

Effects of type and mode of propulsion on hand-cycling biomechanics in nondisabled subjects

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Abstract—This study investigated the range of motion (ROM) (in degrees) of the upper limb and trunk, forces (Newtons), two-dimensional fraction effective force (FEF_{2D}) (in percent), and torque (Newton meters) during hand cycling. Seven nondisabled participants performed a 1 min exercise test at 70 rpm on a hand cycle (HC) fixed to an ergometer in synchronous (SC) mode versus asynchronous (AC) mode and in arm-power (AP) versus arm-trunk-power (ATP) type of propulsion. Higher ($p < 0.001$) flexion/extension of the trunk was found during ATP versus AP type and higher ($p < 0.001$) lateral flexion and rotation of the trunk in AC versus SC mode. The trunk ROM should explain the different force generation patterns observed in this investigation between AC and SC modes and AP and ATP types. However, kinetic results do not allow the most effective type or mode of propulsion (FEF_{2D}: from 72.9% to 89.3%) to be established. We conclude that trunk movement is an important parameter to consider in ergonomically optimizing hand cycling. Nevertheless, future studies in experienced HC users, especially with limited trunk function, should be performed.

Key words: asynchronous, backrest, hand bike, hand cycle, kinematics, kinetics, rehabilitation, synchronous, trunk, wheelchair.

INTRODUCTION

Arm-crank propulsion, also called hand-bike or hand-cycle (HC) propulsion, has been developed over the last 20 years and is now widely used in rehabilitation programs for persons with reduced mobility and in the sports field for the disabled. Indeed, in 2004, it became a Paralympic discipline for the first time. Investigations comparing physiological responses during arm-crank ergometry [1–4] or hand

cycling [5–6] have shown that arm cranking is less strenuous and more efficient—in terms of mechanical efficiency and cardiorespiratory responses—than hand-rim wheelchair propulsion. Because of the current booming development in arm cranking, a variety of HCs exist with different backrest and seat adjustments and crank-axle heights and crank configurations, such as synchronous (SC), where cranks are in parallel position, and asynchronous (AC), where cranks are in alternate position 180° to each other.

Research regarding arm cranking and hand cycling is often limited to studies evaluating the physiological responses [5–11]. Different reviews by Van der Woude et al. report that few studies on the biomechanics of hand cycling exist [12–13]. Physiological literature on SC or AC mode shows contradictory results. Generally, studies on physiological responses between AC and SC arm-crank

Abbreviations: 2-D = two-dimensional, 3-D = three-dimensional, AC = asynchronous, AP = arm-power, ATP = arm-trunk-power, B45 = backrest angle of 45°, B85 = backrest angle of 85°, C7 = seventh cervical vertebra, F/E = flexion/extension, FEF = fraction effective force, HC = hand cycle, K = kneeling position, L3 = third lumbar vertebra, ROM = range of motion, SC = synchronous, SD = standard deviation, WB = without backrest.

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ergometry reveal no difference between the two crank modes [14–16]. Moreover, a recent study by Goosey-Tolfrey and Sindall finds significantly higher efficiencies during submaximal AC versus SC mode of propulsion in subjects who were wheelchair-dependant trained [17]. In contrast to previous results in arm-crank ergometry, different investigations show that SC hand cycling is less strenuous and more efficient than AC hand cycling [18–23]. Among these studies, different authors emit the hypothesis that the beneficial effects of the SC mode may also be caused by the larger effective muscle mass of the trunk [20–21], which would allow the weight of the trunk to be effectively used in propulsion.

Moreover, based on body position on the HC, two types of propulsion exist [24–25]: arm-power (AP) and arm-trunk-power (ATP). The sitting position (upright, semirecumbent, kneeling, and bent forward) determines whether the HC is powered with the arms only or with the arms and trunk [26]. However, only persons with functional trunk muscles and good abdominal strength can use ATP propulsion [25]. We are aware of only one study by Faupin et al. that focuses on a kinematics comparison between AP and ATP propulsions [24]. This recent study investigated the effects of backrest position and gear ratio on hand-cycling sprinting performance in 10 nondisabled participants. The results showed that participants had statistically higher trunk flexion/extension (F/E) and maximal velocity without use of a backrest [24]. The authors suggested that HC users' performance improves when they use ATP propulsion.

From that context, obviously, trunk action is an important factor for mode of propulsion (SC vs AC) and type of propulsion (AP vs ATP). Thus, the main goals of this study are to—

1. Evaluate the effects of HC configuration and mode of propulsion in trunk movement in a group of nondisabled participants.
2. Investigate a possible difference in kinetics and kinematics of the upper limb between SC versus AC mode and AP versus ATP type of propulsion.

