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Research article

Physiological Responses during Cycling With Oval Chainrings (Q-Ring) and Circular Chainrings

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Abstract

The aim of this study was to compare the physiological responses of cyclists using round (C-ring) or oval (Q-ring) chainrings during an incremental test until exhaustion. Following a randomized design, fourteen male elite cyclists [age (mean ± SD): 21.1 ± 2.1 yr; VO_{2max}: 78.5 ± 5.3 mL·kg^{-1}·min^{-1}] performed two incremental maximal tests separated by 48 h (one with C-rings, the other with Q-rings). Starting at 100 W, the workload was increased by 25 W every 3 min until volitional exhaustion. Maximal heart rate, power output and oxygen consumption were compared. Blood lactate was monitored throughout the test. After the incremental test, 4 intermittent 20-s maximal sprints with a 60-s recovery period in between were performed. Maximal isometric voluntary contractions were performed at rest and immediately after each 20-s maximal sprint, and the force and EMG RMS amplitude were recorded from the vastus medialis and vastus lateralis muscles. For the incremental exercise test, no significant differences were found in the maximal power output ($p = 0.12$), oxygen consumption ($p = 0.39$), and heart rate ($p = 0.32$) between Q-rings and C-rings. Throughout the incremental test, lactate levels were comparable when using both the C-rings and Q-rings ($p = 0.47$). During the short sprints, power output was 2.5–6.5% greater for Q-rings than for C-rings ($p = 0.22$). The decline in EMG RMS amplitude observed during the incremental tests was comparable for Q-rings and C-rings (0.42). These findings indicate that the oval chainring design, presented here as "Q-rings", did not significantly influence the physiological response to an incremental exercise test as compared to a conventional chainring.

Key words: Pedaling, chainring, blood lactate, fatigue, biomechanics.

Introduction

It is well established that cycling performance can be enhanced by optimizing biomechanical factors related to the aerodynamics of cyclist posture, such as frontal area, seat height, and seat tube angle (Gregor, 2000). In addition to the aerodynamics aspects, the specific chainring design adopted could also influence the pedalling mechanical performance (Cullen et al., 1992; Hull et al., 1992). The importance of the ring shape for cycling performance is explained by several factors. First, the forces applied to the pedal during a crank cycle are not constant; rather, they are produced in a nearly sinusoidal manner with minimal torque being produced at the top and bottom points of the crank cycle (Gregor, 2000; Hull et al., 1992). Second, the specific shape of the chainring determines the way the force is exerted throughout the pedal-crank revolution, which in turn 'configures' the biomechanical patterns of cyclists (Coyle et al., 1991; Sanderson et al., 2000; Hue et al., 2001). In addition, the chainring design determines how 'smooth' the pedal action is (especially the 'pull-up'), which can have an impact on the metabolic cost of motion (Lucia et al., 2001).

In the last decades, several designs of non-circular rings have been proposed (Cullen et al., 1992; Hull et al., 1992). The main feature of these devices is that they accelerate the upstroke and the downstroke. For example, Cullen et al. (1992) and Hull et al. (1992) described an elliptical chainring with the peak pedal angular velocity occurring when the angle of the cranks was at 66º and 246º from the upper dead spot. In addition, Hull and colleagues (1992) introduced an elliptical shape whose maximum speed was obtained when crank angles were 100º and 280º from the upper dead spot. In both designs, the crank arms were parallel to the longest axis of the ring. Despite the theoretical benefits of these designs, they did not result in improvement in the physiological variables as compared to the standard circular chainring. Subsequent to these pioneering attempts, other designs of non-circular rings were devised, such as the "O.Symetric Harmonic" (Barani et al., 1994; Hintzy et al., 2000; Hue et al., 2001). Remarkably, with this new equipment, Hue et al. (2001) showed that, during an "all-out" 1-km laboratory test, cycling performance was significantly improved (64.25 ± 1.05 s vs. 69.08 ± 1.38 s with the eccentric and the round designs, respectively), although the cardiorespiratory variables were not influenced.

