Effects of ring size on transmission efficiency in cycling: is bigger always better?

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Abstract

Ring size was proved to impact bicycle drivetrain efficiency as larger rings are used to improve this efficiency. However, results from studies focused on sprockets create a gain expectation that is not met when considering ring size at a fixed gear ratio. This study was designed to understand this discrepancy better. Three chainring sizes (58, 60, 62 teeth) and three sprocket sizes (13, 16, 24 teeth) were tested on a dedicated testing rig in conditions that were representative for professional time-trial racing (450 W, 100 rpm). Four derailleur pulley combinations (11 teeth for the upper pulley and 11 for the lower, 14-14, 14-18 and 14-19 teeth) were tested as well. Bigger sprockets allow an increased efficiency, as expected based on the literature. However, a slight trend towards a decrease in efficiency was observed when increasing chainring size. If it was to be confirmed, this trend could be explained by the fact that, at a fixed torque, chainring size governs chain tension, on which efficiency depends. Indeed, a bigger chainring lowers chain tension and therefore could decrease efficiency. This finding could explain the moderate gains in efficiency measured for a fixed gear ratio when compared to studies focused on sprocket size. This study did not find any effect from derailleur pulley size. Overall, bigger rings offer better efficiency, as efficiency is mainly governed by the sprocket effect, but this effect could well be reduced by an opposed chainring effect at a fixed gear ratio and torque.

Keywords: transmission, efficiency, ring size, chainring, sprocket, cycling.

Introduction

High-level road cycling performance is governed by various resistive forces that are opposed to the cyclist's motion. The cyclist's mechanical power output is used to equal these forces at a constant speed. On flat surfaces, the major resistance comes from aerodynamic drag (up to 90% or more at 50 km/h [1]). Weight is the other main force, either resistive, neutral or driving depending on the slope of the road. Complementary, rolling resistance and friction from the bearings and transmission are minor resistances but they must be taken into account when it comes to optimising the athlete-machine system's efficiency. Friction forces from the transmission are usually estimated to represent 2 to 4% of the athlete's power output for a trained athlete (> 150 W) [2]. For lower power outputs, these losses can reach up to 10 % [3]. They rely on multiple parameters, which are:

- Chain tension
- Chain speed
- Lubrication
- Materials
- Surface aspects
- Chain geometry

For a fixed crank geometry, chain tension and speed can be influenced by several factors such as power output, cadence and ring size. Indeed, ring size has been demonstrated to have an influence on chain drive efficiency. Numerous studies demonstrated that a bigger sprocket improves the transmission's efficiency [3-8]. Significant gains in efficiency can be expected as more than 4% were gained at low power and cadence (100W and 60 rpm) between a 11-teeth and a 21-teeth sprocket [3]. Based on these studies, a trend towards the use of bigger sprockets and therefore bigger chainrings has been observed in professional road cycling, especially for time-trials.

Indeed, a bigger sprocket implies using a bigger chainring for a fixed gear ratio. Based on the literature, this would result in a theoretical win-win situation. A preliminary study conducted in our laboratory was designed to measure the effects of ring size on efficiency for a fixed gear ratio (4:1), in representative conditions for high level time-trials. The dedicated testing rig that was used is presented in the materials and methods section. Three gear combinations were tested: 56-14, 60-15 and 64-16. The cadence was fixed at 100 rpm and two different power outputs were tested: 450 W and 200 W. As expected, for a fixed power output, based on the literature, the smallest ring combination (56-14) provides a lower efficiency than the bigger ones. However, the difference in efficiency is rather small: less than 0.5% for both power outputs. Moreover, the 60-15 combination has the same efficiency as 64-16. The results of this study are further detailed in Annex 1. This preliminary result is in line with existing studies, demonstrating that for a sprocket size above 15, efficiency gains are limited when considering a fixed gear ratio [9, 10, 11, 12]. Yet, this finding is opposed to the higher-efficiency gain expectations based on sprockets only and no explanation was proposed to this day. This study was designed to deconvolute the effects on chain drive efficiency of chainring size on one hand and sprocket size on the other hand. The aim is to have a better understanding of the effects of ring size on efficiency. A complementary study concerning derailleur pulleys is also detailed in Annex 2. Even though the effects of wear are known to have an impact on chain drive efficiency, they are not investigated here as it is hypothesized that gear components are replaced soon enough in elite cycling to avoid any effects on efficiency. Moreover, previous work showed that a few hours testing on the testing rig did not show any significant wear [13].

Materials and methods

To evaluate the effects of three chainring sizes on efficiency (58, 60 and 62 teeth), six distinct chainrings were tested. Their specifications are summed up in Table 1. These chainrings were commercially available and had different properties. They could either have a regular teeth design (each tooth is similar) or have a narrow-wide design (large and thin teeth alternate). This latter design was developed to prevent the chain from falling in case of a single chainring use. Moreover, some chainrings had asymmetrical tooth design ("italic", leaning towards the position of the roller from the chain link) and others were symmetrical ("straight"). Finally, while all were made of aluminum, some were hollow for weight purposes whereas others were solid for aerodynamics. The hypothesis was made that the effect of these different properties would be small enough compared to the size effect to be neglected.

Table 1: Specifications of the tested chainrings.

