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Influence of noncircular chainring on male physiological parameters in hand cycling

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Abstract—The purpose of this study was to examine the influence of a noncircular chainring (NCC) compared with a conventional circular chainring (CC) on hand cycling performance. Eleven nondisabled male participants with no hand cycling experience initially completed an incremental exercise test. Afterward, the participants completed two 20 s sprint tests, followed by a 20 min endurance test and then another two 20 s sprint tests. An NCC and a CC were used in random order on two separate occasions. To compare the effects of the NCC and CC on power data of the sprint tests and metabolic response during the endurance test, a two-way analysis of variance for repeated measures was used. Average power values of the sprint tests showed no significant difference between NCC and CC, but over time, values of the first and third sprint tests were higher than those of the second and fourth sprint tests for both chainrings. Values of energy expenditure (kilojoules), gross efficiency (percentage), and net efficiency (percentage) after 10 and 20 min during the endurance test using NCC and CC showed no significant differences ($p > 0.05$) either between tests or over time. Under the current test conditions and focusing on physiological parameters, a performance optimization using an NCC in hand cycling could not be proven.

Key words: aerobic test, chainring, endurance test, energy expenditure, hand cycling, paracycling, Paralympics, performance optimization, performance testing, sprint test.

INTRODUCTION

Hand cycling has existed as a competitive sport since the mid-1980s. It was officially recognized as a form of paracycling by the International Paralympic Committee (IPC) in 1999 and became part of Paralympic road cycling for the first time during the 2004 Athens Paralympic Games. In principle, it is a sport for individuals with lower-limb disabilities, including those with spinal cord injuries (SCIs) and lower-limb amputations. A road-racing hand cycle is designed as a three-wheeled vehicle with the front wheel being chain-driven using the upper limb and/or torso, depending on the individual's level of disability and functionality. In the context of racing and daily living, hand cycling has been shown to be more efficient than handrim wheelchair propulsion [1–3].

Due to an increasing number of athletes and the acceptance of the sport by national cycling federations, combined with a better scientific knowledge of training requirements and improved hand cycle designs, considerable improvements in performance have been observed

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Abbreviations: CC = circular chainring, EE = energy expenditure, GE = gross efficiency, IPC = International Paralympic Committee, NCC = noncircular chainring, NE = net efficiency, RER = respiratory exchange ratio, RPE = rate of perceived exertion, SCI = spinal cord injury, SD = standard deviation, VO_2 = oxygen uptake, WD = work done.

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[4]. In this context, physiological performance analysis [4–6], technological innovations such as the comparison of asynchronous and synchronous crank configurations [5,7–9], and the influence of different crank lengths [10–11] have all been the focus of scientific research associated with this sport. Here we show that mechanical efficiency, in the form of both gross efficiency (GE) and net efficiency (NE), is viewed as an important variable when comparing different hand cycle configurations.

Similar scientific developments have been observed in conventional leg cycling. To improve the propulsion technique in cycling, the benefit of noncircular chainrings (NCCs) has been extensively examined since 1977 [12]. Further studies analyzing different types of NCCs concentrated on short-term, submaximal exercise but reported discrepant results [13–22]. The reasons for such conflicting results in leg cycling could be the varying types of NCCs, test procedures, and characteristics of recruited participants. A theoretical approach used to model and optimize athletic performance has also been undertaken with NCCs [23].

The goal of using an NCC is to reduce the effect of “dead spots” during the crank cycle where minimal torque can be developed and to focus on the phases where power supply is greatest, particularly in the region of the production of maximum, tangential forces. Krämer et al. [24] and Smith et al. [8] showed two maxima in the torque distribution during pulling and pushing in hand cycling. By varying the diameter of the chainring, the duration of low force generation should theoretically be shortened and that of high forces lengthened [23]. Furthermore, the magnitude of the maximal forces should be reduced, resulting in a much smoother distribution of torque throughout the entire crank cycle.

To our knowledge, the issue of NCC has not yet been addressed in the context of hand cycling. More important, it is not possible to directly translate information and knowledge published about leg cycling to hand cycling. The main feature that distinguishes hand cycling from all other forms of cycling is that the propulsion is produced by the upper limb, which is different to the lower limbs from a functional and physiological point of view [25]. Furthermore, a synchronous crank configuration is typically employed in hand cycling, and this mechanical characteristic may have a considerable impact on the effectiveness of using an NCC.

