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

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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 $m \cdot s^{-1}$) 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.

Secondly, the limited use of handcyclists as participants in addition to the non-sport specific range of crank lengths investigated further limits the application of these findings.[12,13] From a methodological perspective, the fixed cadences adopted by Goosey-Tolfrey et al.[12] could confound performance when investigating crank length. At fixed cadences (angular handgrip speeds), participants must move the handgrips at a higher linear speed in a longer crank to match the cadence of a shorter crank and likely accounts for the physiological differences observed with respect to crank length.[12] Finally, performance in different crank length settings have only been described according to power output, physiological cost or muscle activation patterns. No previous studies have considered the kinetic or kinematic implications of crank length adjustments.

Differences in upper limb kinematics such as greater thorax flexion and shoulder extension have recently been associated with performance during recumbent handcycling.[9] Further changes to kinematics have also been observed when manipulating the horizontal crank position of trained handcyclists.[15] Therefore, motion analysis of upper limb kinematics could provide further insight into the optimisation of handbike, and crank length configuration. Furthermore, recent studies have frequently instrumented recumbent handbikes with Schoberer Rad Messtechnik (SRM) power meters to quantify cycle kinetics during handcycling.[16,17] Whilst this research has largely explored able-bodied participants, the technology offers valuable information to further understand the effects of crank length manipulations. Although previous research has included a combination of kinematic and kinetic measures to examine the effects of different handbike configurations,[18-21] no study has combined all these measures to investigate trained handcyclists, cycling at sport-specific intensities in a recumbent handbike. Subsequently the aim of the current study was to explore the impact of crank length on physiological and biomechanical aspects of recumbent handcycling at fixed linear handgrip 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 $h \cdot wk^{-1}$ with a weekly self-reported distance of 153 ± 76 $km \cdot wk^{-1}$). 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 $4\text{mmol}\cdot\text{L}^{-1}$. 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 $20\ \text{W}\cdot\text{min}^{-1}$ for males (5 W every 15 s) and $15\ \text{W}\cdot\text{min}^{-1}$ 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.

Due to the trade-off between cadence and handgrip speed when handcycling at different crank lengths, handgrip speed was controlled (1.6 $m \cdot s^{-1}$). This led to fixed cadences of 102, 96, 90 and 85 rpm at 150, 160, 170 and 180 mm crank lengths respectively. 3-minute trials were performed at 70% PO_{Peak} in a randomised order, with 15 minutes passive recovery between each crank length setting.

Measures

Physiology

During the last minute of each crank length trial $\dot{V}O_2$ was averaged and used to quantify handcycling economy, defined as $\dot{V}O_2$ relative to power ($mL \cdot min^{-1} \cdot W^{-1}$) as documented previously.[9] Heart rate (HR) was collected continuously at 1-s intervals and was averaged over the final minute (Polar RS400, Polar, Kempele, Finland). At the end of each trial participants reported their local (RPE – L), central (RPE – C) and overall (RPE – O) ratings of perceived exertion using Borg's 6-20 scale.[22]

Kinetics

The adjustable handbike was equipped with an SRM Science Power meter and SRM Torque Analysis system (Jülich, Germany), which enabled cycle torque to be measured at 200 Hz. Between each trial, the SRM was calibrated according to the manufacturer's instructions. Cycle torque was collected throughout the last minute of each trial and averaged across the recorded cycles. Based on previous handcycling literature,[23] peak torque and the angle at which peak torque occurred during both the push and pull phase were determined for each crank length.

Kinematics

Upper body kinematics were captured using a 10-camera motion capture system (Vicon T40S; Vicon Motion Systems, Oxford, UK), sampling at 200 Hz. Based on a previous study,[9] retroreflective markers were attached to anatomical locations on the thorax, upper arm, forearm and hand. Acromion marker clusters were attached bilaterally to the acromions to determine scapular kinematics, according to previous guidelines.[24,25] Two further markers were attached bilaterally to the crank arms of the handbike. With participants seated in the anatomical position, a series of static trials were captured with the tip of a calibration wand used to determine the anatomical landmarks from marker clusters.[9,25] A 10 s shoulder circumduction trial was then captured to functionally determine the glenohumeral joint centre.[26] For the experimental trials, the final 20 s of each 3-minute bout was captured to allow at least 10 complete and consecutive cycles in each crank length configuration.

