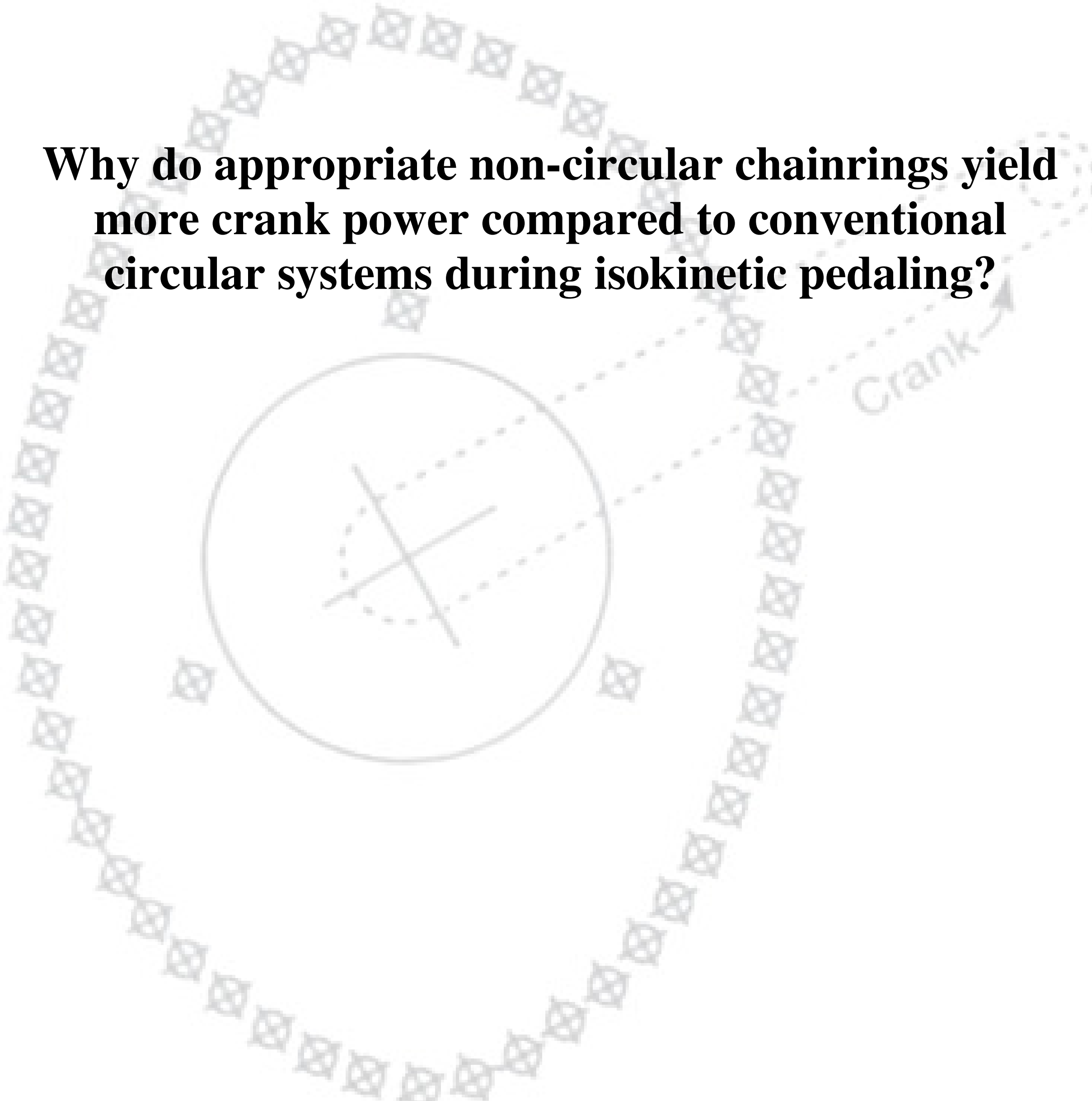
Why do appropriate non-circular chainrings yield more crank power compared to conventional circular systems during isokinetic pedaling?



