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

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

Affiliations:

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

[2] School of Health Sciences, University of Southampton, United Kingdom.

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

Corresponding Author: V. L. Goosey-Tolfrey

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

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

Abstract (275 Words)

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

Key Words: Handcycling, Statistical Parametric Mapping, Paralympic, Sports Ergonomics

Introduction

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

The horizontal crank position has been identified, through a series of interviews of participants with expert views and/or experience of recumbent handcycling, as having a substantial impact on power production, handcycling efficiency and endurance performance (7). Previous literature has defined horizontal crank position, often referred to as crank fore-aft position, as the distance between the user's shoulder and the handgrip while the handgrips are in a horizontal position pointing away from the participant (3,11). Horizontal crank position varies substantially in trained recumbent handcyclists, ranging by 110 mm, which equated to a 13 % difference relative to the handcyclist's arm length (12). Previous research has shown that horizontal crank position affects handcycling technique (6,13) and that positioning the cranks closer to the shoulder (30° of elbow flexion) improved handcycling economy and mechanical efficiency (11,14). Conversely, Arnet et al. (3) found horizontal crank position not to affect mechanical efficiency. However, these findings must be interpreted with caution since participants varied in level of experience (e.g. able-bodied, novice through to moderately trained handcyclists), but more importantly exercising at arbitrarily selected low intensities (≤ 60 W) in upright attachable or touring handbikes, which does not reflect competitive recumbent handcycling. Additionally, these studies manipulated horizontal crank position by measuring elbow extension angle (0°, 15° and 30°) statically with a goniometer, which can be inaccurate and unreliable (15,16). Furthermore, the maximal elbow angles selected in previous research (0° to 30°) differ to those measured in dynamic recumbent handcycling (20° to 50°) (6,12). In leg-cycling, a percentage (%) of inseam length and knee angle have been widely used in the literature to determine saddle height (17,18). The equivalent in handcycling would be to use a % of arm length or elbow angle to determine horizontal crank position. Measuring solely the elbow angle does not consider the position and orientation of the wrist, humerus and shoulder girdle. An advantage of standardising horizontal crank position to a % of arm length is that it is simplistic to determine, it is easily transferable and specific to the anthropometry of the athlete.

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

Methods

Participants

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

Experimental Protocol

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

Following two hours passive rest, participants were fitted into a custom made adjustable recumbent handbike (Schmicking, Germany), which was then attached to the ergometer (Figure 1a). The adjustable handbike was configured to match the configurations of the participant's handbike (backrest height, seat position), allowing a comfortable position to be created. Crank width (330 mm), crank length (170 mm), crank height (20 mm clearance between pedal and abdomen) and handgrip angle (15° pronated) were controlled. Crank fore-aft positions were defined as the distance between the acromion angle to the centre of the handgrip, while the crank arm was parallel to the floor and pointing away from the participant (Figure 1a). Arm length was measured from the acromion angle to the distal end of the fifth metacarpal, in a seated position, while the participant's extended their elbow, with the palms facing towards their side (Figure 1b). Following pilot testing, 94% and 103% were found to be the minimum and maximum horizontal crank positions that could be tested while ensuring that the handgrips did not touch the participant's abdomen (in four instances crank height had to be increased by 10 mm in the 94% condition to prevent an abdominal abrasion) and the back remained in contact with the backrest. Four different horizontal crank positions were tested, 94%, 97%, 100% and 103% of the participant's dominant arm length. Whilst horizontal crank positions were being configured the participant was asked to relax and place their hands on their thighs (Figure 1b). The participants self-selected horizontal crank position was also measured in their recumbent handbike.

*** Insert Figure 1 ***

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

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

Kinematic Analysis

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

The Optimal Common Shape Technique (24) was utilised to reduce soft-tissue artefact and the Symmetrical Centre of Rotation Estimation (25) technique was used to calculate the glenohumeral joint centres. 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 were followed according to International Society of Biomechanics' recommendations (26).

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

Statistical Analysis

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

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

Results

The maximal incremental exercise test resulted in a PO_{Peak} 207 (42) W, which equated to 103 (20) W at 50% PO_{Peak} and 144 (28) W at 70% $PO_{Peak.}$ The participants configured their self-selected horizontal crank position in their recumbent handbikes within a range of 95.5% to 106.7% relative in arm length, averaging 100.1 (3.1)%.