Teeth count	58	60			62	
Weight (g)	229.1	233.0	391.1	261.0	421.9	272.7
Teeth profile	Regular	Regular	Narrow-wide	Narrow-wide	Narrow-wide	Narrow-wide
Teeth height (mm)	5.00	5.00	7.25	7.30	7.25	7.20
Thin teeth width (mm)	2.00	2.00	3.50	3.00	3.50	3.35
Large teeth width (mm)	2.00	2.00	1.70	2.00	1.70	1.80
Teeth design	Italic	Italic	Straight	Straight	Straight	Italic
Chainring design	Hollowed	Hollowed	Plain	Plain	Plain	Plain

The same cassette was used for the whole session (Dura-Ace 12sp 11-30, Shimano, Japan). It contained the following sprockets: 11-12-13-14-15-16-17-19-21-24-27-30. Each chainring was tested on three different sprockets, allowing to test different gear ratios: 13, 16 and 24 teeth sprockets. As the chainring was aligned with the 14 teeth sprocket, chain alignment was variable as schematised on Figure 1. The choice was made to keep a realistic chain angle due to the use of different sprockets to represent the riding conditions as lifelike as possible. The effects of this offset must be kept in mind when analysing the sprocket effect on efficiency.

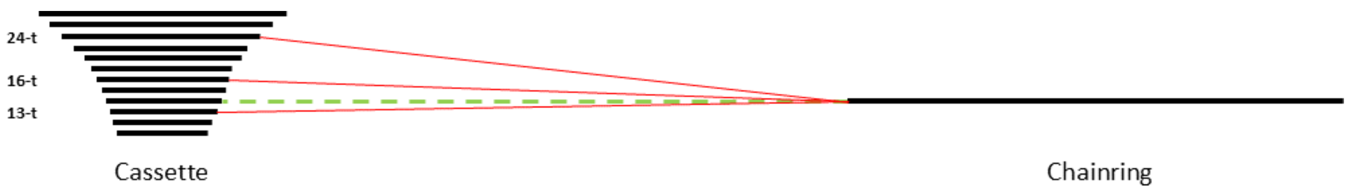

Figure 1: Schematic representation of chain alignment depending on the selected sprocket (red lines). The chainring is aligned with the 14 teeth sprocket (green dotted line).

The rest of the transmission was composed of:

- A chain (CN-MT9100 12sp, 114 links, Shimano, Japan), ½" pitch.
- A rear derailleur (Dura-Ace DI2 12sp, Shimano, Japan) with 11 teeth pulley wheels.

The transmission was cleaned and lubricated with a synthetic oil prior to the testing session. Tests were performed in a clean lab atmosphere (19-23°C, 40-60% relative humidity).

The tests were conducted on a dedicated testing rig, which is representative for the whole transmission (Figure 2). A review [14] concluded that this kind of setup (Full Transmission Rig) was well adapted to measuring chain drive efficiency provided the sensors are accurate and the measurement protocol robust. This testing rig is composed of a brushless motor (CMP80M, SEW-Eurodrive, Germany) connected to a reducer (RXF67, SEW-Eurodrive, Germany). The cassette is mounted on a freehub body fixed on the axle of an electromagnetic powder brake (FVRAT 2002, Mérobel, France) allowing to create resistive torques up to 200 N. As a result, the range of power experienced in professional cycling can be simulated on this rig (0-2000W).

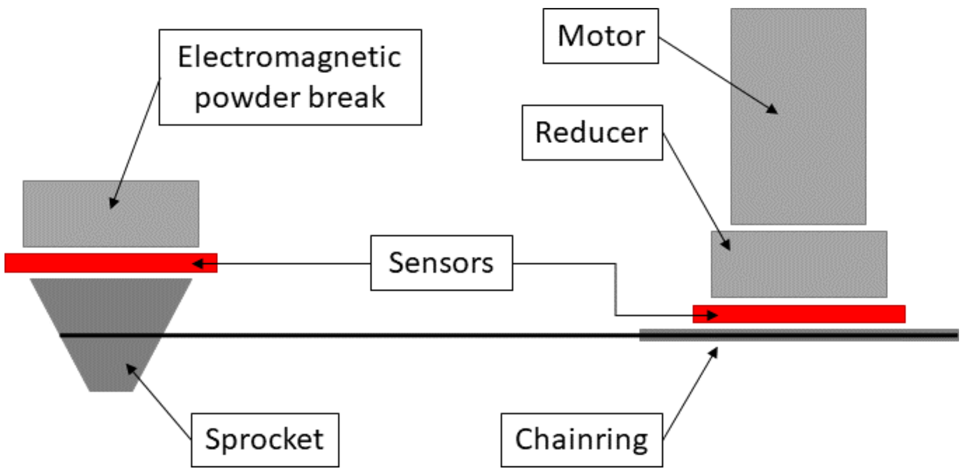

Figure 2: Schematic representation of the full transmission as seen from above. Rear derailleur is not represented here but was present on the rig. A sensor measuring torque and rotation speed is located between the chainring and the reducer (on the motor shaft) and a similar sensor is mounted between the sprocket and the break (on the break shaft). This allows to determine power output entering in the transmission and the power output at the exit of the transmission.

A wireless torquemeter (T40B 200 Nm, HBM, Germany) is mounted on the motor shaft, between the reducer and the chainring. Symmetrically, a similar torquemeter is mounted on the brake shaft, between the sprocket and the brake. Both of these torquemeters also measure rotation speed, meaning that they can measure mechanical power before and after the transmission. Chain drive efficiency is then calculated using torque, rotation speed and efficiency as detailed in Equation 1.

$$E\% = \frac{Po_{out}}{Po_{in}} * 100 = \frac{Tq_{out}\omega_{out}}{Tq_{in}\omega_{in}} * 100 \quad (1)$$

With E% chain drive efficiency (%), Po power output (W), Tq torque (N.m) and ω rotation speed (rad.s^{-1}). “In” and “out” indicate whether the factors are measured at the entrance or at the exit of the transmission.

