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ORIGINAL ARTICLE

Non-circular chainring improves aerobic cycling performance in non-cyclists

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Abstract

Non-circular chainrings alter the crank velocity profile over a pedalling cycle. The aim of this study was to investigate the effect of this altered crank velocity profile on the aerobic performance compared to a circular chainring (CC). Ten male non-cyclists performed two incremental maximal tests at 80 rpm on a cycle ergometer: one with a circular (Shimano) and the other with a non-circular chainring Osymetric[®] (Somovedi), at least 50 h apart. Each test started with a workload of 100 W lasting 3 min. During the first 12 min, the workload was increased by 30 W every 3 min. Thereafter, the workload was increased by 30 W every 2 min until exhaustion. The power output, the intra-cycle crank angular velocity and the physiological parameters were monitored continuously, averaged over the last 30 s of each increment and at exhaustion, and compared for the two chainrings. Results showed a higher maximal aerobic power attained with the non-circular chainring (362.6 ± 37.9 vs. 338.8 ± 32.6 W, $p < .001$; moderate effect), which could be explained by a significantly lower energy expenditure during the first increment at 100 W. It could be hypothesised that the use of the non-circular chainring allowed saving a small part of energy expenditure throughout the test, allowing the exhaustion of the subject at a higher increment for a similar maximal energy expenditure, in comparison with a CC. Although this improvement is obtained only for non-cyclists, it allowed highlighting the link between cycling equipment modifying the pedalling motion and physiological responses.

Keywords: *Technology, biomechanics, performance, fatigue*

Introduction

Non-circular chainrings and pedal-crank systems have been developed to improve cycling performance by altering aspects of the conventional circular pedalling motion. Depending on the non-circular systems, they allowed variations during a crank revolution of the angle between the two cranks (Rotor[®] pedalling system), the crank arm length (Pro-race[®] system) or the radius chainring (non-circular chainrings such as Osymetric[®] and Biopace[®]). The majority of the studies demonstrated kinematic and kinetic alterations (e.g. Horvais, Samozino, Zameziati, Hautier, & Hintzy, 2007; Malfait, Storme, & Derdeyn, 2012, unpublished study; Neptune & Herzog, 2000; Rankin & Neptune, 2008; Strutzenberger, Wunsch, Kroell, Dastl, & Schwameder, 2014): the non-circular chainrings slowed down the crank velocity, allowing riders to apply and increased tangential force during the power downstroke phase. It should be noted that the design of the non-circular systems

(chainrings or pedal-crank systems, ovality and shape of the chainring, orientation of the crank relative to the chainring) has a substantial influence on the mechanical changes observed (Malfait, Storme, & Derdeyn, 2012, unpublished study). As an illustration, increasing the ovality for a non-circular chainring allowed to increase its effects, that is, the decrease of the crank velocity and the increase of the tangential crank force during the downward phase (Strutzenberger et al., 2014). Two studies have reported a significant effect of a non-circular system on joint kinematics (Carpes, Dagnese, Mota, & Stefanyshyn, 2009) and joint kinetics (Strutzenberger et al., 2014) of lower limbs during pedalling. Interestingly, the non-circular chainring systems reappeared during recent international cycling competitions since the first and second place finishers of the Tour de France 2012 were equipped with Osymetric[®] non-circular chainrings (OC).

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However, studies have not consistently shown a transfer of kinetic and kinematic effects of non-circular designs to aerobic cycling performance. Almost all studies failed to show significant enhancement of a common predictor of cycling performance such as oxygen consumption, heart rate, ventilation, blood lactate concentration or maximal aerobic power (MAP) attained at exhaustion, whatever the non-circular system tested (Cordova, Latasa, Seco, Villa, & Rodriguez-Falces, 2014; Dagnese, Carpes, Martins, Stefanyshyn, & Mota, 2011; Lucia et al., 2004; Ratel, Duché, Hautier, Williams, & Bedu, 2004; Rodriguez-Marroyo et al., 2009; Santalla, Manzano, Pérez, & Lucia, 2002). A question that arises from the discrepancy between non-circular system effects is whether or not the modifying kinematic and kinetic pedalling parameters influence physiological responses and thus aerobic cycling performance. Two major explanations could be advanced.

