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Research article

Effects of a Non-Circular Chainring on Sprint Performance during a Cycle Ergometer Test

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Abstract
Non-circular chainrings have been reported to alter the crank angular velocity profile over a pedal revolution so that more time is spent in the effective power phase. The purpose of this study was to determine whether sprint cycling performance could be improved using a non-circular chainring (Osymetric: ellipticity 1.25 and crank lever mounted nearly perpendicular to the major axis), in comparison with a circular chainring. Twenty sprint cyclists performed an 8 s sprint on a cycle ergometer against a 0.5 $N\cdot kg^{-1}$ friction force in four crossing conditions (non-circular or circular chainring with or without clipless pedal). Instantaneous force, velocity and power were continuously measured during each sprint. Three main characteristic pedal downstrokes were selected: maximal force (in the beginning of the sprint), maximal power (towards the middle), and maximal velocity (at the end of the sprint). Both average and instantaneous force, velocity and power were calculated during the three selected pedal downstrokes. The important finding of this study was that the maximal power output was significantly higher (+ 4.3%, $p < 0.05$) when using the non-circular chainring independent from the shoe-pedal linkage condition. This improvement is mainly explained by a significantly higher instantaneous external force that occurs during the downstroke. Non-circular chainring can have potential benefits on sprint cycling performance.

Key words: Elliptical chainring, clipless pedal, maximal power output, equipment design, force-velocity test.

Introduction

In conventional cycling seat position with a circular chainring and a traditional crank-pedal mechanism, the effective force is minimal when the crank is vertical at the top (near 0°) and at the bottom dead centres (near 180°) and maximal when the crank is near the horizontal forward position (90°) (Ericson and Nisell, 1988). The crank angular velocity remains nearly constant during one pedal crank revolution at a regular pedalling rate (Broker, 2003; Horvais et al., 2007). Different crank–pedal systems and chainring shapes have been proposed in an attempt to alter the pedalling motion by varying the crank arm length, the position of the chainring rotation axis, or the radius of the chainring during a pedal revolution (for a review, see Bini and Dagnese, 2012; Faria et al., 2005). Among these, non-circular chainrings were developed with the radius varying proportionally to the effective force applied to the crank as a function of the crank angle. Various chainring shapes and crank orientations relative to the minor and major axes of the chainring have been used to alter the phase of the crank angular velocity variation and the amount of variation, respectively (Hull et al., 1992). Non-circular chainrings (Osymetric, Stronglight, Monaco) have been introduced in which the shape is a skewed ellipse, the major and the minor axes are not perpendicular and the crank lever is mounted nearly perpendicular to the major axis. The lever arm of the force applied on the chain gets short when the crank is near the dead centres (vertical) but long when the crank is in the effective power phase (near horizontal). As a consequence, higher and lower instantaneous pedalling rates are achieved when the crank levers are near vertical and horizontal, respectively, when compared to a circular chainring (Hintzy et al., 2015; Horvais et al., 2007; Strutzenberger et al., 2014). Therefore, the time spent in the effective power phase increases, and inversely decreases around the top and bottom dead centres (Hintzy et al., 2015; Horvais et al., 2007; Neptune and Herzog, 2000). These kinematic alterations of the crank arm affected significantly the pedalling kinematic of the lower limbs: a reduction in sagittal knee joint power and an increase in sagittal hip joint power (Strutzenberger et al., 2014). Authors concluded that this joint-specific power generation might be beneficial for short distance races, especially as the effect sizes increased with higher cadences. Interestingly, both shape and orientation of this non-circular Osymetric chainring were similar to the theoretical optimal chainring shape maximizing the crank power proposed by Rankin and Neptune (2008). Authors showed that this theoretical optimal non-circular chainring could significantly increase the crank power (2.9%). The decrease of the crank velocity during the effective downstroke phase allowed the muscles to generate power longer and produce more external work.