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Abstract
Several studies have been published on the use of eccentric and non-circular chainrings.
The findings of these studies have, however, not been consistent.
Despite the lack of consistent positive results in terms of physiological responses, a consensus appears to prevail that the improved mechanical effectiveness of the oval chainring may lead to performance enhancement (e.g. increased crank power output) compared to the conventional circular chainwheel.
Some authors assume non-circular chainrings may improve pedal dynamics by reducing the effect of the "dead spot" in the pedaling cycle.
Other argue that an elliptical chainwheel should more efficiently match the torque output capability of the rider to the torque input requirement of the pedaling cycle.
Still other researchers conclude that non-circular chainrings can potentially increase crank power relative to a conventional circular chainring by acting to slowdown the crank angular velocity during the downstroke (power phase) which allows muscles to generate power longer and to produce more external work.

The pedal reaction force can be decomposed into a limb-static force and a limb-dynamic force (gravity and inertial effects) component.
Static forces result from pedal forces only.
Dynamic forces and dynamic moments are needed to accelerate/decelerate (to move) the lower limbs.
As a consequence crank power, joint-moments and joint-power are the result of static pedal forces and of the dynamic forces/moments.

In a theoretical model, **by assuming the static pedal forces being zero** it becomes possible to investigate **the specific impact of the *change* of the dynamic force component on the bicycle-rider system**.
Altering the dynamic forces/moments is possible via ovality and shape of the chainring, crank orientation angle, pedaling cadence, anthropometric values and bike geometry.

The objective of this study was, relying on a torque-driven bicycle-rider musculoskeletal model

first,
to study the **dynamic** joint-moments and **dynamic** joint-power as a function of ovality and shape of the chainring, crank orientation angle and pedaling cadence during isokinetic pedaling.
second,
to study the **dynamic** crank power output of non-circular chainrings when applying the instantaneous dynamic joint-moments of the circular chainwheel on the non-circular chainring.
In this case, **per definition**, the instantaneous dynamic crank power and average dynamic crank power equal zero for the circular chainring. But the dynamic average crank power of the non-circular chainring, when applying the dynamic joint-loads of the circular chainring, will result in either an average crank power gain or an average crank power loss compared to circular.
For each of the examined non-circular chainrings, the impact of crank orientation angle and pedaling cadences are investigated.

As a general conclusion, the results of the study indicate that **optimizing** the **dynamic component of the joint-load** by designing an **appropriate** non-circular chainring (ovality, shape, crank orientation angle and cadence)
-gives rise to favourable differences in curve profiles and peak-values for both the dynamic joint-moments and dynamic joint-powers compared to circular
-leads to a measurable crank power gain when applying the dynamic joint-moments of the circular on the appropriate non-circular chainwheel.
This means that the dynamic joint-moments/forces needed to accelerate/decelerate the limbs with a circular chainwheel are delivering the dynamic joint-power needed to move the lower limbs with the appropriate non-circular chainring and are yielding a crank power surplus.

1. Introduction

A considerable number of pedaling studies have been published on the use of eccentric and non-circular chainrings (Henderson et al., 1977; Okajima, 1983; Cullen et al., 1992; Hull et al., 1992; Barani et al., 1994; Hintzy et al., 2000; Hue et al., 2001; Ratel et al., 2004; Martinez et al., 2006; Horvais et al., 2007; Hue et al., 2007; A.D. Jones et al., 2008; Mateo et al., 2010 etc...).
The findings of these studies have, however, not been consistent.
This could be explained by the fact that only well trained cyclists, adapted to the conventional round chainwheel, were recruited as subjects for this research.
Furthermore, it is difficult to set up good and reliable experimental designs to carry out *comparative* studies since any cyclist is likely to be more efficient when using the driving system he is accustomed to, whether circular or non-circular.