An alternative method of increasing power output was provided by the Rotor system (Santalla et al., 2002). This system makes each crank independent from the other such that they are no longer fixed at 180º (Henderson et al., 1977; Santalla et al., 2002). This configuration allows the angle between the cranks to vary so that the dead points (where torque production is minimal) are practically eliminated. Using this configuration, Santalla et al. (2002) demonstrated that, at exercise intensities between 60 and 90% VO_{2max}, delta efficiency was significantly higher with the eccentric than with the round design (24.4 ± 1.9% vs. 21.1 ± 1.1%, respectively). The Rotor Crank has since been shown to have no effect on time trial performance (Jobson et al., 2009).

Rotor Componentes Tecnologicos, S.L., has developed a new type of oval ring: "Variable Gear Rings (Q-rings)". The Q-ring design mimics the pedalling

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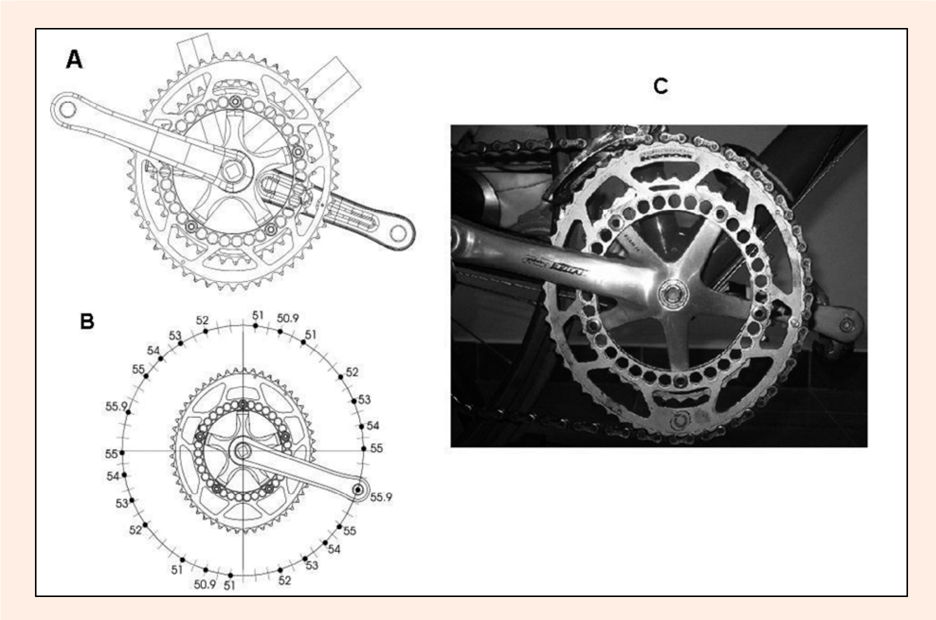

Figure 1. A) Conventional cranks fitted with Q-rings. B) Instantaneous equivalent ring size for a 53T chainring. C) Q-ring installed in a bicycle.

biomechanics of Rotor Cranks during the pedal downstroke, i.e., when cyclists generate their greatest power (Henderson et al., 1977; Santalla et al., 2002). This means that when the pedal is descending, the Q-ring progressively modulates the immediate gear, according to the leg's immediate capacity. Thus, Q-rings increase the diameter at the same time as the cyclist increases the force applied to the pedal during the downstroke (Figure 1). The theoretical advantages of the Q-ring design are that it: (1) eliminates the dead spots (Santalla et al., 2002; Lucia et al., 2004), (2) increases the crank arm length during the downstroke (Hue et al., 2001; Zamparo et al., 2002), and (3) slows the downstroke and accelerates the upstroke (Hull et al., 1992; Martin et al., 2002).

It was the purpose of this study to compare the physiological responses and performance of elite cyclists riding with two different chainring designs, oval Q-rings and conventional rings (C-rings), during an incremental exercise test and subsequent short sprints.

Methods

Participants

Fourteen male cyclists (senior license holders who have been competing in lower categories for several years) participated in this study. Participant characteristics are presented in Table 1. The evaluation protocol was designed according to the Helsinki Conference for research on human beings and according to the ethical standards in sports and exercise science research (Harriss and Atkinson, 2009). All cyclists were informed of the purpose of the study and the possible risks before they provided written consent.