METHODS

Experimental Protocol

Once on the HC attached to the ergometer (**Figure 1**), we gave the participants 10 minutes to get accustomed to the equipment. Each participant performed a submaximal 1 min exercise test at a 70 rpm-cycle frequency, imposed by



Figure 1. Hand cycle fixed to ergometer with dynamometric pedal. Backrest was modified to make marker on trunk visible. x -, y -, and z -axes = three-dimensional coordinates in global reference system.

a metronome (sound signal). They repeated the test according to SC (parallel cranks) and AC (cranks in alternate position, 180° to each other) crank modes and two types of propulsion, AP and ATP, for four body positions on the HC with different backrest and seating adjustments (backrest angle of 45° [B45], backrest angle of 85° [B85], without backrest [WB], and kneeling position [K]) (**Figure 2**) [27]. The different tests were randomly performed among participants to avoid learning and/or fatigue effects during the experiment. A complete recuperation period of at least 5 min was imposed between each test, during which the experimenter adjusted the HC. Moreover, the participant had 5 min to become accustomed to the new adjustments (mode or type of propulsion). Type of propulsion technique was not recommended to the participants before each test.

We collected kinematic and kinetic data on the right side during the last 30 s of the 1 min exercise test. In addition, we analyzed the first five complete crank cycles of the 30 s measurements for all parameters.

Hand Cycle and Ergometer

We use an adjustable sports HC (Sopor, Spirit 470; Heidelberg, Germany) for the study (**Figure 1**). The hand-grips were in a neutral position, and the length of the standard cranks was 180 mm. For all tests, tire pressure was set at 8 bars. The HC was affixed to an electromagnetically braked ergometer (Elite Axiom; Fontaniva, Italy). The Elite Axiom ergocycle is equipped with a motor unit, which

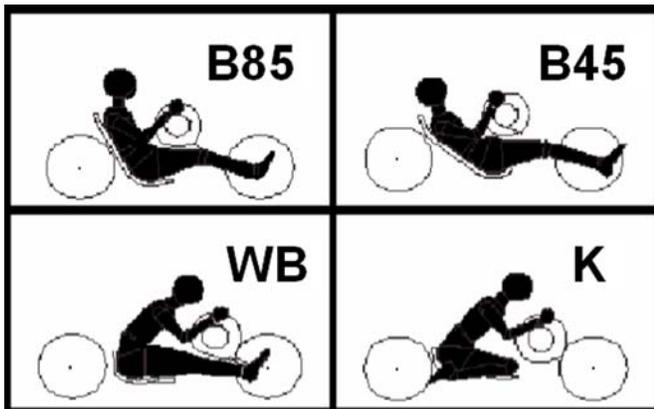


Figure 2.

Schematic of four different hand-cycle testing positions. (Reproduced by permission from Van Breukelen K. Handbikes: Arm power versus arm trunk power, an ergonomic classification of handbikes [Internet]. Gouda: the Netherlands; Arm Powered by Double Performance; 2001 [cited 2010]. Available from: <http://www.handbike.de/archiv/2002/downloads/arm-vs-trunk.pdf>) B45 = backrest angle of 45°, B85 = backrest angle of 85°, WB = without backrest, K = kneeling position.

imposes a constant rolling resistance on the front wheel [28–29]. A virtual slope represents the rolling resistance and is chosen by the investigator using the software of the Elite Axiom (1% in the present study).

For the three seating positions, the participants' feet were placed on the footrests. According to Mossberg et al.'s study, placement of the feet on the footrest reduces participants' ability to use their lower limbs for stabilization [16]. The HC used for the study was an AP bike (Sopur, Spirit 470), so the seating was adapted for kneeling (**Figure 3**). To correct for differences in subject height, we adjusted the seating position by changing seat or back cushions. We adjusted the seating position in relation to the backrest to obtain the same extension of the elbow (15°–20°) for each participant and to not allow complete elbow extension during maximal reach [16].

Kinematic Data

A portion of the kinematic data is similar to Faupin et al.'s protocol [24]. For this portion, we set in quotes.

“A three-dimensional [3-D] movement analysis was performed with a Vicon 370 system (Oxford Metrics; Oxford, United Kingdom), with a sample rate of 60 Hz. This measurement system comprises six digital cameras equipped with an infrared flash system. Marker locations are similar to Faupin et al.'s protocol [24,29–30]. We placed 22 anatomical and technical markers on the participants



Figure 3.

Hand cycle adapted for kneeling position.

(anatomical markers: one on the forehead, the chin, the sternum, the seventh cervical vertebra [C7], and the third lumbar vertebra [L3]; two on the acromions, the temples, the styloid process of the radius and cubitus, and the metacarpals of the auricular and index. Technical markers: four markers are attached to the upper arm and three to the forearm). The reflective markers were spherical: 25 mm for the anatomical markers and 9 mm for the technical markers. The technical markers allowed us to use Roux et al.'s global optimization method, significantly minimizing measurement errors due to sliding of the skin” [31]. We modified the backrest in such a way as to make the marker on L3 visible (**Figure 3**).