Physiology

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

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

*** Insert Table 1 ***

Kinematics

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

Repeated measures ANOVA analysis revealed that horizontal crank position significantly affected clavicle protraction/retraction and elevation/depression, scapular internal/external rotation, shoulder flexion/extension, shoulder abduction/adduction, shoulder internal/external rotation, elbow flexion/extension and wrist flexion/extension ($P < 0.05$) (Table 2). Horizontal crank position had no significant effects on thorax kinematics (flexion/extension, lateral rotation and axial rotation), scapular kinematics (anterior/posterior tilt and upward/downward rotation) and wrist radial/ulnar deviation.

*** Insert Table 2 ***

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

*** Insert Figure 2 ***

*** Insert Figure 3 ***

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

*** Insert Figure 4 ***

Discussion

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

The findings demonstrated that handcycling economy could be optimised by altering horizontal crank position, as has been found previously (11,14). In a population of trained recumbent handcyclists, a horizontal crank position equivalent to 97% of the participant's arm length was ~ 4% more economical than the 94% and 103% positions. A 4% improvement in handcycling economy at 70% PO_{Peak} may translate into significant improvements in endurance performance, during longer duration activities such as a handcycling time trial or road race (34,35). At 50% PO_{Peak}, a small ES indicated that 97% and 100% horizontal crank positions were more economical than the 94% positions, yet no significant effect was found. These findings support the hypothesis made by van Drongelen et al. (11), that greater differences in economy would be expected at higher power outputs.

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

Previous handcycling research, found that a 30° maximal elbow extension angle, at furthest reach, was more efficient than 0° or 15° (11,14). However, in the current study mean maximal elbow extension was greater than 30° in all experimental conditions, as found in previous kinematic studies investigating recumbent handcycling (6,12). Furthermore, maximal elbow extension angle was found to differ by ~ 15° between participants in each horizontal crank position, providing evidence that a combination of movements (shoulder girdle, humerus, wrist) were employed by the participants to accommodate the different horizontal crank positions. At an individual level, the chosen combination of angles differed, potentially depending on their impairment, anthropometry or physical fitness, as participants employed different strategies in each crank position. This emphasises the importance of standardising the horizontal crank position on arm length and not solely elbow extension angle, as reported in previous studies (3,11,14). The current study employed a novel, ecological valid and easily transferable approach to standardise horizontal crank position, allowing athletes, their coaches, handbike manufacturers or other support staff to use such a technique when configuring a recumbent handbike.

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

The improved economy in the 97% and 100% horizontal crank positions are potentially due to the upper limbs moving through a more favourable range of motion to generate force. In the most economical horizontal crank positions, 97% and 100%, maximal elbow extension, elbow flexion and range of motion averaged 36° to 41°, 116° to 120° and 78° to 80° respectively. In the 103% condition, maximal elbow extension reached 33°, this increase in extension could lead to a reduction in the moment arm of the elbow flexors (36) and the force-length characteristics of both the elbow flexors and extensors could have been outside their optimal range (37,38). Equally, an increase in maximal elbow flexion to 122°, as observed in the 94% condition, could extend the muscles of the elbow beyond their optimal joint range for generating force. Similarly, the increased adduction in the 103% condition potentially reduced the moment arm of the pectoralis major, latissimus dorsi, teres major and anterior deltoid (39) and the increased shoulder extension observed in the 94% condition could also inhibit force production. Therefore, the most economical horizontal crank position resulted in elbow flexion/extension between 36° to 120°, shoulder abduction/adduction between -39° to -16° and shoulder flexion/extension between -27° to 40°. From these results, we propose that a further reduction in the minimum and maximum elbow flexion/extension angle could facilitate a further increase in handcycling economy, as the properties of the musculature surrounding the elbow are further optimised. Reducing crank length could have this effect and future research should focus on this issue.

