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review article

Noncircular chainrings and pedal to crank interface in cycling: a literature review

Sistemas de pedivela não-circulares e interfaces pedal-pedivela no ciclismo: uma revisão da literatura

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Abstract – Noncircular chainrings and novel pedal to crank interfaces have been designed to optimize variables related to cycling performance (e.g. peak crank torque and efficiency), with conflicting results in terms of performance. Therefore, the aim of the present article was to review the theoretical background of noncircular chainrings and novel pedal to crank interfaces and their effects on biomechanical, physiological and performance variables. Reducing internal work, crank peak torque, and time spent at the top and bottom dead centres (12 o'clock and 6 o'clock positions, respectively) were among the various targets of noncircular chainrings and novel pedal to crank interface design. Changes in joint kinematics without effects on muscle activation were observed when cyclists were assessed using noncircular chainrings and novel pedal to crank interfaces. Conflicting results for economy/efficiency explain the unclear effects of noncircular chainrings on cycling performance and the positive effects of some novel pedal to crank interfaces on cycling economy/efficiency.

Key words: Efficiency; Electromyography; Kinematics; Performance.

Resumo – *Sistemas de coroas não circulares e novas interfaces entre o pedal e o pedivela vem sendo propostas com o objetivo de otimizar variaveis relacionadas com o desempenho no ciclismo (e.g. pico de torque e eficiência) com resultados conflitantes acerca do desempenho. Nesta perspectiva, o objetivo desta revisão foi abordar aspectos teóricos do uso de sistemas de pedivela não circulares e novas interfaces entre o pedal e o pedivela e seus efeitos em variáveis biomecânicas, fisiológicas e do desempenho. A redução do trabalho interno, pico de torque no pedivela e tempo decorrido nos pontos mortos (posições de 12 horas e 6 horas) estiveram entre as variáveis utilizadas para otimizar o desenho de sistemas de pedivela não circulares e novas interfaces entre o pedal e o pedivela. Alterações na cinemática foram observadas sem mudanças na ativação dos músculos dos membros inferiores de ciclistas utlizando sistemas de pesdivela não-circulares e novas interfaces entre o pedal e o pedivela. Resultados conflitantes foram observados na economia/eficiência indicando beneficios pouco claros do uso de sistemas de pedivela não circulares e resultados positivos do uso de novas interfaces entre o pedal e o pedivela na economia/eficiência.*

Palavras-chave: *Cinemática; Desempenho; Eficiência; Eletromiografia.*

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INTRODUCTION

The progress in training programs and applied technology enabled coaches to improve training monitoring and performance of athletes throughout the years[1]. In cycling, changes in the design of bicycles aimed to reduce rolling resistance and internal work (mechanical work to move the legs) towards greater travelling speed[2]. Aerodynamic force is the major resistive force in cycling, so new designs for wheels[3], shoes[4], frames[5], and handlebars[6] have been presented with the aim of reducing drag force, leading to improved performance. Assuming that lower energy expenditure for cycling at target workload (i.e. greater economy/efficiency) will be related to better performance, declines in energy expenditure may be observed when external and/or internal work decreases (i.e. energy spent to overcome cycling external forces and energy spent to move the leg without external resistance, respectively).

On the other hand, the possibility to increase power output for the same energy expenditure has helped researchers to look for better economy/efficiency markers (i.e. oxygen uptake or heart rate)[7]. Because power output depends on the moment arm of the crank and the tangential force applied on the crank (effective force), for a hypothetical constant force application, a larger moment arm should increase crank torque. However, due to mechanical and anatomical constraints, the effective force is hardly ever constant, which suggests that the moment arm of the crank would change throughout crank revolution to maximize crank torque. With this in mind, changes in crank length[8,9], pedal to crank interface[10,11], and in the regular profile of the chainring have been devised (Figure 1)[12-14]. Even with strong theoretical support, some of these novel devices uncertainly affect biomechanical, physiological or performance variables[15-18].