Therefore, the main objectives of this study were to (1) evaluate how using an NCC compared with a circular chainring (CC) influenced performance parameters during several periods of all-out sprinting and over time and (2) to explore how physiological responses, mechanical GE, and subjective perceptions of effort were influenced by the chainring (NCC vs CC) during a sustained period of submaximal aerobic exercise. It was hypothesized that using an NCC would be more efficient and, due to the smoother torque distribution, elicit less muscular effort and associated fatigue, thus resulting in a lower demand on both the cardiovascular and respiratory systems.

METHODS

Eleven nondisabled men (age: 24 ± 2 yr, height: 183.9 ± 4.1 cm, weight: 77.4 ± 7.3 kg, all mean ± standard deviation [SD]) with no prior experience in hand cycling participated in the study. They were sports sciences students and active in performing the triathlon, swimming, canoeing, and rowing as competitive sports. Prior to any testing, all procedures received institutional ethics approval (according the Helsinki Declaration). Furthermore, after having had the study objectives and all procedures explained to them, each volunteer provided written informed consent.

In this study, a CC and an NCC (each with 52 teeth) were employed and compared. The NCC (Q-Ring, Rotor Bike Components; Madrid, Spain) is designed for road cycling and equipped with five mounting positions (marked by five press cuts). This specific NCC was chosen because it is the most widely used in training and racing in cycling and hand cycling. To ensure that a standard exercising position for all participants was achieved, the fourth mounting position was chosen because this setting used the best compromise between body position in the hand cycle and the individual characteristics of the crank cycles for all participants and their seating positions. In this position, the crank arms were pointing straight to the manufacturer’s fourth default mounting position. Here, the fewest number of teeth (the shortest length of the chain) is given for the position in the racing hand cycle when the participants stretch out their arms to the foremost possible point or flexing maximal. These two points show the two dead spots, in our experience. Between these two points (twice), the greatest power is supplied along with the longest length of the chain. During all tests, a gear ratio of 52/15 was used.

The seating position was adjusted individually to accommodate to the heterogeneous body sizes of the participants. First, the inclination of the backrest was adjusted so that the participants could almost stretch out their arms in the maximal forward point of the crank movement (one of the two dead spots). The adjustment of the backrest has previously been shown to have little or no effect on physiological parameters [26]. Here, the elbows remained slightly flexed and the shoulders were horizontally in line with the crank axle. Second, once each participant was positioned comfortably in the hand cycle, footrests were adjusted in length to accommodate the participants' legs and feet (**Figure 1**).

All tests were conducted using a racing hand cycle (Shark, Sopur; Malsch, Germany) with a synchronous crank configuration, which was mounted on a fully calibrated and validated ergometer (Cyclus2, RBM Electronics; Leipzig, Germany) [27]. The hand cycle was affixed to the ergometer using the front wheel, so no steering was necessary. To obtain a full data set, each participant visited the laboratory on three different occasions. The interval separating these three visits was at least 2 d. Participants were instructed to perform only moderate training intensities and volumes the day before each test day and were advised to standardize their food and fluid intake (e.g., no alcohol or caffeine consumption).

During the first test day, participants completed an incremental exercise test. The initial power output was set at 20 W and increased by 20 W every 5 min either until exhaustion or a cadence lower than 50 rev·min^{-1}. At the end of every level, blood lactate concentration (Biosen C-Line, EKF-Diagnostics; Magdeburg, Germany), heart rate (Polar S710, Polar Electro Inc; Lake Success, New York), oxygen uptake (VO_2), carbon dioxide output, respiratory exchange ratio (RER) (ZAN 600, nSpire Health Inc; Longmont, Colorado), and ratings of perceived exertion (RPEs) were measured. During this test, the CC was used. In addition to measuring peak physiological responses, this test enabled the researchers, using nonlinear interpolation methods [28], to identify the power output corresponding to a fixed blood lactate concentration of 4 mmol·L^{-1}, because this exercise intensity has been shown to be the best metabolic predictor of simulated, laboratory-based hand cycle race performance.*

On the second and third test days, a CC (Shimano Corporation; Irvine, California) and an NCC were employed in a random order (each chainring with 52 teeth). Participants did a 10 min warm-up at a self-selected power output

*Abel et al. Diagnostics and competition in hand cycling. 2005. Unpublished.