The repeatability and reproducibility of the rig have been studied [13] and it was concluded that the error was 0.1% over chain drive efficiency. The measurements are recorded at 5 Hz by the means of an acquisition system (PX460 on PMX, HBM, Germany) and the sensor’s software (Catman Easy, HBM, Germany). Prior to any measurement, a thirty-minutes warm-up is performed to allow the sensors to reach their stabilised temperature.

Each test consisted in five minutes at a constant power output (450 ± 5 W) and cadence (100 ± 1 rpm). Preliminary measurements showed that efficiency was consistent for several hours, allowing to shorten the tests sessions yet still being representative for a longer period. This consistency over time was also demonstrated in the literature [3].

A two-way ANOVA was used as a statistical indicator for assessing the effects of sprocket and chainring on efficiency. The equality of variances (Levene's test) and the sphericity (Mauchly's test) of samples were tested prior to the ANOVA. Greenhouse-Geisser corrections were used as sphericity was not verified. For significant ANOVA results ($p<0.05$), post-hoc tests were made using Holm's p-value and Cohen's d-value for effect size.

Results

The effects of chainring size on mean efficiency are presented for each sprocket on Figure 3.

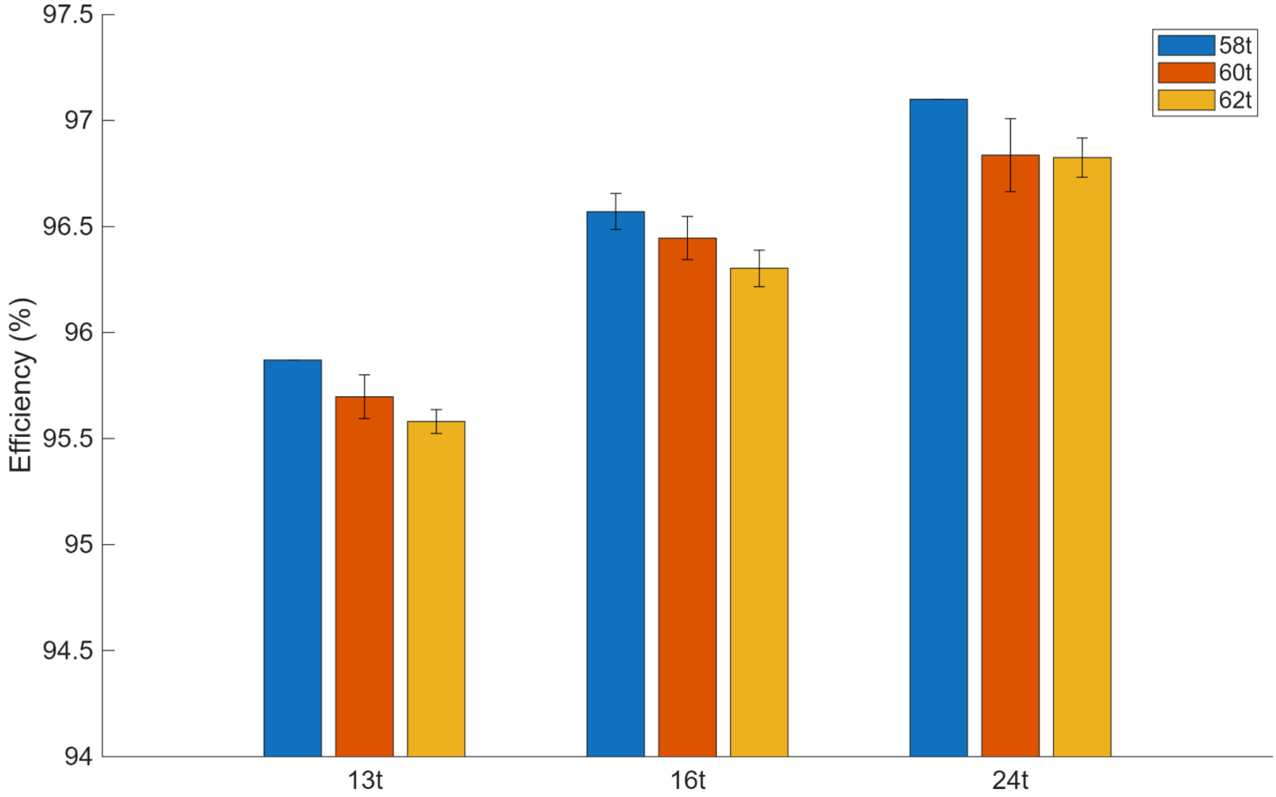

Figure 3: Average efficiency for each chainring size (one colour per chainring) and each sprocket size (abscissa) at 450 W and 100 rpm. The error bars represent the standard deviation for each gear ratio. The bigger the sprocket, the better efficiency (p < 0.001), as expected. However, this effect is not verified for chainring size. Indeed, a trend towards a decrease in efficiency can be observed when increasing chainring size.

As has been shown by previous studies [3, 6, 9], efficiency increases with the size of the sprocket for a constant power output and cadence ($p > 0.001$). Indeed, chain drive efficiency increases by 1.2% when using a 24 teeth sprocket instead of one with 13 teeth. The difference between each sprocket is statistically significant ($p < 0.001$ for both 13t vs 16t ($d = 1.9$) and 13t vs 24t ($d = 3.1$); $p = 0.04$ ($d = 1.7$) for 16t vs 24t).

