ISSN 1750-9823 (print)
International Journal of Sports Science and Engineering
Vol. 06 (2012) No. 01, pp. 025-040

Effects of Chainring Type (Circular vs. Rotor Q-Ring) on 1km Time Trial Performance Over Six Weeks in Competitive Cyclists and Triathletes

Christiane R. O'Hara[1], Robert D. Clark[1, +], Todd Hagobian[1], Karen McGaughey[2]

[1]Kinesiology Department, California Polytechnic State University, San Luis Obispo CA.

[2]Statistics Department, California Polytechnic State University, San Luis Obispo CA.

(*Received August 27, 2011, accepted September 9, 2011*)

Abstract. The purpose of this study was to examine the effects of chainring type (circular vs. the non-circular Rotor Q-Ring) on performance during a 1km time trial and physiological responses over a six week period. Eight competitive male cyclists and triathletes were pre-tested using the original circular chainring. Graded submaximal exercise tests were followed by the 1km time trial with subjects using their own racing bicycle. The circular chainrings were then removed and replaced with Rotor Q-Rings during the intervention period. Subjects trained and raced with this alteration to their bicycles and repeated the submaximal and 1km performance tests for the next four weeks. Post-testing occurred with the original circular chainrings for the final week of testing. Oxygen consumption, carbon dioxide output, heart rate, ventilation, respiratory exchange ratio, and perceived exertion were continuously measured during the submaximal tests. Blood lactate concentration was measured during the last 30 s of each three minute stage. The main findings were: 1) Significant increases in performance in the 1km time trial with Rotor Q-Rings compared to circular chainrings. Subjects completed the time trial on average 1.6 seconds faster ($p < 0.05$), increased average speed approximately 0.7 kph ($p < 0.05$), and increased average power approximately 26 watts ($p < 0.05$). 2) During submaximal testing, oxygen consumption during weeks 2-4 and heart rate during weeks 1-3 were significantly lower ($p < 0.05$) with Rotor Q-Rings compared to circular chainrings. Furthermore, 1km time trial improvements occurred after just one week employing the Rotor Q-Rings and results were consistent over subsequent 1km time trials with the Rotor Q-Rings. Performance levels returned to initial values during final testing with the circular chainrings. The maximal oxygen consumption results from the Pre-test and week 5 Post-test further demonstrated that positive performance effects were only evident with the Rotor Q-Rings. While it appears from this study that there may also be positive long term effects as noted by the significant reduction in submaximal oxygen consumption and heart rate during the intervention period (i.e., cycling with Rotor Q-Rings), the majority of the physiological measures we examined do not equivocally support the notion that an adaptation period is necessary for this increased 1km time trial performance.

Keywords: non-circular chainrings, Rotor Q-Ring, cycling performance, cycling efficiency

1. Introduction

Since the 1890's there have been many technological innovations in cycling leading to increases in performance. For example, stronger and lighter frame materials, lighter weight wheels, and "indexed" shifting. However, since the invention of the derailleur and the ability to change gears, the bicycle drive train has remained essentially unchanged. Recently, there has been an increase use of non-circular (or eccentric or elliptical) chainrings in replacement of the traditional circular chainrings. Among the many determinants of success in cycling, the ability to effectively rotate the chainrings is worthy of greater inspection, especially when the ability to generate torque at the crank is affected by mechanical and physiological constraints that behave in a non-linear manner. For example, maximum power output (developed primarily about the hip and knee joints) is reached when the tangential component of the force applied to the crankarm is greatest. The maintenance of a constant effective force would optimize torque, and hence, power production (1). However, biomechanical constraints result in an uneven production of torque in a nearly sinusoidal manner with minimal torque being produced at the top and bottom dead center

+ Corresponding author. Tel: 805.756.0285; Fax: 805.756.7273
E-mail address: rdclark@calpoly.edu

points of the crank cycle (2). Due to the orientation of the rider on the bicycle, maximum torque is exerted when the crank is positioned midway between top and bottom dead centers (90 degrees from top dead center). The "dead spot" occurs when one of the pedals is up and the other is down, creating a power vacuum due to the cancellation of the tangential component of the forces on the pedals (3).

Using muscle-actuated models and simulations of the pedal stroke, research has identified optimal conditions to improve performance through equipment design (4, 5, 6, 7). For instance, intentional alterations in angular velocity could be accomplished by creating a variable drive radius of the chainring (thereby creating a non-circular, eccentric, or elliptical shape). Three primary design factors exploited in this aim are: orientation factor, elongation factor, and form factor. The orientation factor is defined as the angle between the centerline of the cranks and the largest diameter of the chainring. The elongation factor (also known as ovalization factor) is defined as the ratio between the largest and smallest diameters of the chainring. This is the gear range of the chainring and is directly related to the amount of acceleration and deceleration that is caused during the pedaling stroke. The form factor describes the curves shaping the perimeter of the chainring, such as arcs and ovals, angles or flat sections, and ellipses (8). Modifications based upon these factors would create a chainring with a continually changing gear ratio during the pedaling cycle. For example, a 53 tooth Rotor Q-Ring, around the upper dead-spot is equivalent to a 51 tooth circular chainring, but as the crank rotates forward to a position where the ability to generate greater force to the crank system is available, the equivalent chainring tooth size reaches a 56 tooth circular ring (9). Essentially, this is similar to "shifting" gears, but instead occurs during each pedal stroke (i.e., increasing and decreasing the gear ratio). Additionally, circular chainrings allow for a relatively constant crank angular velocity, whereas elliptical rings facilitate a crank angular velocity that would be considered sinusoidal or non linear (2).

Horavis et al. (10), found significant differences between torque production from a non-circular O.Symetric chainring and circular chainring during submaximal cycling testing. Their results showed that the O.Symetric chainring produced lower net crank torque at top and bottom dead center, and higher torque during the downstroke phase. The O.Symetric chainring also produced a significant increase in the instantaneous pedaling rate during top and bottom of the pedaling stroke and a decrease during the downstroke. This indicates that the crank rotated at a slower rate during the effective activation phase (i.e., more time spent in the downstroke). Theoretically, this can lead to benefits in competitive settings. A variable crank arm length can also alter pedaling dynamics leading to increases in performance. For example Hue et al. (4), found a significant difference in cycling performance during an all out 1km time trial using a crank system that increased the length of the crank arm during the downstroke but no significant differences in any physiological variables. They attributed the increase in performance to the possible higher torque production during the downstroke resulting from the variable length crank system.

Using a theoretical analysis of an optimal chainring shape, Rankin and Neptune (11) suggested that power could be increased by 2.9% with a non-circular chainring compared to a conventional circular chainring. Their work was supported by other studies that found an increase in power output using non-circular chainrings, or a non-traditional or eccentric crank system. For example, Martinez found that subjects using Rotor Q-Rings produced around 3% more power compared to circular rings (12). In other studies using a non-traditional crank system, both peak and mean power output improved due to greater torque afforded by the modified crank (13, 14).

Contrary to the previously discussed work, there were no significant differences in power using an eccentric chainring design in several other studies (1, 6, 14, 15). For example, Hansen et al. (15), found no significant differences in peak torque, min torque, and crank angle at peak torque between a non-circular chainring (Biopace) and circular chainring. When considering performance, Peiffer and Abbiss (16) found no benefits of using an elliptical chainring during a 10km time trial. Jobson et al. (14) also found no increases in power or cycling performance using an eccentric crank system after six weeks of training. Speed was not significantly faster during a 40.23km time trial in a laboratory setting, but the authors did suggest that the system could have acute ergogenic effects if used infrequently.

Another factor that exhibits non-linear effects on torque and power production are activation and deactivation dynamics of the muscles involved in pedaling. Essentially, muscles require time to relax (deactivation) and time to develop tension (muscle activation). These delays are mainly due to calcium dynamics and cross-bridge attachment and detachment (2). During repetitive activities such as cycling, force-time effects may constrain muscular performance, imposing limitation on maximal force production. That is, at the beginning and end of the shortening phase, actual force is decreased because of incomplete activation (17). Therefore, maximal power increases when the portion of the movement cycle spent under muscle shortening is increased. For instance, when the leg was extended for 58% of the pedal stroke (compared to shortening and lengthening for 50% each with circular chainrings), Martin and Spirduso (3) reported a 4% increase in average power and an 8% increase in instantaneous power in a maximal cycling computer model. Another model they created featuring a 70% shortening cycle increased power during the leg extension by 44% (17). Similar results were found by Askew and Marsh (18) who reported that power was 40% greater when the muscle was shortening for 75% of the cycle time. During the downstroke of the pedal cycle (power phase), the eccentric chainring causes a decrease in angular velocity resulting in a longer power phase and therefore more work production. As the crank continues to rotate through the dead spot centers, the angular velocity increases and therefore minimizes negative work during deactivation. This would also coincide with the increased time spent performing positive work and decreasing the time spent performing negative work.

