbow extension, occurring between 18% - 20% ($65^\circ - 72^\circ$) of the cycle,
222 increased incrementally with the horizontal crank position (94% = 44° flexion, 97% = 41°
223 flexion, 100% = 36° flexion, 103% = 33° flexion). Elbow extension was significantly increased
224 for over 85% ($0^\circ - 180^\circ$ and $256^\circ - 360^\circ$) of the cycle when comparing the 103% to 94% and
225 97% horizontal crank positions (Figure 2). Most of the observed kinematic differences occurred
226 between 10% - 50% ($36^\circ - 180^\circ$) of the cycle, when the elbow was extended and the shoulder
227 moved through extension. As horizontal crank position increased, an increase in shoulder
228 flexion was observed between 12% - 57% ($43^\circ - 205^\circ$) of the cycle (Figure 3a). An increase in
229 clavicle protraction, coinciding with maximal elbow extension (12% - 32% ($43^\circ - 115^\circ$) of the
230 cycle), was identified in the 103% horizontal crank position in comparison to 94% and 97%
231 positions (Table 2). Similarly, in the 103% horizontal crank position a significant increase in
232 shoulder internal rotation, 11% - 42% ($40^\circ - 151^\circ$) of the cycle, was identified. An increase in
233 shoulder adduction, 1% - 42% ($3^\circ - 151^\circ$) of the cycle, was also identified when comparing
234 the 97% and 100% to the 103% horizontal crank position (Figure 3b).

235 *** Insert Figure 2 ***

236 *** Insert Figure 3 ***

237 Differences in clavicle elevation/depression, wrist flexion/extension and scapular
238 internal/external rotation occurred during different phases of the cycle. In the 103% horizontal
239 crank position an increase in clavicle depression, $\sim 0\%$ (0°) of the cycle, and wrist flexion, 51%
240 – 61% ($183^\circ - 220^\circ$) of the cycle, was identified. At 0% (0°) and 50% (180°) of the cycle, the
241 handgrips are pointing vertically upwards and vertically downwards, respectively. Significant
242 differences in clavicle elevation/depression and wrist flexion/extension were detected when
243 comparing 97% and 103% but that were not detected when comparing 94% and 103% (Table
244 2). Differences in scapular internal/external rotation were found throughout the cycle (0% –
245 50% ($0^\circ - 180^\circ$), 70% - 80% ($252^\circ - 288^\circ$) and 90% – 100% ($324^\circ - 360^\circ$)) (Figure 4).

246 *** Insert Figure 4 ***

247

248 **Discussion**

249 This was the first study to determine the effect of horizontal crank position on economy
250 and upper limb kinematics in a population of trained recumbent handcyclists exercising at
251 sport-specific intensities. The results confirmed the hypothesis that 97% and 100% horizontal
252 crank positions were more economical than 94% and 103% positions at 70% PO_{Peak} .
253 Positioning the cranks too far (103%) from the shoulders caused an increase in clavicle
254 protraction, scapular internal rotation, shoulder flexion, shoulder adduction and elbow
255 extension. Conversely, positioning the cranks too close (94%) from the shoulders caused a
256 reduction in scapular internal rotation, elbow flexion and shoulder extension.

257 The findings demonstrated that handcycling economy could be optimised by altering
258 horizontal crank position, as has been found previously (11,14). In a population of trained
259 recumbent handcyclists, a horizontal crank position equivalent to 97% of the participant's arm
260 length was $\sim 4\%$ more economical than the 94% and 103% positions. A 4% improvement in
261 handcycling economy at 70% PO_{Peak} may translate into significant improvements in endurance

262 performance, during longer duration activities such as a handcycling time trial or road race
263 (34,35). At 50% PO_{Peak} , a small ES indicated that 97% and 100% horizontal crank positions
264 were more economical than the 94% positions, yet no significant effect was found. These
265 findings support the hypothesis made by van Drongelen et al. (11), that greater differences in
266 economy would be expected at higher power outputs.

267 Horizontal crank alterations equivalent to 3% of arm length (~ 20 mm) were substantial
268 enough to effect recumbent handcycling economy at 70% PO_{Peak} . Therefore, from a
269 physiological perspective, recumbent handcyclists should reconfigure their horizontal crank
270 positions to 97% - 100% of their arm length. Furthermore, the participants' optimal horizontal
271 crank position differed by 3.0 (2.8)% of arm length (20 (18) mm) from the configuration of
272 their recumbent handbike. This meant that only six of the participants' horizontal crank
273 position were within the 97% - 100% range. Even though the participants were accustomed to
274 their horizontal crank position, the findings suggest that recumbent handcyclist should
275 reconsider their horizontal crank position to ensure that it is within the optimal range, 97% to
276 100% of arm length, identified in the current study.