The first one concerned the influence (or not) of these mechanical changes induced by the non-circular systems on muscular or kinetic responses of the lower limbs. Dagnese et al. (2011) and Horvais et al. (2007) indicated that non-circular systems did not affect the muscle activation pattern using electromyography measurements, while intra-cycle net crank torque and pedalling rate were significantly modified (Horvais et al., 2007). The lack of effects of the non-circular systems on the muscular pattern could be related to the lack of effects on the physiological responses and on the aerobic cycling performance. And when effects are revealed, they showed an increase in Electromyography magnitude using a non-circular chainrings (vs. circular), whereas the power output remained constant (200 W) (Neptune & Herzog, 2000). Moreover, Strutzenberger et al. (2014) indicated a significant redistribution of joint-specific power generation with the OC: a reduction in the sagittal knee joint power and an increase in the sagittal hip joint power. The authors hypothesised that this reorganisation maximised the power production instead of the mechanical efficiency of the lower limbs. When changing from the circular to the non-circular chainring, the non-circular chainring may induce changes in both muscular and biomechanical patterns, which could increase the associated metabolic cost. This could explain why no physiological alteration can be consistently proven in the literature so far when using a non-circular chainrings.

Secondly, the experimental procedures (i.e. duration, workload, pedalling rate) and the subjects (i.e. cyclists or non-cyclists, accustomed or not to a non-circular system) adopted in the studies could also partly explain the discordant results on the non-circular systems' effects (Cordova et al., 2014;

Lucia et al., 2004; O'Hara, Clark, Hagobian, & McGaughey, 2012; Ratel et al., 2004). For example, Strutzenberger et al. (2014) showed a significant interaction between the pedalling rate and the chainring effect on the crank angular velocity during the downward phase. Knee and hip joint power alterations caused by non-circular chainrings increased also as the pedalling rate increased (Malfait et al. 2012; Strutzenberger et al. 2014). Moreover, the only studies showing physiological response modifications with a non-circular chainring tested non-cyclists (improvement of the delta efficiency: Santalla et al., 2002) or cyclists with exposure to the non-circular system during five weeks' training and racing (reduction of the oxygen consumption during submaximal testing: O'Hara et al., 2012). The cycling experience of the subjects could be an explanation: well-trained cyclists do not take advantage of non-circular systems since they are too accustomed to the conventional system (Lucia et al., 2004). Although kinematic and kinetic adaptations of the crank occurred very quickly with well-trained cyclists (Neptune & Herzog, 2000), they may not improve the aerobic cycling performance.

When considering the above, the effects of the non-circular chainring on aerobic cycling performance could be highlighted with non-cyclist participants and by testing a non-circular chainring presenting high ovality. It was the purpose of this study to test the effects of an OC compared to a circular chainring (CC) on physiological responses and aerobic performance of physically active non-cyclist participants during an incremental test until exhaustion. The Osymetric[®] chainring was selected because it presented high ovality with regard to other non-circular systems and because its shape was similar to the theoretical optimal chainring shape maximising crank power (Rankin & Neptune, 2008).

Methods

Ten healthy male subjects participated in this study (22.3 ± 1.8 years; height, 181.6 ± 3.3 cm; mass, 75.9 ± 9.0 kg; fat mass percentage, $14.2 \pm 5.9\%$). All subjects were physically active in different sport activities, but none was specifically trained in cycling. Each subject provided written informed consent, and the local Ethics Committee approved the protocol.

The subjects were evaluated while pedalling with a conventional CC (Shimano, Japan) and a OC (Somovedi SAS, Monaco) currently used by cyclists during competition, with the same gearwheel (52 teeth). The OC shape is described as a skewed ellipse where the major and minor axes are not

perpendicular (80°). The angles between major axis and crank arm was 96.5° and between minor axis and crank arm was -3.5° . The major/minor axis ratio was 1.25 (Figure 1; for further information, see Horvais et al., 2007; Ratel et al., 2004 or the Osymetric® web site).

The subjects performed two incremental maximal cycling tests at 80 rpm on a cycle ergometer, 72 h apart (50 h for one subject). One test was performed with the CC and the other with the OC. The two tests were randomly assigned. For both chainrings, the first increment started with a 100-W workload lasting 3 min. During the first 12 min, the workload was increased by 30 W every 3 min. Thereafter, the workload was increased by 30 W every 2 min until exhaustion (Midgley, Bentley, Luttkholt, McNaughton & Millet, 2008). A metronome and a pedal-frequency meter were used to maintain the imposed pedalling rate. Oxygen consumption ($\dot{V}O_2$ in $l \text{ min}^{-1}$) and carbon dioxide production were measured continuously using a breath-by-breath automatic gas analyser system (Cosmed K4b2, Rome, Italy) and were averaged over the last 30 s of each increment. $\dot{V}O_{2\text{max}}$ was determined using the following criteria: identification of a $\dot{V}O_2$ plateau lasting 1 min with a further increase in power output; heart rate higher than 90% of the age-predicted maximum heart rate (± 10 bpm); respiratory exchange ratio higher than 1.1; exhaustion with impossibility to continue despite verbal encouragements. The MAP was defined as the power at which $\dot{V}O_{2\text{max}}$ is reached.