When considering the above, a properly designed non-circular chainring would then more closely match the biomechanical constraints that are found during pedaling while taking advantage of the increases in torque production when they occur. Early incarnations of commercially available non-circular chainrings include the previously mentioned Shimano Biopace in the late 1970's and the O.Symetric "Harmonic" in the 1990's. However, both failed to gain wide acceptance among competitive cyclists mainly due to improper orientation, ovalization, or form factor (8, 19). For example, maximum diameter of the Biopace chainring was placed at the dead centers which required more effort to rotate the cranks and created a very irregular and uncomfortable pedal stroke. (15). This design never realized commercial success, and the chainrings were eventually discontinued. In comparison, the O.Symetric was a more effective design than Biopace. This non-circular chainring created higher gearing during the pedal down stroke but the large change in ovalization created sudden acceleration changes and increased stress through the knee joint compared to circular chainrings (8, 20).

The latest non-circular chainring is ROTOR Bicycle Component's Q-Ring developed in 2005. The designers claim to have the best shape, orientation, and adjustability compared to previous mentioned chainring designs. Rotor claims increase pedaling effectiveness by extending the time spent in the power stroke (where 90% of all power is produced) and smoothly accelerating the crank through the critically weak dead centers (9). Furthermore, a comparative study examining various non-circular chainrings (including Biopace and O.Symetric) suggests that the Rotor Q-Ring created a faster acceleration free of damaging loading peaks and unnatural joint motions (8).

There were several studies comparing the use of non-circular chainrings, but to our knowledge there was only one published study by Peiffer and Abbiss in which power and heart rate were examined during a 10km indoor time trial (16). In their study, no significant differences were found due to the type of chainring used. Martinez et al. in an unpublished study (21), also specifically examined the Rotor Q-Ring and its effect on performance and metabolic cost. Martinez et al. found a reduction in lactate production, a lower heart rate, and increased power output at 90% of VO_2 max during a graded exercise test. In other similar work (6, 22, 23) light increases in cycling efficiency, up to 3%, were found when non-circular chainrings were used in comparison to a circular chainrings or traditional crank systems. Increases in efficiency were also found using the non-circular Biopace chainring (24). In contrast, Rodriguez-Marroyo (25) found no improvements in aerobic cycling efficiency (measured via gross mechanical efficiency and the cycling economy) using a Rotor crank system.

Taken together, previous research has shown mixed results when examining the effect of modifications to the chainring shape or employing a non-traditional crank system on cycling performance (1, 4, 5, 6, 10, 14, 15, 16, 19, 21, 22, 23, 25, 26, 27, 28, 29, 30). Although mechanical relationships between these systems were similar, the Rotor Q-Ring, to date, has only been examined by Peiffer and Abbiss (16). Therefore, the primary purpose of this study was to examine the effect of chainring type (circular vs. non-circular Rotor Q-Ring) on cycling performance with elite competitive cyclists. Several physiological and biomechanical markers were examined including the respiratory exchange ratio (RER), heart rate (HR), ventilation (VE), volume of carbon dioxide expiration (VCO_2), volume of oxygen consumption (VO_2), blood lactate, efficiency, power, and performance in a 1 kilometer time trial. Furthermore, since we were directly introducing a change in pedaling dynamics by replacing the circular chainring with the Rotor Q-Ring, we were also interested in any adaptation effects. That is, there may be benefits of this alteration to the drive train, but for competitive cyclists with several years practicing pedaling with circular chainrings, they may not be readily evident and an adaptation period may be necessary to uncover positive effects (2, 6, 14, 28, 31).

2. Methods

In order to determine the effects of chainring type on cycling performance and possible long term adaptations, a Pre-test, Intervention, Post-test approach was employed. Throughout the study, subjects trained, raced, and were tested on their own bicycle. The study occurred during the middle part of the competitive racing season to avoid any potential off-season or pre-season consequences that could possibly mask the effects of charinring type on the physiological and performance measures chosen for analysis.

2.1. Timeline of laboratory tests

Subjects were pre-tested using the original circular chainrings and also on the initial week of testing. The intervention consisted of cycling with Rotor Q-Rings for the subsequent four weeks. Post-testing occurred with the original circular chainrings for the final week of testing, week 5. Data collection for all subjects occurred during the same time period consisting of seven visits to the Biomechanics Laboratory on the Cal Poly Campus over seven weeks. Visits to the lab were scheduled for Tuesday, Wednesday, or Thursday. On the first visit to the lab (i.e. Pre-test), each subject performed the initial maximal oxygen consumption test (VO_2 max), and the 1km practice time trial. Blood samples were also collected during the VO_2 max test to assess blood lactate concentration (see 2.8 below). The following table describes the order of tests and the type of chainring employed during the test session.

Table 1. Timeline of Laboratory Tests

Week	Chainring	Tests Performed
Pre-test	Round	Maximal Oxygen Consumption + Lactate + 1km Practice Time Trial
0	Round	Graded Submaximal + Lactate + 1km Time Trial
1	Rotor	Graded Submaximal + Lactate + 1km Time Trial
2	Rotor	Graded Submaximal + Lactate + 1km Time Trial
3	Rotor	Graded Submaximal + Lactate + 1km Time Trial
4	Rotor	Maximal Oxygen Consumption + Lactate + 1km Time Trial
5	Round	Maximal Oxygen Consumption + Lactate + 1km Time Trial

2.2. Subjects

Eight healthy, fit men (six cyclists and two cyclists/triathletes) were recruited from California Polytechnic State University at San Luis Obispo and the surrounding area. Anthropometrics such as height, weight, and age were also measured prior to the start of testing (see Table 2). A maximal oxygen consumption test was performed to test for physical fitness as part of the Pre-Test for this study. Inclusion criteria for the study was as follows: 1) VO_2 max >55 ml/kg/min; 2) engage in at least eight hours/week of cycling exercise; 3) USA Cycling License Category 1-3 rider or Men's Collegiate A rider; and 4) age between 18 to 39 years. This study was approved by the Human Subjects Committee at California Polytechnic State University. Subjects were informed of all requirements, benefits, and risks of the study and gave verbal and written consent prior to participation.

Table 2: Subject Characteristics. Values are mean ± SD, n=8.

Age (yr)	22 ± 2.7
Height (cm)	177.8 ± 7.8
Weight (kg)	72.3 ± 8.3
VO_2 max (L/min)	4.53 ± 0.43
VO_2 max (ml/kg/min)	62.9 ± 4.2

2.3. Food Intake and Training Records

Subjects performed all of their scheduled exercise tests in the morning after an overnight fast. They were allowed to drink water the morning of the test, but no solid foods, caffeine, or other beverages were allowed. Subjects were asked to consume the same meal the evening before each test, and were provided with a food journal log to record intake during that time.

Exercise was avoided 12 hours before the test, and no intense exercise sessions occurred 24 hours before the test (e.g., multiple sprint or hill repeats). Subjects were also instructed to perform similar exercise sessions the day before each test session and follow consistent training regimes during the week and throughout the entire seven week time period for the study. In order to facilitate compliance with this request, subjects were also provided with a training journal to record mileage and average speed of their training rides. These records were brought to the lab each testing day for inspection and transferred to a database.

2.4. Instruments and Measures

The CompuTrainer (LAB version) with front fork mount extension, and RacerMate Coaching Software (Seattle, WA, USA) was used for all cycling tests and data collection. The subject's own personal bike was used for all testing sessions and was used exclusively for all training and racing activities during the seven week time period for the study. The CompuTrainer provides resistance to the rear wheel of the bicycle through an electronic load generator and sets the industry standard for accuracy (± 2.5%), and power (1500 watts) (32).

During all test sessions, expired air was analyzed by a Parvo Medics True One 2400 Metabolic Measurement System (Parvo Medics, Salt Lake City, UT) and subjects were also fitted with a heart rate transmitter strap (Polar Electro, Lake Success, NY). Blood lactate concentration was determined through the Lactate Pro analyzer (Arkay Factory Inc., Shiga, Japan).