In addition, all studies have been executed with crank orientation angles versus major axis probably being not optimal (Malfait et al., 2010; Miller et al.,1980).

To validate by experiments the oval chainring's ability to improve performances by analyzing biomechanical and/or physiological variables requires an adequate (large and homogeneous) sample of trained cyclists and multiple (repeated) measurements, being a very time consuming and consequently a very expensive process. Indeed, differences may be small and sometimes not statistically significant and consequently are not easy to record experimentally. Moreover, the variability inherent in human performance tests may possibly obscure the differences (Hull et al., 1992).
Nevertheless in a professional environment where all parameters are optimized, small differences may determine the outcome of a competition.

Research with a mathematical model accurately describing the bike-rider system and closely matching verification data definitely provides useful information and is a powerful tool to support and even to be complementary to experimental work. The use of a computational model is motivated by the fact that it is noise free and therefore allows assessment of model tendencies that are too small to be reliably picked up in an experiment (Hansen et al., 2009).

Despite the lack of consistent positive results in terms of physiological responses (heart rate, oxygen consumption, blood lactate concentration, rating of perceived exertion, carbon dioxide output etc..etc...) a consensus appears to prevail that the improved mechanical effectiveness of the oval chainring may lead to performance enhancement (e.g. increased crank power output) compared to the conventional circular chainwheel.
Indeed, from a pure biomechanical perspective the use of elliptical chainrings should provide theoretical benefits.
As an example, Rankin and Neptune (2008) identified a non-circular chainring with ovality of 1.29 yielding an average crank power gain of 3.0% compared to a conventional circular chainring at a pedaling rate of 90 rpm.

Some authors assume non-circular chainrings may improve pedal dynamics by reducing the effect of the "dead spot" in the pedaling cycle and altering the mechanical leverage. Time spent in positions of low mechanical advantage is reduced, making the pedaling technique more efficient (i.e. Ferrari, 2004; Ratel et al., 2004).
Also, an elliptical chainwheel should more efficiently match the torque output capability of the rider to the torque input requirement of the pedaling cycle than should a circular chainwheel (Henderson et al., 1977).
Other researchers argue that non-circular chainrings can potentially increase crank power relative to a conventional circular chainring by acting to slowdown

the crank angular velocity during a part of the downstroke (power phase) which allows muscles to generate power longer and to produce more external work (Hintzy et al.,2000; Rankin et al., 2008).

Neither the "pedaling fast through the dead spot", the potential advantage of "torque matching" nor the "slowdown during the downstroke" really explains why non-circular chainrings could improve some aspects of the cycling efficiency and performance (e.g. power output).

Several studies have analyzed the effects of non-circular chainrings compared to conventional round chainwheels, but to the author's knowledge, no studies are available answering even the most apparently obvious question:
why do (appropriate) non-circular chainrings yield more crank power compared to conventional circular systems during isokinetic pedaling?

The primary goal of our research is to investigate why a non-circular chainring has the ability to improve cycling performance by increasing average crank power output during isokinetic cycling. But, directly related to this objective, the examination of the dynamic forces/moments/power in the knee- and hip-joints is necessary.

2. Methods

2.1. Basic Study

The "Comparative biomechanical study of circular and non-circular chainrings for endurance cycling at constant speed. Release 2." (Malfait et al., 2010) referred to as the "basic study", delivers more detailed information not necessary reproduced in this paper.

2.2.Torque-driven bicycle-rider musculoskeletal model

The torque-driven musculoskeletal model of the "basic study", developed using the MATLAB® software package, describes the bicycle-rider system.