The Optimal Common Shape Technique was used to minimise soft-tissue artefact within the kinematic data.[27] The Symmetrical Centre of Rotation Estimation technique was used to calculate the glenohumeral joint centres from the circumduction trials.[28] The global coordinate system was defined such that the Y-axis pointed anteriorly, the X-axis aligned with the rotation axis of the crank, and the Z-axis pointed vertically following the right-hand rule. Anatomical local coordinate systems were then constructed and rotation sequences for the thorax, clavicle, scapula, humerus, forearm, and hand segments followed International Society of Biomechanics' recommendations.[29] Three-dimensional bilateral upper body kinematics were analysed for the thorax, clavicle, scapular, shoulder, elbow, and wrist over 10 cycles. A cycle was defined as one rotation of the crank, starting with the cranks in a vertical position pointing upwards (0° or 0%). Crank angle was determined using Euler angles (ZXY sequence) and upper body kinematics were normalized to cycle duration (0%–100%) and then averaged across the 10 cycles.[9] Since no kinematic differences between left and right sides were identified during previous handcycling ergometry,[9] only data from the right side was presented.

Statistical Analysis

Statistical analyses were conducted using the Statistical Package for Social Sciences (SPSS version 24, IBM Statistics, Chicago, IL). All data were checked for normality using Shapiro-Wilk tests. Repeated measures analysis of variance was conducted on all physiological, kinetic and joint range of movement (RoM) kinematic data when normality was assumed. When assumptions of normality had been violated, the non-parametric Friedman test was performed. Statistical significance was accepted as $p < 0.05$. Pairwise comparisons with a Bonferroni correction were conducted as a post-hoc test when a significant main effect had been identified.

Statistical parametric mapping (SPM) was used to further explore upper body joint kinematics using a repeated measures SPM ANOVA.[30] Where significant differences were established, SPM t-tests were conducted as a post-hoc measure to identify the time points throughout the kinematic waveform where a significant difference existed. All SPM analyses were conducted in Matlab (R2016a, 8.3.0.532, The Mathworks Inc., Natick, MA) using the open-source spm1d.code (v.M0.1, www.spm1d.org).

Results

Participants achieved a PO_{Peak} of 232 ± 44 W, subsequently, crank length experimental trials were performed at 163 ± 33 W to reflect 70% PO_{Peak}. Results revealed that crank length had no significant effect on any physiological measure (Table 1).

TABLE 1 HERE

Mean torque traces of each crank length are displayed in Figure 1. Peak torque increased significantly with increased crank length between all settings except between 160 mm and 170 mm (p = 0.107) during the push phase, and 150 mm and 160 mm (p = 0.080) during the pull phase (Table 2). Crank length also significantly affected the angle at which peak torque occurred during the cycle ($p \leq 0.001$). Peak torque occurred earlier into the push phase in a longer crank and occurred closer to top dead centre as crank length reduced, although the difference was only statistically significant between 150 and 180 mm (p = 0.034). Peak torque also occurred earlier during the pull phase in longer cranks and later as crank length decreased. Differences were statistically significant ($p \leq 0.017$) between all crank lengths during the pull phase (Table 2).

FIGURE 1 & TABLE 2 HERE

Crank length had a significant effect on numerous kinematic parameters during handcycling. Joint RoM significantly increased from the shortest (150 mm) to the longest (180 mm) cranks for many joint actions (Table 3). SPM ANOVA indicated that crank length also significantly affected the internal / external rotation at the scapular and shoulder, flexion / extension at the shoulder, elbow and wrist and adduction / abduction at the shoulder. (Table 4). However, significant post-hoc differences were only revealed for shoulder flexion / extension, abduction / adduction and elbow flexion / extension. Figure 2 illustrates these differences between the two extreme crank length settings (150 vs. 180 mm). Shoulder flexion was significantly greater during 0 – 26% and 73 – 100% of the cycle and less flexed during 48 – 63% of the cycle in longer crank lengths. Shoulder abduction significantly increased between 68 – 74% of the cycle in the longer crank lengths. Elbow extension was greater during 12 – 18% of the cycle, with more flexion observed between 42 – 78% of the cycle in longer cranks (Figure 2).