The dependant measures throughout the testing period included the following: Maximum Oxygen Consumption (VO_2 Max in absolute and relative terms, L/min and ml/kg/min), Submaximal Oxygen Consumption (VO_2 in L/min and ml/kg/min), Blood Lactate Concentration (mmol/L), Respiratory Exchange Ratio (RER), Heart Rate (HR in bpm), Ratings of Perceived Exertion (RPE), Ventilation (VE in L/min), Power (W), Carbon Dioxide Production (VCO_2 in L/min), Delta and Gross Efficiency (percent), and 1km Time Trial performance (time to completion in seconds and speed in kph).

2.5. Maximal Oxygen Consumption Test

The maximal oxygen consumption test was a preliminary assessment to determine eligibility for the study and was also repeated at weeks four and five (the last two weeks of the seven week test period). The test began with a 15 minute warm up at 150 watts. After the warm up period, the trainer was calibrated according to industry standards (~ 9.0 N resistance at the rear wheel load generator) and the computer was set to start the test at 150 watts (32).

A clip was placed on the subject's nose with a breathing tube attached to a mouthpiece to ensure that the participant could only breathe through the mouth. Expired air was analyzed via the metabolic cart and RER, HR, VE, VCO_2, and VO_2 Max were all determined by the highest 30-second averaged values obtained through analysis. The last two minutes of each three minute stages were averaged to obtain values for data analysis. Metabolic cost and efficiency were also calculated from the data (33, 34). Subjects were instructed to maintain a pedaling cadence of 90 rpm and resistance was automatically increased by 30 watts every three minutes until the subject reached exhaustion, voluntarily stopped the test, or when cadence dropped below 50 rpm. Blood samples were collected every three minutes for determining lactate concentration and rate of perceived exertion (RPE) was also assessed every three minutes. The test was deemed valid if three of the following four criteria were met: 1) plateau of VO_2 max followed by a prolonged decrease in VO_2 at near maximal intensity; 2) respiratory exchange ratio > 1.15; 3) heart rate was within 10 beats of their age predicted max; and 4) RPE $\geq$18 (35).

After performing their initial maximal oxygen consumption test, subjects underwent a 1km practice time trial. This practice session allowed subjects to become familiar with the performance test that would be administered for subsequent weeks of testing. During this practice trial, subjects were allowed to alter gear ratios to determine a preferred gear and this was recorded to ensure consistency over future test trials. Exact protocol for the 1km time trial is discussed below.

2.6. Submaximal Graded Exercise Test

One week after the initial VO_2 max test (i.e., Pre-test), a submaximal graded exercise test with metabolic sampling was administered and continued every week of testing. The graded exercise test protocol was similar to the maximal oxygen consumption test in that each stage was three minutes long with 30 watt increases each stage. The same warm up was performed (15 minutes) followed by calibration of the CompuTrainer. Blood lactate, heart rate, RPE, and metabolic data were recorded for each stage. In contrast to the maximal oxygen consumption test, this submaximal test ended after the subject reached 300 watts.

2.7. 1 Kilometer Time Trial

After the initial submaximal graded exercise test, the participant was given five minutes to pedal against a lowered resistance of 150 watts before beginning a maximal effort 1km time trial. RacerMate's Coaching Software was used to design a flat 1km course for the time trial. Subjects were instructed to select their preferred gear found during the Pre-test practice trial. Once in the correct gear, pedaling ceased and the bicycle wheel was brought to a complete stop. When heart rate reached a steady value (i.e., did not change for 30 seconds), the subject was given a three second countdown to start the test. Subjects were allowed to pedal out of the saddle for the first five seconds to accelerate, but had to remain seated for the remainder of the test using the same gear. During the test, performance time, average power, maximum power, speed, and heart rate were recorded by the software. Feedback of cadence and heart rate were provided on a visual display, but distance, speed, and power were hidden from view. No instruction or encouragement was given during the test with the exception of an announcement stating the test was halfway over, and that there was 0.02km to completion.

Upon completion of the 1km time trial, the chainrings on the subject's bicycle were removed and replaced with Rotor Q-Rings with the same number of teeth as the original circular rings (53 x 39 or 50 x 34). On weeks 1, 2, and 3, the submaximal graded exercise test was followed by the 1km time trial with the same procedures as mentioned above. Upon completion of week 4 testing (i.e., maximal testing and 1km time trial), the Rotor Q-Rings were removed and replaced with the original circular chainrings. The 1km time trial was also performed after maximal testing on week 5, Post-test, with circular rings.

2.8. Blood Sample Analysis

Blood samples were obtained via ear lobe prick to measure blood lactate concentration. The blood lactate analyzer was calibrated prior to each test session according to the manufacture's recommendations. Blood was obtained during the last 30 seconds of each stage during the maximal and submaximal graded exercise tests. Blood lactate concentration was also measured exactly three minutes upon completion of the 1km Time Trial. Three minutes has been shown to be the duration for capturing peak blood lactate concentration (6). While waiting, the subject remained seated on the bike and was not allowed to pedal or drink any water until after a blood sample was collected.

2.9. Statistical Analysis

All analyses in this study were carried out using SAS/Stat software Version [9.2] for Windows. A one-way ANOVA, blocking on subject, was used to determine the effect of chainring type on each performance measure during the 1km time trial. All data for Time, Average Power (W), Max Power (W), Average speed (kph), Max speed (kph), and Lactate concentration (mmol/L) are presented as mean ± SD. 1km Time Trials were performed after submaximal testing sessions and also after maximal testing. For submaximal testing, post-hoc comparisons of Rotor Q-Ring means during weeks 1, 2, and 3, to circular ring means in week 0 were adjusted using Dunnett-Hsu.

Long term exposure effects to the Rotor Q-Ring were examined by collecting mean values across subjects during maximal and submaximal testing. The effects of Week/Chainring, Power, and the Week/Chainring by power interaction were then analyzed using repeated measures ANOVA, blocking on subject, with Pre-test, week 0 and week 5 Post-test occurring with subjects using circular rings, and week 1 through 4 using Rotor Q-Rings; Power was the repeated measure (i.e., workloads of 150, 180, 210, 240, 270, and 300 watts). Post-hoc comparisons of Week/Chainring main effects were carried out using a Dunnett-Hsu adjustment. All data are presented as mean ± SD and include the following: Absolute Oxygen Consumption (VO_2 in L/min), Relative Oxygen Consumption (VO_2 in ml/kg/min), Heart Rate (bpm), Blood Lactate Concentration (mmol/L), Respiratory Exchange Ratio (RER), Ratings of Perceived Exertion (RPE), Ventilation (VE in L/min), Carbon Dioxide Production (VCO_2 in L/min), Power (W), Delta and Gross Efficiency (percent). All effects were considered significant at $p < 0.05$.

3. Results

3.1. Food intake and training logs.

Examination of food intake and training logs did not reveal any deviations from instructions given to subjects and did not warrant elimination of any particular data set. While variations in training volume were apparent across subjects, within subject variations on a weekly basis were consistent.

3.2. 1km Time Trial performance.

Time to complete the 1km time trial was significantly lower in all trials with Rotor Q-Rings when compared to standard circular chainrings ($p < 0.05$). Average power (watts) and average speed (kph) were significantly higher in all trials with the Rotor Q-Ring compared to circular chainring ($p < 0.05$) (see Table 3, Figure 1a, 2a, 3a, and Table 4, Figure 1b, 2b, 3b). There were no significant differences in Maximum Power or Maximum Speed for the 1km time trial performed after submaximal testing on weeks 0-3 ($p = 0.81$, and $p = 0.31$ respectively) or after maximal testing on weeks 4 and 5 ($p = 0.37$, and $p = 0.07$ respectively). There were no significant differences in blood lactate concentrations when samples were taken upon completion of the 1km time trial that occurred after submaximal testing on weeks 0-3 ($p = 0.097$) or after maximal testing on weeks 4 and 5 ($p = 0.83$).