Conversely, efficiency does not change significantly as chainring size increases ($p=0.238$, $d = [0.2; 0.5]$). One can even observe a trend towards a decrease in efficiency for an increase in chainring size, which is opposed to what is observed for sprockets.

Concerning the effect of derailleur pulley size on efficiency, no statistical difference was measured. The results are detailed in Annex 2.

Discussion

The first part of the results, concerning sprockets, is in line with the literature and indicates that a bigger sprocket is beneficial for efficiency [3, 4, 5, 7]. This result can be emphasized considering that the chain was best aligned with the 13 teeth sprocket and had a high angle when using the 24 teeth sprocket. The main mechanism underneath this gain in efficiency can be the angle of articulation of the chain links around the sprocket. Indeed, the bigger the ring, the smaller the angle, as shown on Figure 4. This reverse relation is particularly important for sprockets as the number of teeth is usually small. Indeed, there is a 5° reduction in angle articulation when using a 16 teeth sprocket instead of a 13. This difference is up to 12° when going from 13 to 24. As a result, the sliding distance of the chain elements that are moving while being in contact is very dependent on sprocket size. Less sliding distance for a constant pressure generates less energy loss due to friction, and therefore a better efficiency.

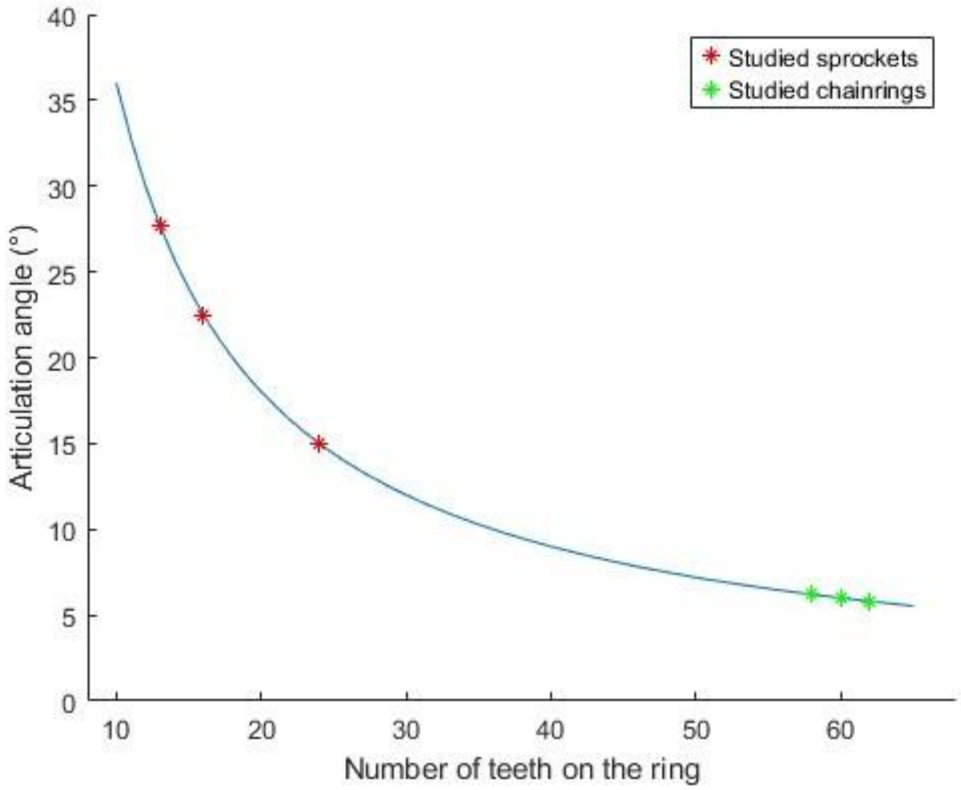

Figure 4: Articulation angle of the chain links depending on the number of teeth on the ring. The rings studied are represented by red stars for sprocket and green stars for chainrings.

Another phenomenon generating friction also exists for small rings. The polygonal effect (or chordal effect) has indeed been well documented [15, 16, 17]. This geometric effect, significant for small ring sizes, generates ripples along the chain (Figure 5). These ripples are induced by the difference in height of the exit points of the link from the ring. When considering bigger rings, this effect tends to be neglectable, but for the 13 and 16 teeth sprockets, it creates additional motion in the chain links and therefore more friction.