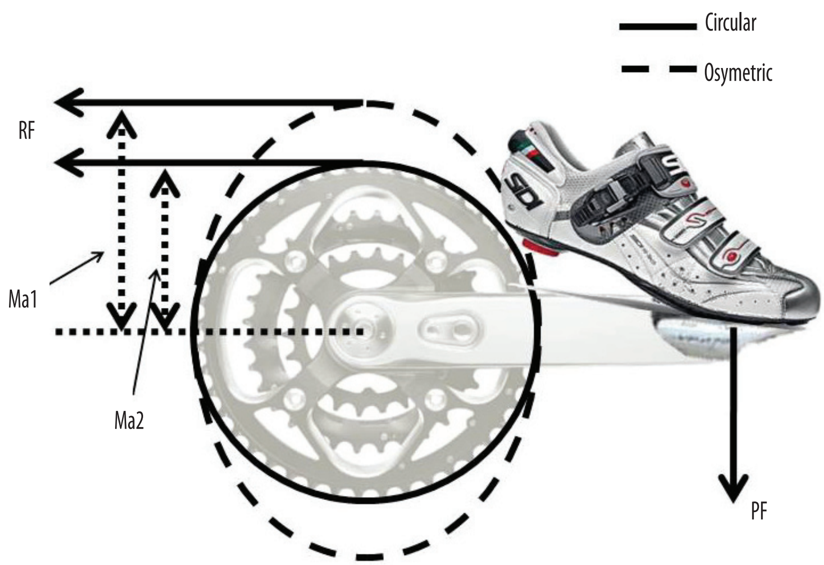

Figure 1. Illustration of the theoretical design of a noncircular chainring (Osymetric noncircular chainring) devised to increase the moment arm at the 12 o'clock position. Moment arm of the noncircular chainring (Ma1), moment arm of the circular chainring (Ma2), resistive force (RF) and pedal force (PF).

Different designs of noncircular chainrings and pedal to crank interfaces have been presented in the literature and have affected physiological and biomechanical variables related to performance in different ways. Better insight needs to be provided for cyclists and coaches when choosing a noncircular chainring system or a particular pedal to crank interface.

Therefore, the aim of the present article was to review the theoretical background of noncircular chainrings and novel pedal to crank interfaces and their effects on biomechanical, physiological and performance variables.

METHODS

Academic databases (MEDLINE, SCOPUS, ISI Web of Knowledge, EBSCO, and Google Scholar) were searched for peer-review journals, books, theses, and conference proceedings published since 1960 with the keywords: 'pedal to crank interface', 'chainring', and 'noncircular'. Within the initial 2,165 references, the keyword 'bicycle' was used to refine the search. Twenty-nine articles were then analyzed through their abstract. Those that focused on presenting theoretical design or experimentally assessed noncircular chairing systems or pedal to crank interfaces were retrieved for the analysis of the full article version. References used by thirteen articles selected after full version analysis were also analysed by article title, which was followed by abstract and full article analysis. A total of 39 references were selected for this review, including 37 journal articles, one book, and one web page. We opted to include a large range of study designs (i.e. cross-sectional to computer simulations) to expand the discussion from the theoretical to the practical benefits of using noncircular chanrings and/or different pedal to crank interfaces.

DISCUSSION

Reducing internal work, crank peak torque, and time spent at the top and bottom dead centres (12 o'clock and 6 o'clock positions, respectively) were among the various targets of noncircular chainring and novel pedal to crank interface design. Changes in joint kinematics without effects on muscle activation were observed when cyclists were assessed using noncircular chainrings and novel pedal to crank interfaces. Conflicting results in cycling economy/efficiency and performance were observed using most of the noncircular chainrings. Novel designs for pedal to crank interfaces have provided increments in cycling economy/efficiency.