277 Previous handcycling research, found that a 30° maximal elbow extension angle, at
278 furthest reach, was more efficient than 0° or 15° (11,14). However, in the current study mean
279 maximal elbow extension was greater than 30° in all experimental conditions, as found in
280 previous kinematic studies investigating recumbent handcycling (6,12). Furthermore, maximal
281 elbow extension angle was found to differ by ~ 15° between participants in each horizontal
282 crank position, providing evidence that a combination of movements (shoulder girdle,
283 humerus, wrist) were employed by the participants to accommodate the different horizontal
284 crank positions. At an individual level, the chosen combination of angles differed, potentially
285 depending on their impairment, anthropometry or physical fitness, as participants employed
286 different strategies in each crank position. This emphasises the importance of standardising the

287 horizontal crank position on arm length and not solely elbow extension angle, as reported in
288 previous studies (3,11,14). The current study employed a novel, ecological valid and easily
289 transferable approach to standardise horizontal crank position, allowing athletes, their coaches,
290 handbike manufacturers or other support staff to use such a technique when configuring a
291 recumbent handbike.

292 Increasing horizontal crank position was found to significantly impact upon kinematics
293 of the upper limbs as the arms are constrained by the circular path of the handgrips. To facilitate
294 the 103% horizontal crank position the clavicle protracted, the scapular internally rotated, the
295 shoulder adducted, internally rotated and flexed and the elbow extended. Differences in
296 clavicle, scapular, shoulder and elbow kinematics tended to occur between 0 to 50% (0° -
297 180°) of the cycle, enabling the greater reach of the arm when the handgrips were furthest from
298 the shoulders. Maximum elbow extension occurred between 18 to 20% (65° - 72°) of the cycle
299 which coincides closely with the observed increase in clavicle protraction, as horizontal crank
300 position increases. Differences in shoulder kinematics were identified as the shoulder moved
301 through extension, between 10% to 50% (36° - 180°) of the cycle, while no differences were
302 observed through shoulder flexion, 60% to 100% (216° - 360°) of the cycle. During this phase
303 of the cycle, the handgrips are closest to the shoulders, allowing the participants greater
304 freedom to move their upper limbs. This potentially leads to an increase in movement
305 variability, between 60% to 100% (216° - 360°) of the cycle, due to the reduction in constraints
306 imposed on the upper limbs.

307 The improved economy in the 97% and 100% horizontal crank positions are potentially
308 due to the upper limbs moving through a more favourable range of motion to generate force.
309 In the most economical horizontal crank positions, 97% and 100%, maximal elbow extension,
310 elbow flexion and range of motion averaged 36° to 41°, 116° to 120° and 78° to 80°
311 respectively. In the 103% condition, maximal elbow extension reached 33°, this increase in

312 extension could lead to a reduction in the moment arm of the elbow flexors (36) and the force-
313 length characteristics of both the elbow flexors and extensors could have been outside their
314 optimal range (37,38). Equally, an increase in maximal elbow flexion to 122°, as observed in
315 the 94% condition, could extend the muscles of the elbow beyond their optimal joint range for
316 generating force. Similarly, the increased adduction in the 103% condition potentially reduced
317 the moment arm of the pectoralis major, latissimus dorsi, teres major and anterior deltoid (39)
318 and the increased shoulder extension observed in the 94% condition could also inhibit force
319 production. Therefore, the most economical horizontal crank position resulted in elbow
320 flexion/extension between 36° to 120°, shoulder abduction/adduction between -39° to -16°
321 and shoulder flexion/extension between -27° to 40°. From these results, we propose that a
322 further reduction in the minimum and maximum elbow flexion/extension angle could facilitate
323 a further increase in handcycling economy, as the properties of the musculature surrounding
324 the elbow are further optimised. Reducing crank length could have this effect and future
325 research should focus on this issue.