A friction-loaded cycle ergometer (Monark 818E, Stockholm, Sweden) was used for both incremental tests. The configuration (height of the saddle and of the handle bar) was adjusted to each subject before the first test and was strictly identical for the second test. The pedal crank displacement was measured at 20 000 Hz using an optical encoder (Hengstler type RIS IP50, Aldingen, Germany) fixed on the pedal crank, with a precision of 6 000 points per pedal revolution. The crank revolution was divided into 36

sectors, each covering 10° ($5\text{--}15^\circ$, $15\text{--}25^\circ$, $25\text{--}35^\circ$, etc.), 0° corresponding to the top dead centre. The instantaneous pedalling rate (PR_{inst} in rpm) was calculated using the pedal crank displacement and the duration between two points of the pedal crank displacement, and was averaged over each sector during the last 30 s of each increment. The PR_{inst} parameter informed on the change of the pedalling rate within a crank revolution, whereas the mean pedalling rate was fixed at 80 rpm during the whole maximal cycling test for all subjects and both OC and CC chainrings. Three increments of the cycling test were selected to compare OC vs. CC responses: the first (100 W: submaximal exercise and low power output), the fourth (190 W: submaximal exercise and moderate power output) and the last increments (PMA: MAP). It is worth noting that the OC vs. CC comparison at PMA was made at different absolute power outputs if the PMA differed according to the chainrings.

The normal distribution of the data was checked by the Shapiro-Wilk normality test. Student *t*-tests were used to compare physiological and mechanical data obtained at each submaximal stage and at MAP with the OC vs. the CC. The comparison of PR_{inst} was assessed using a two-way (chainrings \times sections of the crank revolution) analysis of variance for repeated measures. When the ANOVA test was significant, the Newman-Keuls *post hoc* test was conducted. The magnitude of the observed differences across chainring conditions was quantified using effect size statistics (ES, Cohen's *d*), with the thresholds for small, moderate and large effects being set at 0.2, 0.5 and 0.8, respectively (Cohen, 1988). The limit for statistical significance was set at $p < .05$ in all tests.

Results

Four subjects attained a higher increment at exhaustion by using the OC vs. CC, six others stayed on the

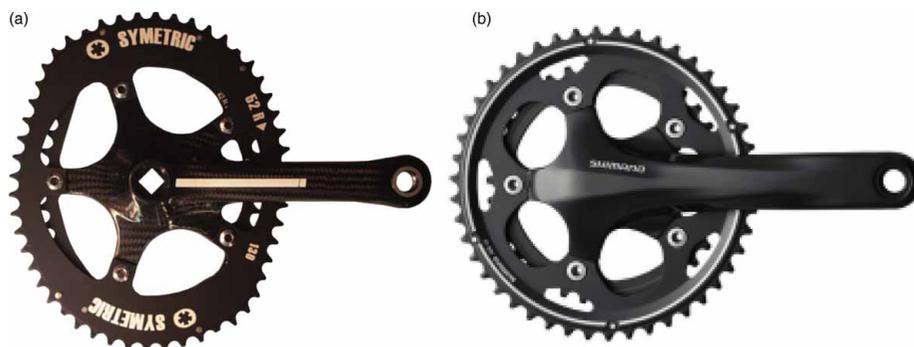


Figure 1. Studied chainrings: (a) OC; (b) CC.

Table I. Variables measured during the incremental test with the OC and the CCs

	Chainrings		p-Values	ESs
	OC	CC		
MAP (W)	362.6 ± 37.9	338.8 ± 32.6	< .001	.71
$\dot{V}O_{2\max}$ (l min ⁻¹)	4.12 ± 0.57	4.09 ± 0.49	.69	.06
RER _{max}	1.12 ± 0.04	1.10 ± 0.06	.52	.41
HR _{max} (bpm)	195.4 ± 8.1	194.1 ± 9.0	.4	.16

Note: Values are expressed as means ± SD. MAP, $\dot{V}O_{2\max}$, RER_{max} and HR_{max} represent the maximum aerobic power output, the maximum oxygen consumption, the maximum respiratory exchange ratio and the maximum heart rate attempt, respectively.

same increment, but they maintained it longer. MAP was significantly higher with the OC than with the CC ($p < .001$; ES = 0.71 medium effect; Table I). No significant difference was found in $\dot{V}O_{2\max}$, HR_{max} and RER_{max} between the OC and the CC (Table I). Figure 2 presents the average $\dot{V}O_2$ (± SD) during each power output increment for both chainrings independently, as well as the number of subjects per increment and the ES. $\dot{V}O_2$ measured during the first increment at 100 W, was significantly lower with the OC than with the CC ($p < .05$; ES = 0.9 large effect), but no significant differences were found during all the other sub-maximal increments.