We calibrated the capture volume before the start of each test. Based on the static trial, anatomical frames were defined according to the recommendations of the International Society of Biomechanics [32]. Before the actual measurement, we used a static trial to determine the joint rotation centers. In the absence of movement and thus of skin movement, we measured the anatomic marker positions. “According to the method of Schmidt et al. [33], the shoulder center is assumed to be 7 cm inferior to the acromion marker, which is the average of visually determined distances using a ruler. The elbow joint center is the middle between the medial and lateral elbow markers. The joint center of the wrist is the middle between the ulnar and radial wrist marker.” We identified the trunk using markers on the C7, L3, sternum, and two acromions. We considered the upper part of the human body an articulated system

composed of rigid bodies corresponding to the following body segments: head, trunk, arm, forearm, and hand. We chose Euler angles to describe the relative movement of the body segments [31]. During the test, we calculated the maximum and minimum angles and the total range of motion (ROM) (in degrees) of the trunk, shoulder, elbow, and wrist. We placed two reflective markers on the pedal and one on the crank axis (**Figure 1**), which allowed us to measure the crank angle and the angle position of the pedal. “The kinematic data were filtered through a fourth-order digital Butterworth filter with a 6 Hz cutoff frequency [30].” We used MATLAB (MathWorks, Inc; Natick, Massachusetts) programs to calculate the kinematic data.

Kinetic Data

We used a freely rotating, instrumented, dynamometric right pedal (Sensy, 9PED version, aluminum; Jumet, Belgium) with an attached handgrip to measure the reaction forces, both radial and tangential [29]. We calibrated this dynamometric pedal by hanging weights from a dynamometric calibration device attached to the pedal while amplifying and recording voltage outputs from foil strain gauges. Weights between 0 and 1,500 N in the radial direction and from 0 to 500 N in the tangential direction were used in the calibration. A linear regression equation showed that pedal voltage was a strong predictor of pedal force ($R^2 = 0.99$).

We attached two reflective markers to each end of the handgrip—allowing the handgrip center to be calculated—and one on the crank axis to allow the handgrip’s angular position (θ_2) to be obtained and the crank angle (θ_1) (**Figure 4**) to be measured with basic trigonometry. In the handgrip reference system, we measured the forces in two dimensions, along the x - and y -axes. We used these force components, measured along the handgrip orientation (θ_2) and the crank angle (θ_1), to calculate the total, the radial, and the tangential forces, $F_{\text{tot}2D}$, F_r , and F_{tang} , respectively. We calculated the resultant force ($F_{\text{tot}2D}$), which is the total force applied to the handgrip, mathematically using the vector sum of the force components, such as

$$F_{\text{tot}2D} = \sqrt{F_x^2 + F_y^2} = \sqrt{F_r^2 + F_{\text{tang}}^2} \text{ (N)} . \quad (1)$$

We obtained the crank torque (T_c) by multiplying the tangential force (F_{tang}) and the crank length (L_c) as

$$T_c = F_{\text{tang}} \times L_c \text{ (N}\cdot\text{m)} . \quad (2)$$

F_{tang} is the only force component that contributes to the HC’s forward motion. The 3-D effectiveness of the force application has been defined as the fraction effective force (FEF) [34]. Since FEF has been previously defined in wheelchair literature as a 3-D measure and because our study only involves two-dimensional (2-D) forces measurements, we will use the notation FEF_{2D} for FEF [29] as

$$\text{FEF}_{2D} = \frac{\int_0^{360} F_{\text{tang}}(\theta_1) \cdot d\theta_1}{\int_0^{360} F_{\text{tot}}(\theta_1) \cdot d\theta_1} \times 100(\%) . \quad (3)$$

A cable connected the dynamometric pedal to the Vicon system. The Vicon system synchronously collected the 3-D kinematic data (60 Hz) and the 2-D kinetic data (1,200 Hz). We then low-sampled this 1,200 Hz signal (from 1,200 to 60 Hz) using a cubic spline function to synchronize it with the kinematic data. We filtered the kinetic data using a fourth-order digital Butterworth filter with a 10 Hz cutoff frequency [35] and processed the data of the kinetic measurements with MATLAB.

Statistical Analysis

For each parameter in each trial, we calculated the mean averages \pm standard deviation (SD) values for the five consecutive complete crank cycles. For kinematic parameters, we calculated the total ROM for the trunk (F/E, rotation, and lateral flexion), the shoulder (F/E, internal/external

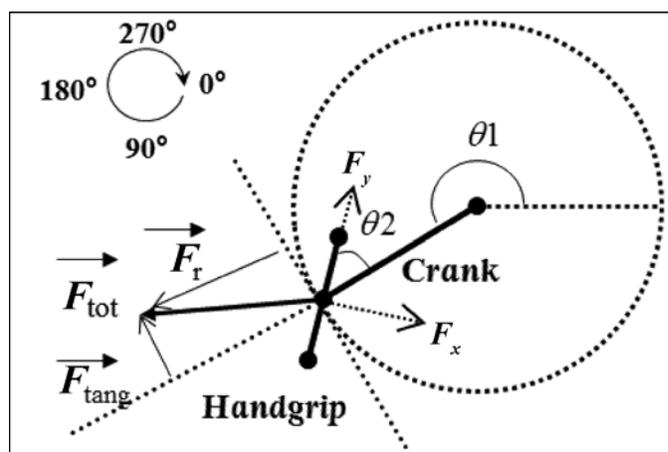


Figure 4.