Table 3: 1km Time Trial performance after Submaximal testing

Week/ Chainring	Time (s)	Avg Power (W)	Max Power (W)	Avg Speed (kph)	Max Speed (kph)	Lactate (mmol/L)
0/Circular	85.4 ± 3.0	421 ± 53	705 ± 89	42.3 ± 1.5	46.2 ± 2.5	9.4 ± 2.3
1/Rotor	83.9 ± 2.9 *	447 ± 54 †	732 ± 97	43.0 ± 1.5 †	47.6 ± 2.0	10.0 ± 1.9
2/Rotor	83.7 ± 3.1 *	449 ± 58 †	717 ± 115	43.1 ± 1.6 †	46.9 ± 2.4	10.4 ± 2.0
3/Rotor	83.9 ± 2.6 *	446 ± 53 †	740 ± 108	43.0 ± 1.5 †	46.9 ± 1.8	9.4 ± 2.3

Values expressed as mean ± SD. *Significantly lower than Circular chainring ($p < 0.05$). † Significantly greater than Circular chainring ($p < 0.05$). n = 8.

Table 4: 1km Time Trial performance after Maximal testing.

Week/ Chainring	Time (s)	Avg Power (W)	Max Power (W)	Avg Speed (kph)	Max Speed (kph)	Lactate (mmol/L)
4/Rotor	84.2 ± 1.8 *	440 ± 32 †	739 ± 110	42.8 ± 0.9 †	46.9 ± 1.6	11.7 ± 2.3
5/Circular	85.5 ± 2.4	422 ± 39	733 ± 118	42.2 ± 1.1	46.2 ± 1.2	11.6 ± 2.0

Values expressed as mean ± SD. *Significantly lower than Circular chainring ($p < 0.05$). † Significantly greater than Circular chainring ($p < 0.05$). n = 8.

Figures. 1a-3b: Mean 1km Time Trial performance. Values expressed as mean ± SE. *Significantly lower than Circular chainring ($p < 0.05$). †Significantly greater than Circular chainring ($p < 0.05$). n = 8.

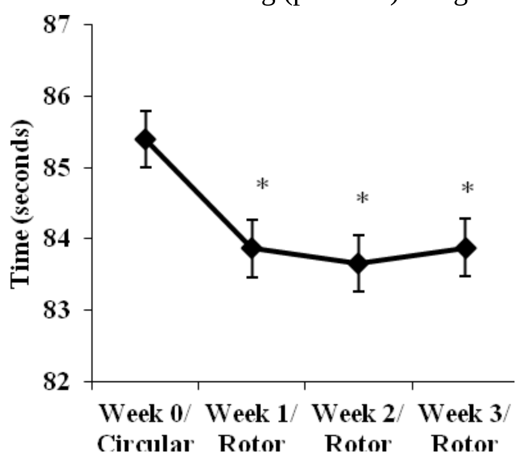

Figure 1a: Average time after submaximal testing.

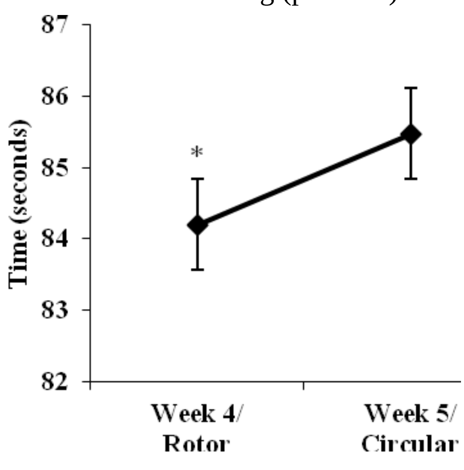

Figure 1b: Average time after maximal testing.

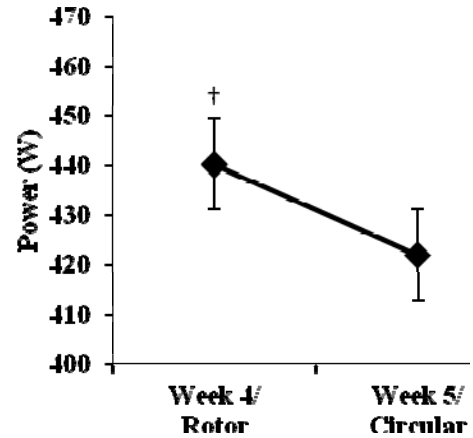

Figure 2a: Average power after submaximal testing.

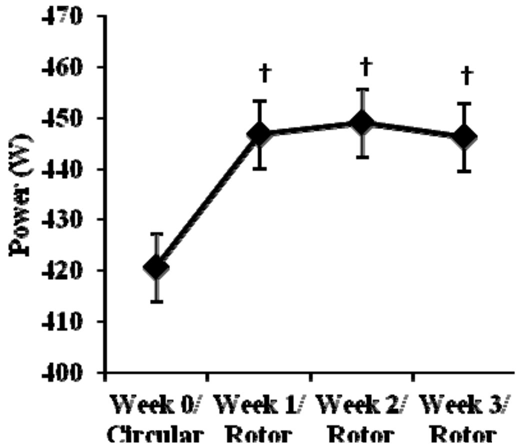

Figure 2b: Average power after maximal testing.

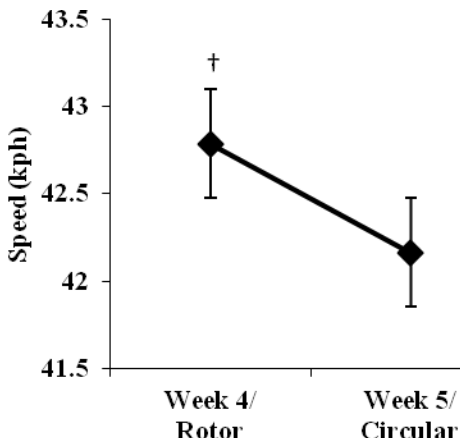

Figure 3a: Average speed after submaximal testing

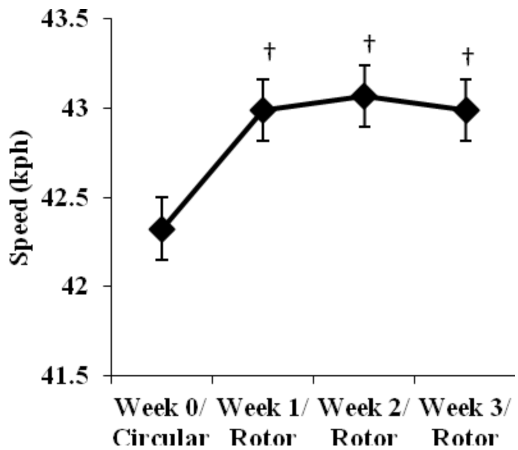

Figure 3b: Average speed after maximal testing.

3.3. Submaximal Graded Exercise Tests

Physiological data from all submaximal graded exercise tests (i.e., absolute VO_2, relative VO_2, Heart Rate, Lactate) are presented in Figures 4 and 5, and Tables 5-8. Graded exercise tests stopped after six workstages (i.e., 150, 180, 210, 240, 270, 300 watts) and occurred during weeks 0-3. In week 4, data from the first six workstages of the VO_2 max test were used for submaximal comparisons. However, subjects continued to cycle beyond 300 watts to ascertain the effect of chainring type under maximal testing. This allowed for additional comparisons of physiological data from maximal testing that occurred during Pre-testing, week 4, and week 5 Post-test. These findings are presented in Figure 6 and Table 9.

3.4. Oxygen Consumption

A significant main effect for week/chainring type was observed for submaximal absolute oxygen consumption (VO_2 in L/min) ($p < 0.01$). As seen in Figure 4, post hoc analysis revealed that absolute VO_2 was lower in weeks 2, 3, and 4 compared to week 0 with the circular rings ($p < 0.05$). There was no significant interaction found between week/chainring type and power ($p = 0.998$). Although slight differences can be seen during each workstage (i.e., 150, 180, 210, 240, 270, 300 watts), these data display increases that are generally indicative of an increase in exercise workloads. Oxygen consumption was not significantly different when comparing the final week of testing (i.e., week 5 Post-test) to the initial week of testing (i.e., week 0) on circular chainrings ($p = 0.11$) (see Table 5).