TABLE 3 & 4 & FIGURE 2 HERE

Discussion

The current study was the first to provide a comprehensive insight into the effect of crank length on the physiological, kinetic and kinematic responses of trained handcyclists, whilst exercising at sport-specific intensities in a highly standardised recumbent handbike. Competitive handcyclists typically select crank lengths between 170 – 175 mm,[9] and this study has revealed that although biomechanical adaptations exist, no physiological gains (or decrements) were experienced in settings either side of this range when handgrip speed is controlled.

The lack of physiological differences contrasts the only previous study in the area,[12] and is likely the result of different protocols employed and the complex relationship that exists between crank length, handgrip speed and cadence.[31] Unlike the current study Goosey-Tolfrey et al.[12] manipulated crank length at fixed cadences. Consequently, the reduced mechanical efficiency observed in longer (220 mm) compared to shorter (180 mm) cranks was likely due to increased muscle shortening velocity required to maintain the same cadence in a longer crank.[32] In cyclic sports such as handcycling, changing crank length concurrently affects cadence and handgrip speed and ultimately performance.[31] However, under no additional constraints it was perceived that athletes would automatically adjust their cadence across different crank length settings rather than maintain a fixed cadence. Subsequently, although cadence can alter the physiological demand of handcycling,[33,34] it was deemed more ecologically valid to control handgrip speed in the current study.

Under such experimental conditions, the absence of any physiological and perceptual differences between crank lengths suggest that other factors must be considered to establish optimal crank length configurations, of which aerodymanics could be one. The current study 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.

Consequently, it was no surprise that upper body kinematics were also significantly altered when handcycling with different crank lengths. During the push phase, the shoulder was significantly more flexed and the elbow more extended to lift up and drive forward the longer (180 mm) cranks compared to the shorter (150 mm) cranks. The shoulder was also shown to be significantly more abducted at the onset of the push phase in the longest cranks. This kinematic change was likely associated to the standardised horizontal crank position maintained across settings. Subsequently, a longer crank will pass closer to the thorax of a handcyclist, who likely compensates by abducting the shoulders to help drive the cranks up and forward, which could again make the athlete less aerodynamic in longer cranks outside of a laboratory. Conversely, during the pull phase the shoulder was significantly more extended and the elbow more flexed to pull the longer cranks down and back towards participants. Consequently, joint RoM increased for all these motions in the longest crank setting. Whether or not these biomechanical adaptations associated with different crank lengths are positive or negative remains to be seen and future research should explore the implications for injury risk in different crank length settings owing to the lack of physiological changes in performance currently observed. Such future research could investigate internal joint forces to better understand the impact of handbike configuration on upper limb loading and injury risk.

Research into the effects of cadence alongside crank length and handgrip speed are required in future to understand the interrelationships between these phenomena and to better inform athletes about optimal crank lengths. Lower cadences (50 – 60 rpm) have been shown to be more mechanically efficient at low handcycling intensities (15 – 70 W).[33,34] At a slightly higher intensity (90 W), no differences in efficiency were observed between moderate cadences (70 – 85 rpm).[12] Whereas during maximal sprinting, peak power output increased up until 114 rpm, before steadily decreasing.[13] Subsequently different crank lengths could be more 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, aerodynamics and preferred cadence could be used to inform crank length selection and is of relevance to handcyclists, coaches, practitioners and also handbike manufacturers in particular.

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

		P	150 mm	160 mm	170 mm	180 mm
Economy	($mL \cdot min^{-1} \cdot W^{-1}$)	0.942	16.5 ± 3.0	16.2 ± 2.0	16.3 ± 2.6	16.2 ± 2.2
Heart rate	($beats \cdot min^{-1}$)	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	$N \cdot m^{-1}$	<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	$N \cdot m^{-1}$	<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.