Theoretical background for changing crank length or pedal to crank interface, or using noncircular chainring

Noncircular chainring systems and devices aiming to change pedal to crank interface introduced throughout the years are presented in Table 1. When introducing the different chainring and pedal to crank interface systems, the definition of the crank angle of the major axis (greater moment arm of the chain to the bottom bracket – i.e. resistive force) was based on the position of the crank at 3 o'clock, following the assumption that the peak crank torque is usually measured at this crank angle[19] (see Figure 1).

Table 1. Summary of the noncircular chainring systems and pedal-crank interfaces presented throughout the years, including inventor and year, ovality, crank angle of the major axis, aim of the design, and if the referred system has been experimentally tested. All results are based on a similar exercise condition using a circular and a noncircular chainring system.

Chainring	Inventor and year	Ovality[A] and crank angle of major axis	Aim	Experimentally tested	Effectiveness for cycling
Circular	Unknown[B]	1	Evenly transfer of the torque applied on the cranks to drive the back wheel throughout the pedal revolution.	Yes[C]	Yes[C]
Osymetric-Harmonic	J.L. Talo & M. Sassi (1993)	1.215 –12 o'clock	Relate the ovality of the chainring to the evenness of the crank torque.	Yes[22]	Lower peak torque (7%) for the osymetric chainring.
Hull oval	Prof M.L. Hull, Univ. California, Davis, USA (1991)	1.55 - 3 o'clock	Eliminate internal work during cycling.	Yes[21,40]	Lower cost functional (joint moments) for the oval chainring (1.4%)[21] and no changes in VO_2 during incremental workload cycling test[40].
Q-Ring (Rotor)	Pablo Carrasco, Rotorbike, Spain	1.10	Reduce time spent at the top and bottom dead centres.	Yes[18,24,27,33,,39]	Higher power output (7-11%) during Wingate tests for the Q-Ring. No changes in electromyography, VO_2, and 40-km time trial performance. One study[27] reporting higher range of motion for the hip (14%), knee (21%) and ankle (10%) for the Q-Ring. One study reporting 14% higher economy/efficiency using the Q-Ring.
Biopace oval	Shimano, Japan (Prof. Okajima)	1.04, ~3 o'clock	Enhance inertial load contribution to power output and minimize muscle activation.	Yes[12,38]	Lower lactate levels (28%) for the oval chainring.
Pro-Race	Unknown	Unknown	Increase the torque during downstroke and reduce the torque during upstroke.	Yes	Greater performance (7%) during a 1-km time trial[25], 9% greater power output, and 23% greater force during a force-velocity assessment [36] using the Pro-Race system. No differences in performance, lactate level or heart rate using the Pro-Race system during a 1-km time trial[34].
Bike power saver	Unknown inventor	Ovality not informed on the publications	Increase the torque during the propulsive phase (from 12 o'clock to 6 o'clock) and reduce the torque during the recovery phase (from 6 o'clock to 12 o'clock) for a set workload level.	Yes[11]	Greater ankle range of motion. Greater activation of tibialis anterior and quadriceps muscle group using Bike power saver compared to regular pedal to crank interface.
Vista Pedal	Vista® 2008[26]	Not applied[D]	Reduce the moment-arm during the recovery phase and at the top dead centre.	Yes[26]	Greater power output at 40 rpm (1.8%) and 120 rpm (6%) during maximal isokinetic cycling exercise. Enhancement in cycling economy/efficiency (8%)[26].
Unnamed pedal-crank interface	Zamparo et al.[10]	Not applied	Increase the torque during downstroke and reduce the torque during upstroke.	Yes[10]	Increase in economy/efficiency (2%) using the novel pedal-crank interface.

[A]Ratio between the major and the minor axis; [B]Unknown origin. Possible inclusion in the bicycle drive system in 1860[2].
[C]Used as a reference system for comparison with the noncircular chainrings.
[D]Increase in the distance between the pedal axis and the centre of pedal in 1.8 cm. Reduction in height from the pedal axis to the pedal surface in 2 cm.