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

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

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

This study investigated trained handcyclists, exercising at sport-specific intensities, to make the findings as transferable as possible to the sport of recumbent handcycling. However, only H3 and H4 handcyclists were recruited limiting the applications to H1 or H2 handcyclists who have more severe upper limb disabilities, impaired triceps and hand function (5). The current study employed a multidisciplinary approach, allowing differences in economy to be associated with changes in upper limb kinematics. In addition to this, future studies should incorporate cycle kinetics and electromyography into their experimental designs, allowing the mechanism causing a change in economy, and potentially injury risk, to be further explored. Moreover, it is of interest to determine if a horizontal crank position equivalent to 97% – 100% arm length are also optimal in sprint conditions and maximal exercise tests.

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

Conflicts of Interest and Source of Funding

This study was funded by the Engineering and Physical Sciences Research Council (grant no. EP/M507489/1) and supported by the English Institute of Sport, British Cycling and the Peter Harrison Centre for Disability Sport.

The authors declare that the results of the study are presented clearly, honestly, and without fabrication, falsification, or inappropriate data manipulation, and statement that results of the present study do not constitute endorsement by American College of Sports Medicine. The authors report no conflict of interest.

References

1. Hettinga FJ, Valent L, Groen W, van Drongelen S, de Groot S, Van Der Woude LH. Hand-cycling: An active form of wheeled mobility, recreation, and sports. *Phys Med Rehabil Clin*. 2010;21(1):127–40.

2. Perret C. Elite-adapted wheelchair sports performance: a systematic review. *Disabil Rehabil*. 2017;39(2):164–72.

3. Arnet U, van Drongelen S, Schlüssel M, Lay V, van der Woude LH V., Veeger HEJ. The effect of crank position and backrest inclination on shoulder load and mechanical efficiency during handcycling. *Scand J Med Sci Sport*. 2014;24(2):386–94.

4. Krämer C, Schneider G, Böhm H, Klöpfer-Krämer I, Senner V. Effect of different handgrip angles on work distribution during hand cycling at submaximal power levels. *Ergonomics*. 2009;52(10):1276–86.

5. Union Cycliste Internationale. Union Cycliste Internationale Cycling Regulations - Part 16 Para-cycling [Internet]. 2018 [cited 2018 Apr 13]. p. 1–81. Available from: http://www.uci.ch/mm/Document/News/Rulesandregulation/16/80/73/1-GEN-20160101-E_English.pdf

6. Litzenberger S, Mally F, Sabo A. Biomechanics of elite recumbent handcycling : a case study. *Sport Eng*. 2016;19:1–11.

7. Stone B, Mason BS, Bundon A, Goosey-Tolfrey VL. Elite handcycling : a qualitative analysis of recumbent handbike configuration for optimal sports performance. *Ergonomics*. 2018;62(3):449–58.

8. Mason BS, van der Woude LH V., Goosey-Tolfrey VL. The ergonomics of wheelchair configuration for optimal performance in the wheelchair court sports. *Sport Med*.

2013;43(1):23–38.

9. Krämer C, Hilker L, Böhm H. Influence of crank length and crank width on maximal hand cycling power and cadence. *Eur J Appl Physiol*. 2009;106(5):749–57.

10. Goosey-Tolfrey VL, Alfano H, Fowler N. The influence of crank length and cadence on mechanical efficiency in hand cycling. *Eur J Appl Physiol*. 2008;102(2):189–94.

11. van Drongelen S, Maas JCC, Scheel-Sailer A, Van Der Woude LH. Submaximal arm crank ergometry: Effects of crank axis positioning on mechanical efficiency, physiological strain and perceived discomfort. *J Med Eng Technol*. 2009;33(2):151–7.

12. Stone B, Mason BS, Warner MB, Goosey-Tolfrey VL. Shoulder and thorax kinematics contribute to increased power output of competitive handcyclists. *Scand J Med Sci Sports*. 2019;29(6):843–53.

13. Faupin A, Gorce P, Meyer C, Thevenon A. Effects of backrest positioning and gear ratio on nondisabled subjects' handcycling sprinting performance and kinematics. *J Rehabil Res Dev*. 2008;45(1):109–16.

14. Miller TL, Mattacola CG, Santiago MC. Influence of varied, controlled distances from the crank axis on peak physiological responses during arm crank ergometry. *J Exerc Physiol Online*. 2004;7(3):61–7.