When considering the above, the benefits of crank-pedal designs and non-circular chainring systems should be apparent in short and maximal cycling trials. The non-circular chainring significantly improved performance during an all-out 1 km test (Pro-race: Hue et al., 2001; Rotor Q-Ring: O'Hara et al., 2012) and during a sprint BMX (Rotor Q-Ring: Mateo-March et al., 2010, 2014). The power output attained during intermittent 20 s maximal sprints was 2.4 to 6.7% greater with non-circular chainring (Rotor Q-Ring) than with circular, although this difference was not statistically significant (Cordova et al., 2014). In addition, the maximal power output calculated

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from the theoretical force–velocity relationship was significantly increased with a non-circular chainring (Osymetric: Hintzy et al., 1999a; Pro-race: Hue et al., 2008) over circular chainrings. Unfortunately, the mechanical explanations were not presented since intra-cycle pedalling kinetic was not measured.

Explaining the improvement of sprint performance with a non-circular chainring to understand the mechanisms involved requires instantaneous measures during the entire sprint. In addition, the upstroke and the downstroke phases of the pedal revolution should be analysed separately. Indeed, the radius variation of the present non-circular chainring slowed down the crank angular velocity when the cranks were near horizontal during the effective part of the downstroke phase for one crank as well as during the ineffective part of the upstroke phase for the opposite crank (Hintzy et al., 2015; Horvais et al., 2007; Neptune and Herzog, 2000). An experimental condition without clipless pedals will allow testing the effects of the non-circular chainring only during the downstroke phase with a pushing action. In contrast, the clipless condition will allow testing the effects of the non-circular chainring during the entire pedal revolution because clipless pedals can modify the force pattern during both upstroke and downstroke phases, by respectively pulling and pushing actions (Tate and Shierman, 1977).

Therefore, the purpose of this study was to assess the effects of a non-circular chainring on the maximal force, power and velocity attained during a sprint, as well as on the intra-cycle kinetic evolution. It was hypothesized that (a) the present non-circular chainring would improve the maximal power output during a sprint and that (b) the improvement would be due to a higher instantaneous force developed during the effective phase of the pedal revolution.

Methods

Participants

Twenty male cyclists (age: 24 ± 6 years, height: 1.78 ± 0.05 m, body mass: 68.0 ± 7.3 kg) participated in this study. Instructions were previously given to subjects: not to ingest caffeine the morning; not to perform an exhausting exercise during the previous 24 hours; to bed early and have a normal meal the night before the test. Regional road riders were selected, excluding track cycling specialists. All of the participants had regularly participated in regional level competitions for 5 years prior to the participation in this study and were in the competitive period of the year (from March to April) at the time of the study. Their weekly training volume covers approximately 350 ± 50 km. None of the participants had previous experience in using non-circular chainring. Since it has been reported that adaptation of muscle coordination on a non-circular chainring occurs over a short period of time (within the first 10-20 cycles for Neptune and Herzog, 2000), all participants were familiarized with the use of the non-circular chainring during two 10 min sessions. The Institutional Ethics Review Board of the University of Savoy approved the study and the participants gave written informed consent for participation.

Chainring and shoe–pedal interface

Two 44-tooth chainrings were investigated: a standard circular chainring (XTR Shimano American; Irvine, CA, USA) and a commercially available non-circular chainring (Osymetric, Monaco). Comparing chainrings with the same number of teeth (i.e. the same circumference) provided conditions in which the same mechanical work was performed per pedal revolution even if the shapes differed. The non-circular chainring shape was described as a skewed ellipse or a twincam, where the major and the minor axes are not perpendicular (Figure 1). The eccentricity (the ratio of the major and minor axes) was 1.23. The major and minor axis angles (the smallest angle between the arm cranking and the major or minor axis, respectively) were 96.5° and −3.5°, and the angle between the major and minor axes was fixed at 80° (for technical information, see Horvais et al., 2007 or Ratel et al., 2004).

Personal cycling shoes with cleats fixed to clipless pedals (RXS, Times, Nevers, France or Kéo, Look, Nevers, France) were used in the clipless condition and personal standard jogging shoes were put to a standard pedal with no attachment in the simple pedal condition.