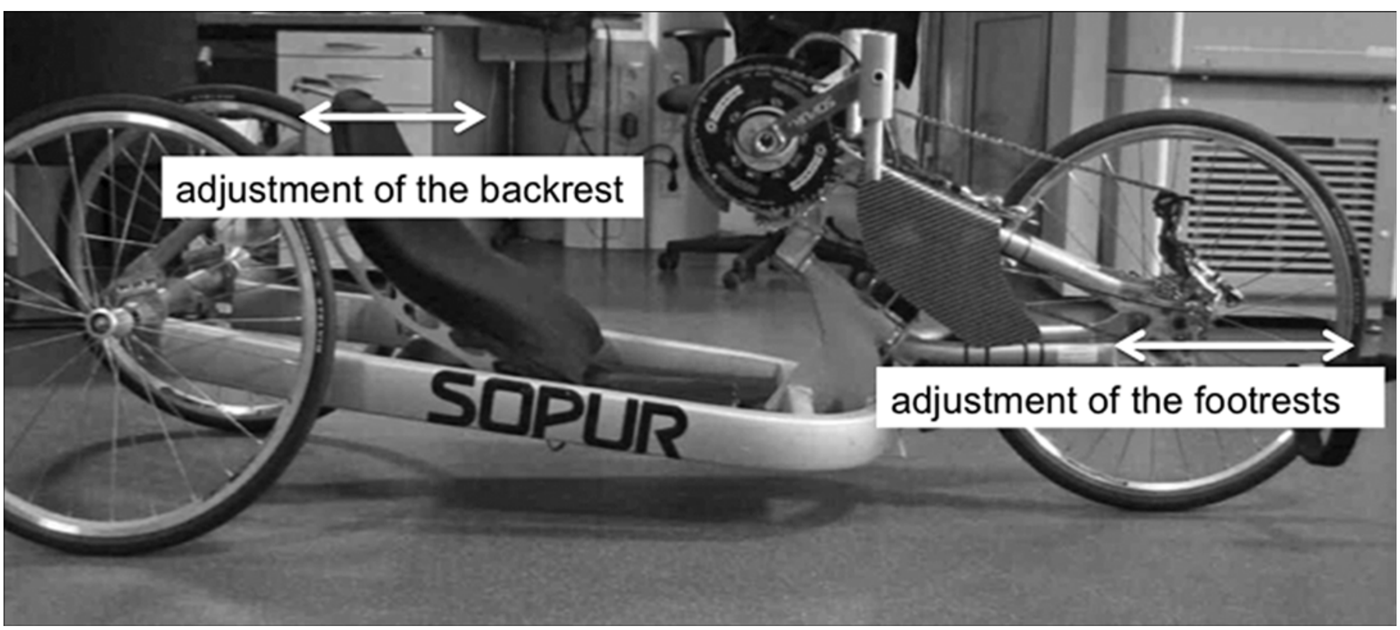

Figure 1.
Configuration of hand cycle (Shark, Sopur; Malsch, Germany).

followed by a 5 min rest. The main test included two 20 s sprints (sprint test), separated by a 2 min passive rest period. Thereafter, following a further 10 min period of passive recovery, a 20 min endurance test (aerobic test) was completed before two further sprint tests were completed, separated by a passive rest period of 2 min. This protocol was used because it simulated an intensive race start, a constant main effort, and a strong finish, while an IPC time trial in hand cycling is about 30 min of duration.

All sprint tests were executed using an isokinetic format; the cadence was limited to 110 rev·min^{-1} and the initial torque (defining the test start) was set at 20 N·m. During the sprint tests, maximum and average power output were measured and recorded. The maximum peak power value is the highest recorded data point during the whole test. Immediately after each sprint test and 1 min before the endurance test, a small capillary blood sample was obtained from a hyperaemic earlobe for the determination of whole blood lactate concentration.

The endurance tests included continuous measurements of heart rate, VO_2, carbon dioxide output, RER, and cadence. Additionally, capillary blood samples were obtained at 5 min intervals in order to measure whole blood lactate concentration. Furthermore, participants reported subjective RPEs throughout this test using the 6–20 Borg Scale [29]. While a fixed intensity (*W*) equating to the previously determined 4 mmol·l^{-1} fixed blood lactate concentration was used during the endurance tests, the participants were able to freely choose their cadence. Using information relating to work done (WD), VO_2, RER, and an updated table of thermal equivalents of oxygen for nonprotein respiratory quotients [30], measures of GE and NE (percentage) were calculated [31] (**Equations 1–2**):

$$GE = (W/E) \times 100 \text{ and} \qquad (1)$$

$$NE = (W/E - E_R) \times 100\,, \qquad (2)$$

where W = external work, E = total energy expended, and E_R = energy expended at rest.