From the start of the season (beginning of November) to the initiation of the tests (fourth week of February), participants cycled 5215 ± 178 km in training. Cyclists underwent an electrocardiographic evaluation and a blood test (biochemical and haematological parameters) screening prior to participation. None of the participants had previous experience in using Q-rings (Figure 1). Two weeks previous to the experiments, participants had the opportunity to test the Q-ring in order to become familiarized with this configuration. During these two weeks, participants followed the same programmed training consisting of approximately 400 km per week. The training protocol during a week comprised: two days of resistance training (RT, approximately 180 km each day), two days of interval training (IT, normally submaximal series of 5 min), and two days of "light" training (LT, approximately 60 km each day). These sessions were interspersed during the week: LT, IT, RT, LT, RT, IT, LT, etc.

Table 1. Participants' physical characteristics. Mean (SD).

N	Age (yr)	Body mass (kg)	Stature (m)	VO_{2max} ($ml \cdot kg^{-1} \cdot min^{-1}$)
14	21.1 (2.1)	69.3 (6.9)	1.76 (.06)	78.5 (5.3)

Experimental procedure

Each participant was evaluated on two separate sessions: one with the C-ring, the other with the Q-ring. Sessions were randomly assigned and they were separated by 48 h. The participants were tested at approximately the same time of day (0900), and under similar environmental conditions (average temperature, 22ºC; relative humidity, 65–70%), to minimize the influence of biological variability.

Laboratory tests were performed with a Computrainer (RacerMate - FloScan Instrument Co, USA). The advantage of this cyclotrainer is that it allows each participant to use the most suitable Q-ring regulation setting by means of the "spinscan", a tool that provides information about each individual's pedalling style. Moreover, each participant could use his own bicycle for the test. For all tests, the same rear wheel was used at the same inflation pressure (8 atm), and for each bicycle, a Q-ring or C-ring was used, depending on the corresponding test.

After selecting the suitable regulation of the Q-ring, the experimental tests were performed. The first exercise consisted of an incremental exercise test to exhaustion, which was performed on the cyclosimulator (Computrainer RacerMate - FloScan Instrument Co USA), with the participants using their own competition bicycles (Faria et al., 2005; Santalla et al., 2002). The incremental test was initiated at a workload of 100 W. Thereafter, workload was increased in steps of 25 W every 3 min until volitional exhaustion. During the cycling test, pedalling cadence was maintained at 70 rev·min^{-1}. Continuous electrocardiograph (Schiller AG, Baar, Switzerland) and breath-by-breath respiration gas analysis during the whole effort (Medical Graphics System CPX-Plus, Medical Graphics Corporation, St Paul, MN) were analyzed. Heart rate and pedal cadence were monitored telemetrically throughout the test (Polar 610 Plus, Polar Electro Oy, Kempele, Finland). Blood lactate samples were taken seven times: (every 50-W increment, and 30 seconds after the test ended). Blood lactate was analysed using an automatic analyzer (YSI Model 1500 Sport, Yellow Springs, USA).

After the incremental exercise test was completed, participants were asked to perform 4 maximal sprints in order to induce additional fatigue. The sprint procedure consisted of 4 intermittent 20-s maximal sprints with 60-s recovery periods. The maximal power corresponding to each of the 20-s sprints was calculated. In addition, 4 maximal isometric voluntary contractions were performed at rest (before the incremental test) and one maximal isometric contraction was completed immediately after each 20-s maximal sprint.

Force and electromyographic (EMG) signals were recorded from the dominant quadriceps muscle during maximal isometric contractions. Participants were seated on a custom-built bench with the knee flexed at 90°. Extraneous movements of the upper body were minimized by two crossover shoulder harnesses and a belt across the lower abdomen. Quadriceps force was recorded using a dynamometer gauge (leg-Jamar, USA) that was attached to the ankle. The force signal was recorded at 1 kHz using an AD conversion system (Electromyography MEGA, muscle tester ME 3000, 8 channels, software megawin version 2.1).

Electromyography

Electromyographic signals were recorded from the vastus lateralis and vastus medialis muscles during the maximal isometric contractions. Pairs of silver chloride, circular (recording diameter, 30 mm) surface electrodes (blue sensor, type M-00-S, medicotest) were positioned lengthwise over the muscle belly, with an inter-electrode distance (center-to-center) of 30 mm. Less than 5 kΩ impedance at the skin-electrode surface was each time obtained by shaving and cleaning the skin. The ground electrode was fixed over the ipsilateral patella. EMG signals were amplified with a bandwidth frequency ranging from 10 to 500 Hz, digitized online at a sampling frequency of 2 kHz, and recorded by the AD conversion system (see above for details).