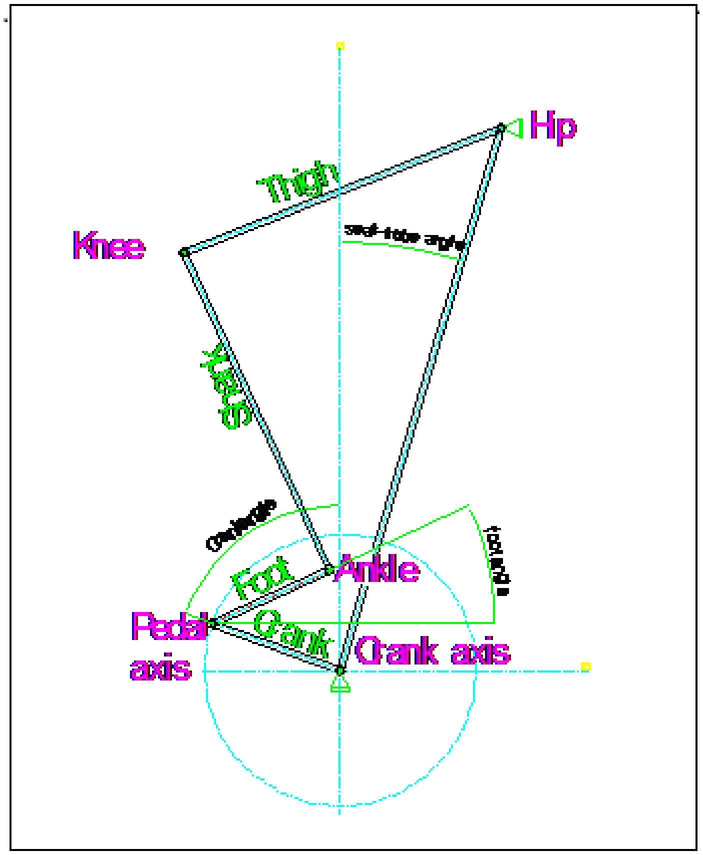


Figure 1: Five bar linkage model of the bicycle-rider system

Model set-up (the bars, the links, the limbs, the joints, the pivot points, the kinematic variables i.e. crank angle, the pedal forces and decomposition, the joint forces and joint moments, the muscle groups involved, the anthropometric parameters, the system geometry, etc...) is explained in the "basic study".

2.3. The dynamics of the pedaling process.

*While in this study the term "dynamics" is being used, in many Anglo-Saxon publications we read the term "**kinetics**".*

The pedal reaction force can be decomposed into a limb-static force and a limb-dynamic force (gravity and inertial effects) component.
As a consequence crank power, joint-moments and joint-power are the result of static pedal forces and the dynamic forces/moments.
Dynamic forces and dynamic moments are needed to accelerate/decelerate (to move) the lower limbs. This is explained in the chart below.

It is obvious that, assuming identical joint-loads, the crank power will be changed by altering the dynamic components.

Altering the dynamic forces and the dynamic moments is possible via ovality and shape of the chainring, crank orientation angle, pedaling cadence, anthropometric values and bike geometry.