STATISTICS

The statistical analysis of the data was accomplished using Excel 2007 (Microsoft Corporation; Redmond, Washington) and Statistica software version 9.0 (StatSoft Inc; Tulsa, Oklahoma). To compare peak and average values of the sprint tests separately for the NCC and CC, overall, and over time and for all physiological data during the endurance tests, separate two-way analyses of variance with repeated measures were used. All combinations of the sprint tests were tested against each other. Where a significant main effect was observed, pairwise, Bonferroni post hoc tests were used to determine the precise location of any significant differences. Separate Wilcoxon matched pairs tests were used to explore differences in RPE within and between the endurance tests. Statistical significance was accepted at $p < 0.05$, and all subsequent data are presented as mean ± SD.

RESULTS

All participants were able to complete the incremental stage test, the sprint tests, and the endurance tests. **Table 1** summarizes the values of peak aerobic power (*W*) and wattages associated with the fixed 4 mmol·L^{-1} blood lactate concentration derived from the incremental exercise test.

Figure 2 presents mean ± SD values of the peak and average power output achieved during the four sprint tests. There were no significant differences ($p > 0.05$) between NCC and CC.

There was a significant difference ($p = 0.03$) in peak power for all tests and for both types of chainrings over time. Peak power values of the first and third sprint tests

Table 1.
Peak values of incremental exercise test and calculated values equating to 4 mmol·L^{-1} blood lactate concentration (La).

Value	Mean ± SD
Peak	
PO (W)	134.5 ± 18.1
VO_2 max (L·min^{-1})	2.73 ± 0.43
La max (mmol·L^{-1})	8.88 ± 2.31
HR max (bpm)	150.0 ± 19.7
RER max	1.03 ± 0.07
4 mmol·L^{-1} La Calculated	
PO (W)	89.8 ± 17.8
HR (bpm)	121.5 ± 16.2
VO_2 (L·min^{-1})	1.89 ± 0.34
RER	0.98 ± 0.03

bpm = beats per minute, HR = heart rate, max = maximum, PO = power output, RER = respiratory exchange ratio, SD = standard deviation, VO_2 = oxygen uptake.

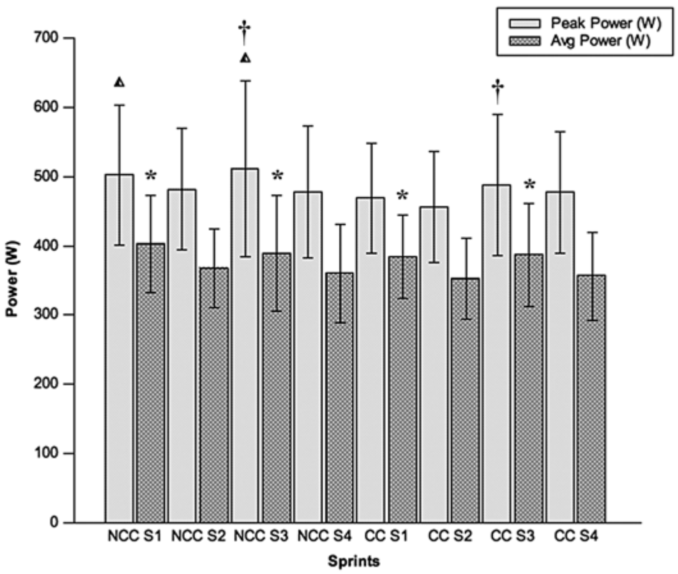

Figure 2.
Peak and average (Avg) power values of sprint tests (S) for circular chainring (CC) and noncircular chainring (NCC). For both chainrings together, third sprint test showed significantly (*) (p = 0.03) higher peak power values. Peak power values of first and third sprint tests (NCC) were significantly (△) (p = 0.01) higher than second and fourth sprint tests. Average power values of first and third sprint tests were significantly (†) (p = 0.01) higher than second and fourth sprint tests for CC and NCC.

using the NCC were significantly higher (p = 0.01) than those achieved during the second and fourth tests using the NCC. For CC, the highest value (p = 0.03) of peak power output was achieved during the third sprint test.

