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Felipe P. Carpes a, Frederico Dagnese b, Carlos B. Mota b, Darren J. Stefanyshyn c
a School of Physical Education, Applied Neuromechanics Group, Federal University of Pampa, Uruguaiana, Brazil
b School of Physical Education and Sports, Biomechanics Laboratory, Federal University of Santa Maria, Santa Maria, Brazil
c Faculty of Kinesiology, Human Performance Laboratory, University of Calgary, Calgary, Canada

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Cycling with noncircular chainring system changes the three-dimensional kinematics of the lower limbs

FELIPE P. CARPES¹, FREDERICO DAGNESE², CARLOS B. MOTA², & DARREN J. STEFANYSHYN³

¹School of Physical Education, Applied Neuromechanics Group, Federal University of Pampa, Uruguaiana, Brazil, ²School of Physical Education and Sports, Biomechanics Laboratory, Federal University of Santa Maria, Santa Maria, Brazil, and ³Faculty of Kinesiology, Human Performance Laboratory, University of Calgary, Calgary, Canada

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Abstract

This study investigated the three-dimensional (3-D) pedaling kinematics using a noncircular chainring system and a conventional system. Five cyclists pedaled at their preferred cadence at a workload of 300 W using two crank systems. Flexion/extension of the hip, knee and ankle as well as shank rotation, foot adduction/abduction, and pedal angle were measured. Joint range of motion (ROM) and angular displacements were compared between the systems. Sagittal plane ROM was significantly greater ($P < 0.05$) at the hip (noncircular system = $39 \pm 3\degree$; conventional system = $34 \pm 4\degree$) the knee (noncircular system = $69 \pm 4\degree$; conventional system = $57 \pm 10\degree$), and ankle (noncircular system = $21 \pm 2\degree$; conventional system = $19 \pm 4\degree$) resulting in greater pedal ROM (noncircular system = $43 \pm 3\degree$; conventional system = $37 \pm 5\degree$) while using the noncircular system. Shank rotation ROM was significantly lower ($P < 0.05$) while using the noncircular chainring (noncircular system = $10 \pm 1\degree$; conventional system = $14 \pm 1\degree$). These results support a significant effect of the noncircular chainring system on pedaling kinematics during submaximal exercise.

Keywords: Noncircular chainring, submaximal pedaling, lower limb kinematics, cycling, motion analysis, equipment design

Introduction

Elite competitions are the best places to find athletes interested in new technologies applied to cycling equipment design, such as new pedals and chainring designs (Zamparo et al., 2002) as well as modified geometric features (Kautz and Hull, 1995) and dimensions (Martin et al., 2002). According to the rules of Union Cycliste Internationale (UCI), new equipment must be evaluated as prototypes to be approved or not for official use in competitions. As a result, most equipment modifications remain only as prototypes or are available for purchase without UCI permission for official use. Among the equipment approved by the UCI are noncircular chainrings.
The main purpose of noncircular chainring systems is to minimize the effects of pedaling dead spots (Santalla et al., 2002; Lucia et al., 2004). This is achieved by means of alteration in effective crank arm length during the crank revolution (Hue et al., 2001; Zamparo et al., 2002; Rodriguez-Marroyo et al., 2009), thereby slowing the downstroke and accelerating the upstroke pedaling phases (Rodriguez-Marroyo et al., 2009). Previous studies on modeling performance suggested that during submaximal cycling the chainring’s shape influences joint torques (Kautz and Hull, 1995). Optimization studies considering maximal power output suggested effects of chainring shape on muscle activation-deactivation dynamics and average crank power output during the downstroke pedaling phase (Rankin and Neptune, 2008). However, any physiological advantage of noncircular over round chainrings have been found for athletes during submaximal intensity cycling (Hull et al., 1992; Santalla et al., 2002; Lucia et al., 2004; Rodriguez-Marroyo et al., 2009). Rotor Cranks® is a commercial noncircular system which has previously been investigated by exercise scientists (Santalla et al., 2002; Lucia et al., 2004; Rodriguez-Marroyo et al., 2009). The effects of similar models of modified crank systems on joint range of motion (ROM) have been observed (Shan, 2008), but no previous study addressed 3-D lower limb movements when pedaling with the commercial system aforementioned. Shan (2008) reported changes in ankle kinematics such as range of motion (ROM) while pedaling with a noncircular crank system. ROM could modify the muscle length of the lower leg muscles (Sanderson and Amoroso, 2009), which could change the muscle activation patterns (Dingwell et al., 2008; Shan, 2008), the knee extension force (Li and Caldwell, 1998), and finally, influence the muscle force production by altering muscle mechanics characteristics (Herzog et al., 1990; Herzog et al., 1991). These effects could influence pedaling performance, but in this regard few quantitative data are available.