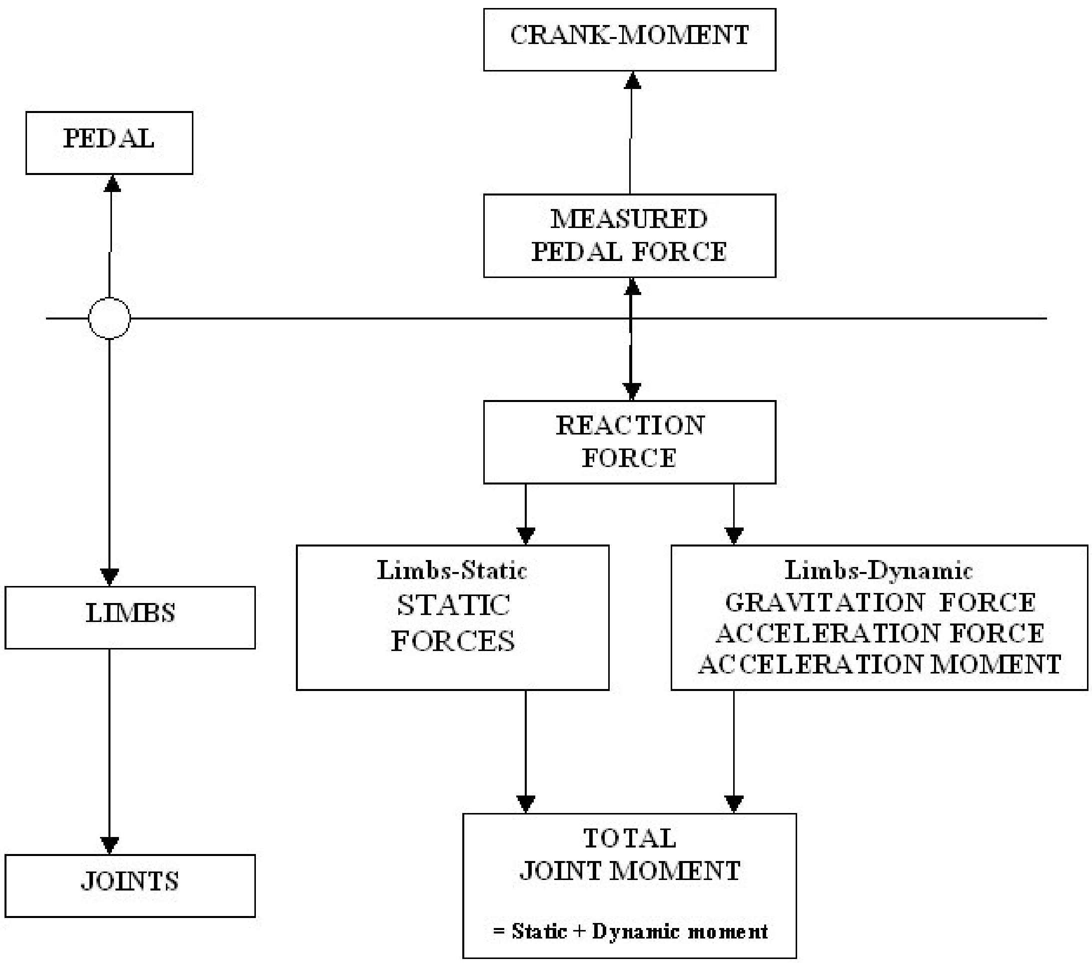


Figure 2: Schematic decomposition of pedal reaction force giving insight into the dynamics of the pedaling process.

2.4. The free body diagram

To determine the kinetics of the model , free body diagrams of each link were constructed.
The equations of motion were written.
From the free body diagram, the reaction forces in the joints and the joint moments can be calculated for the ankle, the knee and finally for the hip.
The relations indicate the need to specify values of anthropometric parameters.
Additional input data were also necessary such as bike geometry, pedaling rate etc...