Average power values of the sprint tests were similar ($p > 0.05$) between NCC and CC; however, differences (p = 0.01) were identified between tests for both chainrings (**Figure 2**). Here, average power values of the first and third sprint tests were higher than those of the second and fourth sprint tests for CC and NCC.

There were no significant results ($p > 0.05$) comparing NCC and CC during the endurance tests. **Table 2** summarizes the mean ± SD values of energy expenditure (EE) (kilojoules) and GE and NE (percentage) after 10 and 20 min of exercise using the NCC and CC. Although GE and NE remained slightly higher after 20 min using the NCC, no significant differences ($p > 0.05$) were observed either between tests or over time.

DISCUSSION

The purpose of this study was to compare values of power measured during all-out sprinting as well as submaximal physiological responses, including calculations of GE and NE using either a CC or NCC. To our knowledge, no previous study has examined this topic in hand cycling. The results show no effect of using an NCC in hand cycling in the context of sprint performance, submaximal physiological parameters, or subjective RPEs during aerobic endurance tests. Therefore, it can be summarized that under the current test conditions, the use of an NCC does not offer an advantage compared with a conventional CC in hand cycling.

Maximum anaerobic power and mean power output was measured during two pairs of sprint tests before and after a 20 min endurance effort using both types of chainring while employing a Cyclus2 ergometer. No studies in leg or hand cycling have examined the influence of NCC on such short maximum sprint tests. The results of the maximum power during the sprint tests provide information about the extent of benefit offered by the different chainrings during short-term maximal efforts. Overall, the average values of the first and third sprint tests were significantly higher than those of the second and fourth sprint tests for both chainrings; specifically, the highest value of peak power output was observed during the third sprint test for both chainrings. Therefore, it appears that an intensive warm-up before such sprint tests should take place in further work when high peak power values are desired. Comparable effects were found in kayaking, where an intermittent high-intensity warm-up resulted in a higher supramaximal performance capacity [32]. However, when comparing the single and overall performances using the two types of chainrings, no significant differences were noted.

The power output employed during the endurance tests (134.5 ± 18.1 W) was supposed to elicit a blood lactate concentration of 4 $mmol \cdot L^{-1}$. However, after 10 and 20 min of the endurance tests, blood lactate concentrations using the NCC and CC were much higher than predicted. It is likely that the intensive nature of the sprint tests completed before each endurance test and the short break between these tests was largely responsible for this discrepancy. As in leg cycling, no influence of NCC on metabolic submaximal parameters was identified [15,21–22]. Previously, only one study has reported a lower blood lactate concentration during submaximal cycling

Table 2.
Physiological and efficiency values (mean ± standard deviation) during endurance tests.

Physiological and Efficiency Values	Noncircular Chainring		Circular Chainring	
	10 min	20 min	10 min	20 min
VO_2 ($L \cdot min^{-1}$)	1.82 ± 0.30	1.85 ± 0.32	1.82 ± 0.30	1.86 ± 0.33
CO_2 ($L \cdot min^{-1}$)	1.68 ± 0.34	1.71 ± 0.34	1.69 ± 0.28	1.69 ± 0.32
RER	0.91 ± 0.05	0.92 ± 0.05	0.93 ± 0.04	0.91 ± 0.03
HR (bpm)	120 ± 13	121 ± 15	124 ± 17	125 ± 17
La ($mmol \cdot L^{-1}$)	6.31 ± 1.25	5.02 ± 1.30	6.23 ± 1.59	5.08 ± 1.53
RPE (6–20 Borg Scale score)	13.0 ± 0.8	13.0 ± 0.8	13.0 ± 0.7	13.0 ± 0.8
EE (kj)	37.8 ± 6.5	38.5 ± 6.9	37.8 ± 6.2	38.4 ± 6.9
GE (%)	13.7 ± 3.6	14.4 ± 3.6	14.2 ± 0.9	14.1 ± 0.9
NE (%)	22.3 ± 12.0	21.9 ± 1.2	20.2 ± 1.2	20.0 ± 1.8
Cadence* ($rev \cdot min^{-1}$)	73.5 ± 14.2		71.1 ± 12.7	

*Refers to total test duration of 20 min.
bpm = beats per minute, CO_2 = carbon dioxide output, EE = energy expenditure, GE = gross efficiency, HR = heart rate, La = blood lactate concentration, NE = net efficiency, RER = respiratory exchange ratio, RPE = rate of perceived exertion, VO_2 = oxygen uptake.

when cadence was freely chosen [17]. Here, the type and choice of the NCC seems to be of major importance; theoretically, using different chainring shapes could lead to an optimization of physiological parameters during submaximal exercise [17,23].