Schematic representation of force using two-dimensional dynamometric pedal (on right side). Total force (F_{tot}), radial force (F_r), and tangential force (F_{tang}) were calculated from handgrip orientations (θ_2) and crank angle (θ_1) in global reference system.

rotation, and abduction/adduction), the elbow (F/E) and the wrist (F/E and radial/ulnar deviation). For kinetic parameters, we calculated mean and peak forces of F_{tot} , F_r , F_{tang} , and FEF_{2D} . Furthermore, to investigate kinetics pattern, we divided the T_c cycle into four 90° segments: 0° to 90°, 90° to 180°, 180° to 270°, and 270° to 360°. We applied a two-factor analysis of variance for repeated measures with a 2 × 4 design (crank modes: SC and AC, and types of propulsion: AP and ATP [body positions of B45, B85, WB, and K]) to determine the effects of crank modes and type of propulsion on the biomechanical parameters. Then, we applied a Bonferroni post hoc test to determine the location of any significant main effects. The level of significance was set at $p < 0.05$. We performed all statistical analyses with MATLAB and SPSS statistical software (SPSS, Inc; Chicago, Illinois).

RESULTS

Kinematic Data

Table 1 represents the results of kinematic data, expressed as mean ± SD values for the eight testing conditions. We found significant differences for trunk movement ($p < 0.001$) according to both crank modes and the two types of propulsion, with interaction ($p < 0.01$) between those two factors. The results showed significantly higher elbow ($p < 0.001$) and shoulder ($p < 0.01$) F/E in the SC mode versus AC mode. We also found influences of the type of propulsion on internal/external shoulder rotation ($p < 0.001$) and F/E elbow ($p < 0.001$).

Concerning the trunk ROM, the locations of any significant main effects obtained by the Bonferroni post hoc test (not represented in **Table 1**) are represented in **Figure 5**. The analyses revealed a significant major effect of crank mode on trunk ROM, showing lower lateral flexion and rotation for SC compared with AC. Moreover, the ROM of rotation and lateral flexion of the trunk was higher in the AC mode for ATP propulsion (WB and K). As for the type of propulsion, the statistical analyses showed significant differences in the trunk movement between B45 versus WB, B45 versus K, B85 versus WB, and B85 versus K. Although the F/E of the trunk was higher for both ATP positions (WB and K) in the SC (vs AC) mode, this result was not significant for the two other AP propulsion types (B45 and B85).

Kinetic Data

Table 2 represents the mean averages and SD values of the studied kinetic variables over the five consecutive complete crank cycles. Contrary to results obtained during the kinematic analysis, we found few significant differences between the various test conditions for kinetic parameters. Indeed, the results of Bonferroni post hoc test showed significant differences only for the radial peak force between B45 versus WB, B45 versus K, B85 versus WB, and B85 versus K for the SC mode. The results also revealed lower FEF_{2D} mean (in percent) for WB and K compared with B45 and B85 but no significant differences ($p = 0.06$).

Table 1.

Mean ± standard deviation values of kinematic data obtained from each hand-cycle testing condition.

Range of Motion (°)	B45		B85		WB		K		ANOVA (p-Value)		
	SC	AC	SC	AC	SC	AC	SC	AC	Type	Mode	Inter
Trunk											
F/E	2.1 ± 1.7	1.4 ± 0.7	1.3 ± 0.9	1.1 ± 0.7	11.9 ± 4.4	2.6 ± 1.4	12.8 ± 5.3	1.7 ± 0.8	0.001	0.001	0.01
LFr/LFl	0.8 ± 0.5	5.0 ± 2.9	0.7 ± 0.4	3.9 ± 2.8	1.0 ± 0.4	7.5 ± 2.3	1.3 ± 0.5	6.1 ± 1.9	0.001	0.001	0.01
Rr/RI	1.8 ± 0.4	15.1 ± 8.1	1.9 ± 1.0	13.1 ± 6.9	3.2 ± 2.3	31.4 ± 10.6	3.4 ± 2.0	26.8 ± 7.6	0.001	0.001	0.01
Shoulder											
F/E	62.0 ± 4.7	52.8 ± 7.2	65.6 ± 4.3	59.2 ± 6.7	56.1 ± 2.3	46.5 ± 6.1	58.5 ± 1.4	51.9 ± 6.0	0.001	0.01	NS
Ad/Ab	14.6 ± 5.5	13.2 ± 5.5	13.9 ± 7.2	12.6 ± 6.2	13.0 ± 4.8	17.3 ± 4.8	11.0 ± 1.6	17.6 ± 3.4	NS	NS	NS
Ri/Re	11.4 ± 5.6	9.7 ± 4.2	10.2 ± 4.6	8.5 ± 4.0	11.1 ± 3.6	13.5 ± 8.1	12.8 ± 6.2	16.7 ± 6.6	0.01	NS	0.05
Elbow F/E	76.3 ± 7.5	69.2 ± 8.4	73.9 ± 11.9	68.4 ± 6.3	63.4 ± 13.9	57.6 ± 9.4	60.5 ± 6.7	60.7 ± 10.3	0.001	0.001	NS
Wrist											
F/E	18.2 ± 10.3	16.8 ± 9.7	15.7 ± 11.0	15.7 ± 9.3	15.4 ± 8.4	19.3 ± 8.3	13.7 ± 5.9	14.5 ± 7.9	NS	NS	NS
Ir/Iu	15.1 ± 6.1	15.4 ± 6.1	17.9 ± 6.9	19.2 ± 13.1	15.0 ± 4.0	13.1 ± 6.1	14.8 ± 4.1	14.7 ± 5.2	NS	NS	NS