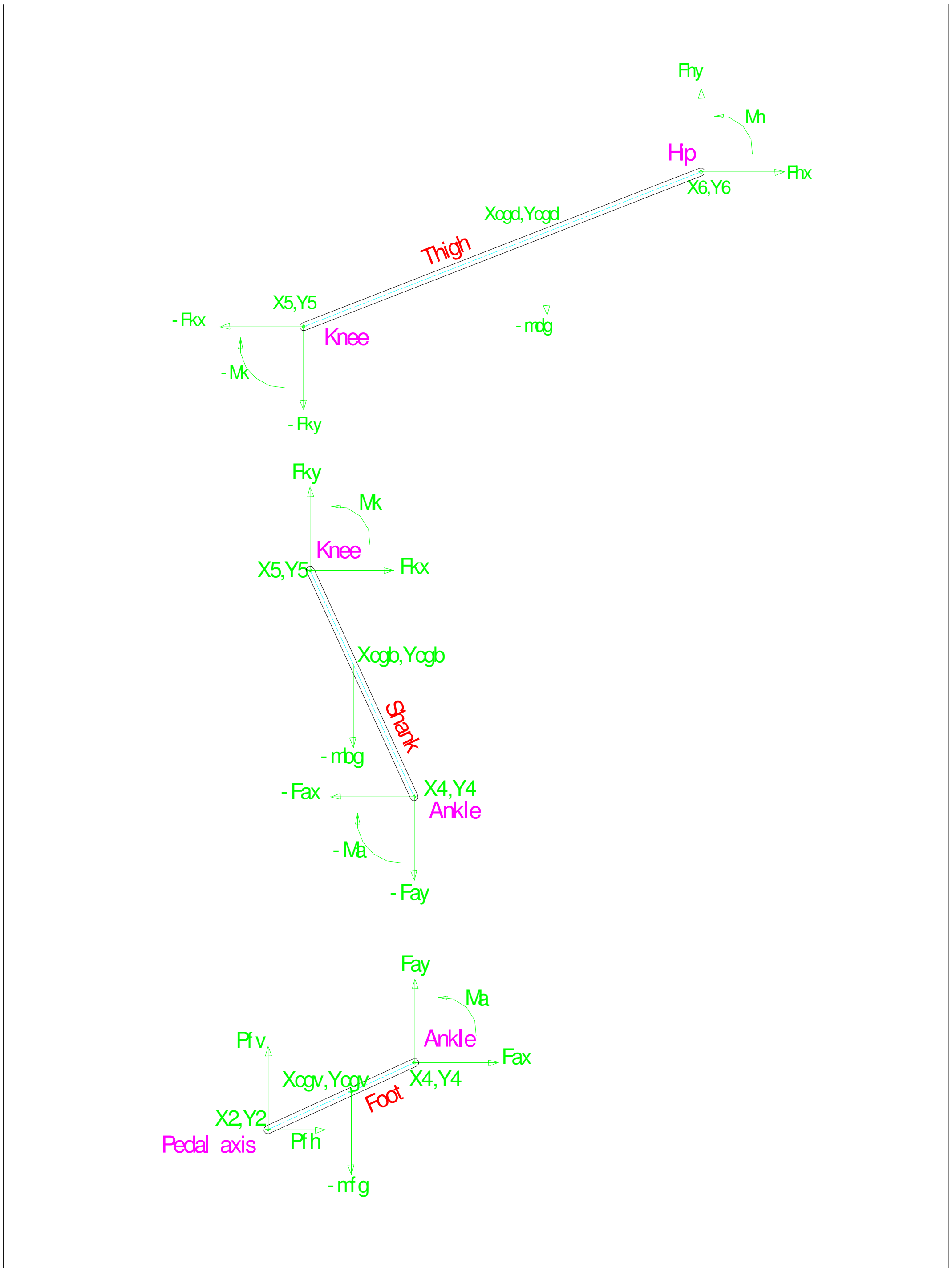


Figure 3: Free body diagrams of each link: balances of forces and moments.

$Pf_v = -F_y$ F_y = vertical force component exerted by the foot on the pedal

$Pf_h = -F_x$ F_x = horizontal force component exerted by the foot on the pedal

2.5. Basic relations for each link in the torque-driven model

From the free-body diagram (see figure 3) the reaction forces in the joints and the joint moments can be calculated for the ankle, the knee and finally for the hip.

For the foot with ankle joint:

$F_{ax} = m_f * aX_{cgf} - Pf_h$

$F_{ay} = m_f * aY_{cgf} - Pf_v + m_f * g$

$$M_a = I_f * a_{footangle} - Pf_v * (X_4 - X_2) + Pf_h * (Y_4 - Y_2) - F_{ay} * (X_4 - X_{cgf}) + F_{ax} * (Y_4 - Y_{cgf})$$

Nomenclature:

M_a = ankle moment.
I_f = moment of inertia of the foot about its centre of gravity.
$a_{footangle}$ = angular acceleration of the foot.
Pf_v = reaction force at the pedal, vertical component.
Pf_h = reaction force at the pedal, horizontal component.
X_2, Y_2 = coordinates of pedal spindle.
X_4, Y_4 = coordinates of ankle axis.
X_{cgf}, Y_{cgf} = coordinates of the centre of gravity of the foot.
F_{ax} = force at the ankle joint, X component.
F_{ay} = force at the ankle joint, Y component.
m_f = mass of the foot.
aX_{cgf} = linear acceleration of the centre of gravity of the foot, X component.
aY_{cgf} = linear acceleration of the centre of gravity of the foot, Y component.
g = acceleration of gravity (9.81 m/s^2)

Similar equations are defined for the shank with the knee joint ($F_{kx,}$ $F_{ky,}$ M_k) and for the thigh with the hip joint ($F_{hx,}$ $F_{hy,}$ M_h)

2.6 Values of anthropometric parameters and bike geometry.

Lengths, masses, moments of inertia and centre of gravity locations (CG) are estimated using the work of Wells and Luttugens (1976). These parameters were estimated for an average man who was 177.8 cm tall and weighed 72.5 kg.

Foot length: 0.161 m
Shank length: 0.436 m
Thigh length: 0.426 m
Moment of inertia foot about CG: 0.0023 $kg.m^2$

Moment of inertia shank about CG: 0.0422 kg.m²
Moment of inertia thigh about CG: 0.0690 kg.m²

Mass foot: 0.98 kg
Mass shank: 3.04 kg
Mass thigh: 6.86 kg

Distance of CG foot to proximal joint: 0.069 m
Distance of CG shank to proximal joint: 0.189 m
Distance of CG thigh to proximal joint: 0.189 m

Bike geometry:
-crank arm length: 0.170 m
-seat tube angle: 73°
-saddle hight: 0.713 m (distance from crank spindle centre to hip joint)

2.7. Non-circular chainring types and definitions.

Definitions: 1. Crank angle
* crank arm vertical is the reference and equals 0°, position **arbitrary** defined as being "Top-Dead-Centre" (T.D.C.)
*rotation: positive is counter clockwise

2. Crank orientation angle: the angle being measured from T.D.C (= crank arm vertical), counter clockwise, to major axis of oval.
3. Optimal crank orientation angle: crank orientation angle yielding highest average crank power, combined with the lowest peak power load in the extensor joint muscles of knee and hip, given the same joint moments for both, circular and non-circular chainring at **90 rpm** (see "basic study").
4. Ovality: ratio of major axis to minor axis length

Following chainrings are examined in this paper:

-Conventional circular chainring-ovality 1.00
"Circular"
-O.symetric original - crank orientation angle 78° - ovality 1.215
"Osy-Orig_78°"
-O.symetric optimal - crank orientation angle 110° - ovality 1.215
"Osy+4_110°"
-Q-Ring original - crank orientation angle 74° - ovality 1.10
"Q-Ring-Orig_74°"
-Q-Ring optimal - crank orientation angle 107° - ovality 1.10
"Q-Ring+4_107°"

-Ogival 140 original - crank orientation angle 75° (*) - ovality 1.428
"Ogival-140_73°"
-Ogival 140 optimal - crank orientation angle 107° - ovality 1.428
"Ogival-140_107°"
-Optimal - crank orientation angle 107° (**) - ovality 1.31
"Optimal_107°"
-Optimal+1 - crank orientation angle 114° - ovality 1.31
"Optimal+1_114°"
-Polchlopek original - crank orientation angle 102° - ovality 1.214
"Polchlopek-Orig_102°"
-Polchlopek optimal - crank orientation angle 109° - ovality 1.214
"Polchlopek+1_109°"
-OVUM 124 - crank orientation angle 106° - ovality 1.24
"OVUM 124+2_106°"

All chainrings considered in the study are 'normalised' in AutoCAD to 50 teeth. Explanations and pictures about the non-circular chainrings can be reviewed in the "basic study".
(*) differs from Ogival in "basic study" in terms of ovality and crank orientation angle.
(**) named "LM-Super" in "basic study".