We can observe that the various noncircular chainring designs and systems to change pedal to crank interface had different target variables for optimization (e.g. crank torque) based on changing the ratio between the major and the minor axis of the chainring or the distance between pedal and bottom bracket (e.g. pedal to crank interface systems). The crank angle of the major axis may also affect the torque produced by the resistive force, as shown in Figures 1 and 2. The resistive force is a sum of the drag, bearing, rolling and inertial forces applied to the bicycle and transferred to the crank set via the gears and chain.

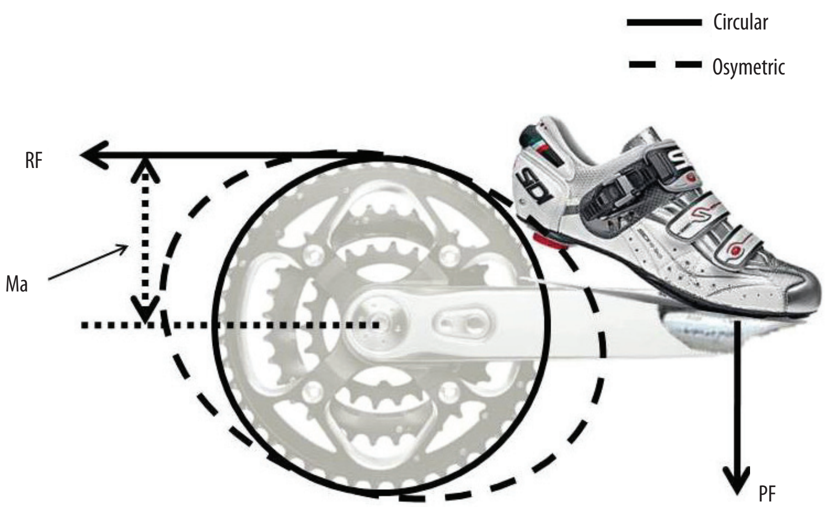

Figure 2. Illustration of the Biopace noncircular chainring devised to increase the moment arm close to the 3 o'clock position. Moment arm of the noncircular chainring (Ma), resistive force (RF) and pedal force (PF).

In Figure 2, we can observe that the major axes of the chainring are close to the 3 o'clock and 9 o'clock positions, different from the design presented in Figure 1, in which the major axes are close to the 12 o'clock and 6 o'clock positions for the same position of the crank. Following a pedal force profile as shown in Figure 3, when the maximal pushing force on the pedal is applied close to 90° of the crank angle (3 o'clock crank position), both noncircular chainrings shown in Figure 1 and 2 may present different results. The greater moment arm of the noncircular chainring of Figure 1 may require larger pedal force application to sustain a similar crank torque, compared to the noncircular chainring presented in Figure 2.

The effectiveness of each chainring system could be theoretically assessed by whether the major axes might properly increase the moment arm of the resistive force when the pedal is close to the crank angle of peak pedal force (3 o'clock). Therefore, increasing the moment arm of the resistive force may increase the torque produced by the resistive force and require greater peak pedal force application for a set workload level.