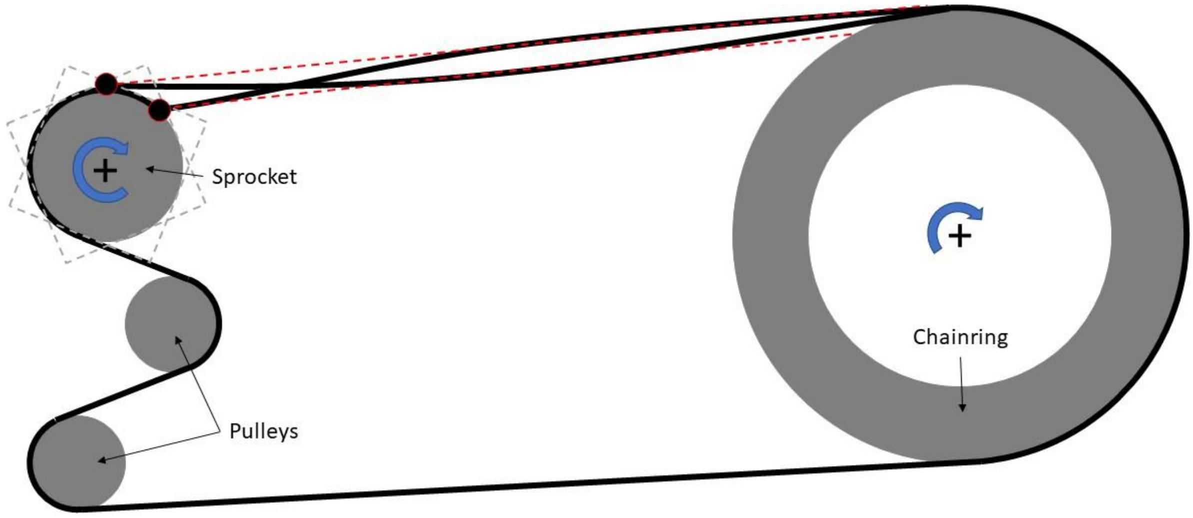

Figure 5: Schematic representation of the polygonal effect (chordal effect) in a hypothetical bicycle transmission between an eight teeth sprocket and chainring. Other oscillations such as ones from the pulleys are neglected here for demonstration purposes. Depending on the exit points from the sprocket, the height position of chain links varies. This phenomenon generates additional friction due to the oscillation induced in the tight chain strand and is significant for small ring sizes. The smaller the sprocket, the bigger the oscillation and friction.

The addition of the two phenomena described previously explains the important differences in efficiency for a change in sprocket size. These phenomena apply to every ring size, and therefore both pulleys and chainrings are expected to follow the same trend. However, neither pulley size nor chainring size has a significant effect on efficiency in the results. For pulleys, it could be mainly due to the low tension in the lower chain span (Annex 2). For chainrings, a trend towards a decrease in efficiency can even be observed. This trend could well explain the lower-than-expected effects of ring size found for a fixed gear ratio (Annex 1). The mechanisms that could explain it are envisaged hereafter.

First, the polygonal effect can be neglected for chainrings as the number of teeth is much higher than for sprockets and well above 30 teeth. Concerning the difference in articulation angle, it is low between a 58 and a 62 teeth ring: only 0.4°. As a result, both of the main effects influencing efficiency when considering sprocket size have low to no effect in the case of chainrings. On the other hand, the chainring is a driving ring, opposite to the cassette or the derailleur pulleys which are driven rings. As a result, the chainring has a direct impact on chain tension. For a fixed power output and cadence, an increase in chainring size implies a decrease in chain tension (Figure 6).

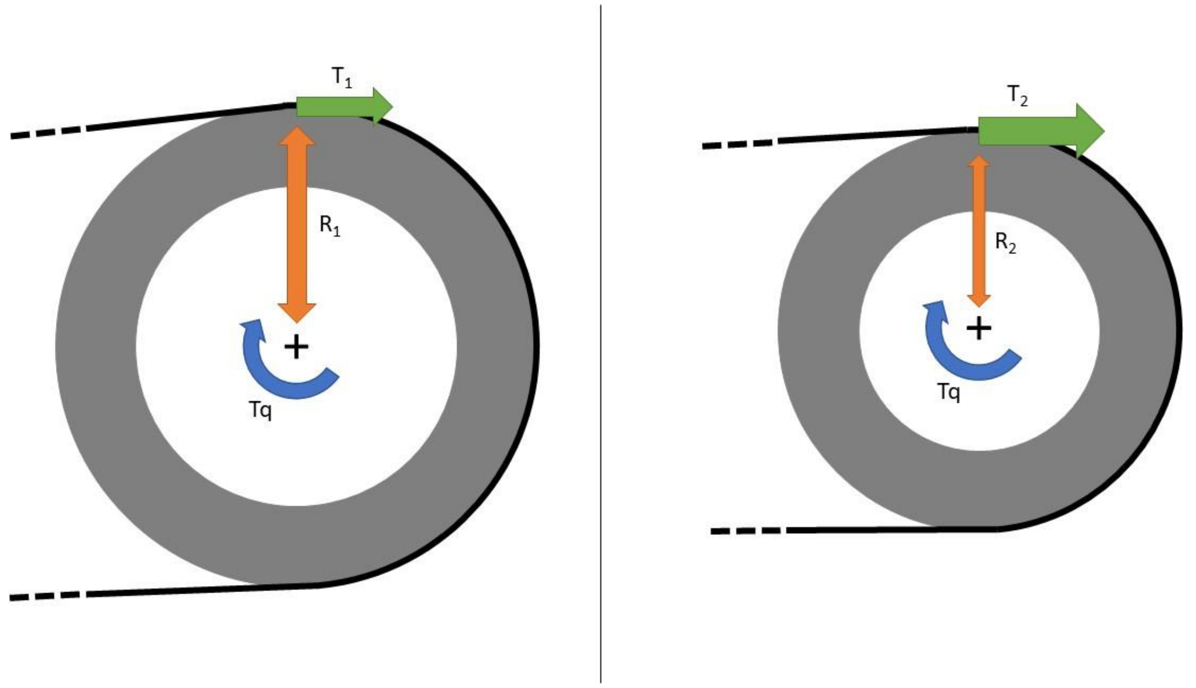

Figure 6: Schematic representation of the effect of chainring size (R) on chain tension (T) for a fixed torque (Tq). The driving part of the transmission (chainring and chain) is represented here. On the left, a big chainring and on the right a small chainring. For a fixed Tq, a bigger chainring generates less chain tension. Indeed, chain drive efficiency is related to chain tension. As a result, efficiency decreases for a chainring size increase.