15. Chapleau J, Canet F, Petit Y, Laflamme GY, Rouleau DM. Validity of goniometric elbow measurements: Comparative study with a radiographic method. *Clin Orthop Relat Res*. 2011;469(11):3134–40.

16. van Rijn SF, Zwerus EL, Koenraadt KL, Jacobs WC, van den Bekerom MP, Eygendaal D. The reliability and validity of goniometric elbow measurements in

adults: A systematic review of the literature. *Shoulder Elb*. 2018;10(4):274–84.

17. Ferrer-Roca V, Roig A, Galilea P, GarcíA-Lopez J. Influence of saddle height on lower limb kinematics in well-trained cyclists: Static vs. dynamic evaluation in bike fitting. *J Strength Cond Res*. 2012;26(11):3025–9.

18. Bini R, Hume PA, Croft JL. Effects of bicycle saddle height on knee injury risk and cycling performance. *Sport Med*. 2011;41(6):463–76.

19. Graham-Paulson T, Perret C, Goosey-Tolfrey V. Improvements in cycling but not handcycling 10 km time trial performance in habitual caffeine users. *Nutrients*. 2016;8(7):1–11.

20. Borg G. *Borg's perceived exertion and pain scales*. Champaign, IL: Human Kinetics; 1998. 104 p.

21. Jones AM. The physiology of the world record holder for the women's marathon. *Int J Sports Sci Coach*. 2006;1(2):101–16.

22. Shaheen AF, Alexander CM, Bull AMJ. Effects of attachment position and shoulder orientation during calibration on the accuracy of the acromial tracker. *J Biomech*. 2011;44(7):1410–3.

23. Warner MB, Chappell PH, Stokes MJ. Measuring scapular kinematics during arm lowering using the acromion marker cluster. *Hum Mov Sci*. 2012;31(2):386–96.

24. Taylor WR, Ehrig RM, Duda GN, Schell H, Seebeck P, Heller MO. On the influence of soft tissue coverage in the determination of bone kinematics using skin markers. *J Orthop Res*. 2005;23(4):726–34.

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

determining the centre of rotation of ball joints. *J Biomech*. 2006;39(15):2798–809.

26. Wu G, Van Der Helm FCT, Veeger HEJ, Makhsous M, Van Roy P, Anglin C, et al. ISB recommendation on definitions of joint coordinate systems of various joints for the reporting of human joint motion - Part II: Shoulder, elbow, wrist and hand. *J Biomech*. 2005;38(5):981–92.

27. Girden ER. *ANOVA - Repeated measures*. Newbury Park: CA: Sage; 1992. 6–31 p.

28. Cohen J. *Statistical power analysis for the behavioral sciences*. 2nd ed. Hillsdale, NJ: Associates., Lawrence Earlbaum; 1988. 567 p.

29. Batterham AM, Hopkins WG. Making meaningful inferences about magnitudes. *Int J Sports Physiol Perform*. 2006;1(1):50–7.

30. Friston KJ, Ashburner JT, Kiebel SJ, Nichols TE, Penny WD. *Statistical parametric mapping: the analysis of functional brain images*. Amsterdam: Elsevier; 2007.

31. De Ridder R, Willems T, Vanrenterghem J, Robinson M, Pataky T, Roosen P. Gait kinematics of subjects with ankle instability using a multisegmented foot model. *Med Sci Sports Exerc*. 2013;45(11):2129–36.

32. Pataky TC, Robinson MA, Vanrenterghem J. Vector field statistical analysis of kinematic and force trajectories. *J Biomech*. 2013;46(14):2394–401.

33. Pataky T. Generalized n-dimensional biomechanical field analysis using statistical parametric mapping. *J Biomech*. 2010;43(10):1976–82.

34. Fischer G, Figueiredo P, Ardigò LP. Physiological performance determinants of a 22 km handbiking time trial. *Int J Physiol Perform*. 2015;10(8):965–71.

35. Abel T, Burkett B, Thees B, Schneider S, Askew CD, Strüder HK. Effect of three

different grip angles on physiological parameters during laboratory handcycling test in able-bodied participants. *Front Physiol*. 2015;6:331.