Changes in the pedalling rate during a crank revolution are presented for both chainrings in Figure 3. PR_{inst} was significantly affected by chainring x sections of the crank revolution conditions ($p < .01$). *Post hoc* tests showed that PR_{inst} was significantly ($p < .05$) higher with the OC between 5° and 15°, 145° and 195°, 325° and 360° and significantly lower between 45° and

115°, 215° and 305° in relation to those of the CC for the first (100 W), the fourth (190 W) and the last (MAP) increments.

Discussion

The major result of the study was that the present OC can significantly improve (+ 7.5%, moderate effect) one of the main determinants of aerobic performance: MAP. This significant increase of MAP allowed highlighting the link between cycling equipment modifying the pedalling motion and the physiological responses of the participant.

The MAP improvement observed with OC can be explained by the difference of $\dot{V}O_2$ evolution during the incremental tests between OC and CC (Figure 2). The $\dot{V}O_2$ was significantly lower with the OC vs. CC during the first increment at 100 W, with an ES corresponding to a large difference. The use of OC reduced the $\dot{V}O_2$ (but not significantly), with an ES corresponding to a moderate or slight difference,

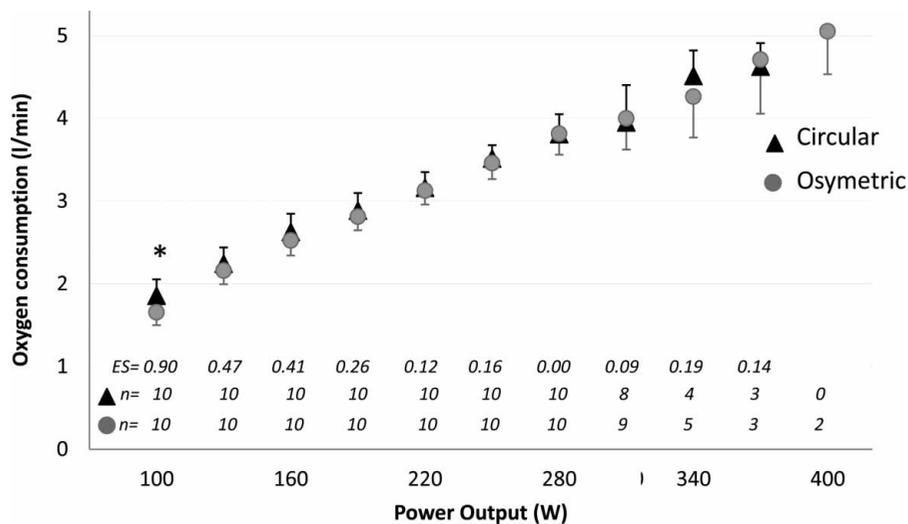


Figure 2. Oxygen consumption (mean ± SD) plotted against the power output during the incremental maximal test with the OC and the CC. *Significant difference between OC and CCs ($p < .05$). The number of subjects per increment (n) and the ES were also presented.