Quantitative data are necessary to verify the effectiveness of the new equipments, since most of the new equipment in cycling is based only on empirical data without confirmation of its positive effects on factors affecting performance (Rankin and Neptune, 2008). Consequently, the purpose of this study was to quantify the effects of a commercial noncircular chainring system on lower limb kinematics during submaximal pedaling in trained mountain bike cyclists.

Methods

Subjects

Five trained amateur mountain-bike cyclists volunteered for this study (23 ± 4 yrs, body mass 79 ± 7 kg and height 1.83 ± 0.06 m). All subjects had at least five years of experience with competitive mountain-bike events, and they were training at the time of the study. Their weekly training cycling was approximately 300 km. The evaluated cyclists had never previously used the noncircular chainring system. All cyclists signed an informed consent form in agreement with the local Committee of Ethics in Research with Humans.

Experimental design

The cyclists performed two tests on two consecutive days using an 18-speed bicycle (Scott Blackstone, Scott, United States) mounted on a wind-load cycling simulator (Cateye CS 1000, Cateye Co., Japan). The rolling resistance when pedaling using this type of wind-load simulator has been documented to be similar to that occurring during actual cycling conditions (McCole et al., 1990; Hue et al., 2001). Saddle and handlebar positions were
individually adjusted by the athletes to optimize comfort according to their own bicycle adjustments, and then recorded after the first evaluation to keep constant for the second evaluation. The crank arm length used was the same for all the subjects (170 mm), and all the subjects used clip pedals (SPD 505L, Shimano Corp., Japan). The first evaluation was always conducted with the conventional crank system for all the cyclists and the same bicycle’s rear wheel, which was always inflated to the same pressure (120 psi). Pedaling cadence (rpm) and heart rate (bpm) were continuously monitored using cadence and heart rate sensors (S725, Polar Electro, Oy, Finland). On the first day, the athletes cycled using a conventional crank system and on the second day the subjects performed the trial cycling with the noncircular chainring system. Cyclists performed a warm-up protocol of stationary cycling that included a period of five minutes at 100 W followed by five minutes at 200 W. After the warm-up, the cyclists were asked to pedal at 200 W for two minutes and then increase to 300 W and sustain this work load for a period of approximately five minutes. Images for kinematics’ evaluation were acquired after the third minute of pedaling at 300 W. The cyclists were asked to pedal at their preferred cadence during all the trials.

**Noncircular chainring system and conventional cranks system**

Cyclists were evaluated while pedaling with a conventional crank system and a model of noncircular chainring system. For the conventional crank system evaluation, the bicycle was equipped with a standard bottom bracket system (XT, Shimano Corp., Japan). In the other test the bicycle was equipped with a noncircular chainring system (Rotor Technologies, Spain). This system provides a relative angular movement between right and left cranks regulated by means of eccentric bearings working to shift forwards the right and left cranks throughout the crank revolution. The crank arms are not aligned throughout the whole crank revolution (Figure 1). These eccentric bearings work to avoid abrupt movements between the cranks permitting a smooth and progressive movement throughout the pedal revolution. The mechanical characteristics of this system were extensively described in previous reports and thus are not fully presented here (Santalla et al., 2002; Lucia et al., 2004; Garcia-López et al., 2005; Rodriguez-Marroyo et al., 2009). The noncircular system was placed in position 1, as previously assessed for road cyclists (Rodriguez-Marroyo et al., 2009).