The EMG root mean square (RMS) was calculated using the formula:

$$RMS\,(t) = \sqrt{\frac{1}{T}\int_{-T/2}^{T/2} EMG^{\,2}(t)\,dt}$$

where T = 0.375 s and t = time variable.

For each maximal contraction, the RMS was quantified for a 0.5-s interval around the peak force (in order to avoid the rising and falling transitions of the contraction). The EMG RMS amplitude ratio was then calculated and used as an index of muscle fatigue during the contractions (Place et al., 2007).

Statistical analysis

Statistical analysis was carried out using Statgraphics Plus 5.1 (Statistical Corporation S.A. USA). The Kolmogorov-Smirnov test was applied to ensure a Gaussian distribution of the results. A two-factor ANOVA [ring design (C-ring vs. Q-ring) x power output (75, 100, 125 W, ..)] with repeated measures on the second factor (power output) was performed to determine whether or not there was a significant ring-design × power-output interaction in the blood lactate results. Differences in the maximal values of power output, heart rate, and oxygen consumption between Q-rings and C-rings were assessed using Student's paired t-tests (two tailed). Statistical significance was set at $p < 0.05$. The results were expressed as mean ± SD.

Results

When the participants performed the incremental test, they produced comparable maximal power with Q-rings (371 ± 30 W) and C-rings (355 ± 29 W, p = 0.12). The maximal oxygen consumption was also similar for the two chainrings tested (Table 2). No statistical differences were found in the heart rate of participants using Q-rings and C-rings. The two-factor ANOVA showed no significant ring-design × power-output interaction for mean values of blood lactate (Figure 2).

Table 2. Values of variables measured during the incremental test for the oval Q-rings and the conventional rings (C-rings). Mean (±SD).

	Q-ring	C-ring
VO_{2max} (ml·kg^{-1}·min^{-1})	80.3 (5.8)	78.7 (6.1)
Heart rate max (beats·min^{-1})	189 (7)	190 (5)
Power (W)	371 (30)	355 (29)

VO_{2max}: maximum oxygen consumption.

For the intermittent 20-s maximal sprints performed after the incremental test, the power production was higher with Q-rings than with C-rings, although this difference was not statistically significant (Table 3). Specifically, the power output developed with Q-rings was 4.2, 2.4, 5.1, and 6.7% greater than that produced with C-rings for the first, second, third, and fourth sprints, respectively.

The values of maximal voluntary force obtained during the maximal isometric contractions before and after the incremental test are shown in Table 4. As can be seen, for both the Q-rings and C-rings, the voluntary force was greater for the contractions performed before the incremental test, although this difference did not reach statistical significance. There was no significant difference between the force exerted with C-rings and Q-rings (both before and after the incremental test).

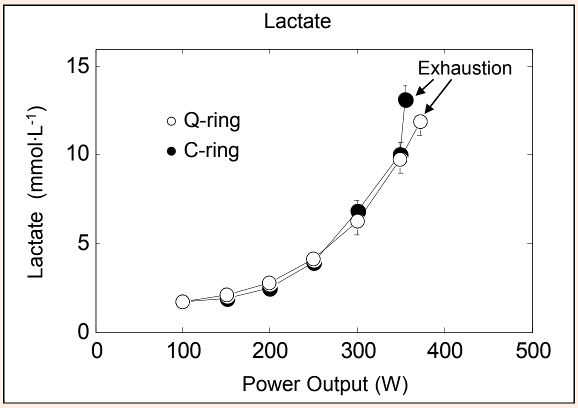

Figure 2. Comparison of blood lactate at submaximal workloads between the conventional (C-rings) and the oval Q-rings. Values are mean ± SEM.

Table 3. Power output (mean ± SD) (W) obtained during the short sprints performed after the incremental test for the oval Q-rings and the conventional rings (C-rings). Differences in power output between Q-ring and C-ring are expressed as a percentage (Δ%).

	Q-ring	C-ring	Difference (Δ%)
1st sprint	715 (74)	682 (100)	4.6
2nd sprint	582 (47)	568 (62)	2. 4
3rd sprint	526 (78)	499 (71)	5.1
4th sprint	510 (84)	476 (74)	6.7

The values of EMG amplitude obtained during the maximal isometric contractions before and after the incremental test (shown in Table 5) followed the same pattern: EMG RMS was greater for the contractions made before the increasing test, although this difference was not statistically significant. Regarding the comparison between C-rings and Q-rings, no significant differences in EMG RMS were observed between these two ring designs before and after the incremental test.

