PEDAL FORCES, LOWER LIMB JOINT KINEMATICS AND KINETICS IN CYCLING WITH CIRCULAR AND NON-CIRULAR CHAINRINGS

Gerda Strutzenberger, Tobias Wunsch, Josef Kröll, Hermann Schwameder

Department of Sport Science and Kinesiology, University of Salzburg, Austria

Non-circular chainrings theoretically enhance cycling performance by increasing effective chainring diameter and varying crank velocity. Yet, scientific proof has failed to consistently reproduce the theoretical benefits in cycling trials. Therefore, the aim of this study was to analyse kinematics and kinetics between circular and two different shapes of non-circular chainrings. 14 elite cyclists pedalled at two submaximal (90 rpm: 180 W, 300 W) two-minutes cycling trials using three chainrings ranging from circular to ovality of 1.10 and 1.215. A significant increase of tangential pedal forces, sagittal ankle and hip joint moments and a significant decrease of sagittal knee joint moments were observed. Non-circular chainrings do not evidently seem to enhance performance, but facilitated conditions for muscle activation as well as a reduction of knee joint moments can occur.

KEY WORDS: cycling performance, chainring design, pedal forces.

INTRODUCTION: In cycling the applied force on the pedal varies over a cycle revolution (Ericson & Nisell, 1988): The effective (tangential) force exertion is maximal when the position of the crank is approximately horizontal (crank angle at 90°) and minimal when the position of the crank is near vertical alignment. The vertical positions are commonly referred to upper and lower dead-points (crank angle at 0° and 180°).
Considerations for a possible optimization of pedalling efficiency by chainring design led to the introduction of non-circular chainrings. Non-circular chainrings change the chainring diameter with respect to the crank position leading to two alterations: 1) change of chain lever arm over the pedal revolution and 2) change of crank angular velocity over the cycling revolution. The first aspect means that when the pedal is in vertical position the current radius of the non-circular chainring is small. While progressing to the downward-phase the radius of the chainring increases, which coincides with the phase of highest tangential forces generation (e.g. Horvais, Samozino, Zameziati, Hautier & Hintzy, 2007; Rankin & Neptune, 2008; Carpes, Dagnese, Mota & Stefanyshyn, 2009; Bisi, Stagni, Gnudi & Cappello, 2010; Peiffer & Abbiss, 2010) (Figures 1 and 2). The second aspect outlines the fact that the non-circular design leads to a decrease of duration around the dead points and an increase of duration in the downward-phase (Horvais et al., 2007). Both alterations are theoretically assumed to increase cycling performance (Rankin & Neptune, 2008; Malfait, Storme & Derdeyn, 2010). However, research conducted on actual cycling trials could not consistently proof a transfer from the theoretical benefits of non-circular chainrings to cycling performance. Studies reporting differences in physiological items (Martinez, Vicente, Calvo & Zudaire, 2006, ↓heart rate, ↓lactate), kinematics (Carpes et al., 2009, ↑ sagittal ROM) and kinetics (Horvais et al., 2007, ↓ net crank torque) are opposed to research reporting no significant differences in physiological (Horvais et al., 2007; Bisi et al., 2010; Peiffer & Abbiss, 2010), kinematic (Bisi et al., 2010) and electromyographical (Horvais et al., 2007; Dagnese, Carpes, Martins & Stefanyshyn, 2011) variables.
Theoretically the change in chainring-diameter induces an alteration in crank velocity and concurrently an adaptation in pedal force in order to generate the same power output. If power output for cycling with different chainring shapes was on average held constant, biomechanical adaptations induced by the design need to occur within a cycle. Since effective propulsive pedal force can be mainly generated in the downward-phase (Figure 2), adaptations occurring in this phase most likely are significant for the overall power-output (Ericson & Nisell, 1988). Differences in pedal forces might also affect joint moments, which could imply effects on injury mechanisms. However, the amount of different chainrings studied in terms of shape, ovality and orientation of the crank-position (e.g. Rankin &

Neptune, 2008; Malfait et al., 2010; Peiffer & Abbiss, 2010) increase the difficulty to draw consistent conclusions, and it is yet not well understood how theoretical considerations are transferred to the actual cycling performance. Therefore, the aim of this study is to analyse pedal forces and lower extremity joint kinematics and kinetics for different chainring designs at two constant power outputs. It is hypothesized that for the same power output higher tangential force will be applied in the downward-phase, and higher sagittal joint moments occur respectively. Additionally, it is hypothesized that this effect increases with increased chainring ovality.