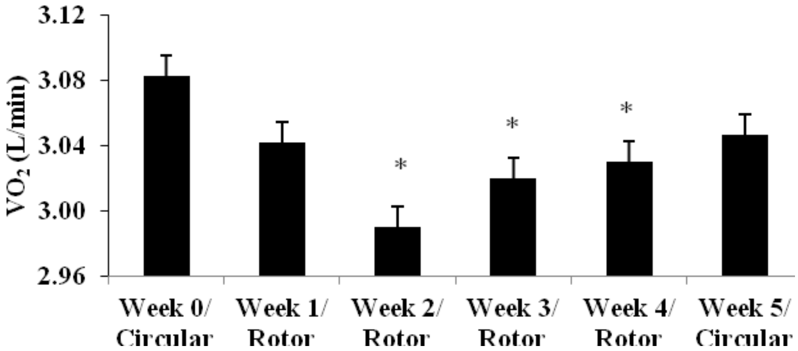

Figure. 4: Main Effect of week/chainring type on absolute VO_2 (L/min) measured during submaximal testing. Values are expressed as mean ± SE. *Significantly lower than week 0 Circular chainring ($p < 0.05$). n = 8.

Table 5: Submaximal values of absolute VO_2 measured during cycling with a Circular and Rotor Q-Ring

	Power Output (Watts)					
Week/Chainring	**150**	**180**	**210**	**240**	**270**	**300**
0/Circular	2.3 ± 0.2	2.5 ± 0.1	2.9 ± 0.1	3.2 ± 0.2	3.6 ± 0.1	4.0 ± 0.2
1/Rotor	2.2 ± 0.2	2.5 ± 0.2	2.8 ± 0.2	3.2 ± 0.2	3.6 ± 0.5	4.0 ± 0.1
2/Rotor	2.2 ± 0.2	2.4 ± 0.3	2.8 ± 0.2	3.2 ± 0.4	3.5 ± 0.4	3.9 ± 0.1
3/Rotor	2.2 ± 0.4	2.5 ± 0.4	2.8 ± 0.3	3.2 ± 0.3	3.5 ± 0.3	3.9 ± 0.2
4/Rotor	2.3 ± 0.5	2.5 ± 0.2	2.8 ± 0.2	3.2 ± 0.2	3.5 ± 0.2	3.9 ± 0.1
5/Circular	2.2 ± 0.1	2.5 ± 0.1	2.8 ± 0.1	3.2 ± 0.1	3.6 ± 0.1	4.0 ± 0.1

Absolute VO_2 in L/min. Values are expressed as mean ± SD. n = 8.

A similar main effect for week/chainring type was found for relative oxygen consumption (VO_2 in ml/kg/min) ($p < 0.05$). However, post hoc analysis indicated week 2 with the Rotor Q-Ring as the only significantly lower occurrence compared to week 0 with the circular ring ($p < 0.05$). In a similar manner as absolute VO_2, the increases in relative VO_2 correspond with increased demands of each exercise stage (see Table 6). There was no significant interaction between week/chainring type and power ($p = 1.00$).

Table 6: Submaximal values of relative VO_2 measured during cycling with a Circular and Rotor Q-Ring

	Power Output (watts)					
Week/Chainring	**150**	**180**	**210**	**240**	**270**	**300**
0/Circular	31.4 ± 3.4	35.4 ± 3.6	40.2 ± 4.1	44.7 ± 4.5	50.0 ± 5.1	55.1 ± 4.3
1/Rotor	30.5 ± 5.4	34.7 ± 5.9	39.4 ± 6.5	44.6 ± 6.7	49.6 ± 6.5	54.5 ± 4.9
2/Rotor	30.1 ± 6.8	33.7 ± 7.9	38.6 ± 8.1	43.8 ± 5.6	48.9 ± 5.5	53.9 ± 5.3
3/Rotor	31.0 ± 8.4	34.8 ± 9.5	39.4 ± 5.2	44.3 ± 5.6	49.6 ± 6.0	54.9 ± 6.7
4/Rotor	31.3 ±10.5	34.8 ± 2.8	39.2 ± 3.4	44.1 ± 3.4	49.3 ± 4.0	54.4 ± 4.8
5/Circular	30.4 ± 3.3	34.4 ± 3.5	39.0 ± 3.4	43.9 ± 3.8	49.4 ± 4.1	55.0 ± 5.0

VO_2 in ml/kg/min. Values are expressed as mean ± SD. n = 8.

3.5. Heart Rate

A significant main effect for week/chainring type was observed for heart rate ($p < 0.01$). Post hoc analysis revealed that heart rate was significantly lower in weeks 2 and 3 compared to week 0 ($p < 0.05$). Heart rate was also significantly lower during weeks 1, 2, and 3 compared to week 5 Post-testing ($p < 0.05$) (see Figure 5 and Table 7). There was no significant interaction found between week/chainring and power ($p = 1.00$).

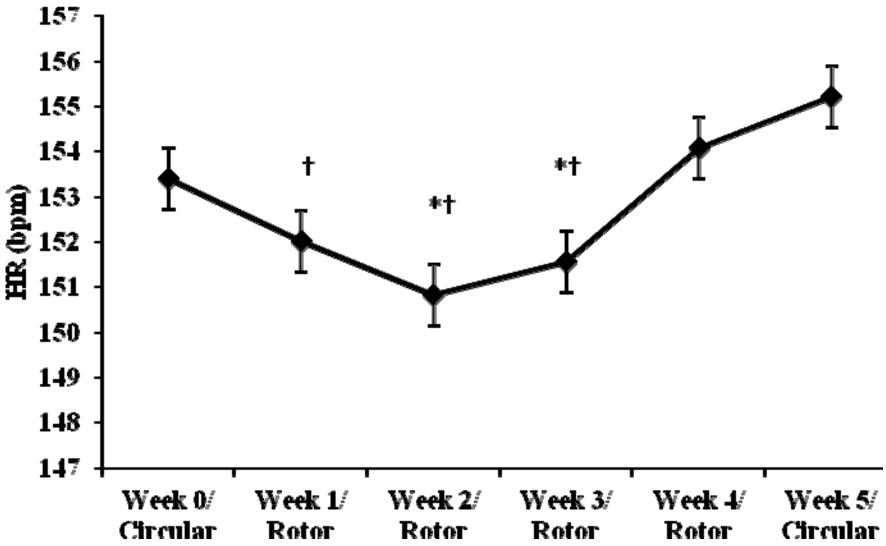

Figure 5: Main effect week/chainring type during submaximal testing. Values are expressed as mean (SD). *Significantly lower compared to week 0 Circular chainrings ($p < 0.05$). †Significantly lower compared to week 5 Circular chainrings ($p < 0.05$). n = 8.

Table 7: Submaximal values of heart rate measured during cycling with a Circular and Rotor Q-Ring

	Power Output (watts)					
Week/Chainring	150	180	210	240	270	300
0/Circular	129 ± 8	139 ± 8	149 ± 7	158 ± 8	168 ± 8	176 ± 7
1/Rotor	128 ± 11	136 ± 12	147 ± 13	158 ± 11	167 ± 16	175 ± 8
2/Rotor	126 ± 13	136 ± 14	147 ± 13	157 ± 11	166 ± 11	174 ± 8
3/Rotor	127 ± 17	137 ± 15	148 ± 12	158 ± 11	166 ± 9	174 ± 7
4/Rotor	130 ± 18	140 ± 10	150 ± 10	160 ± 8	168 ± 7	177 ± 7
5/Circular	130 ± 7	141 ± 9	151 ± 9	161 ± 7	170 ± 7	179 ± 7

Heart Rate in bpm. Values are expressed as mean ± SD. n = 8.

3.6. Blood Lactate Concentration

No main effect was observed for week/chainring type for measured blood lactate concentration ($p = 0.86$). There was a main effect for power ($p < 0.05$), however, the increases in blood lactate correspond to the increases in workload during the graded exercise test (see Table 8). There was no interaction between week/chainring type and power ($p = 0.99$).

Table 8: Blood Lactate Concentration during Submaximal Testing

	Power Output (watts)					
Week/Chainring	150	180	210	240	270	300
0/Circular	1.0 ± 0.2	1.1 ± 0.3	1.5 ± 0.4	2.3 ± 0.8	3.8 ± 1.5	6.3 ± 1.6
1/Rotor	1.1 ± 0.2	1.1 ± 0.6	1.6 ± 1.3	2.5 ± 2.3	3.9 ± 1.4	5.8 ± 1.8
2/Rotor	1.1 ± 0.6	1.2 ± 1.3	1.7 ± 2.5	2.5 ± 0.9	4.0 ± 1.3	5.5 ± 1.6
3/Rotor	1.1 ± 1.4	1.2 ± 2.5	1.6 ± 0.2	2.4 ± 0.6	3.7 ± 0.8	5.3 ± 1.7
4/Rotor	1.3 ± 2.0	1.4 ± 0.3	1.7 ± 0.3	2.5 ± 0.7	3.7 ± 1.2	5.4 ± 1.8
5/Circular	1.1 ± 0.3	1.3 ± 0.4	1.7 ± 0.5	2.6 ± 0.7	4.1 ± 0.9	5.7 ± 1.4

Lactate in mmol/L. Values are expressed as mean ± SD. n = 8.