Values of VO_2 observed during both endurance tests were much lower than predicted from the incremental stage test, even though blood lactate concentrations were typically higher than those predicted. A reason for this could be a high muscular load of relatively smaller muscle groups of the upper limbs and a lower general strain over time, which resulted in a lower VO_2; therefore, a higher metabolic steady-state than 4 $mmol \cdot L^{-1}$ can be assumed. Values of VO_2 observed during a hand cycling marathon competition simulation were about 62 percent of maximum VO_2 [1]. Our subjects reached a percentage of 67 percent; thus, this higher relative utilization of maximum VO_2 might have been due to a higher aerobic fitness of the recruited athletes combined with a shorter duration of the endurance test completed. Furthermore, pacing guidelines for hand cycling races should consider the potential for a higher maximal lactate steady state, depending on the format and duration of the competition in question.

WD, EE, NE, and GE were calculated during the endurance tests. Power output was prescribed according to a fixed blood lactate concentration of 4 $mmol \cdot L^{-1}$. However, it was interesting to note that relatively low values of RER were recorded throughout both 20 min endurance tests in comparison with the predicted values. This finding was somewhat surprising and confirmed that EE during both tests was predominantly derived from aerobic pathways and could be supported by the values of VO_2 described previously. This finding might hold important practical implications for upper-body exercise and training prescription. Values of GE achieved while using the NCC were slightly higher toward the end of the 20 min endurance tests, though no significant differences ($p > 0.05$) were observed between tests. Values of GE and NE were marginally lower than those reported by Goosey-Tolfrey et al. [10], but comparable (GE) with the results of Verellen et al. [33] when synchronous, recumbent, arm-powered hand cycling was employed. This could be caused by the selection of participants and the study design. Wheelchair-dependent, high-performance athletes of the British national team, who were both used to hand cycling [10] and moderate to highly trained male participants (SCI), were examined [33]. Therefore, GE values of the participants of this study can be compared with these experienced hand cycle users. Interestingly, the type of chainring used had no effect on average cadence employed during the NCC (73.5 ± 14 $rev \cdot min^{-1}$) and CC trials (71.1 ± 13 $rev \cdot min^{-1}$), respectively. Verellen et al. showed that the use of higher cadences resulted in lower values of GE [33].

During the incremental stage test, participants achieved, on average, a peak power output of 134.5 ± 18.1 W. Compared with the maximum achievements in the studies by Abel et al. [7] and Martel et al. [34], our participants achieved a higher peak aerobic power. In another study, participants achieved a higher peak power output of 171 ± 15 W [35]; however, this discrepancy can easily be explained by differences in the work rate durations employed. In the current study, exercise stages of 5 min were used while the higher values were reached by shorter (1 min) stages. Therefore, the aerobic capacity of the upper body of participants used in the present study can be assumed to be above average. Additionally, due to the peak aerobic power output achieved and the fact that high values of peak blood lactate concentration were observed, it can be concluded that our volunteers truly experienced volitional exhaustion.

CONCLUSIONS

In conclusion, under the current test conditions and focusing on physiological parameters, performance optimization using an NCC in hand cycling could not be proven. The knowledge about the heterogeneous performances throughout the series of four sprint tests indicates, however, that an intensive warm-up phase should be considered as highly necessary prior to such efforts if a high peak power is the aim of such tests. Future studies should focus on the importance of individual fitting of the NCC, which should be supported by an analysis of torque distribution and physiological parameters to identify crank cycle phases where minimal and optimal torque development is achieved. In doing this, it might be possible to optimize individual performance and develop future shapes of NCCs in hand cycling.

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Study concept and design: S. Zeller, T. Abel.
Acquisition of data: S. Zeller.
Analysis and interpretation of data: S. Zeller, P. M. Smith.
Drafting of manuscript: S. Zeller, T. Abel, P. M. Smith.
Critical revision of manuscript for important intellectual content: T. Abel, P. M. Smith.
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Participant Follow-Up: The authors do not plan to inform participants of the publication of this study. However, participants have been encouraged to check the study Web site for updated publications.

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