36. Murray WM, Delp SL, Buchanan TS. Variations of muscle moment arms with elbow and forearm position. *J Biomech*. 1995;28(5):513–5.

37. Murray WM, Buchanan TS, Delp SL. The isometric functional capacity of muscles that cross the elbow. *J Biomech*. 2000;33(8):943–52.

38. Guenzkofer F, Bubb H, Bengler K. Maximum elbow joint torques for digital human models. *Int J Hum Factors Model Simul*. 2012;3(2):109.

39. Ackland DC, Pak P, Richardson M, Pandy MG. Moment arms of the muscles crossing the anatomical shoulder. *J Anat*. 2008;213(4):383–90.

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

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

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

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

Table

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 ($\dot{V}O_2$ mL·min^{-1}·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 ($\dot{V}O_2$ mL·min^{-1}·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 % ($P < 0.05$)

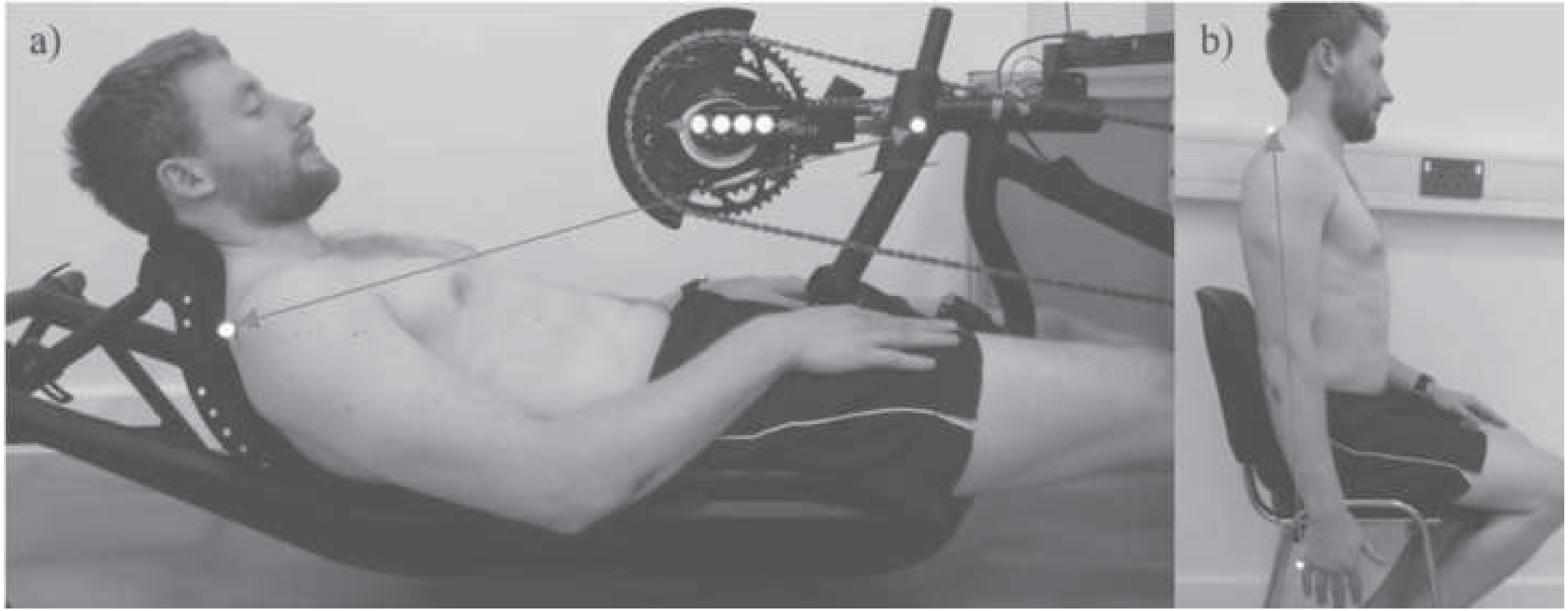
Note. # Significant difference in comparison to 100 % ($P < 0.05$)

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 (N=15)		Post-hoc comparisons (P)					
	F	(P)	94% vs 97%	94% vs 100%	94% vs 103%	97% vs 100%	97% vs 103%	100% vs 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