Using a circular chainring, the instantaneous velocity of the crank varies ±22% for an average pedalling cadence of 90 rpm[20], which has been related to higher internal work[21]. Therefore, increasing the axis of the chainring at the areas of the pedal revolution of lower velocity (e.g. 3 o'clock position) resulted in smoother instantaneous velocity of the crank and lower internal work[21]. Based on a similar perspective, some noncircular chainrings were devised to focus on increasing the evenness of crank torque, which resulted in lower peak torque[22] (similar to models as per shown in Figure 1). Other chainrings had focus on reducing the time spent at the top and bottom dead centres (12 o'clock and 6 o'clock positions, respectively) (e.g. Rotor system) because little force is applied on the pedal in these areas of pedal revolution[23]. The Rotor system is a circular chainring including a decoupled mechanism that detaches the cranks at the 12 o'clock and 6 o'clock positions by moving the driving crank forward in relation to the opposite crank. Therefore, some systems were developed to reduce the axes at the top and bottom dead centres[21] and others to mechanically decoupled the cranks in these areas of pedal revolution[24]. Another system was developed to increase the axis at the 3 o'clock position and reduce the axis at the 9 o'clock position (i.e. Pro-Race) [25]. This last system would reduce the retarding torque produced by the force applied on the pedal during the recovery phase (from 6 o'clock to 12 o'clock positions of the crank), but there is no supporting data for this hypothesis. Because the target optimization variable of these systems was different (e.g. internal work or lower crank torque), it is not clear how they can affect biomechanical, physiological and performance markers. It is unclear if the noncircular chainring should be designed to increase the moment arm of the resistive force at the 12 o'clock position of the crank to improve the torque of the resistive force (e.g. model of Figure 1) or if it should reduce the moment arm of the resistive force at the 3 o'clock position to reduce internal work and peak crank torque (e.g. model of Figure 2).

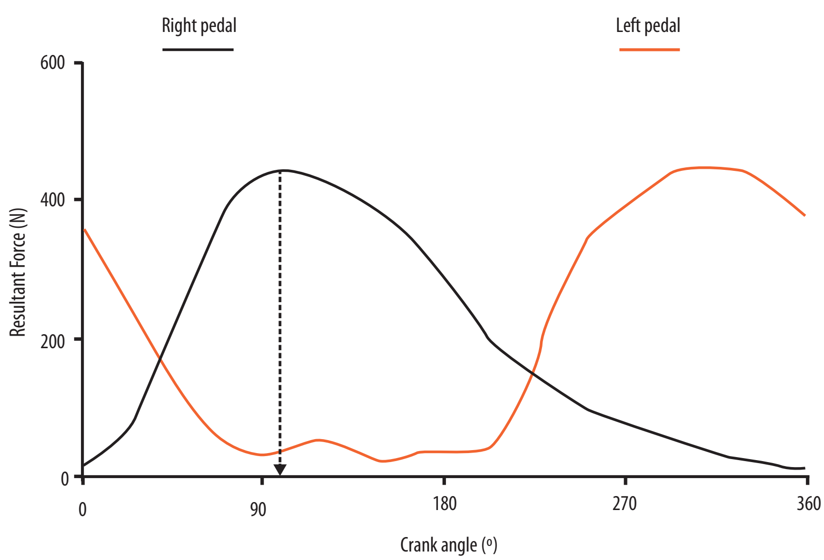

Figure 3. Resultant force applied on the right and left pedals as a function of the crank angle. Unpublished data of one competitive cyclist riding a 4-km time trial on a stationary cycle ergometer using circular chainrings.

In regards to crank length and pedal to crank interfaces, increasing crank length at the 3 o'clock position of the crank and reducing crank length at the 9 o'clock position of the crank may enhance power output. This was the aim of the novel pedal to crank interface devised by Zamparo et al.[10] and by Koninckx et al.[26] and of the system assessed by Shan[11], which are illustrated in Figure 4.