AC = asynchronous, Ad/Ab = adduction/abduction, ANOVA = analysis of variance, B45 = backrest angle of 45°, B85 = backrest angle of 85°, F/E = flexion/extension, Inter = interaction between propulsion type and crank mode, Ir/Iu = inclination radial/inclination ulnar, K = kneeling position, LFr/LFl = lateral flexion right/lateral flexion left, NS = nonsignificant, Ri/Re = internal rotation/external rotation, Rr/RI = rotation right/rotation left, SC = synchronous, WB = without backrest.

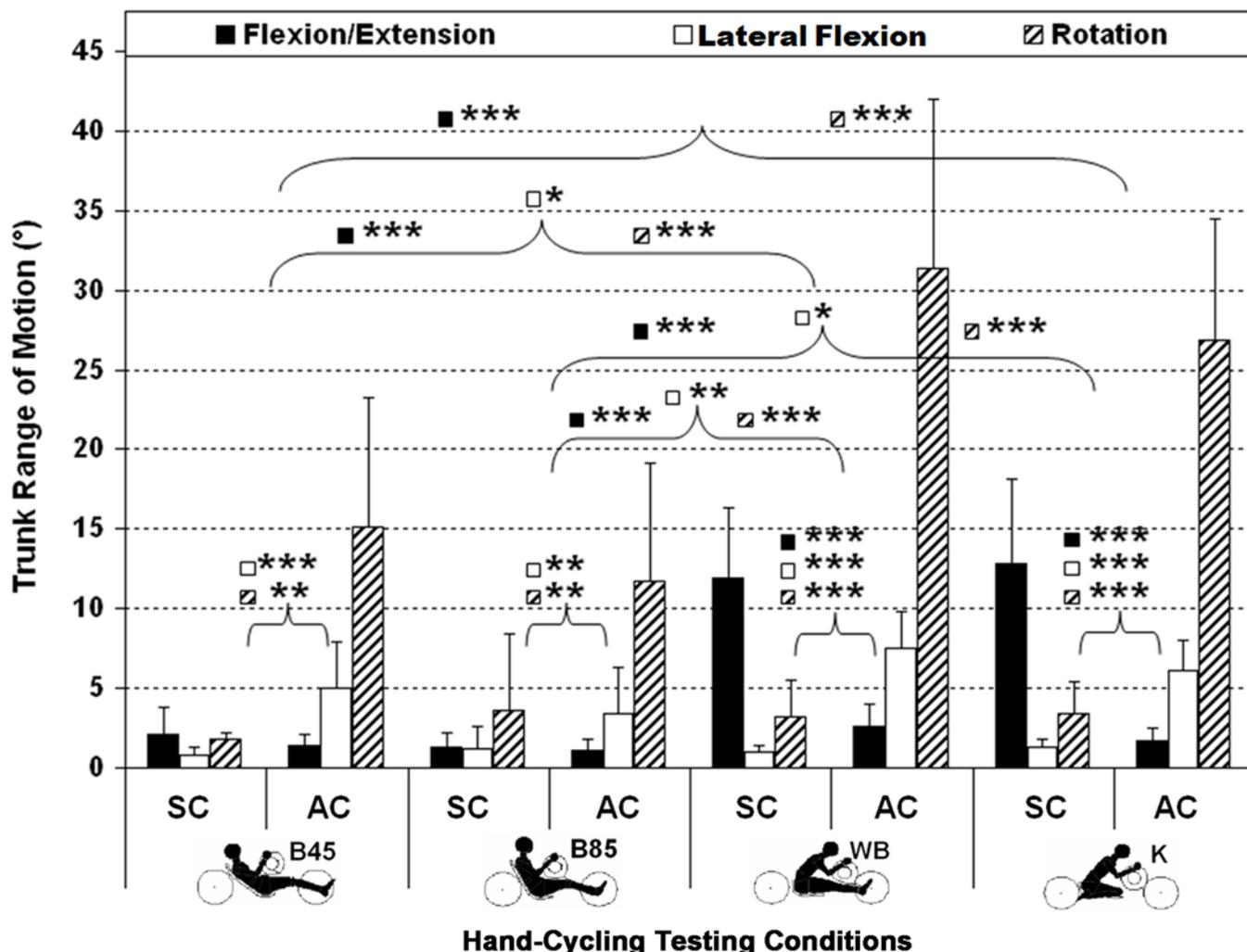


Figure 5.