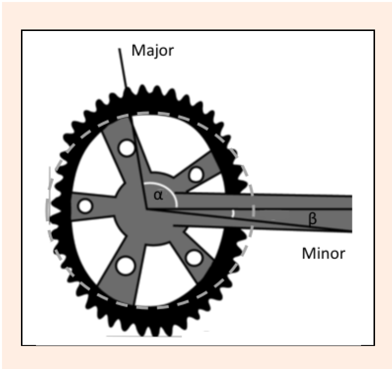

Figure 1. Non-circular chainring and specific parameters. The angles between major axis and crank arm (96.5°) and between minor axis and crank arm (−3.5°) are described by α and β, respectively. The angle between major and minor axes was fixed at 80°. The grey dotted line corresponds to a circular 44-tooth chainring.

Testing protocol

The participants carried out a standardized warm-up with both chainrings and standard pedals, followed by four maximal 8 s sprints against a friction force of 0.5 N$\cdot$kg^{-1} body mass on a cycle ergometer. The four sprints (circular chainring, clipless pedals; circular chainring, simple pedals; non-circular chainring, clipless pedals; non-circular chainring, simple pedals) were performed in randomized and counterbalanced order. A 5 minutes rest period was imposed between the warm-up and the first sprint and between the sprints. For each test, the starting position was standardized with the preferred foot placed at 45° from vertical. At the signal given by the experimenter, the participants were vigorously encouraged to reach the maximal pedalling rate as quickly as possible until the end of the sprint. Participants were instructed to stay seated on the saddle during the whole test.

Data collection

A standard friction-loaded cycle ergometer (Monark 818E, Stockholm, Sweden) was used for this study. It was equipped with two 172.5 mm crank arms and the gear ratio was 5.07 m (flywheel revolutions per pedal crank revolution). The height of the saddle was adjusted to each participant's lower limbs (1.05 × trochanter height; Hamley and Thomas, 1967). The cycle ergometer was specifically equipped with a strain gauge (Interface MFG type, Scottsdale, AZ, USA) and an optical encoder (Hengstler type RIS IP50, Aldingen, Germany). The strain gauge was mounted on the friction belt that surrounded the flywheel for measurement of the instantaneous friction force applied to the belt. It was calibrated with an unloaded condition and a 1.9 kg mass. The optical encoder was fixed on a wheel in contact with the flywheel to measure the flywheel displacement with an accuracy of 1980 digits per metre of linear displacement. Brake belt force and flywheel angular displacement were sampled at 100 Hz and stored on a PC computer via a specially designed 12-bit interface card (Analog device, AD1B31AN, Norwood, MA, USA).

Data analysis

The instantaneous flywheel velocity ($m{\cdot}s^{-1}$) and acceleration ($m{\cdot}s^{-2}$) were calculated by a first- and second-order derivative of the flywheel displacement signal, respectively. Instantaneous external force (N) applied to the flywheel was determined as the sum of the frictional force and the inertial force (dependent on the acceleration of the flywheel: Force = 5.34 • acceleration −0.59), as explained in Arsac et al. (1996). Power (W) was calculated as the product of external force by the flywheel velocity.

Instantaneous force, velocity and power were then recorded during each sprint and were averaged for each pedal downstroke, i.e. between the two minimal consecutive values of instantaneous power corresponding to the top and bottom dead centres of a crank revolution (Arsac et al., 1996). Eight seconds sprints provided a minimum of 12 pedal downstrokes and the first pedal downstroke of each sprint was not taken into account for the analysis since it was not complete (Hautier et al., 1996). Figure 2 illustrates a typical example of the time course of instantaneous force, velocity and power. Three characteristic pedal downstrokes were selected to describe each sprint condition: the pedal downstroke at maximal average force (the first entire pedal downstroke in the beginning of the sprint), the pedal downstroke at maximal average power (towards the middle of the sprint) and the pedal downstroke at maximal average velocity (at the end of the sprint). Both average force and velocity occurring during the pedal downstroke at maximal power were calculated, called optimal force (Fopt) and optimal velocity (Vopt), respectively. Within-cycle parameters were also measured during the three selected pedal downstrokes with maximal instantaneous values of force ($Finst_{max}$). Figure 2 illustrates how each mechanical parameter was calculated.