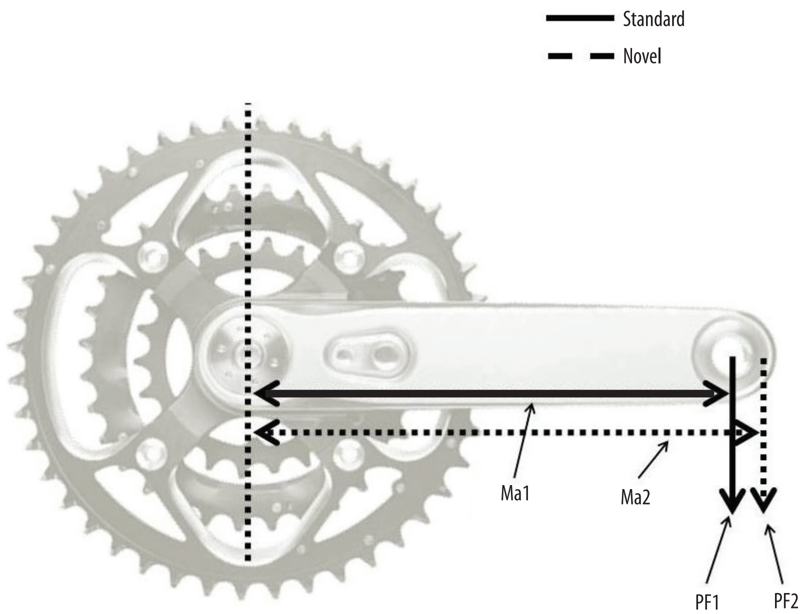

Figure 4. Illustration of a shorter (Ma1) and longer (Ma2) crank moment arm due to a different pedal to crank interface (PF2) compared to the standard pedal to crank interface (PF1).

Economy/efficiency (ratio between mechanical work and energy expenditure) improved using the systems developed by Zamparo et al.[10] (2%) and by Koninckx et al.[26] (8%), which suggests a positive effect of reducing crank length at the 9 o'clock position of the crank potentially due to reduced resistive torque on the crank.

Changes in chainring characteristics were varied in the developed models, with focus ranging from the change in crank length of the 3 o'clock and 9'clock positions[25] to changes in moment arms of the resistive force. It is likely that noncircular chainring models should reduce the moment arm of the resistive force at the 3 o'clock position to reduce internal work and peak crank torque (e.g. model of Figure 2).

Effects of changing pedal to crank interface or using noncircular chainring on biomechanical variables

From the theoretical design of the noncircular chainring illustrated in Figure 1, the greater axis at the 12 o'clock position of the crank may enhance the moment arm of the resistive force when the pedal is at the 3 o'clock position, which will require a greater pedal force application for a set workload level. The great moment arm may be also related to lower instantaneous velocity of the pedal at this position of the crank[20], which may affect joint kinetics, kinematics and muscle activation of the lower limb. Following another path, a larger crank length, as the prototype developed by Zamparo et al.[10], increases the moment arm of pedal force when the pedal is at the 3 o'clock position. On the other hand, Shan[11] observed that the "Bike saver" system resulted in a shorter crank length between the 12 o'clock and the 3 o'clock positions of the crank, in contrary to the purpose of the manufacturer. Therefore, the design of the system must account for reducing crank length at the 9 o'clock position of the crank and/or increase crank length at the 3 o'clock position of the crank. Another option would be to reduce the chainring axes at the 12 o'clock and 6 o'clock position when the crank is at the 3 o'clock position, as per shown in Figure 2. These changes may result in reduced resistive crank torque at the 9 o'clock position of the crank, smaller fluctuations in crank angular velocity, and reduced resistive force to the cyclists.

Some studies focused on the effects on joint kinematics using noncircular chainrings or different pedal to crank interfaces. When changing pedal to crank interface, Shan[11] observed greater range of motion for the ankle joint, compared to the use of normal pedal to crank interface. The shorter crank length between the 12 o'clock and the 3 o'clock positions of the crank may explain the greater range of motion observed at the ankle joint.

Greater range of motion for the ankle (10%), knee (21%) and hip (14%) was found for five cyclists riding at 300 W when using the Rotor system[27], which intended to reduce the time spent at the 12 o'clock position of the crank. Another study observed 30% greater range of motion for the ankle and 5% greater range of motion for the knee joint among 15 professional cyclists riding at a workload 10% lower than the anaerobic threshold using the Rotor system[28]. These results have been linked to the possible increase in effective crank arm length using the Rotor system[27], without further information on the mechanism related to this increase. Hip, knee and ankle angles did not differ when non-athletes cycled at steady state workload using a noncircular chainring that had the major chainring axis at the 12 o'clock position (similar to Figure 1) compared to a circular chainring[29].