Trunk range of motion (in degrees) according to eight hand-cycle testing conditions. Significant differences: * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$. AC = asynchronous, B45 = backrest angle of 45°, B85 = backrest angle of 85°, K = kneeling position, SC = synchronous, WB = without backrest.

With respect to T_c (Figure 6), the statistical analysis revealed a significant main effect of crank mode with lower T_c in SC versus AC for phase 1 (0°–90°) and inversely a higher T_c in SC versus AC for phase 3 (180°–270°). As for the type of propulsion, only SC between B45 and K for phases 3 and 4 (270°–360°) showed significant differences.

DISCUSSION

Effects of Mode of Propulsion and Hand-Cycle Configuration in Trunk Range of Motion

The statistical analyses (Table 1 and Figure 5) revealed a significant major effect of crank mode on the

ROM of the trunk. The result showed a higher F/E of the trunk for the ATP type of propulsion (WB and K) in the SC versus AC mode. Indeed, trunk F/E was the highest for WB ($11.9^\circ \pm 4.4^\circ$) and K ($12.8^\circ \pm 5.3^\circ$) in the SC mode than for WB ($2.6^\circ \pm 1.4^\circ$) and K ($1.7^\circ \pm 0.8^\circ$) in the AC mode. Inversely, the lateral flexion and rotation are lower in SC versus AC whatever the type of propulsion. The biggest difference of the ROM between SC versus AC is for trunk rotation amplitude in WB ($3.2^\circ \pm 2.3^\circ$ vs $31.4^\circ \pm 10.6^\circ$).

To our knowledge, no previous study has determined the effect of crank mode on the ROM of the trunk. However in the literature, two studies emit the hypothesis that the beneficial effects of the SC arm mode may also be

Table 2.Mean \pm standard deviation values of different kinetic parameters measured during eight hand-cycle testing conditions.

Parameter	B45		B85		WB		K		ANOVA (<i>p</i> -Value)		
	SC	AC	SC	AC	SC	AC	SC	AC	Type	Mode	Inter
T_c (N·m)	9.4 \pm 0.8	10.0 \pm 3.4	8.7 \pm 2.0	9.9 \pm 2.5	9.1 \pm 1.6	9.4 \pm 1.7	8.0 \pm 1.7	8.8 \pm 2.2	NS	NS	NS
FEF _{2D} (%)	89.3 \pm 5.4	81.1 \pm 7.8	85.1 \pm 10.8	80.6 \pm 11.4	76.6 \pm 12.0	76.9 \pm 9.1	72.9 \pm 11.4	74.9 \pm 10.8	NS	NS	NS
(0.06)											
Peak Forces											
Radial	31.7 \pm 12.3	47.3 \pm 15.0	42.6 \pm 17.2	50.1 \pm 24.7	76.8 \pm 31.1	58.8 \pm 23.4	70.5 \pm 17.3	46.5 \pm 19.2	0.05	NS	0.05
Tangential	97.0 \pm 15.2	99.6 \pm 29.4	79.1 \pm 15.2	103.6 \pm 26.3	97.1 \pm 15.3	99.2 \pm 31.6	91.2 \pm 34.2	91.7 \pm 29.4	NS	NS	NS
Total	101.6 \pm 16.1	107.9 \pm 37.0	88.1 \pm 13.3	111.2 \pm 24.7	112.6 \pm 21.0	109.5 \pm 28.0	114.0 \pm 26.0	98.2 \pm 26.8	NS	NS	NS

AC = asynchronous, ANOVA = analysis of variance, B45 = backrest angle of 45°, B85 = backrest angle of 85°, FEF_{2D} = two-dimensional fraction effective force, Inter = interaction between propulsion type and crank mode, K = kneeling position, NS = nonsignificant, SC = synchronous, T_c = crank torque, WB = without backrest.

caused by the larger effective muscle mass of the trunk, which allows the weight of the trunk to be effectively used in propulsion [20–21]. With proper trunk control, trunk flexors and extensors will actively produce power. On the contrary, the alternating character of the movement in AC requires more trunk stabilization.

Our results do not fully agree with this hypothesis. Although the F/E of the trunk is greater for both ATP positions (WB and K) in the SC (vs AC) mode, we did not find this result for the two other AP propulsion types (B45 and B85). Consequently, F/E of the trunk does not have a main role in these conditions. Moreover, AC causes a higher rotation and lateral flexion of the trunk in the ATP versus AP propulsion. Thus, we conclude that, in AC mode, the trunk muscles not only stabilize but also propel the nondisabled participant.