**3-D kinematics**

Three-dimensional kinematics data were acquired using a Peak Motus System (Peak Performance Technologies Inc., Englewood, CO, USA) with two synchronized high-speed cameras (Peak HSC) perpendicularly positioned and sampling at 180 Hz. The individual trials were recorded on standard SVHS tape using a video cassette recorder (Panasonic AG–5700, Panasonic Matsushita Electric Corporation of America, Secaucus, NJ, USA).

![Figure 1. The kinematics of the noncircular system. The vertical crank orientation shows the angular difference between the cranks, which is designed to eliminate the dead spot and provide a lever for torque generation by the leg starting the crank cycle.](image-url)
Reflective markers were positioned over the following specific anatomical landmarks of the right pelvis and lower limb: anterior-superior iliac spine, greater trochanter, lateral femoral epicondyle, anterior face of the patella, tibial tuberosity, calcaneous, lateral tibia epicondyle, II metatarsal, V metatarsal, centre of rotation of the pedal spindle, and center of rotation of the bottom bracket system (Figure 2). Angular displacement reliability of 0.99 and measurement error of 0.5% were assumed (Scholz and Millford, 1993).

Rigid aluminum wands (length of 25 cm) were used to measure the shank rotation angle (Levinger et al., 2005). The first wand (Figure 2, arrow “a”) was positioned at 40% of the shank length distal to the knee joint and aligned parallel to the hallux. This wand was fixed to an armlet that had a soft spongy surface and attached to the leg using double sided adhesive tape and a elastic belt, which conforms to the anatomy of the shank and reduces the effect of soft tissue movement (Cappozzo et al., 1996; Manal et al., 2000). The second wand (Figure 2, arrow “b”) was attached to the pedal body and was used to calculate the pedal angle relative to the global x-axis (defined in Figure 2). Spherical markers (proximal and distal) were mounted to each wand to permit computation of shank rotation and pedal movements.

The direct linear transformation (DLT) method was employed to obtain 3-D coordinates from the 2-D data of the synchronized cameras (Abdel-Aziz and Karara, 1971) in attempt to describe segmental projected angles. The defined global laboratory orthogonal coordinate system followed the right hand rule with the positive x-direction oriented in the cyclist’s forward facing direction, the positive y-direction oriented to the left and the positive z-direction oriented vertically upwards (Abdel-Aziz and Karara, 1971) and local segment coordinate system were used for the computation of segment projected angles. The raw 3-D

Figure 2. Landmarks for kinematics assessment positioned on specific sites of the right lower limb of one subject. Details of the metallic structures placed on the tibial tuberosity (arrow ‘A’), and pedal (arrow ‘B’).
coordinates were smoothed using a quintic spline function with a smoothing factor of 0.003 (Winter, 1990). The path data of the markers were filtered using a fourth-order low-pass Butterworth filter with a cutoff frequency of 6 Hz (Winter, 1990). The flexion/extension angles of the hip (relative to global x-axis), knee (relative to femoral x-axis) and ankle (relative to tibial x-axis) were computed. Also measured were angles of foot adduction/abduction (relative to longitudinal tibial x-axis) and shank rotation (relative to longitudinal tibial x-axis), pedal angle (relative to global x-axis), and crank angle (relative to global x-axis). Data were calculated for every crank revolution and then averaged considering ten complete crank revolutions. The crank angle was set as 0° at the top-dead-center and positive in the clockwise direction.

**Statistical procedures**

Results were reported for mean and standard-error of an ensembled curve obtained from average 10 consecutive crank revolution cycles of each subject. Data normality was verified using a Shapiro-Wilk’s test. Students’ t-tests were used to compare the range of motion between crank systems for each joint movement as well as to compare heart rate, speed and cadence between the systems. An analysis of variance (ANOVA) for repeated measurements with Bonferroni corrections was applied to compare the angular displacement between the crank systems. Where significant interactions were found, comparisons between systems considering each pedaling quadrant (1st quadrant, from 0° to 90° of crank revolution; 2nd quadrant, from 90° to 180°; 3rd quadrant, from 180° to 270°, and 4th quadrant, from 270° to 360°) were performed using Student’s t-test. Wilcoxon’s matched pair test was used to compare data from pedaling cadence, pedaling speed and heart rate. The statistical package Statistica 5.1 (StatSoft Inc., Tulsa, OK, United States) was used for all procedures considering a statistical significance level set at 0.05.