3.7. Maximum Oxygen Consumption

As seen in Figure 6 and Table 9, the type of chainring used during maximal testing failed to produce significant differences when comparing pre-testing to week 4 and week 5 Post-test. There were no significant differences in either absolute ($p = 0.99$) or relative oxygen consumption ($p = 0.84$) between pre-testing with the circular chainrings, Rotor Q-Rings at the end of four weeks of training, and final testing with circular chainrings (i.e., week 5 Post-test).

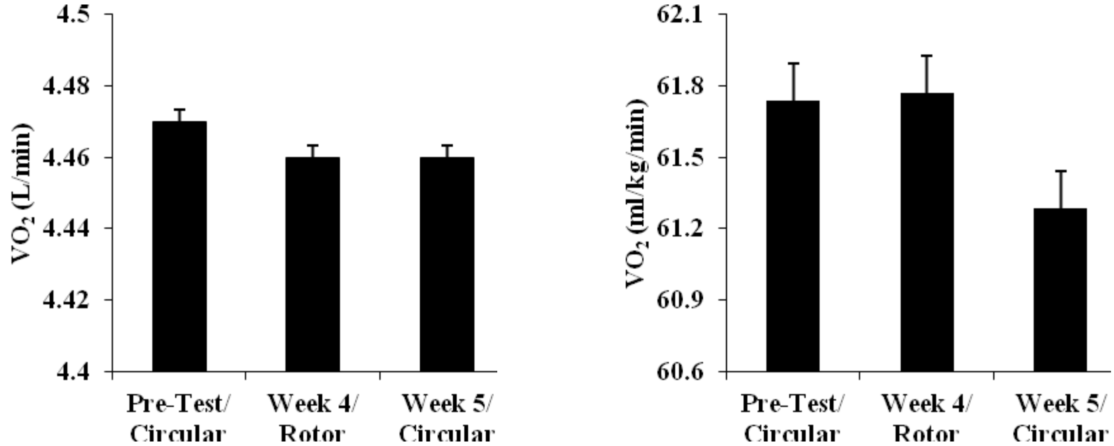

Figure 6: Absolute and relative VO_2 max values with week/chainring type. Values expressed as mean ± SE. n = 8. No significant differences were found between any of the week/chainring conditions.

Table 9: Absolute and relative VO_2 max values during maximal testing.

Week/Chainring	VO_2 Max (L/min)	VO_2 Max (mL/kg/min)
Pre-Test/Circular	4.47 ± 0.41	61.74 ± 4.86
4/Rotor	4.46 ± 0.44	61.77 ± 4.55
5/Circular	4.46 ± 0.44	61.29 ± 4.49

Values expressed as mean ± SD. n = 8.

3.8. Respiratory Exchange Ratio (RER), Ratings of Perceived Exertion (RPE), Ventilation (VE in L/min), Carbon Dioxide Production (VCO_2 in L/min), Delta and Gross Efficiency (DE and GE in percent).

There was a significant effect of week/chainring type for Respiratory Exchange Ratio ($p < 0.05$). However, post hoc analysis indicated no significant differences when comparing the Rotor Q-Ring to circular chainrings (p = 1.0). There were no significant differences in Ratings of Perceived Exertion (RPE) due to week/chainring type (p = 0.054). As the workstages increased during the graded exercise tests, the RPE increased in a systematic manner regardless of the type of chainring employed. There were also no significant differences in Ventilation (p = 0.83), and Carbon Dioxide Production (p = 0.21) with both measures indicating a systematic increase due to increasing workloads across all chainring conditions. There were no significant differences in Delta Efficiency (p = 0.53) due to week/chainring type, and in a similar manner, the results show a decrease in efficiency as workloads progressed during the graded exercise tests. There was a significant effect of week/chainring type on Gross Efficiency ($p < 0.05$), but post hoc analysis indicated that there were no significant differences when comparing the Rotor Q-Ring to circular chainrings (p = 0.99).

4. Discussion

The primary purpose of this study was to examine the effect of chainring type (circular vs. non-circular Rotor Q-Ring) on cycling performance during a 1km time trial. Performance measures during the time trial (i.e., time to completion; speed; power) were used to assess the efficacy of the Rotor Q-Ring compared to circular chainrings. In order to examine possible adaptation effects, physiological measures (i.e., oxygen consumption, heart rate, blood lactate, efficiency) collected during maximal and submaximal testing were also examined over the entire time span of the study (i.e., seven weeks).

4.1. 1km Time Trial

Results from the 1km time trial indicated significant increases in performance with Rotor Q-Rings. Subjects lowered their time by an average of 1.6 seconds, increased mean power by an average of 26 watts, and increased their mean speed by an average of 0.7 kph compared to the same test using circular chainrings. For comparison purposes, this equates to approximately a 1.8% decrease in time, 6.2% increase in average power, and a 1.8% increase in average speed. This is in line with Hue et al. (6) that employed a 1km all out performance test in a laboratory setting using an eccentric crank system. However, when performing the 1km time trial on a 333m outdoor track, Hue and co-workers found no difference in performance (4). Our findings are also in line with those of Martinez et al. in that a variable crank system (12) and Rotor Q-Ring (21) allowed cyclists to produce greater power. Previous work that examined performance over longer distances failed to show significant improvements in performance while employing an elliptical chainring during a 10km time trial (16), or an eccentric crank system in a 40.23km time trial (14). In contrast, during 30 second Wingate tests, elite level cyclists were able to produce significantly greater power using Rotor cranks compared to a traditional crank system (25). In the current study, completion of the 1km time trial took about 84 seconds, almost three times longer than the Wingate test. For either of these relatively short duration performance tests, it appears that cyclists can more readily take advantage of the mechanical alteration provided by the non-circular design of the chainring when higher efforts are expected. That is, if the cyclist is able to exert greater amounts of force during cycling, there are notable gains in performance that are not elicited in longer duration events in which the cyclist intentionally limits the application of force in order to complete the distance.

4.2. Physiological measures

During week 0 through week 5, metabolic measures were recorded during graded submaximal test sessions and also during maximal test sessions for the Pre-test, week 4, and week 5 (Post-test). While all of the response variables displayed trends typically observed due to increases in workload, there were two notable effects due to cycling with the Rotor Q-Ring and are discussed below.

4.3. Oxygen consumption; Heart Rate

First, as seen in Figure 4 during submaximal testing, cycling with the Rotor Q-Ring lowered absolute oxygen consumption in weeks 2, 3, and 4. Our results also indicated that oxygen consumption was not significantly different between the Pre-test and final testing on week 5 (Post-test), both occurring while cycling with circular chainrings. This Pre-test, Post-test comparison is notable since it demonstrated that subjects in this study were not realizing improvements simply through repeated exercise bouts over the course of five weeks, but instead clearly show that the Rotor Q-Ring was directly responsible for the observed changes in performance.

Hue and his co-workers (6) found that at a constant power output, oxygen consumption was lower in an eccentric crank system, and Zamparo and his co-workers (23) found similar effects in their study. In contrast, other studies found no differences in oxygen consumption when comparing circular versus non-circular chainrings (12, 27, 28, 29). Rodriguez-Marroyo et al. (25) also found no significant difference between the Rotor crank system and circular chainring systems in submaximal aerobic tests. However, when comparing findings from the anaerobic test, mean power output increased with the altered crank system used in their study. Rodriguez-Marroyo and his co-workers also suggested that the subject must be adapted to the equipment in order to improve performance. Our findings would partially support this idea in that significantly lower absolute oxygen consumption was not evident until the second week of testing with the Rotor Q-Ring (i.e., week 2). Subjects in their study were tested only once in each condition and long term exposure to the non-circular chainring was not examined.