Figure_1



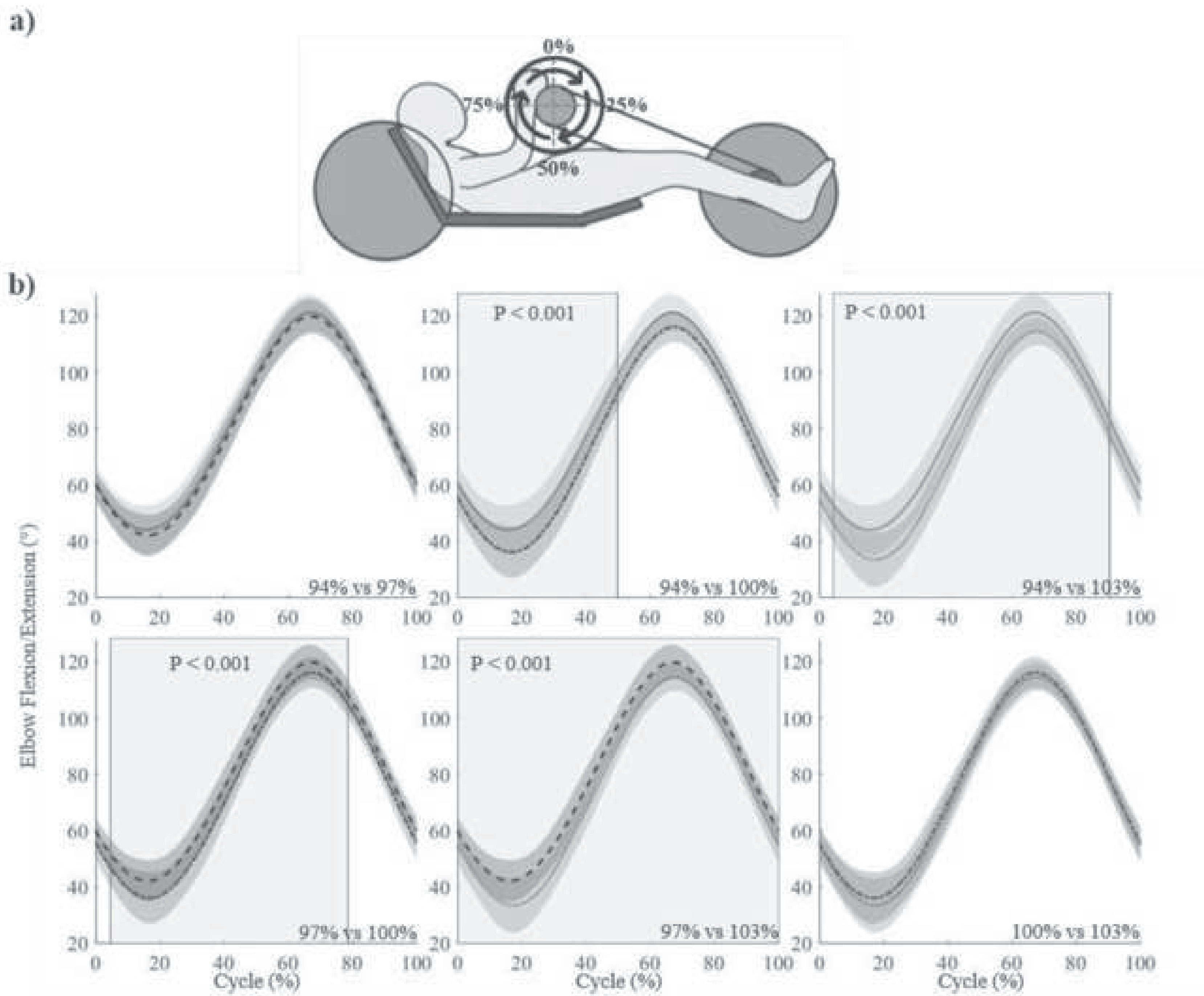

a)
0%
25%
50%
75%
b)
Elbow Flexion/Extension (°)
Cycle (%)
P < 0.001
94% vs 97%
94% vs 100%
94% vs 103%
97% vs 100%
97% vs 103%
100% vs 103%