METHODS: 14 male elite cyclists (179 ±6.3 cm, 73 ±4.9 kg) with an annual cycling training of ≥5000 km participated in this study. All subjects had no previous experience with non-circular chainrings (except one) and were free of injury at time of testing. Written consent form was signed. Cycling was conducted on a road race-bicycle mounted on an indoor ergotrainer (TacX Flow) with individually adjusted bike-settings for each subject. A crank arm of 175 mm length and the subjects' individual click pedals were used. Subjects pedalled using three different 52 teeth chainrings: 1) circular chainring Dura Ace ("C", Shimano), 2) oval chainring Q-Rings ("R", Rotor, ovality: 1.10) and 3) oval chainring Osymetric ("O", Osymetric, ovality: 1.215) (Figure 1).
For each chainring condition the cyclists performed a 15 min habituation phase at individual speed followed by pedalling 2 min with a cadence of 90 rpm at 180 W and 300 W, respectively. Data was recorded for 30 pedal revolutions. Between each chainring condition a 15 min brake was provided to change the chainring and to avoid fatigue effects. Both the order of the chainrings and the order of the intensity conditions were randomized.

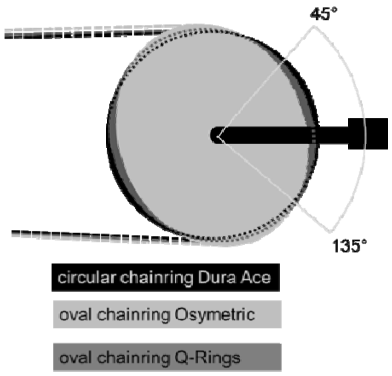

Figure 1: Ovality and crank position of the 3 used chainring designs.

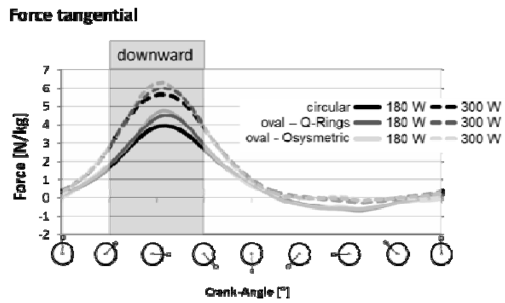

Figure 2: Tangential pedal force over a cycle for the 3 chainrings at 180W and 300 W (90 rpm).

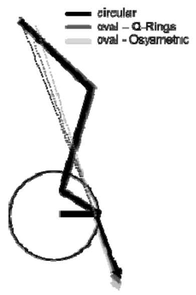

Figure 3: Pedal force vectors and orientation for 3 chainring conditions.

Kinematic and kinetic recordings were collected simultaneously by an eight camera three-dimensional motion analysis system (VICON, MX camera system, Oxford Metrics Ltd, UK; 250 Hz) and a two-dimensional pedal force system (Powertec, O-tec, Bensheim, Germany; 500 Hz), which was adapted at the left crank to receive tangential and radial pedal forces. Reflective markers were placed according to the Cleveland Clinic lower body marker set with additional markers on the crank and pedal for kinematic analysis. The pedal forces were transformed into the laboratory reference system for computation of the sagittal lower limb inverse dynamics (POSE estimation, Visual3D, c-Motion Inc., Germantown). All kinetic data was normalized to body weight and moments were expressed as internal moments. Variables were averaged over 30 pedal revolutions for each subject. Statistical analysis was performed for the mean values during the downward-phase (45°-135° crank position, Figure 1) by a one-way repeated measure ANOVA including a Bonferroni adjustment. The level of significance was set at $p \leq 0.05$. Effect sizes were calculated for the ANOVA via partial eta² (η^2_p) (Cohen, 1973) and post-hoc tests using Cohens'd (Cohen, 1992).

RESULTS: Mean (sd) values, respective p-values and effect sizes of test parameters revealing significant differences are presented in Table 1. Effects were mostly more pronounced for the Osymetric system compared to the less oval Q-Rings system and the percentual change was similar for both power outputs. Average joint angles did not differ between the systems. Mean tangential force significantly increased by ~3.5% using the less oval chainring ("R"), and by ~6% using the more pronounced oval system ("O") compared to the circular chainring (Figure 2). When using non-circular chainrings mean sagittal joint moments significantly increased at the ankle by ~13% ("R") and ~30% ("O") and at the hip by ~290% ("R") and ~630% ("O"). The knee flexion moment significantly decreased by ~5% for the Osymetric chainring ("O"). Maximum crank velocity significantly decreased during a pedal revolution by ~1% ("R") and ~ 4.5% ("O").

Table 1: Means (sd) and respective statistics for parameters of pedal force, joint moments and crank angular velocity for mean values of the downward-phase.