Statistical analysis

Means and standard deviations were calculated for each variable. The normal distribution of the data was checked by the Shapiro-Wilk's test. Statistical analysis for each mechanical parameter measured during the pedal downstrokes at Fmax, Pmax, Vmax was carried out by a two-way repeated-measure ANOVA (2 chainrings × 2 shoe–pedal interfaces). Post-hoc comparisons using the Scheffé procedure followed the analysis of variance. Chainring was chosen as the primary factor of interest as well as the interaction of chairing to shoe-pedal interface. Consequently, only the chainring effects were presented. The magnitude of the observed differences across 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 level of significance was set at $p < 0.05$.

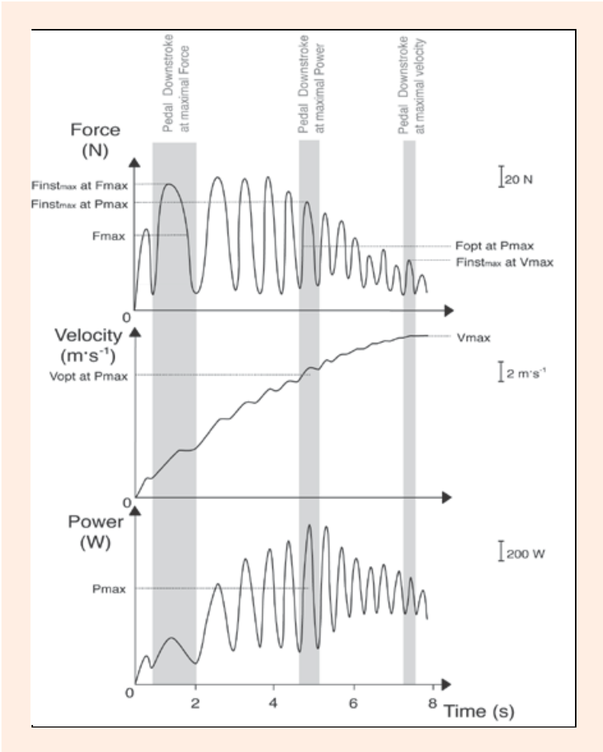

Figure 2. Typical example of the time course of instantaneous force, linear velocity of the flywheel and power output during an 8 s sprint. Pedal downstrokes at maximal force, maximal power and maximal velocity were described by the averaged and instantaneous mechanical parameters defined above.

Results

The mechanical and temporal parameters obtained during the three characteristic pedal downstrokes of the sprint are reported in Table 1.

Results from a two-way repeated-measure ANOVA revealed no significant interactions between the chainring type factor and the shoe–pedal interface factor for any of the mechanical parameters studied.

However, chainring effects were observed for some parameters independently of the shoe–pedal interface factor. The use of the non-circular chainring *vs.* circular induced a significantly ($p < 0.05$) higher maximal average power (ES = 0.37, small effect) and corresponding optimal force (ES = 0.2, small effect) during sprinting, as well as significantly ($p < 0.05$) higher $Finst_{max}$ during the pedal downstrokes showing maximal velocity (ES = 0.32, small effect) and maximal power (ES = 0.33, small effect).

Table 1. Values of parameters measured during the sprints. Data are means (±SD).

	NON-CIRCULAR		CIRCULAR	
	Clipless	**Simple**	**Clipless**	**Simple**
Pedal downstroke at maximal force				
Fmax (N)	83.2 (10.0)	67.1 (9.2)	80.2 (11.6)	66.9 (8.6)
$Finst_{max}$ (N)	118.4 (12.6)	90.6 (11.2)	121.3 (17.3)	94.4 (10.1)
Pedal downstroke at maximal velocity				
Vmax ($m·s^{-1}$)	15.5 (.3)	14.3 (1.2)	15.5 (.9)	14.2 (1.0)
$Finst_{max}$ (N)	63.3 (11.7)	54.3 (9.6)	55.6 (6.9)	55.3 (13.8)
Pedal downstroke at maximal power				
Pmax ($W·kg^{-1}$)	10.7 (1.9)	9.6 (1.2)	10.1 (1.1)	9.4 (1.0)
Fopt (N)	53.4 (9.2)	49.1 (5.8)	51.2 (6.6)	48.6 (6.9)
Vopt ($m·s^{-1}$)	13.7 (1.3)	13.3 (1.6)	13.4 (1.2)	13.3 (1.5)
$Finst_{max}$ (N)	80.5 (10.0)	71.1 (11.4)	74.2 (11.1)	68.9 (14.8)

Fmax: average maximal force, Vmax: average maximal velocity, Pmax: average maximal power, $Finst_{max}$: instantaneous maximal force, Fopt: average optimal force at Pmax, Vopt: average optimal velocity at Pmax.