Figure_3

Click here to access/download;Figure;Figure_3.jpg

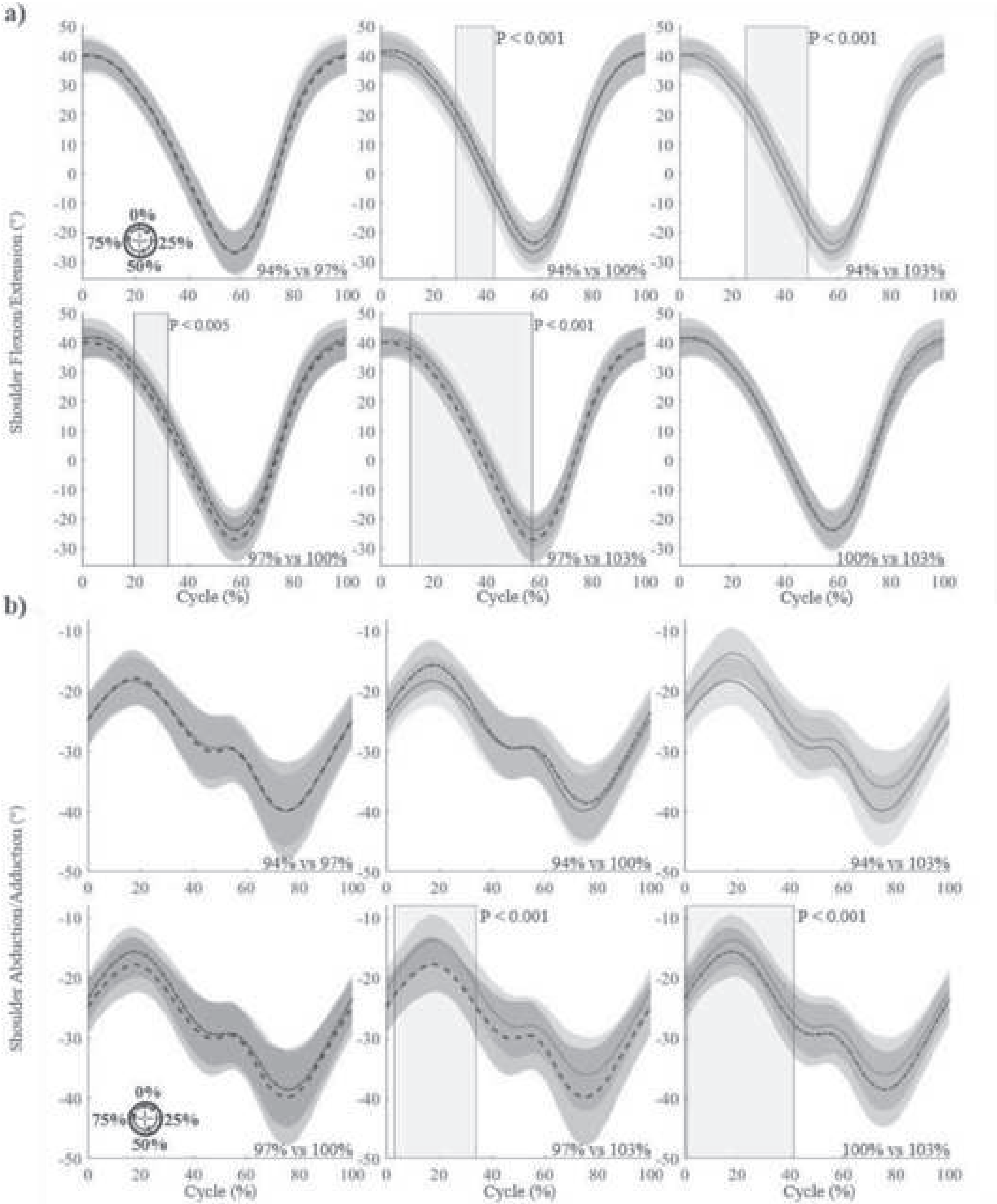
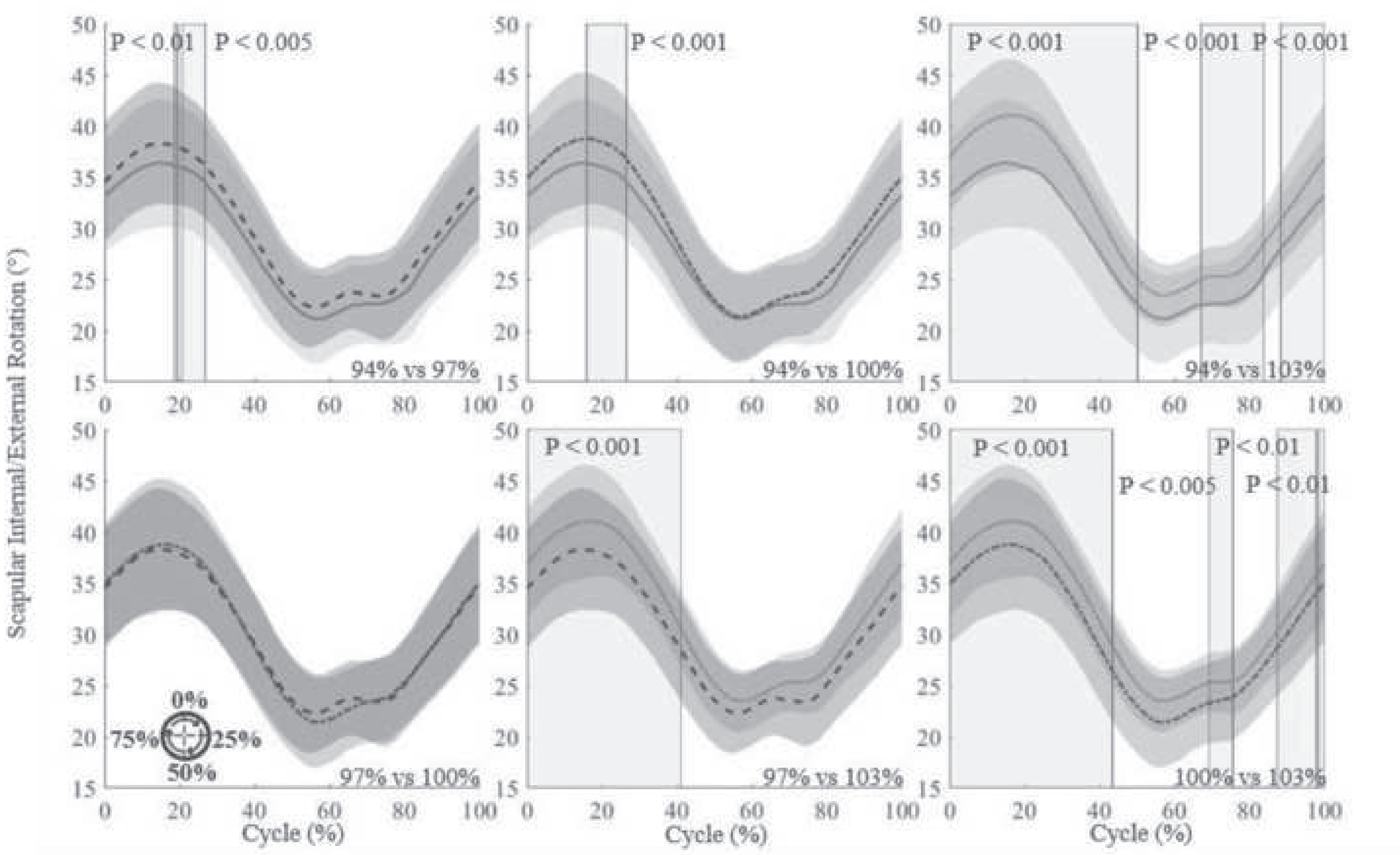


Figure_4



Scapular Internal/External Rotation (°)
P < 0.01
P < 0.005
94% vs 97%
P < 0.001
94% vs 100%
P < 0.001
P < 0.001
P < 0.001
94% vs 103%
0%
75%
25%
50%
97% vs 100%
P < 0.001
97% vs 103%
P < 0.001
P < 0.005
P < 0.01
P < 0.01
100% vs 103%
Cycle (%)
Cycle (%)
Cycle (%)