	180 W 90rpm							300 W 90rpm						
Variable	mean C (sd)	mean R (sd)	mean O (sd)	ANOVA sig (η^2p)	sig C-R (d)	sig C-O (d)	sig O-R (d)	mean C (sd)	mean R (sd)	mean O (sd)	ANOVA sig (η^2p)	sig C-R (d)	sig C-O (d)	sig O-R (d)
Force tangential [N/kg]	3.43 (0.31)	3.59 (0.29)	3.65 (0.31)	<0.001 (0.7)	0.002 (-0.51)	<0.001 (-0.69)	--- (-0.2)	4.81 (0.33)	4.97 (0.31)	5.10 (0.34)	0.001 (0.49)	--- (-0.52)	<0.001 (-0.89)	--- (-0.4)
Moment Ankle dors-flex [Nm/kg]	0.003 (0.00)	0.004 (0.00)	0.004 (0.00)	0.019 (0.29)	0.701 (-0.26)	0.019 (-0.57)	--- (-0.28)	0.004 (0.00)	0.005 (0.00)	0.006 (0.00)	<0.001 (0.58)	--- (-0.36)	<0.001 (-0.89)	0.007 (-0.52)
Moment Knee ext [Nm/kg]	-0.164 (0.02)	-0.161 (0.02)	-0.156 (0.02)	<0.001 (0.52)	--- (-0.21)	0.001 (-0.53)	0.010 (-0.32)	-0.160 (0.02)	-0.159 (0.02)	-0.151 (0.02)	0.003 (0.43)	--- (-0.07)	0.006 (-0.57)	0.018 (-0.43)
Moment Hip flex [Nm/kg]	-0.009 (0.04)	0.022 (0.03)	0.044 (0.03)	<0.001 (0.84)	<0.001 (-0.87)	<0.001 (-1.44)	0.001 (-0.69)	-0.007 (0.04)	0.023 (0.04)	0.053 (0.04)	<0.001 (0.83)	<0.001 (-0.75)	<0.001 (-1.43)	0.002 (-0.76)
Ang-Vel Crank [Nm/kg]	546.1 (13.21)	540.8 (13.92)	518.1 (13.5)	<0.001 (0.82)	0.215 (0.39)	<0.001 (2.09)	<0.001 (1.65)	549.5 (16.82)	546.1 (17.67)	514.6 (13.04)	<0.001 (0.84)	--- (0.2)	<0.001 (2.32)	<0.001 (2.03)

DISCUSSION: To our knowledge this study is the first combining pedal forces and kinematic data measured in actual cycling trials to analyse a range of different non-circular chainring designs. In order to produce the same power output the hypothesized decrease in angular crank velocity with an instantaneous increase of tangential pedal force occurred. It is mandatory that a higher force is generated due to the increase in chainring radius, as has already been shown for varying circular chainring radii (Cavanagh & Sanderson, 1986). The additional aspect of slower angular crank velocity occurring for oval chainrings might pronounce this effect. Since a higher force is needed in order to reach the same power output the non-circular chainring is not evidently beneficial. However, considering the dependency of muscle force production on the force-velocity relationship (Neptune & Herzog, 2000) the setting of a slower crank movement could imply a facilitated condition for muscle activation and higher force might be produced with the same activation. Probably this could explain why studies failed to report electromyographical changes so far (Horvais et al., 2007; Neptune & Herzog, 2000).

Since no significant differences in mean joint angles occurred, the altered force vector magnitudes and orientations occurring with non-circular chainring shape are responsible for alterations in sagittal joint moments (Fig 3.), which are significantly increased for hip and ankle flexion moments and significantly decreased for the knee extension moment. It has to be considered that maximum sagittal ankle and hip moments occur in the backward-phase (crank angle 135°-225°) and that in the downward-phase ankle and hip joint moments change from extension to flexion moments. This results in the circular chainring condition in the downward-phase in means close to zero. Hence, high percentual changes occur for the comparison to oval chainrings for the ankle and hip moment, which might be less relevant though. The situation is different for the knee extension moment, which reaches its maximum in the downward-phase. Knee flexion moment is significantly reduced by 5% for the most eccentric chainring ("O"). A similar reduction for lower power outputs was reported in a mathematical model by Bisi et al. (2010).

Considering that the lower limb has to generate the higher pedal force in combination with altered crank angular velocities and altered joint moments, non-circular chainring will most likely affect the distribution of joint power. The ankle joint, as the direct link joint for transferring lower limb force to the pedal, is likely most affected by the design of chainring shapes and further research is needed to better understand the mechanisms for the lower limb. The argument that the duration of the effective downward-phase is expanded with non-circular chainrings is not clearly evidential to enhance cycling performance, since simultaneously higher pedal forces are needed to produce the same power output. This might explain why little benefits for non-circular chainrings have been observed so far. Describing the joint movement and moments restricted to one phase does not fully represent the actual movement and should consequently be analysed more detailed in order to better understand the effect of different chainring designs.

CONCLUSION: This study showed that the postulated theoretical benefits for non-circular chainrings do not evidently lead to an increase in performance. To generate the same power output both non-circular chainrings induced a significantly higher tangential force, because of the decrease in crank angular velocity in the downward phase. However, the slowdown of the movement could facilitate muscle performance due to the force-velocity relationship. For both non-circular chainrings significantly higher ankle and hip joint moments occurred. Only the more pronounced oval non-circular chainrings revealed a significantly lower knee extension moment in the downward phase, which could be beneficial in terms of knee injury-prevention.

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