Figure 3 shows typical examples of instantaneous external force applied to the flywheel measured over the pedal downstroke at Pmax with both chainrings in the clipless condition.

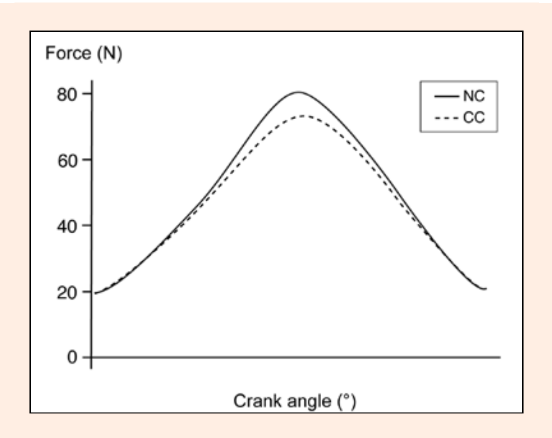

Figure 3. Typical examples of instantaneous external force induced by non-circular (NC) and circular (CC) chainrings plotted as a function of crank angle during the pedal downstroke at maximal power.

Discussion

The main finding of this study was that the present non-circular chainring significantly increases the maximal crank power output by 4.3% during sprinting. Even if the magnitude of differences was small (ES = 0.37), this improvement of maximal power output could be a significant help during short strategic phases of final sprints, distancing other competitors and acceleration phases. This higher maximal power output was due to a significant improvement of the corresponding optimal force (+ 2.6%) without improvement of optimal velocity. The use of the non-circular chainring made it possible to modify the pedalling kinetics and thus improve the external force produced during the pedal downstroke at maximal power. The intra-cycle force analysis showed that the instantaneous maximal force ($Finst_{max}$) developed when the crank was in the effective power phase, significantly increased when using the non-circular chainring (+6%). The higher non-circular chainring radius used when the crank was in the effective power phase slowed the crank angular velocity during this phase (Hintzy et al. 2015; Horvais et al., 2007; Neptune and Herzog, 2000; Ranking and Neptune, 2008, Strutzenberger et al., 2014), which allowed (a) the hips to produce larger sagittal joint power (Strutzenberger et al., 2014) and (b) the muscles to generate power longer and produce more external work (Ranking and Neptune, 2008). A theoretical analysis proposed by Ranking and Neptune (2008) showed that hip and knee extensor muscles produced increased muscle work during the effective power phase, between 45° and 135° with a non-circular chainring, which was very similar to the non-circular chainring tested herein. These authors also refer to the Askew and Marsh (1997) study, which provided a number of examples showing that animals dramatically increase muscle power output during cyclical movements by prolonging the positive work phase. An interesting study reported by Martin et al. (2002) confirmed our explanations. They manipulated the proportion of the pedal cycle occupied by the leg-extension phase during maximal single-leg cycling power. They showed that both instantaneous power and average power over a complete revolution were 12% and 8% respectively greater when the leg-extension phase occupied 58% of the cycle time *vs.* the traditional 50%. The increase in instantaneous power resulted from increased muscle excitation allowed by the increased time and reduced crank velocity for the leg-extension phase. An interesting finding of the present study was that the optimal velocity at maximal power output was not influenced by the non-circular chainring. Two explanations can be proposed. Firstly the optimal velocity, i.e. the mean crank angular velocity of the entire pedal revolution at maximal power, was not modified with the non-circular chainring since the crank moves more slowly during the effective power phase and faster during the ineffective phases. Secondly, the optimal velocity is the direct expression of the relative contribution of slow and fast twitch fibres to maximal power (Hautier et al., 1996; Hintzy et al., 1999b) and therefore is especially influenced by the participants' intrinsic characteristics.