Only Shan[11] assessed muscle activation during pedalling using a novel pedal to crank interface. Higher activation of quadriceps muscle group and tibialis anterior was observed. The explanation for this result may be related to the shorter crank length between the 12 o'clock and the 3 o'clock positions and the greater range of motion of the ankle joint when using this system compared to a standard pedal to crank interface. Only one study measured muscle activation of the lower limb of cyclists using a Rotor system noncircular chainring[30] without significant differences compared to the circular chainring system. No study was found with measurements of muscle activation of subjects using other designs of noncircular chainring or pedal to crank interfaces.

Generally, the studies describing noncircular chainrings aimed to determine an optimal major to minor axis with focus on reducing joint moments[14,21] or crank torque[31] for a set workload level or increasing maximal power output for a set distance or time of exercise[32]. One study reported no substantial difference between a circular and a noncircular chainring aiming to increase the axis at the 12 o'clock position on joint moments (similar to Figure 1)[14]. Another study presented ~12% lower peak crank torque for the noncircular chainring (epicyclical) aiming to enhance the axis between the 12 o'clock and the 3 o'clock positions of the crank compared to the circular chainring[31] (similar to Figure 1). On the other hand, the increase in the axis of the chainring at 3 o'clock position of the crank (similar to Figure 2) have lead to lower average joint moment (1.4%)[21]. Malfait et al.[32] compared various designs of noncircular chainrings through computer simulations of constant workload or constant joint power. The authors reported that only the Hull oval system, which aimed to increase the axis at the 3 o'clock position of the crank (similar to Figure 2), resulted in improvements in power output when the major axis was changed clockwise by 17.5° from its original design (4.5%). When changing the position of the crank of the major axis of the chainring, Malfait et al.[32] observed that most systems have improved power output (1-13%). Changes in joint power were varied, with some systems improving knee and hip joint extensor power while others affected only the flexor power of these joints. However, it is not clear how individual changes in joint power may lead to improvements in performance.

There is a gap of studies with focus on assessing biomechanical variables (e.g. pedal forces and joint kinetics) of noncircular chainrings and pedal to crank interfaces. The validity of the adapted design of the chainrings devised by Malfait et al.[32] could give substantial evidence for the benefits of using these systems in terms of cycling biomechanics. At the moment, noncircular chainrings that aim to increase the axis of the chainring at the 3 o'clock position of the crank (similar to Figure 2) may provide more benefits compared to the ones that increase the axis of the chainring at the 12 o'clock position (similar to Figure 1). Pedal to crank interface systems[10,26] have not been assessed in terms of biomechanical variables. Another pedal to crank interface system resulted in greater ankle range of motion and greater activation of tibialis anterior and quadriceps muscle group[11], which precludes its application for cycling training.

Effects of changing pedal to crank interface or using noncircular chainring on physiological variables

Based on the expected reduction in internal work using most noncircular chainrings systems, overall energy expenditure would be expected to decline for a set level of workload. In this regard, most studies looked at physiological markers related to endurance performance when assessing noncircular chainrings in cycling[12,18,33]. In a similar direction, the novel pedal to crank interfaces presented by Zamparo et al.[10] and Shan[11] were assessed by measuring oxygen uptake at constant workload tests to infer on cycling economy/efficiency, with 2% greater economy/efficiency for the pedal to crank interfaces presented by Zamparo et al.[10]. The Biopace chainring (greater axis of the chainring at the 3 o'clock position – Figure 2) was tested without substantial changes in oxygen uptake[12] compared to circular chainrings. The Pro-race system, which aimed to increase crank length at the 3 o'clock position and reduce it at the 9 o'clock position, did not improve maximal power output or VO_{2max} during incremental maximal tests[34]. The "Harmonic" system, which also aimed to increase the axis of the chainring close to the 3 o'clock position (78° of crank angle, similar to Figure 2), was analyzed in terms of economy/efficiency in thirteen competitive cyclists at different workload levels without significant differences compared to circular chainrings[16]. On the other hand, conflicting results were found for the Rotor system. Greater economy/efficiency (14%) was observed in eight non-cyclists riding at 60% and 90% of VO_{2max}[24], which differed from the trivial changes in VO_{2max} and economy/efficiency for ten cyclists during a constant workload test at 80% of the peak power output[18] and for another group of fifteen cyclists performing a similar cycling exercise[28].

