KNEE JOINT FORCES IN CYCLING AT TWO WORKLOADS WITH CIRCULAR AND NON-CIRCULAR CHAINRINGS

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The purpose of this study was to investigate the knee structure forces at two power outputs with circular and non-circular chainrings. 14 male cyclists pedalled using three different chainrings with a cadence of 90 rpm at 180 W and 300 W. Kinematics (Vicon) and kinetics (Powertec) were recorded. The knee structure forces were calculated using a 2D knee model. The tangential pedal forces were higher in the oval chainring conditions in both workloads. No differences were observed for the knee forces. The higher workload lead to significantly higher pedal and knee forces in all chainring conditions. Oval chainrings do not affect knee joint forces. Knee joint loading is highly affected by the work load, independently from the chainring systems used. The recommendation for using non-circular chainrings has not to be based on knee joint loading aspects.

KEY WORDS: chainring, pedal forces, knee joint forces.

INTRODUCTION: Several studies investigated the mechanical and physiological effect of non-circular chainrings on performance in cycling. The conditions varied and the findings were inconsistent (e.g. Ratel, Duche, Hautier, Williams & Bedu, 2004; Horvais, Samozino, Zameziati, Hautier & Hintzy, 2007; Peiffer & Abbiss, 2010). Theoretical considerations and force measurements show that the crank power (Rankin & Neptune, 2008) and the tangential pedal forces (Strutzenberger, Wunsch, Kröll & Schwameder, 2012) are increased in non-circular chainring cycling during the down stroke phase. Therefore, also higher knee joint forces might occur in this condition. Due to the altered kinematics, kinetics and muscle activation (Carpes, Dagnese, Mota & Stefanyshyn, 2009; Dagnese, Carpes, Martins & Stefanyshyn, 2011), however, the effect of the chainring conditions on knee joint loading during the down stroke phase is not clear (Bisi, Stagni, Gnudi & Cappello, 2010; Ranking & Neptune, 2008). Several attempts have been made to estimate knee joint structure forces during cycling (e.g. Ericson & Nisell, 1986; Ericson & Nisell, 1987; Ericson & Nisell, 1988). To the best of our knowledge, not experimental data have been presented in literature reporting the effect of chainring design (circular vs. non-circular) on knee joint structure forces. Thus, the purpose of this study was to investigate the knee structure forces at two power outputs with circular and non-circular chainrings using an experimental design. It is hypothesized (1) that knee joint structure forces increase with chainring ovality and (2) that knee joint structure forces increase with power output. This information is beneficial for athletes and coaches regarding the recommendation of non-circular chainrings in terms of performance enhancement in relation to optional knee joint loading aspects.

METHODS: 14 male elite cyclists (179 ±6.3 cm, 73 ±4.9 kg, annual cycling training of ≥5000 km) pedalled on an indoor ergotrainer (TacX Flow) using three different chainrings (Figure 1): (1) circular chainring "C", (2) Q-Rings Rotor "R", ovality: 1.10 and (3) Osymetric "O", ovality: 1.215. Bike-settings were individually adjusted for each subject. A crank arm of 175 mm length and the subjects' individual click pedals were used. For each chainring condition the cyclists performed a 2 min measuring phase with a cadence of 90 rpm at 180 W and 300 W, respectively. Data was recorded for 30 pedal cycles. 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.
Kinematics and kinetics were collected simultaneously with a 3D VICON system (8 MX 1.3 cameras, 250 Hz) and a 2D pedal force measuring system (Powertec, 500 Hz) yielding 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 local knee coordinate system

(Figure 2). Knee joint structure forces were calculated during the down stroke phase (45°-135° crank position, Figure 1) using the quasi-static knee model "Plakmos" (Schwameder, Roithner, Müller, Niessen & Raschner, 1999; Figure 2). The relative error of the knee structure force calculation was found to be similar to net knee joint moment calculations using inverse dynamics (Schwameder, 2004). The standard error calculations of the knee joint forces yielded relative values of less than 1%. All knee joint forces were normalized to body weight (BW). Statistical analysis was performed for the down stroke peak values (max) by a one-way repeated measure ANOVA including Bonferroni adjustment and effect size calculation (Cohen's d).

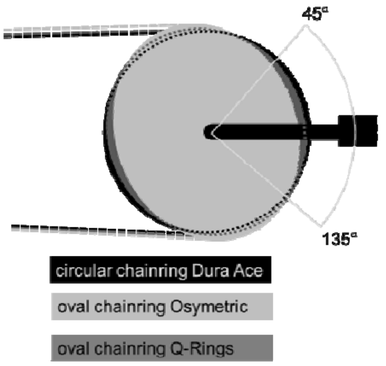

Figure 1: Ovality and crank position of the 3 used chainring designs

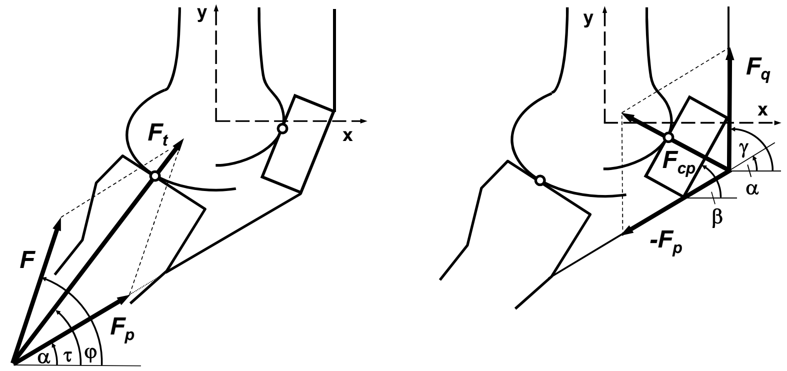

Figure 2: Schematic representation of the 'Plakmos' knee model. 'F' presents the resultant pedal forces relative to knee kinematics, 'Fcp': patella-femoral compression force, 'Ft': tibio-femoral contact force, 'Fct': tibio-femoral compression force, component of 'Fct' perpendicular to the tibia plateau