**Results**

The average pedaling cadence did not differ between the systems (mean ± s of 95 ± 3 rpm and 96 ± 3 rpm for the noncircular and conventional systems, respectively). The pedaling speed did not differ between cycling with noncircular chainring and conventional system (37.5 ± 1 km/h and 36.4 ± 2 km/h for the noncircular and conventional systems, respectively). The average heart rate did not differ between the crank systems (174 ± 3 bpm and 166 ± 5 bpm for the noncircular and conventional systems, respectively). The differences in the total ROM between the two systems were statistically significant for hip, knee and ankle (P = 0.039) as presented in Table I. Figure 3 depicts the kinematic

<table>
<thead>
<tr>
<th>Joint</th>
<th>Noncircular chainring</th>
<th>Conventional system</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Max-Flex</td>
<td>Max-Ext</td>
</tr>
<tr>
<td>Hip</td>
<td>19 ± 5</td>
<td>55 ± 7</td>
</tr>
<tr>
<td>Knee</td>
<td>72 ± 13</td>
<td>140 ± 5</td>
</tr>
<tr>
<td>Ankle</td>
<td>14 ± 9</td>
<td>-5 ± 7</td>
</tr>
</tbody>
</table>

* Statistically significant difference between the crank systems (P < 0.05). Max-Flex, maximal flexion; Max-Ext, maximal extension; ROM, range of motion.
pattern (angular positions) of the hip, knee, ankle, foot, shank rotation and the pedal angle throughout the crank revolution.

There were statistically significant differences for knee angular positions during the second and fourth quadrants of the pedaling crank cycle ($P = 0.040$). The angular positions of the ankle joint elicited statistically significant differences between the crank systems for all quadrants ($P = 0.023$). The foot adduction movements presented statistically significant differences between the crank systems for the second quadrant ($P = 0.043$) (Table II). However, the total foot range of motion did not differ between the crank systems. Shank rotation ROM ($10 \pm 1^\circ$ and $14 \pm 1^\circ$ for noncircular and conventional systems, respectively) and angular positions throughout the crank cycle were statistically different between the

Figure 3. Lower limb and pedal angular positions throughout the crank cycle. For all angles, the top-dead center point is at $0^\circ$ and positive in the clockwise direction (NC: noncircular system; CS: conventional crank system). * indicates statistically significant differences between the crank systems for the indicated quadrant ($P < 0.05$). Data expressed as mean and standard-deviation.
crank systems \((P = 0.019)\), except for angular positions at the second quadrant. Using the noncircular chainring system, the shank maintained a position near to neutral (no prominent internal or external rotation) for the first quadrant. When the conventional crank system was analyzed, the pedaling cycle started with internal shank rotation (eliciting a hip adduction). The pedal angle did statistically differ \((P = 0.038)\) between the systems only at the second quadrant.

**Discussion and implications**

The purpose of this study was to investigate the effects of a noncircular chainring system design for cycling on the 3-D pedaling kinematics of cyclists new to the system. Statistical significant differences in pedaling kinematics were found between the noncircular chainring system evaluated and a conventional crank system. The main findings were related to an association between noncircular chainring and higher ROM for hip, knee and ankle accompanied by changes in angular positions for joint and pedal angles.

The variation of effective crank arm length during the pedal revolution may be the most likely factor to influence the increased ROM while pedaling with a noncircular chainring system (Rodriguez-Marroyo et al., 2009). Our results from pedaling kinematics agree with a previous investigation of noncircular chainring (Shan, 2008). Shan (2008) demonstrates that a noncircular chainring system was related to increased ankle ROM, increased ankle instability and influenced the variability of kinematic data. Those effects were related to additional muscular work as depicted by increased EMG frequencies in *tibialis anterior*. As the author stated (Shan, 2008), the noncircular system led to higher energy consumption resulting in acceleration of fatigue process.