326 In this study, the athletes propelled a custom made adjustable recumbent handbike. The
327 adjustable handbike replicated recumbent handcycling closely, as the recorded upper limb
328 kinematics align closely with those reported in populations of recumbent handcyclists (6,12).
329 No differences in thorax kinematics were observed in the current study and the data was more
330 consistent (reduced SD and range) than findings from a similar population of recumbent
331 handcyclists exercising at 50%, 70% PO_{Peak} and during a sprint (12). This suggests that, as the
332 position and shape of the backrest were standardised in the current study, the shape and position
333 of the backrest could affect thorax kinematics. Stone et al. (8), implied that elbow
334 pronation/supination and wrist kinematics could be influenced by the position, angle and shape
335 of the handgrips. However, the variability observed in elbow supination/pronation and wrist
336 kinematics remained in the current study despite all the participants using the same handgrips.

337 This suggests that wrist kinematics and elbow pronation/supination reflect differences in
338 technique, not handbike configuration. Therefore, wrist kinematics and elbow
339 pronation/supination can technically be targeted by coaches and athletes to improve
340 performance.

341 In the current study, significant differences in clavicle elevation/depression, shoulder
342 abduction/adduction and wrist flexion/extension were identified when comparing the 97% and
343 103% horizontal crank position but not when comparing the 94% and 103%. These results are
344 likely to be explained by the increase in crank height in the 94% horizontal crank position by
345 10 mm in four instances, to prevent the handgrip rubbing against the stomach of the participant.
346 This subtle increase in crank height is unlikely to impact on economy, as more substantial
347 changes in crank height have been found to have no effect on handcycling efficiency (3).
348 Significant differences in clavicle elevation/depression and wrist flexion/extension were found
349 to occur at the top (0% (0°)) and bottom (50% (180°)) of the cycle when comparing 97% and
350 103% and thus, logically, changing crank height could affect these kinematic variables.
351 Similarly, shoulder abduction/adduction was found to differ between from the top of the cycle
352 (1% (3°)) through to ~ 40% (144°) of the cycle and could have been affected by crank height.
353 This increase in crank height is likely to have affected the measured kinematics, potentially
354 explaining why, in some instances, significant differences were not observed between 94% and
355 103% but were between 97% and 103% instances.

356 This study investigated trained handcyclists, exercising at sport-specific intensities, to
357 make the findings as transferable as possible to the sport of recumbent handcycling. However,
358 only H3 and H4 handcyclists were recruited limiting the applications to H1 or H2 handcyclists
359 who have more severe upper limb disabilities, impaired triceps and hand function (5). The
360 current study employed a multidisciplinary approach, allowing differences in economy to be
361 associated with changes in upper limb kinematics. In addition to this, future studies should

362 incorporate cycle kinetics and electromyography into their experimental designs, allowing the
363 mechanism causing a change in economy, and potentially injury risk, to be further explored.
364 Moreover, it is of interest to determine if a horizontal crank position equivalent to 97% – 100%
365 arm length are also optimal in sprint conditions and maximal exercise tests.

366 In conclusion, horizontal crank position has a significant effect on handcycling
367 economy and upper limb kinematics. A horizontal crank position equivalent to 97% to 100%
368 of the participant's arm length was consistently found to be more economical than 94% or
369 103%. These differences in economy are potentially explained by differences in upper limb
370 kinematics, potentially placing the musculature surrounding these joints in a biomechanically
371 optimal range. The results of the current study suggest that recumbent handcyclists should
372 modify their horizontal crank position to 97% to 100% of their arm length to ensure that their
373 handbike configuration is set-up to optimise economy.

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378 The authors declare that the results of the study are presented clearly, honestly, and without
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380 present study do not constitute endorsement by American College of Sports Medicine. The
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382

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482

483 Figure 1: a) Configuring the horizontal crank position of the recumbent handbike. b)
484 Measurement of arm length.

485 Figure 2: a) An illustration of the propulsion cycle in recumbent handcycling (%). b)
486 Comparison of elbow flexion/extension (mean kinematic trajectory \pm SD cloud) between
487 94% (solid line), 97% (dashed line), 100% (dot-dash line) and 103% (dotted line) horizontal
488 crank positions at 70% PO_{Peak} . Shaded regions identify significant differences between
489 groups. P values are provided for each supra-threshold cluster.

490 Figure 3: a) Comparison of the shoulder flexion/extension (mean kinematic trajectory \pm SD
491 cloud) and b) the shoulder abduction/adduction (mean kinematic trajectory \pm SD cloud) 94%
492 (solid line), 97% (dashed line), 100% (dot-dash line) and 103% (dotted line) horizontal crank
493 positions at 70% PO_{Peak} . Shaded regions identify significant differences between groups. P
494 values are provided for each supra-threshold cluster.