Indeed, it has been shown multiple times that efficiency increases with chain tension [3, 9]. Therefore, an increase in chainring size lowers efficiency at a fixed torque. The size difference between 58 and 62 teeth is 6.5%. This tension effect could be the main explanation for a loss in efficiency when increasing chainring size, if this trend was to be confirmed. Chain tension effect would be predominant over articulation angle effect, as was proposed by Walton [18].

Moreover, the centre-to-centre distance between sprocket and chainring is fixed on the rig, as it is on a real bicycle. As a result, a bigger chainring will shorten the length of the free chain span between the chainring and the sprocket. In the case of cross chaining (e.g., using a big chainring with a big sprocket), this will affect the cross angle from the chain slightly. In the present case, considering that the chainring is aligned with the 14 teeth sprocket, cross chaining on 62 teeth instead of 58 teeth increases cross angle from 6.7° to 6.9°. This slight effect could add a little more friction and be detrimental for efficiency, as demonstrated in literature [19].

Despite the low number of measurements performed in this study, the trend showing the slightly detrimental effect of chainring size on efficiency could be a key to understanding the missing link between the strong effect of sprocket size and the low effects of ring size on efficiency for a fixed gear ratio. When considering the whole transmission and its practical applications, for a fixed power output and cadence, if this trend was to be confirmed, a choice should be made between an increased sprocket size and a decreased chainring size. Indeed, the gear ratios must suit the needs of the athlete. In the practical case of elite time-trialing, the choice must be made at a fixed gear ratio, as presented in the introduction. In this case, sprocket size takes precedence over chainring size. This hierarchy goes along with the choices of big gears that have been used for a few years in professional cycling. However, this study suggests that the bigger is better law does not systematically apply. Further measurements would need to be performed to confirm or deny the effects of chainring size on efficiency. More measures would be needed to confirm the trend on the effects of chainring size. Complementary studies could also be designed to investigate the effects of teeth design on efficiency. Indeed, this effect was neglected during this study. However, large narrow-wide chainring teeth tend to be as thick as chain links. Therefore, additional friction could be generated, especially when cross chaining.

Conclusion

Existing literature established that for a given power output and cadence, bigger rings were beneficial for efficiency. Indeed, based on existing works focused on sprockets, one could expect big gains in efficiency. However, fixed gear ratio gains for bigger rings are lower than expected and this needs an explanation. This study had the objective to permit a better understanding of the effects of ring size on chain drive efficiency. Through the use of a full transmission rig, efficiency of different gears was measured in clean lab conditions. As expected, sprocket size increase was beneficial for transmission efficiency. This result is mainly due to a lower articulation angle for chain links that are wrapping around the sprocket, and to a diminished polygonal effect. Conversely, increasing chainring size was not found to impact chain drive efficiency significantly. A slight trend towards a detrimental effect of chainring size on efficiency could even be observed. If it was to be confirmed, this trend could be explained by the fact that the chainring is the driving ring, so the one responsible for chain tension at a fixed torque. As efficiency increases with chain tension, a smaller chainring could increase chain drive efficiency thanks to a higher chain tension at a given torque. This tension effect would overcome the slight increase of articulation angles for chainrings. Finally, derailleur pulley size does not affect chain drive efficiency in a significant way in the conditions of the test mostly due to the low chain tension in the lower span. Overall, at a fixed gear ratio, a choice must be made between a small chainring and sprocket, or a big sprocket and chainring. This choice must be made regarding the sprocket as a priority, its effect being much larger than the one from the chainring. In this perspective, larger rings are beneficial for chain drive efficiency, but not as much as expected when only the sprocket effect is considered. Small sprockets increase friction losses in an exponential form: for instance, the use of a 10 teeth sprocket instead of an 11 teeth sprocket increases the articulation angle by 10% as a 15 teeth instead of a 16 teeth sprocket increases the articulation angle by 6.3%.

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Conflicts of interest
The authors declare no conflicts of interest.

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Annex 1: Ring size effect at a fixed gear ratio

The objective of this study is to measure the difference in efficiency between three gear combinations that give an equivalent gear ratio (4:1). This study is particularly relevant when considering real world application as gear ratio must be adapted to the cyclist's needs, and not conversely. Indeed, wheel size is limited by UCI (International Cycling Union) regulations, making gear ratios the only way to adapt pedaling cadence to speed. The gears tested here are representative for elite time-trialing.

The measurements were performed on the same set-up as the one described previously. Three gear combinations were tested: 56-14, 60-15 and 64-16. The same cassette was used for the whole session (Dura-Ace 12sp 11-30, Shimano, Japan). It contained the following sprockets: 11-12-13-14-15-16-17-19-21-24-27-30. The tested chainrings are presented in Table 2.

Table 2: Specifications of the tested chainrings for the fixed gear ratio study.

Teeth count	56	60	64
Weight (g)	196.4	233.0	274.6
Teeth profile	Regular	Regular	Narrow-wide
Teeth height (mm)	5.00	5.00	7.20
Thin teeth width (mm)	2.00	2.00	3.35
Large teeth width (mm)	2.00	2.00	1.80
Teeth design	Italic	Italic	Italic
Chainring design	Hollowed	Hollowed	Plain

As described previously, the chainring and sprocket were aligned in the 56-14 condition. The chain offset was small for the other sprockets (up to 1.6° for the 16 teeth). The choice was made to keep a realistic chain angle due to the use of different sprockets to represent the riding conditions as life likely as possible. The effect of this offset must be kept in mind when analysing the sprocket effect on efficiency.