Concerning HC configuration, the kinematic characteristic (Table 1) substantially showed significant differences, especially for the trunk ROM according to the four types of body positions (B45, B85, WB, and K). The results indicated no significant difference in the trunk ROM between B45 versus B85 and between WB versus K. Thus, the ROM of the trunk was higher in ATP propulsion (WB and K) than in AP propulsion (B45 and B85). Our results are consistent with the first results of Faupin et al. [24]. Although their study design differed from the present study with respect to the test condition (8 s maximal sprints), they also reported both a statistically higher trunk F/E and maximal-reached velocity without use of a backrest compared with two backrest adjustments (angle slope ranging to 45° and 65°).

Indeed, we can hypothesize that the ATP types of propulsion (WB and K) would allow the athlete to use the trunk muscles actively during the propulsive phase. Contrary to ATP, the use of the trunk muscles during AP propulsion

(B45 and B85) was difficult because of the semilengthened position. The AP propulsion is realized because of the arms. As a result, a better stability of the user in the HC was achieved in AP propulsion. Disabled persons with limited trunk function, such as spinal cord injuries, mainly use this type of propulsion, whereas persons with less-severe disabilities, such as athletes with lower-limb amputees, more often use ATP HC. For verifying the current findings, future studies should focus on disabled HC users.

Kinetic and Kinematic Responses of Upper-Limb to SC Versus AC Propulsion Mode and AP Versus ATP Propulsion Type

In a general way, whatever type and mode of propulsion, torque values (N·m) are not significantly different (Table 2). However, concerning the torque pattern for the four 90° segments, Figure 6 shows a significant effect of crank mode with lower torque in SC compared with AC for phase 1 (0°–90°) and inversely a higher torque in SC versus AC for phase 3 (180°–270°) whatever the type of propulsion. Moreover, significant differences appeared in SC between B45 and K for phases 3 and 4. This result may be related to the different uses of the trunk and joint ROM of the shoulder and elbow. Indeed, the statistical results revealed a higher elbow and shoulder F/E in ATP (WB and K) versus AP (B45 and B85) and a significantly higher elbow and shoulder F/E in the SC mode versus AC mode. Such angle variations may be caused by the trunk ROM, and the fact that in K, the shoulders were above the cranks, whereas for B45, they were below the cranks.

In the current study, the calculated FEF_{2D} value is between 72.9 and 89.3 percent. Our results are consistent with the first results of Hettinga et al., who found mean FEF between 79 and 83 percent [25]. However, results in