RESULTS: Table 1 shows the peak tangential pedal forces (Ftang-max), the peak patello-femoral compression forces (Fcp-max) and the peak tibio-femoral compression forces (Fct-max) for the diverse conditions. While the tangential pedal forces were significantly higher in the oval chainring conditions in both workloads (between 5.0% and 10.7%, Table 2), no significant differences were observed for the knee structure forces (between -1.9% and 7.5%, Table 2). The higher workload lead to significantly higher pedal (27%-38%) and knee structure forces (11%-27%) in all chainring conditions (Table 3).

Table 1: Means (sd) for peak tangential pedal force (Ftang-max), peak patello-femoral compression force (Fcp-max) and peak tibio-femoral compression force (Fct-max), '*' indicates significant differences to the other chainring conditions and d the corresponding effect sizes.

	180 W 90 rpm					
	C	R	O	d(CR)	d(CO)	d(RO)
Ftang-max [N/BW]	0.48 (0.06)^{*R,O}	0.52 (0.05)^{*C}	0.53 (0.06)^{*C}	0.70	0.87	0.25
Fcp-max [N/BW]	2.85 (0.56)	2.87 (0.69)	2.80 (0.71)	0.04	0.08	0.10
Fct-max [N/BW]	1.68 (0.38)	1.71 (0.48)	1.73 (0.40)	0.07	0.12	0.04
	300 W 90 rpm					
	C	R	O	d(CR)	d(CO)	d(RO)
Ftang-max [N/BW]	0.63 (0.04)^{*R,O}	0.66 (0.04)^{*C,O}	0.68 (0.04)^{*C,R}	0.73	1.19	.55
Fcp-max [N/BW]	3.32 (0.55)	3.25 (0.67)	3.33 (0.66)	0.12	0.02	0.13
Fct-max [N/BW]	2.03 (0.46)	2.00 (0.42)	2.19 (0.46)	0.05	0.35	0.41

Table 2: Peak tangential pedal force (Ftang-max), peak patello-femoral compression force (Fcp-max) and peak tibio-femoral compression force (Fct-max) relative to the condition 'C', '*' indicates significant differences to the other chainring conditions.

	180 W 90 rpm			300 W 90 rpm		
	C	R	O	C	R	O
Ftang-max [%C]	100 (0.0)	+8.2 (2.7)*C	+10.7 (3.0)*C	100 (0.0)	+5.0 (1.3)*C,O	+8.4 (2.3)*C,R
Fcp-max [%C]	100 (0.0)	+0.7 (0.2)	-1.6 (0.3)	100 (0.0)	-1.9 (0.7)	+0.3 (0.1)
Fct-max [%C]	100 (0.0)	+1.71 (0.4)	+2.8 (0.7)	100 (0.0)	-1.4 (0.6)	+7.5 (2.0)

Table 3: Peak tangential pedal force (Ftang-max), peak patello-femoral compression force (Fcp-max) and peak tibio-femoral compression force (Fct-max) relative to the condition '180W, 90rpm', '*' indicates significant differences and '[d]' the effect sizes.

	180 W 90 rpm			300 W 90 rpm		
	C	R	O	C	R	O
Ftang-max [%180]	100 (0)	100 (0)	100 (0)	+30.8 (8.9)* [3.2]	+28.5 (8.2)* [3.4]	+27.3 (7.9)* [3.1]
Fcp-max [%180]	100 (0)	100 (0)	100 (0)	+16.7 (5.3)* [1.0]	+19.3 (6.7)* [0.7]	+11.4 (4.1)* [0.9]
Fct-max [%180]	100 (0)	100 (0)	100 (0)	+20.8 (7.5)* [0.9]	+26.7 (8.5)* [0.7]	+17.5 (6.1)* [1.1]

DISCUSSION: The results for pedal and knee joint structure forces are in line with previously presented data (Ericson & Nisell, 1986; Ericson & Nisell, 1987). As expected the peak tangential pedal forces are higher in the oval chainring conditions during the down stroke phase. This is also true for the mean values during this phase, which are not presented here. The knee joint structure forces, however, are not systematically and significantly affected by the chainrings. As the kinematics in the closed kinematic chain (leg, foot and bike) is hardly affected by the chainrings, the enlarged tangential forces in the non-circular chainring conditions lead to smaller knee joint moment lever arms. The combination of higher pedal forces and smaller knee joint moment lever arms in the non-circular chainring conditions result in similar amount of knee moments in all chainring conditions. This explains that the knee joint structure forces are hardly affected by the chainrings used.
The increase of knee joint structure forces with higher power output is also in line with previously presented data (Ericson & Nisell, 1986; Ericson & Nisell, 1987), both in terms of absolute values and relative changes. In the higher power output conditions the dynamics are enhanced, while the kinematics remains nearly unchanged. This consequently leads to higher knee joint structure forces in all of the investigated chainring conditions.

CONCLUSION: Oval chainrings do not affect knee joint structure forces, although changes regarding the magnitude and the direction of pedal forces have been observed. These findings can be applied to the group analysis only. It has still to be shown, if the effect of non-circular chainrings on knee joint structure forces is subject specific or not.
Knee joint loading is highly affected by the work load, independently from the chainring systems used. The recommendation for using non-circular chainrings has to be based on performance enhancement and comfort issues. Knee joint loading aspects seem to play if at all a minor role in this context.

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