The rest of the transmission was composed of:

- A chain (CN-MT9100 12sp, 114 links, Shimano, Japan), ½" pitch.
- A rear derailleur (Dura-Ace DI2 12sp, Shimano, Japan) with 11 teeth pulley wheels.

The transmission was cleaned and lubricated with a synthetic oil prior to the testing session. Tests were performed in a clean lab atmosphere (19-23°C, 40-60% RH).

Each test consisted of five minutes at a constant power output (450 ± 5 W) and cadence (100 rpm), followed by five minutes at a lower power output (200 ± 5 W) at the same cadence. The objective was to check whether the results were torque-dependent or not.

The results are presented on Figure 7, where average efficiencies for both power outputs are represented for every gear combination.

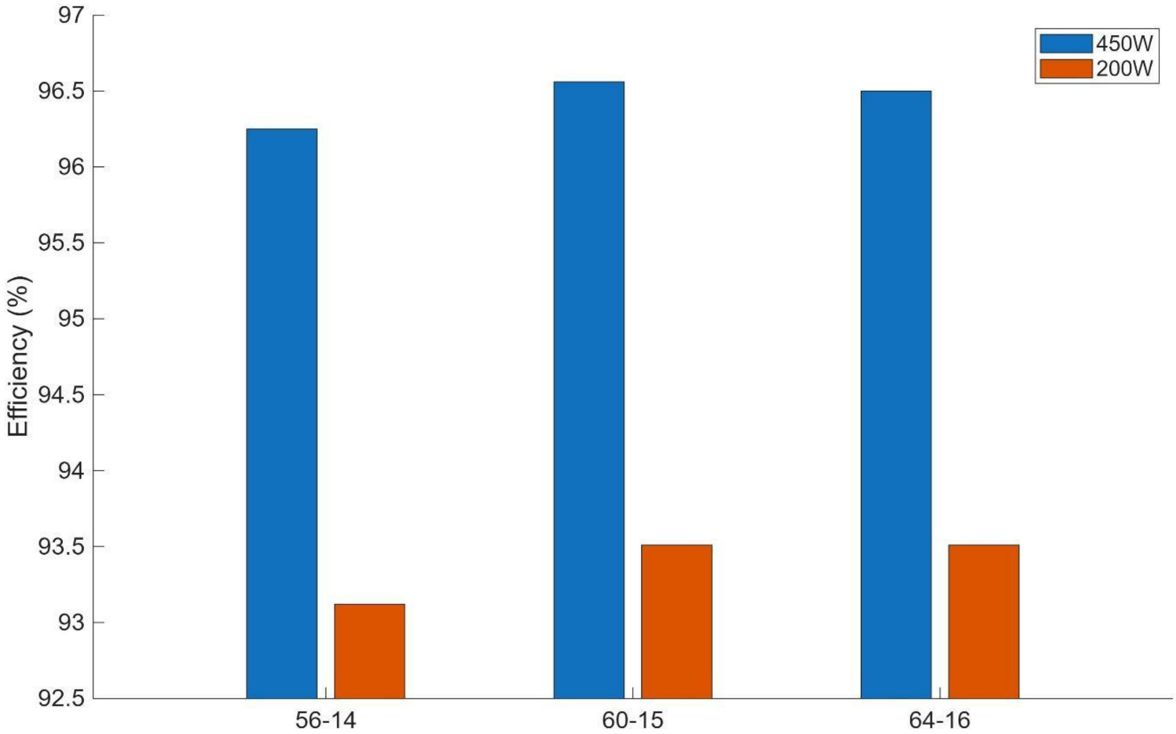

Figure 7: Chain drive efficiency for different gear combinations at a fixed gear ratio (4:1). Two powers were tested (450 and 200 W) at a fixed cadence (100 rpm). As expected from the literature, the smallest gears (56-14) present a lower efficiency when compared to bigger rings. However, the 60-15 and 64-16 conditions are similar.

The smallest ring combination (56-14) provides a lower efficiency than the bigger ones. However, the difference in efficiency is rather small: less than 0.5% for both power outputs. Torque has an influence on the magnitude of the efficiency measured, but not on the hierarchy of the gear ratios. Moreover, the 60-15 combination has a similar efficiency as the 64-16 combination. These results do not match the gains, reaching more than 1%, that sprocket-specific studies could let expect [3]. Yet, this is in line with fixed gear ratio studies, showing that efficiency gains decrease with sprocket size, reaching a stabilized plateau above 15 teeth [9, 10, 11, 12].

Annex 2: Pulley size effect on efficiency

Along its journey around the transmission, a chain link encounters four distinct rings: the chainring, a sprocket and two pulleys assembled on the derailleur cage. Both these derailleur pulleys are located on the lower strand of the chain, where the chain tension is at its lowest. However, they are usually the smallest rings of the transmission: 11 teeth. Based on the results of the other driven rings in the transmission (sprockets), gains in efficiency could be expected if one used bigger derailleur pulleys. To verify this hypothesis, a study was designed to test four derailleur cages with different pulley combinations. The specifications of each cage are presented in Table 3. These cages were mounted on the same rear derailleur (Dura-Ace DI2 12sp, Shimano, Japan). Some of them used ceramic instead of steel ball bearings. It was hypothesized for this study that the effect of the bearings would be small enough in regard of the effect of pulley size to neglect it.

Table 3: Specifications of the tested cages for the pulley study.