The present benefit provided by the non-circular chainring on pedalling kinetics differed depending on the sprint phase. The pedal downstroke at maximal force occurring at the beginning of the sprint was not influenced by the chainring conditions. The specificity of this pedal downstroke was that the crank angular velocity was very low, and therefore no significant modification of the crank angular velocity could be obtained during this pedal revolution. This assumption is based on the results of Strutzenberger et al. (2014) showing that the knee and hip joint power alterations due to the non-circular chainring increased with the cadence. Another explanation for the inability of the non-circular chainring to modify the kinetics of pedal downstroke at maximal force is that the load is too high, thus preventing the muscles from generating more external work.

In contrast, the non-circular chainring significantly changed pedalling kinetics during the pedal downstroke at maximal velocity, with significantly higher $Finst_{max}$ (+7%). This is also explained by the slowing down of the crank during the effective power phase to allow the muscles to generate power for a longer duration (Hintzy et al. 2015; Horvais et al., 2007). Nevertheless, the maximal velocity attained at the end of the sprint was not improved with the use of the non-circular chainring. This finding corroborates the main explanation proposed for the present optimal velocity parameter: the mean angular velocity of an entire pedal revolution was not modified with the non-circular chainring since the crank moved more slowly during the effective power phase and faster during the ineffective phases (Hintzy et al. 2015; Horvais et al., 2007). With regard to the present results, the crank angular velocity is then an important factor that influences the effects of the non-circular chainring on pedalling kinetics. A high pedalling rate seems to be necessary to provoke this effect since the maximal instantaneous force was significantly increased only at high (pedal downstroke at Pmax) and maximal (pedal downstroke at Vmax) pedalling rates, but not at the low (pedal downstroke at Fmax). This result was consistent with Malfait et al.'s unpublished study (2012), which showed that the kinetic benefit of the non-circular chainring increases exponentially as the pedalling rate increases. This may also explain why there was no consistent improvement on the physiology and performance variables observed in previous studies testing the effects of crank–pedal systems and chainring shapes since the pedalling rates tested were relatively low (Buscemi et al., 2012; Cullen et al., 1992; Henderson et al., 1977; Zamparo et al., 2002).

The used of the two type of shoe–pedal interfaces allows to complete our results by separating the effect of non-circular chainring on the pedalling kinetics only during the downstroke phase (simple pedal without linkage) and during both downstroke and upstroke phases (clipless). Indeed, the flexor muscles could generate power longer in the upstroke phase (backwards near 270°) when using clipless pedals (assuming participants were able to pull the crank) since the crank stays longer. In contrast, the experimental condition with simple pedal without shoe linkage will allow testing only the downstroke phase since it does not allow the cyclist to pull the crank during the upstroke phase. It is therefore expected that the non-circular chainring has substantial favourable kinetic effects on the external work when it is used with clipless pedals. Yet, the present study demonstrated that the mechanical benefits of the non-circular chainring on the maximal power output during sprinting are obtained for both types of shoe–pedal interface, without interaction between chainring shapes and shoe–pedal interface conditions. The non-circular chainring could therefore alter pedalling kinetics during the downstroke (with simple pedals or clipless pedals) and/or the upstroke (only with clipless pedals). However, the present measurements did not distinguish these two phases in the clipless condition since force and velocity were measured on the flywheel and not separately on each crank. We can only speculate that it is mainly the downstroke phase, which is modified by the use of the non-circular chainring, as it is the common phase of both pedal conditions. Further studies directly measuring the force on the pedals, will answer our questions.

Conclusion

The maximal power output was significantly improved during a sprint by means of a non-circular chainring in trained cyclists, when compared with a circular chainring having the same number of teeth. Although the gain is small (+ 4.3%, ES = 0.37), it should not be overlooked during cycling events for which victory depends on small differences of time or location of the rider relative to other at key moments. The non-circular chainring could thus have potential benefits on cycling performance during short and explosive situations. Road cyclists could improve their acceleration during sprints; Mountain bike cyclists could develop higher power during brief high-rises.

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Key points

- The Osymetric non-circular chainring significantly maximized crank power by 4.3% during sprint cycling, in comparison with a circular chainring.
- This maximal power output improvement was due to significant higher force developed when the crank was in the effective power phase.
- This maximal power output improvement was independent from the shoe-pedal linkage condition.
- Present benefits provided by the non-circular chainring on pedalling kinetics occurred only at high cadences.

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