Secondly, in the current study, we observed a significantly lower heart rate (approximately 2%) during submaximal testing with the Rotor Q-Ring during weeks 1, 2, and 3 across all workstages. Martinez and his co-workers (12, 36) found that the use of Rotor Q-Rings led to a lower heart rate when compared to circular rings at the same workload (also about 2% lower). In an unpublished study, Conconi (37) found a similar relationship between heart rate and wattage with subjects able to produce greater work (approximately 7-9%) with an eccentric crank system, but at the same heart rate using a conventional crank system. However, in the study by Cullen et al. (27), there were no significant differences in heart rate across varying load and cadences. Similar results were also reported by Lucia et al. (28) in that the type of chainring had no influence on heart rate during an incremental cycle-ergometry test.

4.4. Blood Lactate; Efficiency

Several studies have examined the effects of chainrings and eccentric crank systems on blood lactate, but the findings are inconsistent. Martinez et al. (12) found that cycling with Rotor Q-Rings led to a lower production of lactate at the same workload compared to circular chainrings, and when testing the Biopace chainring, Hansen et al. (15) found a significant difference in lactate (on average 0.2 mmol/L lower). In the previously mentioned study by Conconi (37), he found that after 12 incremental tests, the lactate concentration was always higher with a traditional crank system compared to the eccentric crank system. In comparison, Belen et al. (1), and Cullen et al. (27), found no significant differences in blood lactate between circular chainrings and eccentric crank systems. In the current study, we did not observe a significant main effect of week/chainring type on blood lactate. While a closer inspection of Table 8 indicated that blood lactate decreased while cycling with Rotor Q-Rings compared to circular chainrings at 270 and 300 watts, without a significant interaction, we urge caution when reading the findings even though the differences in lactate production appear to be ecologically meaningful.

Gross mechanical efficiency has been defined as ratio of work done to the total metabolic cost (33). This variable can provide insight into the effects due to different equipment used, in our case, between different types of chainrings. Delta efficiency can be defined as the change in power over the change in metabolic rate with increasing work rate (33). Examining delta efficiency can also be used to analyze changes as workloads increase, such as our study. An increase in efficiency would lower the rate of oxygen uptake at any given power output or speed, and be advantageous for longer duration exercise/performance (15).

Slight increases in cycling efficiency, up to 3%, were found when the Rotor crank system was compared to a traditional crank system (22, 23). Henderson et al. (19) also found that caloric outputs were 2.5% lower with a noncircular system at respective workloads versus a circular system. However, Jobson et al. (14) found no changes in gross efficiency after six weeks of training with a Rotor crank system, and neither did Lucia and his co-workers during testing on four separate days separated by 24 hours (28). In the current study, we did not observe a significant difference in gross efficiency or delta efficiency due to chainring type. While the formulas used to calculate efficiency from observed metabolic and workload data are widely accepted, variations in test procedures (i.e., duration, workload, pedaling rate) could possibly lead to differences in reporting efficiency. While the procedures used in the current study were similar to other work that did report improvements in efficiency (22, 23), our results support other studies in which efficiency was not affected by a non-traditional crank system (14, 28). Since we did not observe significant differences in blood lactate concentration, ventilation, respiratory exchange ratio, and carbon dioxide production, the failure to find a significant difference in efficiency is not remarkable. A thorough examination of this measure is beyond the scope of the current study, but for an in depth discussion of efficiency measures during cycling, see Ettema and Lorås (33).

5. Conclusion

In this study, we employed a Pre-test, Intervention, Post-test approach to examine the efficacy of cycling with Rotor Q-Rings compared to traditional circular chainrings. Most of the previous work examining the effects of using a non-circular, eccentric chainring (or non-traditional, eccentric crank system) on cycling performance did so with minimal exposure to the modified system (4, 5, 6, 10, 12, 15, 16, 22, 25, 27, 28, 29, 33) with Jobson et al. (14) as the exception. In the current study, we were also interested in uncovering physiological signs indicating that adaptations were necessary to exploit the claimed benefits of the Rotor Q-Ring and subjects were required to train and race with this modification to their personal bicycle for five weeks. Since many competitive cyclists and triathletes have an "off season," repeated 1km time trials and graded exercise tests occurred during the middle part of the competitive racing season to avoid any confounding effects of progressively increasing cardiovascular efficiency that would most likely be evident during pre-season training.

Evidence from this study indicated that for these well-trained cyclists and triathletes, performance improved after just one week employing the Rotor Q-Rings. The maximal oxygen consumption results from the Pre-test and week 5 Post-test further demonstrated that positive performance effects were only evident with the Rotor Q-Rings. Furthermore, these improvements were specific and did not transfer to circular rings after four weeks of training, racing, and testing with Rotor Q-Rings. While it appears from this study that there may also be positive long term effects as noted by the significant reduction in submaximal oxygen consumption and heart rate during the intervention period (i.e., cycling with Rotor Q-Rings), the majority of the physiological measures we examined do not equivocally support the notion that an adaptation period is necessary for this increased 1km time trial performance.

In the current study, we also compared the effects cycling with Rotor Q-Rings on 1km time trial performance over four weeks and found that the positive effect was essentially the same over four weeks.

Consequently, when subjects discontinued using the Rotor Q-Rings and were tested on circular rings at the conclusion of the study (i.e., week 5), performance measures returned to week 0 values with circular rings. The 1km performance tests and metabolic data collected during the submaximal and maximal testing also suggest that the central nervous system was not confronted with a task that is markedly different than pedaling with circular chainrings. That is, the Rotor Q-Rings did not cause an initial increase in oxygen consumption or heart rate indicating a disruption to the coordinative structure used to apply force to the pedals. Conversely, it appears that the well-established coordination pattern used in conventional cycling is well suited to take advantage of this alteration to the bicycle drive train.

We did not collect respiratory gasses during the 1km time trial and therefore, cannot thoroughly evaluate the metabolic consequences during this maximal effort test. However, Hue et al. (6) did analyze respiratory gases during the same test employed in the current study (i.e., 1km time trial in a laboratory setting) and found no significant differences in metabolic measurements. In the current study, we did analyze blood lactate concentration three minutes after completing the 1km time trial and found no significant differences across weeks 0, 1, 2, and 3 (see Table 3). Our subjects also repeated the 1km time trial after maximal testing on weeks 4 and 5. As expected, blood lactate concentrations in this condition were greater compared to samples taken after submaximal testing, but the type of chainring failed to produce a significant difference (see Table 4).

Previous work examining differences in muscle activation patterns via electromyography (EMG) also indicated that a significant reorganization of lower limb musculature was not taking place during cycling with eccentric chainrings. For example, Horvais et al. (10) collected EMGs and found no differences in duration and magnitude between circular chainrings and the O.Symetric non-circular chainring. Dagnese and co-workers (30) also showed similar EMG patterns when using the Rotor Crank system during a graded exercise test compared to a traditional crank system. Herzog and Neptune (31) did observe a slight, but significant shift in EMG patterns due to the elliptical chainring used in their study. Additionally, they reported that subjects experienced an adaptation period that occurred within the first 10-20 crank cycles. This finding is meaningful since it demonstrates how quickly the central nervous system responded to this alteration in pedaling dynamics and coincides with other work in which metabolic measurements did not significantly vary due to the type of chainring employed (12, 25, 27, 28, 29).

Our performance test was limited to a 1km time trial in a laboratory setting, but in contrast to the work by Hue et al. (4, 6), in which they conducted separate indoor and outdoor studies, they speculated that alterations to the cyclist's position and increased aerodynamic drag (elicited by a crank system with a continually changing crank arm length) could be the determinants to the non-significant findings. They also mentioned that skill level could have influenced their results since they did not test elite level track racers in the outdoor study. In comparison to the current study, the Rotor Q-Ring would not alter the cyclist's position since the crank arm length does not change during pedaling. In this case, aerodynamic drag would only increase if the cyclist increased velocity. Therefore, the gain in performance noted in the laboratory may be negated as greater drag forces are produced outdoors. Outdoor testing with skilled track cyclists could possibly elucidate this discrepancy in performance results, but indoor testing in a controlled setting is still highly preferable in cycling research since multiple confounding factors can be controlled (e.g., temperature, humidity, wind) especially across multiple testing dates spanning seven weeks.