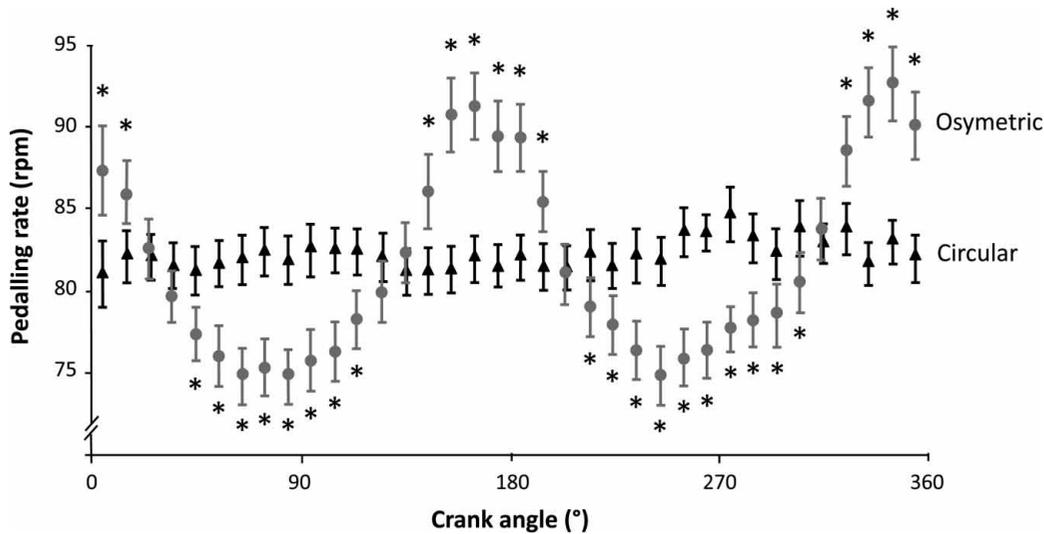


Figure 3. Mean (\pm SD) of all subjects of instantaneous pedalling rate during the crank revolution with the OC and the CC during the first increment at 100 W. Zero degree corresponded to the top dead centre. Instantaneous pedalling rate evolution for the fourth and the last MAP output increments was identical.

*Significant difference between OC and CCs ($p < .05$).

throughout the first sub-maximal increments. Similar results were recently found by O'Hara et al. (2012) with minimal exposure to the non-circular modified system. Authors showed that cycling with a non-circular chainring lowered significantly the $\dot{V}O_2$ compared to a CC, during submaximal testing (from 150 to 300 W). Finally, four subjects of the present study achieved a higher power increment at $\dot{V}O_{2\max}$ with OC. It could be hypothesised that the use of the OC allowed saving a small part of energy expenditure throughout the test, allowing the exhaustion of the subject at a higher increment for a similar $\dot{V}O_{2\max}$, in comparison with a CC.

From a mechanical point of view, the difference in energy expenditure between OC and CC can be explained by the present significant crank velocity variation during a crank revolution observed with OC: higher instantaneous crank velocity during top and bottom dead centres and lower instantaneous crank velocity during the effective part of the downstroke phase (Figure 3). Since the duration of the crank revolution is constant (pedalling rate fixed at 80 rpm), the crank stayed longer in the effective power phase and less time in the ineffective phase in the OC vs. the CC conditions. This modified crank profile was explained by the variation in the chainring radius as a function of the crank angle. Similar alterations in crank angular velocity were experimentally observed by several studies during submaximal cycling with non-circular chainrings (Horvais et al., 2007; Neptune & Herzog, 2000; Rankin & Neptune, 2008; Strutzenberger et al., 2014). The modified pedalling motion when using

the OC probably induced lower energy expenditure, especially by the decrease in the duration of the ineffective phase of the crank revolution. This hypothesis can be supported by the theoretical mechanical analysis proposed by Hull et al. (1991). They showed that an angular velocity profile similar to the present OC angular velocity profile made it possible to maintain the total mechanical energy of both legs constant and then to reduce the internal work significantly over a range of pedalling rates from 80 to 100 rpm. This argument can be further strengthened with the review by Kautz and Neptune (2002), where they affirmed that external and internal work are not independent in cycling. The change in external work profile using the OC will require a change in internal work profile. As a consequence, the present OC angular velocity profile will theoretically reduce the energy expenditure during cycling since reducing the internal work reduces the energy expenditure (Wells, Morrissey, & Hughson, 1986). Interestingly, the present $\dot{V}O_2$ was significantly affected by the use of OC.

Finally, the fact that the OC had no effect on maximal physiological parameters ($\dot{V}O_{2\max}$, RER_{\max} and HR_{\max}) was expected. $\dot{V}O_{2\max}$ is indeed a strong fitness level-related parameter and it may be difficult to precisely define an exact threshold to improve cardiorespiratory fitness. A single alteration of the pedalling motion caused by a non-circular system might not be a sufficient stimulus to significantly improve the performance of the cardiorespiratory system. The only possible aerobic performance improvement induced by a non-circular system could be a higher

power production (MAP) at equal maximal physiological responses.

To conclude, the major result of the present study was that changes in bicycle equipment – a noncircular Osymetric[®] chainring – can improve MAP during cycling. This performance improvement was explained by a modification of the crank velocity profile over a crank revolution, which increases the time spent in the effective power phase and decreases the time spent in the ineffective phases. Although this improvement was obtained only for non-cyclists, we were able to partially explore the relation between the kinetics and kinematics of the pedalling motion and the subject's physiological responses. However, it is not possible to directly generalise these findings to cycling performance, because well-trained cyclists were not tested. These results open perspectives for further research on competitive cyclists, by proposing a period of accommodation with the non-circular system.

Disclosure statement

No potential conflict of interest was reported by the authors.

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