Discussion

The main findings of the present study were: (1) for the incremental exercise test, no significant differences were found in maximal power production, oxygen consumption, or heart rate when using either Q-rings or C-rings; (2) over the course of the incremental test, blood lactate levels were comparable for the C-rings and Q-rings; (3) during the short sprints performed after the incremental test, there were no statistical differences in power production between Q-rings and C-rings; and (4) the changes in EMG and force variables from rest to post fatiguing sprints were similar when using C-rings and Q-rings.

The theoretical benefit of the Q-ring design is based on the assumption that it optimizes the way the force is exerted throughout the pedal-crank revolution. This is achieved by placing the maximum gear of the oval in such a way as to enhance the participants' power delivery (Figure 1). Specifically, Q-rings place the maximum gear moment when the pedal is around 15–20° below the horizontal axis on the downstroke (when the ring's maximum diameter transfers propulsion forces to the rear wheel). This is because the tangential forces are highest when the crank is approximately horizontal. Once the pedal has passed the upper dead spot, the pedal begins the downstroke and the tangential component of force applied on the pedal increases progressively. Such increase in the tangential force component occurs concurrently with an increase in the diameter of the Q-ring, which further enhances the pedalling mechanical performance (Ericson and Nisell, 1988). In addition to the higher force power production during the downstroke, a lower negative momentum (negative force x distance) is produced during the upstroke.

There is conflicting evidence about the effect of

Table 4. Values of force (mean ± SD) (N) obtained during the maximal isometric voluntary contractions (MVCs) performed before and after the incremental test for the oval Q-rings and the conventional rings (C-rings).

	Q-ring		C-ring	
	Before incremental test	After incremental test	Before incremental test	After incremental test
1st MVC	**65.5 ± 2.9**	**60.1 ± 3.2**	**64.3 ± 3.4**	**62.4 ± 3.1**
2nd MVC	**62.3 ± 3.5**	**59.8 ± 3.4**	**60.8 ± 3.6**	**57.8 ± 3.4**
3rd MVC	**61.8 ± 4.6**	**58.2 ± 2.3**	**61.3 ± 4.2**	**57.6 ± 2.3**
4th MVC	**57.7 ± 3.9**	**55.4 ± 1.8**	**61.7 ± 3.1**	**59.3 ± 3.1**

Table 5. Values of EMG RMS (mean ± SD) (μV) obtained from the vastus lateralis and vastus medialis muscles during the maximal isometric voluntary contractions (MVCs) performed before and after the incremental test for the oval Q-rings and the conventional rings (C-rings).

		Q-ring		C-ring	
		Before incremental test	After incremental test	Before incremental test	After incremental test
Vastus Lateralis	**1st MVC**	991 (137)	813 (117)	1091 (124)	768 (98)
	2nd MVC	757 (112)	661 (95)	808 (112)	678 (94)
	3rd MVC	841 (124)	670 (105)	783 (105)	694 (102)
	4th MVC	858 (115)	678 (123)	864 (114)	771 (114)
Vastus Medialis	**1st MVC**	1120 (158)	768 (127)	1191 (135)	940 (123)
	2nd MVC	819 (134)	661 (123)	937 (122)	778 (102)
	3rd MVC	799 (126)	712 (122)	1032 (142)	767 (112)
	4th MVC	872 (129)	774 (120)	1059 (126)	764 (123)

non-circular chainrings on cycling performance. Several authors have shown significant improvements during anaerobic tests using the Rotor system, i.e., the system on which the oval Q-ring is inspired (Faria et al., 2005; Santalla et al., 2002). Hue et al. (2001) demonstrated enhanced cycling performance using an eccentric ring design during an all-out 1-km laboratory test. However, there are several studies showing that the gross efficiency of cycling is not improved by any of the non-circular chainrings (Belen et al., 2007; Cullen et al., 1992; Hull et al., 1992; Ratel et al., 2004). These discordant results could be partly explained by differences in the methodological aspects adopted in the studies, including the exercise test performed, pedalling frequency, cycling position, the possibility to use the cyclist's own bicycle, etc. The above factors have been shown to have a tremendous impact on cycling performance (Córdova et al., 2004; Majerczak et al., 2008; Takaishi et al., 1998; Passfield and Doust, 2000; Patterson and Moreno, 1990).