In a study addressing the learning of proper force direction during pedaling, the largest kinematic changes to the altered task mechanics were observed at the ankle joint, which depicts its capacity of adaptation (Hasson et al., 2008). Since pedal angle was statistically different between the crank systems only in the second quadrant, the ankle kinematics appear to reflect changes of knee and hip angles in an attempt to keep the expected general lower limb pattern of motion during pedaling. Increase of ankle ROM could result from a strategy to overcome alterations in contractile properties of muscles crossing the ankle (Sanderson et al., 2006). Indeed, the alteration of knee and ankle kinematics may influence changes in the recruitment of medial *gastrocnemius* and *soleus* (Sanderson and Amoroso, 2009). Additionally, changes in knee extension, i.e. ROM, affects the production of active force for *gastrocnemius* — medial and lateral heads (Herzog et al., 1990).

The increased knee extension in the second quadrant using the noncircular chainring system may be related to additional exigency of hip and knee extensors throughout the

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**Table II. Mean and standard-deviation angle values in degrees (°) for movements of shank, foot and pedal for noncircular chainring and conventional crank systems.**

<table>
<thead>
<tr>
<th>Crank system</th>
<th>Foot</th>
<th>Shank rotation</th>
<th>Pedal movement</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Add</td>
<td>Abd</td>
<td>ROM</td>
</tr>
<tr>
<td>Noncircular chainring</td>
<td>6 ± 1</td>
<td>0 ± 1</td>
<td>6 ± 1</td>
</tr>
<tr>
<td>Conventional system</td>
<td>7 ± 1</td>
<td>2 ± 3</td>
<td>6 ± 1</td>
</tr>
</tbody>
</table>

Add, adduction; Abd, abduction; ROM, range of motion; Int, internal shank rotation; Ext, external shank rotation; Plant, pedal movement related to ankle joint at plantar flexion; Dors, pedal movement related to ankle joint at dorsal flexion.
downstroke phase (Li and Caldwell, 1998), which do not reflect advantages of this noncircular chainring over the conventional system. At the beginning of the pedaling cycle, the similar knee angles between the noncircular chainring system and the conventional system suggest similar participation of the vasti group.

Considering the rectus femoris muscle, cyclists produce less active force as rectus femoris is lengthened (Herzog et al., 1991). The changes in hip ROM probably did not influence rectus femoris force generation because hip extension occurs near 180° of the crank cycle, which is coincident with inability of the rectus femoris for active force production (Herzog et al., 1990). This action could support similar participation of rectus femoris regardless of the crank system used. The shank rotation pattern during cycling was similar to that reported during normal walking (Levinger et al., 2005), whereas cyclists pedaling with the noncircular system showed a pattern of shank rotation with ROM less than found for walking (Levinger et al., 2005). The high variability among subjects reported in the literature was also observed in the present study (Gregersen and Hull, 2003; Levinger et al., 2005). Indeed, shank rotation elicits increased recruitment of the vastus lateralis to guide the knee movement along the crank cycle (MacIntosh et al., 2000). This could also be related to less stress on the knees, which is frequently related to injuries due to low-level repetitive loading during cycling (Holmes et al., 1991). The actual effect of the noncircular system on tibia stress should consider mechanical models for determination of joint moments. The practical implication of our results concerns the changes in kinematics of pedaling for the subject first time use of the noncircular system.

Conclusion

The results of this investigation indicate that the noncircular chainring system evaluated affects the 3-D lower limb kinematics in cyclists who had no previous experience with this crank system. The increase of ankle ROM may explain the changes in ROM of hip and knee during pedaling with the noncircular chainring system. The decreased frontal plane ROM using the noncircular chainring system may minimize the muscular work to resist the internal and external axial moments on the knee. These results support a significant effect of the noncircular chainring system on pedaling kinematics during submaximal exercise.

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