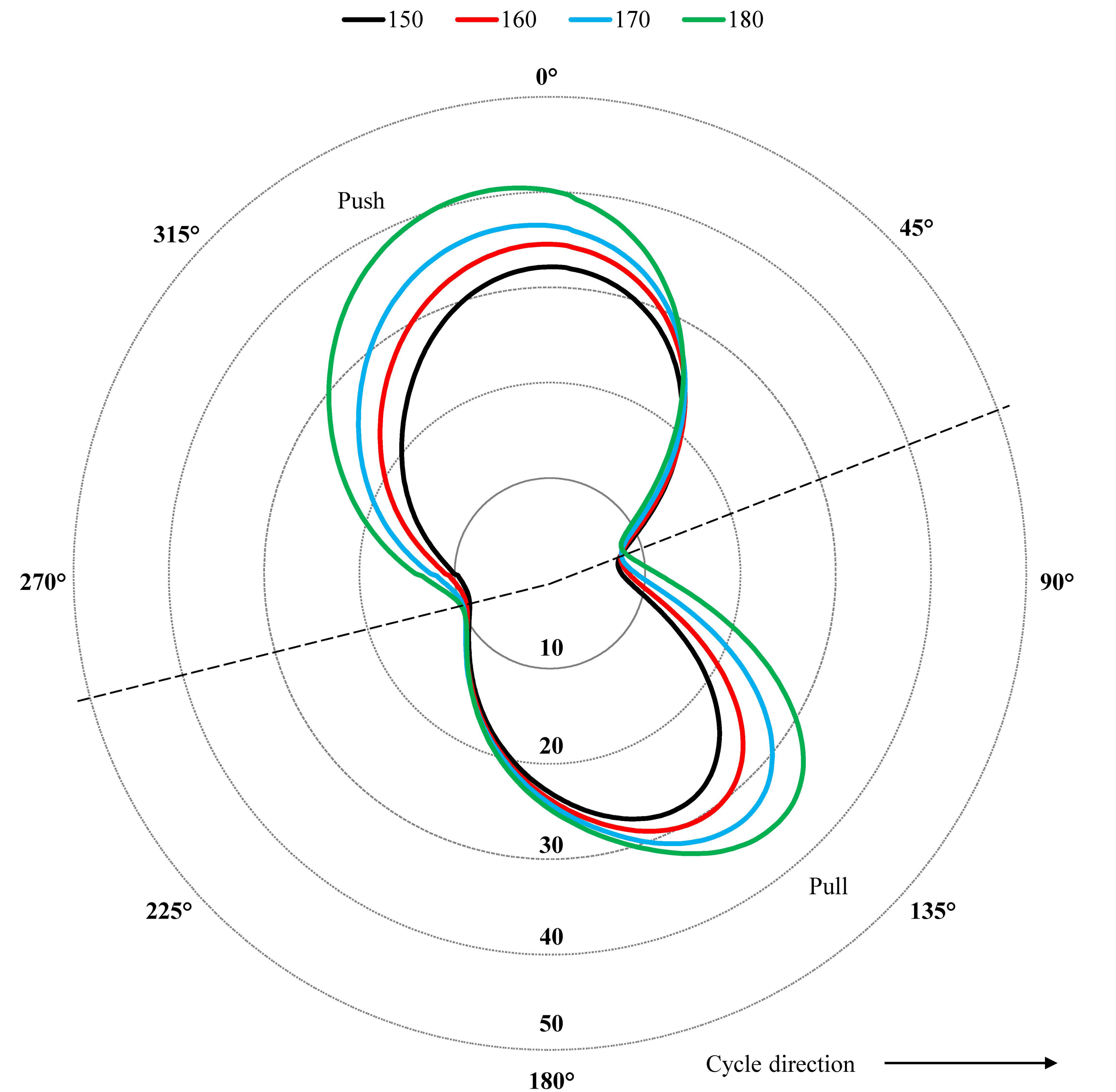
	p	**150 v. 160**	**150 v. 170**	**150 v. 180**	**160 v.170**	**160 v. 180**	**170 v. 180**
Thorax							
Flexion/extension	ns	-	-	-	-	-	-
Clavicle							
Protraction/retraction	ns	-	-	-	-	-	-
Elevation/depression	ns	-	-	-	-	-	-
Scapular							
Internal/external rotation	0.048	ns	ns	ns	ns	ns	ns
Upward/downward 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	-	-	-	-	-	-