The present study showed no statistical differences in maximal power output, oxygen consumption or heart rate between the oval Q-rings and the conventional circular rings. These findings suggest that Q-rings did not result in any improvement of cycling performance. In addition, over the course of the exhausting test, the levels of lactate production were comparable for the Q-rings and C-rings. This implies that the metabolic cost associated with the use of Q-rings is similar to that associated with the use of conventional chainrings.

Cyclists participating in the present study were accustomed to ride with circular rings and thus their cycling positions as well as other biomechanical parameters were optimized according to such conventional chainring design (Neptune and Herzog, 2000). When changing from C-rings to Q-rings, the oval chainring design might alter the usual pattern of force application, which may induce changes in the biomechanical patterns of cyclists. In theory, such changes could increase the associated metabolic cost, most likely due to the recruitment of different muscle fibres. However, we found similar levels of lactate production and oxygen consumption for both chainring designs. A possible explanation is that the particular design of the Q-rings not only optimizes the way the force is exerted throughout a crank cycle, but it also makes power delivery through the duty cycle more continuous. Importantly, all the cyclists participating in the experiments reported that pedalling with the Q-rings was "smoother". Thus, it might be hypothesized that the "smoother" pedal action associated with the Q-rings would bring about energy savings that would compensate for the supposed muscular disadvantage (change in biomechanical pattern) associated with this design. In this connection, it should be mentioned that, while the smooth pedalling of the Q-rings may be theoretically ideal, from a physiological point of view it may be beneficial to reduce pedal force during sections of the pedal stroke to allow localized recovery and reduce pressure to allow blood flow to the muscle, especially at high exercise intensities.

In our protocol, fatigue was assessed directly through measurements of maximal isometric force and also indirectly by the average amplitude of the EMG signal (Vollestad, 1997). It was found that the changes in force between the isometric contractions performed before and after the incremental test were comparable for Q-rings and C-rings (Table 4), which suggests that the same fatigue was experienced under both chainring conditions. Similarly, the decline in EMG produced by the fatiguing incremental test was comparable for Q-rings and C-rings (Table 5), thereby reinforcing the view that circular and non-circular rings result in similar fatigue.

It must be mentioned that, for the incremental maximal test, the maximal power production values were higher for Q-rings than for C-rings (371 ± 30 vs. 355 ± 29 W, respectively), and that, for each of the subsequent short sprints, power values were 2.5–6.5% greater for the Q-rings. Interestingly, the extent of the improvements with the Q-rings found here resembled those obtained by other authors using the Rotor system (Rodríguez-Marroyo et al., 2009). Thus, although the differences in physiological variables between circular and non-circular chainrings did not reach statistical significance, the possibility that Q-rings result in slight improvement during on-road cycling performance cannot be excluded. Thus, whether or not the oval Q-rings could induce any improvement in time trial performance remains to be elucidated (Peiffer and Abbiss, 2010). Indeed, the determinants of performance in an individual time trial are more complex and the experimental protocol followed in the present study did not allow conclusions to be drawn in this direction (Abbiss and Laursen, 2005; De Koning et al., 1999).

Conclusion

In conclusion, the oval chainring design, presented here as "Q-rings", did not significantly influence the physiological response to an incremental exercise test (maximal power output and VO_{2max}). In addition, the metabolic cost associated with Q-rings use was similar to that of conventional circular chainrings. The slight tendency towards improvement in power output when using the oval Q-rings (increase of 2.5–6.5 % relative to circular chainrings) suggests that Q-rings could result in slight improvement during on-road cycling performance. However, future studies are necessary to elucidate whether or not the particular design of the Q-ring could improve performance in other cycling tests.

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Key points

- During the incremental exercise test, no significant differences were found in power output, oxygen consumption or heart rate between oval “Q-rings” and conventional chainrings.
- Over the course of the incremental test, blood lactate levels were comparable for the oval “Q-rings” and conventional chainrings.
- During the short sprints performed after the incremental test, there were no statistical differences in power production between oval “Q-rings” and conventional chainrings.

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