495 Figure 4: Comparison of scapular internal/external rotation kinematics (mean kinematic
496 trajectory \pm SD cloud) between 94% (solid line), 97% (dashed line), 100% (dot-dash line)
497 and 103% (dotted line) horizontal crank positions at 70% PO_{Peak} . Shaded regions identify
498 significant differences between groups. P values are provided for each supra-threshold
499 cluster.

500

Table 1. Effect of horizontal crank position on physiological parameters while handcycling at 50% and 70% PO_{peak} (N=15, values are Mean (SD)).

Parameters	Horizontal crank position (% arm length)			
	94%	97%	100%	103%
50% PO_{peak}				
Cadence (rpm)	88 (8)	88 (8)	88 (8)	88 (8)
Economy ($\dot{V}O_2 \text{ mL} \cdot \text{min}^{-1} \cdot \text{W}^{-1}$)	18.1 (2.7)	17.7 (2.8)	17.8 (2.8)	17.9 (2.3)
Overall RPE	12 (2)	12 (2)	12 (2)	12 (3)
Heart Rate (bpm)	141 (17)	142 (16)	142 (16)	142 (15)
70% PO_{peak}				
Cadence (rpm)	87 (8)	88 (9)	88 (8)	88 (8)
Economy ($\dot{V}O_2 \text{ mL} \cdot \text{min}^{-1} \cdot \text{W}^{-1}$)	16.7 (2.4)*	16.0 (2.1)	16.2 (2.0)	16.6 (2.1)*#
Overall RPE	16 (2)	16 (2)	15 (1)	15 (2)
Heart Rate (bpm)	162 (14)	161 (12)	162 (11)	162 (12)

Note. * Significant difference in comparison to 97 % ($P < 0.05$)

Note. # Significant difference in comparison to 100 % ($P < 0.05$)

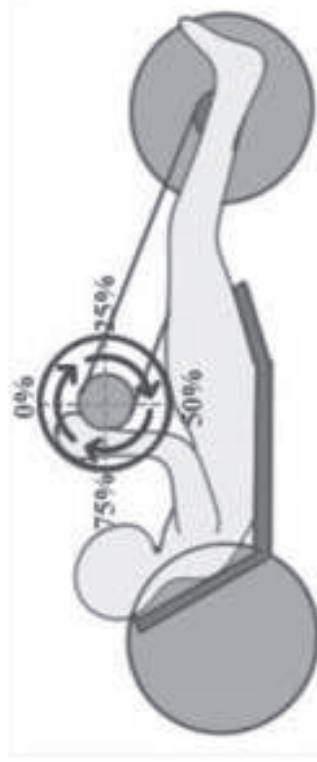
Table 2. SPM ANOVA and post-hoc analysis of upper limb kinematics in four horizontal crank positions at 70% PO_{Peak} (N=15)

Parameters	ANOVA		Post-hoc comparisons (P)					
	(N=15)		94% vs	94% vs	94% vs	97% vs	97% vs	100% vs
	F	(P)	97%	100%	103%	100%	103%	103%
Clavicle								
Protraction/Retraction	12.936	0.02	NS	NS	<0.01	NS	<0.001	NS
Elevation/Depression	7.855	<0.01	NS	NS	NS	NS	<0.01	NS
Scapular								
Internal/External Rot.	40.632	<0.001	<0.01	<0.001	<0.001	NS	<0.001	<0.01
Upward/Downward Rot.	8.414	<0.005	NS	NS	NS	NS	NS	NS
Shoulder								
Flexion/Extension	16.375	<0.005	NS	<0.01	<0.001	<0.01	<0.001	NS
Abduction/Adduction	8.064	<0.01	NS	NS	NS	NS	<0.001	<0.001
Internal/External Rot.	24.374	0.02	NS	<0.001	<0.001	NS	<0.001	<0.005
Elbow								
Flexion/Extension	29.367	<0.001	NS	<0.001	<0.001	<0.001	<0.001	NS
Pronation/Supination	4.551	0.049	NS	NS	NS	NS	NS	NS
Wrist								
Flexion/Extension	6.571	0.03	NS	NS	NS	NS	<0.01	<0.01

Note. NS Not significant, Rot. Rotation



a)



b)