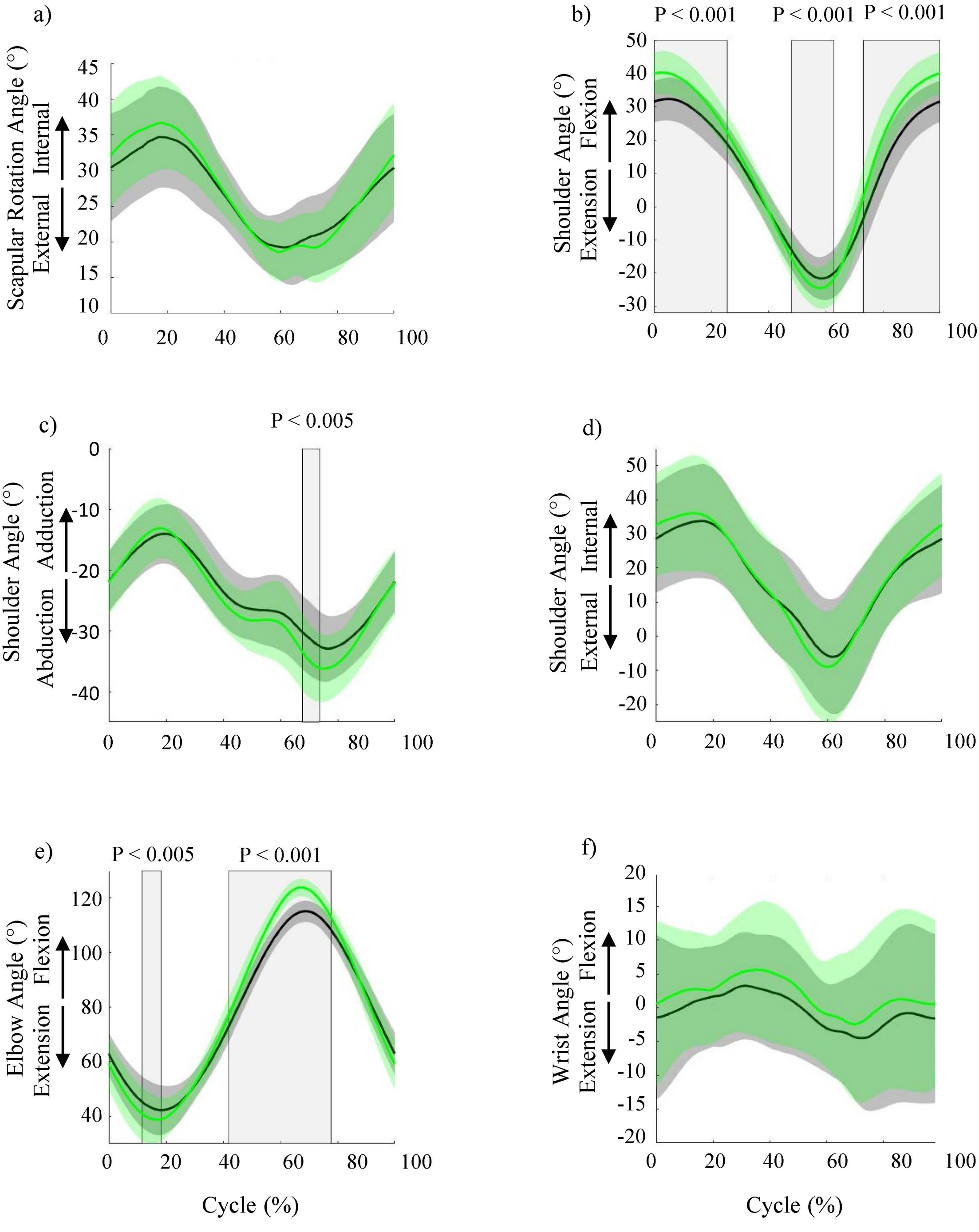
ns = non significant

Figure Legends

Figure 1 – Mean torque ($N \cdot m^{-1}$) 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


150
160
170
180
0°
45°
90°
135°
180°
225°
270°
315°
10
20
30
40
50
Push
Pull
Cycle direction



a)
Scapular Rotation Angle (°)
Internal
External
b)
P < 0.001
P < 0.001
P < 0.001
Shoulder Angle (°)
Flexion
Extension
c)
P < 0.005
Shoulder Angle (°)
Adduction
Abduction
d)
Shoulder Angle (°)
Internal
External
e)
P < 0.005
P < 0.001
Elbow Angle (°)
Flexion
Extension
f)
Wrist Angle (°)
Flexion
Extension
Cycle (%)
Cycle (%)