In conclusion, our findings indicated that Rotor Q-Rings provide an ergogenic effect that is apparent after only one week of exposure. Our performance test was limited to a 1km time trial, but the Rotor Q-Ring could also prove beneficial in criterium style racing events or at the end of a road race in which bicycle racers typically pedal at similar intensities and durations as the 1km test. Furthermore, when considering the reduction in oxygen consumption and heart rate observed during submaximal testing, it also seems tenable that a greater energy savings could be realized for endurance type cycling. Further testing in outdoor settings at various distances (i.e., time trials) would be the next logical step in determining the ecological validity of this modification to the bicycle drive train.

6. Acknowledgements

We are grateful to Garrett Smith at SRAM/TruVative for lending us cranksets for use with the Rotor Q-Rings; Francesca Castellucci, Kate Allen, Hilary Coates, and Joe Ricci for their tireless assistance during data collection. We are also grateful to the dedicated subjects who showed up for multiple weeks of testing and faithfully adhered to the requirements asked of them to help insure validity of the results.

7. References

[1] L. Belen, M. Habrard, J. P. Micallef, S. Perrey, D. Gallais. Cycling performance and mechanical variables using a new prototype chainring. *European Journal of Applied Physiology.* 2007, **101**: 721-726.

[2] R. R. Neptune, S. A. Kautz. Muscle activation and deactivation dynamics: the governing properties in fast cyclical human movement performance. *Exercise and Sport Sciences Reviews.* 2001, **29**: 76-81.

[3] J. C. Martin, W. Spirduso. Determinants of maximal cycling power: crank length, pedaling rate and pedal speed. *European Journal of Applied Physiology.* 2001, **84**: 413-418.

[4] O. Hue, K. Chamar, M. Damiani, S. Blonc, C. Hertogh. The use of an eccentric chainring during an outdoor 1km all-out cycling test. *Journal of Science and Medicine in Sport.* 2007, **10**: 180-186.

[5] O. Hue, S. Racinais, K. Chamari, M. Damiani, C. Hertogh, S. Blonc. Does an eccentric chainring improve conventional parameters of neuromuscular power? *Journal of Science and Medicine in Sport.* 2008, **11**: 264-270.

[6] O. Hue, O. Galy, C. Hertogh, J. Casties, C. Prefaut. Enhancing cycling performance using an eccentric chainring. *Medicine & Science in Sports & Exercise.* 2001, **33**: 1006-1010.

[7] M. L. Hull, M. Williams, K. Williams, S. Kautz. Physiological response to cycling with both circular and noncircular chainrings. *Medicine & Science in Sports & Exercise.* 1992, **24**: 1114-1122.

[8] L. Malfait, G. Storme, M. Derdeyn. Comparative biomechanical study of circular and non-circular chainrings for endurance cycling at constant speed. Release 2: 2010.

[9] ROTOR Bicycle Components USA. www.rotorbike.com. 2010.

[10] N. Horvais, P. Samozino, K. Zameziati, C. Hautier, F. Hintzy. Effects of a non circular chainring on muscular, mechanical and physiological parameters during cycle ergometer tests. *Isokinetics and Exercise Science.* 2007, **15**: 271–279.

[11] J. W. Rankin, R. R. Neptune. A theoretical analysis of an optimal chainring shape to maximize crank power during isokinetic pedaling. *Journal of Biomechanics.* 2008, **41**: 1494–1502.

[12] A. C. Martínez. Study about the metabolic efficiency of the rotor system compared with a conventional bicycle. Unplublished study. 2006.

[13] E. W. Faria, D. L. Parker, I. E. Faria. The science of cycling: physiology and training-part 2. *Sports Medicine.* 2005, **35**: 313-337.

[14] S. A. Jobson, J. Hopker, A. Galbraith, D. A. Coleman, A. M. Nevill. Effect of the Rotor crank system on cycling performance. *Journal of Sports Science and Medicine.* 2009, **8**: 463–467.

[15] E. A. Hansen, K. Jensen, J. Hallén, J. Rasmussen, P. K. Pedersen. Effect of chain wheel shape on crank torque, freely chosen pedal rate, and physiological responses during submaximal cycling. *Journal of Physiological Anthropology*. 2009, **28**: 261–267.

[16] J. J. Peiffer, C. R. Abbiss. The influence of elliptical chainrings on 10km cycling time trial performance. *International Journal of Sports Physiology and Performance*. 2010, **5**: 459-468.

[17] J. C. Martin. Muscle power: the interaction of cycle frequency and shortening velocity. *Exercise and Sport Sciences Reviews* 2007, **35**: 74-81.

[18] G. N. Askew, R. L. Marsh. Optimal relative shortening velocity (V/Vmax) of skeletal muscle during cyclical contractions: length-force effects and velocity dependent activation and deactivation. *Journal of Experimental Biology*. 1998, **201**: 1527-1540.

[19] S. C. Henderson, R. W. Ellis, G. Klimovitch, G. A. Brooks. The effects of circular and elliptical chainwheels on steady-rate cycle ergometer work efficiency. *Medicine & Science in Sports & Exercise.* 1977, **9**: 202–207.

[20] J. M. Tricás-Moreno, J. M. Cozar-Bartos. Rotor, generator of health: analysis of the effects of the rotor propulsion system upon the knee joint. University of Zaragoza, Spain. Unpublished study, N.D.

[21] D. Martinez, D. Vicente, D. Calvo, I. Zudaire. Preliminary report on q-rings. University of Vallodolid, Spain. Unpublished study, 2006.

[22] A. Santalla, J. M. Manzano, M. Perez, A. Lucia. A new pedaling design: the Rotor-effects on cycling performance. *Medicine & Science in Sports & Exercise.* 2002, **34**: 1854-1858.

[23] P. Zamparo, A. E. Minetti, P. E. di Prampero. Mechanical efficiency of cycling with a new developed pedal-crank. *Journal of biomechanics.* 2002, **35**: 1387–1398.

[24] R. R. Neptune, C. P. McGowan, J. M. Fiandt. The influence of muscle physiology and advanced technology on sports performance. *Annual Review of Biomedical Engineering.* 2009, **11**: 81-107.

[25] J. A. Rodriguez-Marroyo. The rotor pedaling system improves anaerobic but not aerobic cycling performance in professional cyclists. *European Journal of Applied Physiology.* 2009, **106**: 87–94.

[26] D. Barani, F. Commandre, A. Digoin. The “Harmonic” chainring: presentation and biomechanical characteristics.

Medicina Dello Sport. 1994, **68**: 77–81.

[27] L.K. Cullen, K. Andrew, M. Lair, M. J. Widger, B. F. Timson. Efficiency of trained cyclists using circular and noncircular chainrings. *International Journal of Sports Medicine.* 1992, **13**: 264–269.

[28] A. Lucia, J. Balmer, R. C. R. Davison, M. Perez, A. Santalla, P. M. Smith. Effects of the rotor pedalling system on the performance of trained cyclists during incremental and constant-load cycle-ergometer tests. *International Journal of Sports Medicine.* 2004, **25**: 479-485.

[29] S. Ratel, P. Duche, C. A. Hautier, C. A. Williams, M. Bedu. Physiological responses during cycling with noncircular "Harmonic" and circular chainrings. *European Journal of Applied Physiology.* 2004, **91**: 100-104.

[30] F. Dagnese, F. P. Carpes, E. de Assis Martins, D. Stefanyshyn. Effects of a noncircular chainring system on muscle activation during cycling. *Journal of Electromyography and Kinesiology*. 2011, **21**: 13-17.

[31] R. R. Neptune, W. Herzog. Adaptation of muscle coordination to altered task mechanics during steady-state cycling. *Journal of Biomechanics*. 2000, **33**: 165-172.

[32] RacerMate, Inc. Bicycling training technology for world class performance. Computrainer Stand Alone User Guide. 2009.

[33] G. Ettema, H. W. Lorås. Efficiency in cycling: a review. *European Journal of Applied Physiology.* 2009, **106**: 1-14.

[34] E. W. Faria, D. L. Parker, I. E. Faria. The science of cycling: physiology and training-part 1. *Sports Medicine.* 2005, **35**: 285–312.

[35] S. Powers, E. Howley. Exercise Physiology: *Theory and application to fitness and performance (7th Edition).* McGraw-Hill Higher Education, 2009.

[36] J. C. Martin, S. M. Lamb, N. A. T. Brown. Pedal trajectory alters maximal single-leg cycling power. *Medicine & Science in Sports & Exercise*. 2002, **34**: 1332-1343.

[37] I.E. Conconi. Unpublished study. 1998