Despite different designs, similarities in physiological markers between noncircular and circular chainrings have been related to the similar demand imposed by the noncircular chainrings to the musculoskeletal system. Only Zamparo et al.[10] and Koninckx et al.[26] showed increments in cycling economy/efficiency using a custom-made pedal to crank interface. Conflicting results were found for most of the noncircular chainrings. Kautz and Hull[35] suggested that muscle force-velocity relationship is not usually taken into account on the design of the noncircular chainrings, which may explain why physiological variables are not affected using noncircular chainrings.

Effects of changing pedal to crank interface or using noncircular chainring on cycling performance

Apart from their influence in economy/efficiency, the use of noncircular chainrings or different pedal to crank interface should lead to improvements in cycling performance. Endurance performance has been measured through elapsed time[25] or average power output during time trial tests[34]. Greater average power output in an isokinetic maximal cycling exercise was observed using the novel Vista® pedals for cyclists pedalling from 40 rpm (1.8%) to 120 rpm (6%)[26]. Greater performance during a 1-km time trial in the laboratory[25] and no improvements during a similar time trial on the track[34] were found using the Pro-race system (greater axis of the chainring at 3 o'clock position and smaller axis at the 9 o'clock position). Potential variability in the characteristics of the cyclists (e.g. maximal lower limb strength) during the 1-km time trial on the track was observed by the authors to affect the differences between chainring systems. This system was also effective during a force-velocity test in a cycle ergometer, with 9% greater power output and 23% greater force applied on the cranks by ten non-cyclists[36]. During a 40-km time trial, twelve competitive cyclists did not improve their performance using the Rotor system[15], as per findings of Dagnese et al.[30] for a time to exhaustion trial with seven competitive cyclists. Differently, greater average power output (8%) and peak power output (9%) were found during a Wingate test using the Rotor system[28]. During an incremental test to exhaustion, competitive cyclists did not improve peak power output using the Rotor system[18,33].

Future research

In theory, noncircular chainrings have the potential to enhance cycling performance due to smoother fluctuations in crank angular velocity and reductions in internal work[14,21]. However, future research may look at the design of the noncircular chainring with the purpose of optimizing the section of crank revolution of the major axis of the chainring. Simulation studies may indicate in what sectors of crank revolution greater/smaller chainring axis should be used. Characteristics of the musculoskeletal system (e.g. force-length and force-velocity relationships) should be taken into account, because they determine optimal joint angles for muscle power production. Experimental studies with cyclists may indicate whether or not the noncircular chainrings tested in simulation models are effective to improve performance. A comparison across different pedalling technique styles may add to the existing simulation models that are limited to a standard pedal force application profile[32]. At the moment, noncircular chainrings with focus on increasing the axis of the chainring at the 3 o'clock position and reducing the axis of the chainring at the 9 o'clock position (similar to Figure 2) may have provided better results[25,34,36].

CONCLUSIONS

The unclear effects of using most commercial noncircular chainrings in biomechanical and physiological variables preclude their effectiveness to enhance cycling performance. Different designs of noncircular chainrings limit the rationality of most of these systems for cycling performance, once they focus on optimizing different variables that may not lead to optimal performance. Custom-made systems focused on increasing crank moment arm or chainring axis at the 3 o'clock position and reducing the crank moment arm or axis at the 9 o'clock position have provided improvements in cycling economy/efficiency and performance.

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