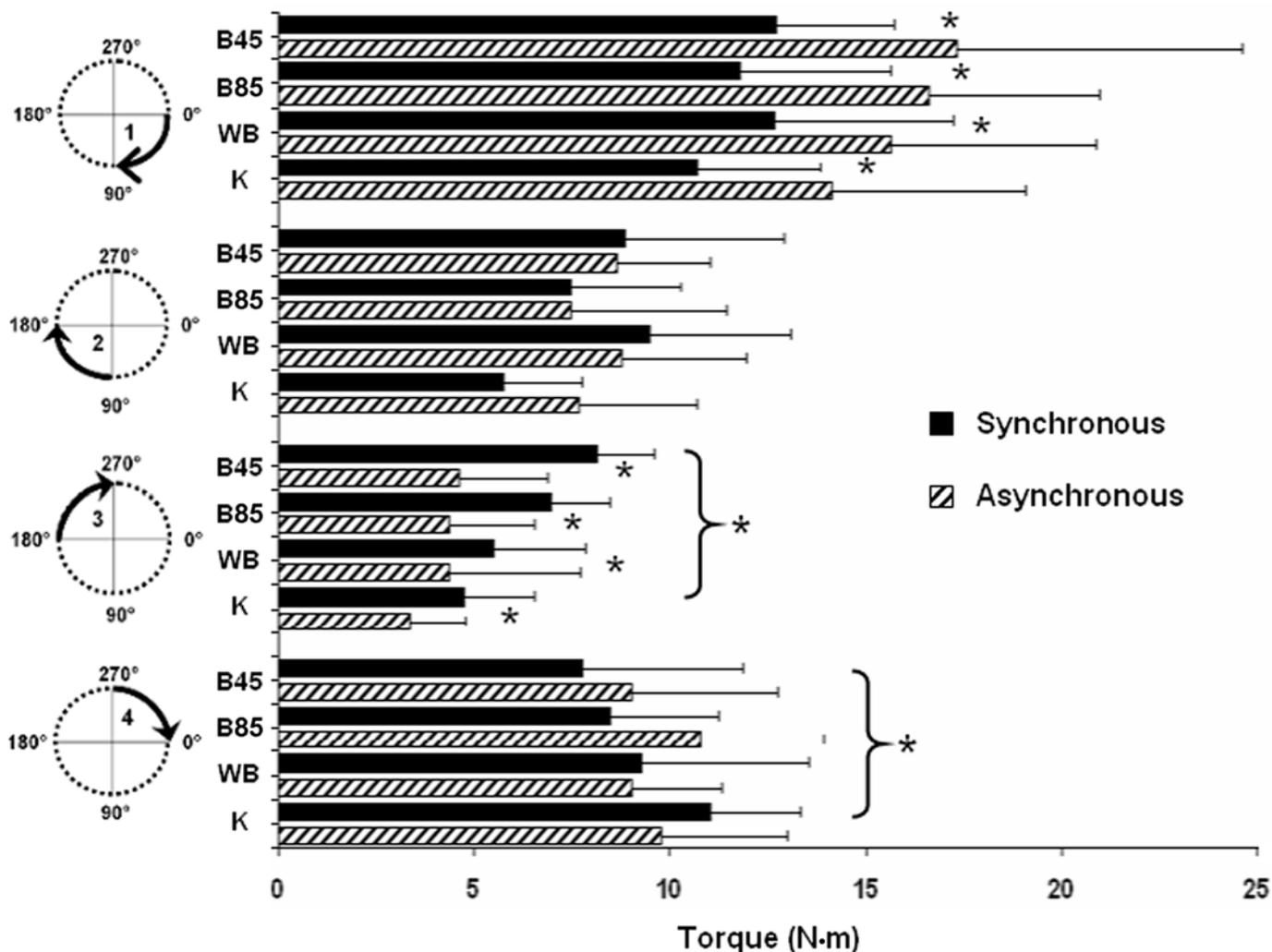


Figure 6. Torque (N·m) for four 90° segments according to eight hand-cycle testing conditions. *Significant difference ($p < 0.05$) between synchronous and asynchronous crank mode or between K and B45. B45 = backrest angle of 45°, B85 = backrest angle of 85°, K = kneeling position, WB = without backrest.

Table 2 do not indicate which mode and type of propulsion were the most effective (FEF). We found no significant difference between AC versus SC and ATP (WB and K) versus AP (B45 and B85) for the FEF parameter (**Table 2**). Moreover, these counterintuitive findings showed results with relative lower FEF_{2D} mean (percent) in WB and K than in B45 and B85 (but no significant difference, $p = 0.06$). Indeed, the results of the Bonferroni post hoc test revealed, for the SC mode, a higher radial peak force in ATP (WB and K) versus AP (B45 and B85). To explain this latter finding, we can assume that the use of the trunk during ATP propulsion might lower stability, and conse-

quently, the application of force would be less effective. Indeed, instability would cause the participant to apply less tangential force and increase radial force.

Limitations and Future Recommendations

All participants in our study had no previous experience in hand cycling. Studying the effects of ergonomic adjustments and design within an inexperienced population has already demonstrated their value in hand cycling [20–24,36–37]. Consequently, this study was completed within a homogenous and equally trained subject group. Moreover, the participants could not be accustomed in any

way to a specific trunk ROM, especially to a particular type or mode of propulsion. A shortcoming might be that we collected our data from nondisabled participants: these results are thus not completely transferable to novice wheelchair-dependent users. Although our results help us better understand trunk use during the hand-cycling propulsion phase, future studies with different populations, especially persons with limited trunk function, still need to be done.

In the current study, we placed the HC on a stationary ergometer (Elite Axiom). The use of a stationary ergometer could explain why the participants had no problem keeping the front wheel parallel to the propelling direction during the AC mode in hand cycling. One should be cautious extrapolating these data since a steering condition was not permitted. Indeed, steering is suggested to involve trunk function in a different way. Moreover, the ergometer does not measure precisely the rolling resistance on the two back wheels, thus precisely calculating power output was not possible. In addition, the Elite Axiom tends to overestimate the average power [27]. However, the calculated values for rolling resistance on the front wheel are reliable and thus can be used for inter-subject comparisons. Both mechanical efficiency (from power output and oxygen uptake) and biomechanical parameter must be studied in the field condition for further ergonomic optimization of HC.

CONCLUSIONS

In this study performed with seven novice nondisabled subjects, the main findings are the differences in the use of the trunk movement according to both crank modes (SC and AC) and two types of propulsion (AP and ATP). Higher F/E of the trunk was observed during ATP versus AP propulsion, and higher lateral flexion and rotation of the trunk in AC versus SC mode. These results demonstrated more trunk movement during ATP type and AC mode of hand cycling. Trunk ROM should explain the different force generation patterns observed in this investigation between AC and SC modes and AP and ATP types. However, kinetic results did not establish the most effective type or mode of propulsion. In conclusion, trunk movement is an important parameter to consider for ergonomic optimization of hand cycling. The results of this study should be confirmed in experienced HC

users, especially with limited trunk function, and in conditions that are more realistic.

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Study concept and design: A. Faupin, P. Gorce.

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Analysis and interpretation of data: A. Faupin, P. Gorce, C. Meyer.

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