Designation	11-11	14-14	14-18	14-19
Upper pulley size (teeth)	11	14	14	14
Lower pulley size (teeth)	11	14	18	19
Bearings	Steel	Ceramic	Ceramic	Ceramic
Max. sprocket size capacity (teeth)	34	30	34	34
Weight (g)	49.1	63.0	104.6	125.1

The measurements were performed on the same set-up as the one described previously. The chainring had 56 teeth (Dura-Ace 12sp, Shimano, Japan). The same cassette was used for the whole session (Dura-Ace 12sp 11-30, Shimano, Japan). It contained the following sprockets: 11-12-13-14-15-16-17-19-21-24-27-30. Three gear combinations were tested: 56-11, 56-15 and 56-24. The objective was to test the pulleys both in an aligned condition (56-15) and in poor alignment conditions (56-24 and 56-11).

The rest of the transmission was composed of a chain (CN-MT9100 12sp, 110 links, Shimano, Japan), ½" pitch. The transmission was cleaned and lubricated with a synthetic oil prior to the testing session. Tests were performed in a clean lab atmosphere (20-22°C, 40-60% RH).

Each test consisted of 30 minutes at a constant power output (450 ± 5 W) and cadence (100 rpm).

The results are presented on Figure 8, where efficiencies are averaged over every gear combination and represented for each pulley combination. An ANOVA was used as statistical indicator for comparing the results.

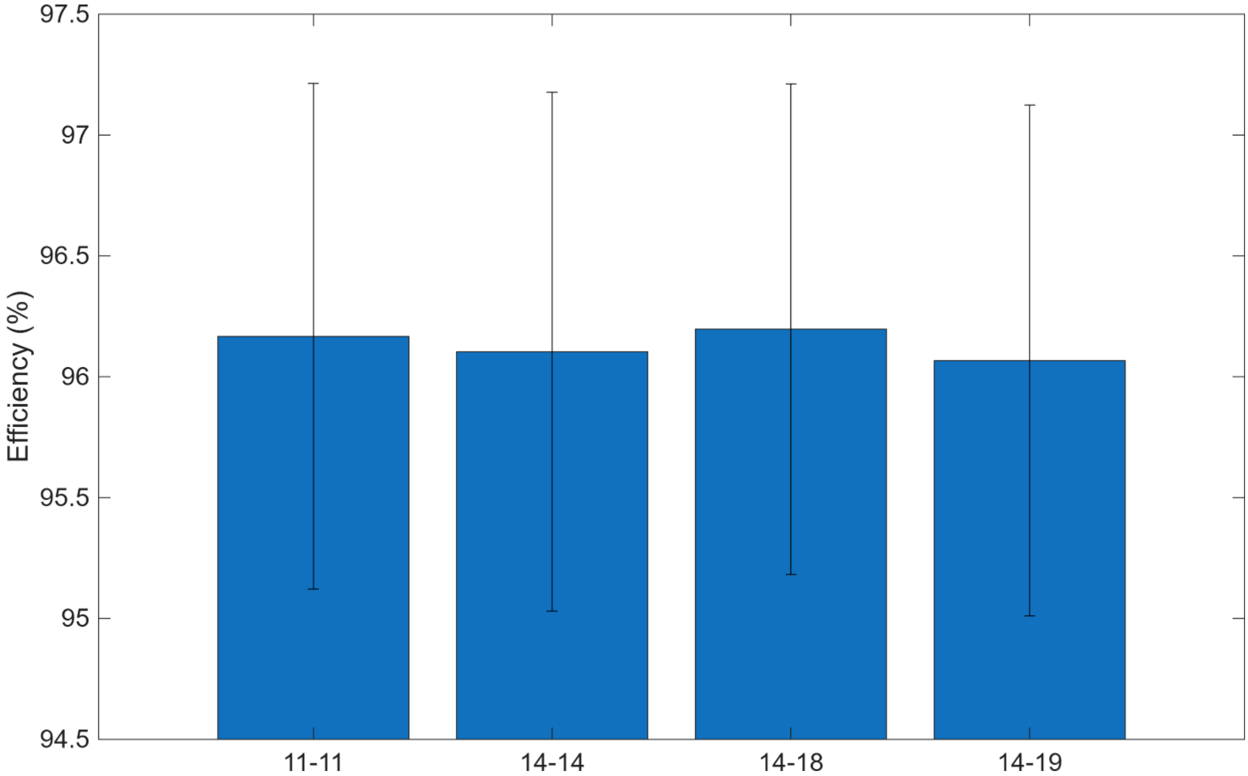

Figure 8: Average efficiency for each pulley combination – all gear ratios mixed. The error bars represent the standard deviation for each pulley. There is no significant difference (p=0.999).

No significant difference was measured for these cages (p=0.999). The hypothetic differences are too small compared to the uncertainty attributed to the rig, meaning that they are below 0.1%. This result does not match the gains that were expected, based on the results of the sprockets. Even though the same arguments as those proposed for sprockets are valid for pulleys (articulation angle and polygonal effect), the main difference here is that chain tension is very low. Indeed, in the lower strand of the chain, the tension is independent of the rider's actions and is only governed by the tension set by the derailleur spring (8-15 N). This tension is much lower than the one of the upper strand (tight strand), especially at the considered powers (around 350 N here). As a result, the eventual decrease in friction losses generated using bigger pulleys is not visible at such power outputs. One could study this effect for low powers (e.g., 100 W), but the practical applications would not concern high level athletes. As a conclusion, this study shows that the use of oversized pulleys does not affect chain drive efficiency enough to be measured in these conditions.