Isokinetic pedaling is defined as cycling at a **constant pedaling rate** e.g. 90 revolutions per minute, with both a circular chainring and a non-circular one.

During isokinetic pedaling with a **circular chainring**, the path of the foot is circular and the **crank angular velocity is constant.**

During isokinetic pedaling with a **non-circular chainring**, the path of the foot is circular and the **crank angular velocity is varying** through one revolution. The **phazing** of the angular velocity variation and the **amount** of variation is determined by the **orientation of the crank arm** along with the **degree of ovality.**

The **ovality** of the non-circular chainring defines the **maximum** and the **minimum** crank angular **velocity**. This means that oval chainrings with identical ovality have identical maximum and minimum crank angular velocity.

The **shape** of the oval chainring defines the **shape** of the crank angular **velocity** curve profile and by derivation the **shape** of the crank angular **acceleration** curve and together with the crank angular velocity, the **amplitude** of the crank angular acceleration.

Consequently, non-circular chainwheels with identical ovality but with dissimilar shape have different angular acceleration curves. This gives the opportunity for **dynamic (kinetic) optimization**.

By **varying the crank arm orientation angle** versus the major axis, the **phazing** of the crank angular velocity and the crank angular acceleration curves are changed throughout the pedaling cycle, which also gives an opportunity for **dynamic (kinetic) optimization.**

Transformation formula for crank orientation angle:

Subtracting the above "scientific" defined crank orientation angle from 180° gives a crank orientation angle measured from the major axis of the oval being vertical with a positive angle in the direction of crank rotation when pedaling forward.
As an example:
Q-Ring original - crank orientation angle 74° - can be easier "visualised" by calculating 180° - 74° = 106°.
This means, having the major axis of the Q-Ring vertical, the crank arm is oriented at 106°, clockwise, measured from vertical. This is also the notification of the designer/manufacturer. This notification is more currently used.

Please notice that all the crank orientation angles mentioned in this study are according to the "scientific" definition (see above).

2.8. Objective of the study

The objective of this paper was, relying on a torque-driven bicycle-rider musculoskeletal model
first,
to study the **dynamic** joint-moments and **dynamic** joint-power as a function of ovality, shape and crank orientation angle during isokinetic pedaling with circular and non-circular chainrings at cadences of 40, 60, 80, 90, 100, 120 and 140 revolutions per minute (rpm).
second,
to study the **dynamic** crank power output of non-circular chainrings when applying on the non-circular chainring the instantaneous dynamic joint-moments of the circular chainwheel at cadences of 40, 60, 80, 90, 100, 120 and 140 revolutions per minute (rpm).
In this case, **per definition**, the instantaneous dynamic crank power and average dynamic crank power equal zero for the circular chainring. The dynamic average crank power of the non-circular chainring, when applying the dynamic

joint-loads of the circular chainring, will be either an average dynamic crank power gain or an average dynamic crank power loss compared to circular.
For each of the non-circular chainrings the impact of the crank orientation angle is investigated in two specific positions: the original crank orientation position of the designer/manufacturer and the optimal position as defined in paragraph 2.7..

The analysis is based, purely on the laws of the theoretical mechanics.
The results are (bio-)mechanically correct. Physiological aspects are, primarily, not taken into account because they are not part of the core-skills of the authors. Although in an appendix, some physiological considerations will be made.

Minor errors or deviations may have a limited impact on the figures (assumed anthropometric values, conversion of CAD drawings to crank angles, polynomial conversion, assumed constant linear chain velocity throughout the crank cycle, assumed pedal angle).

As mentioned above, in this analysis, **only dynamic components are taken into consideration.**
This is possible by equalling the pedal forces Pf_v *and* Pf_h *to zero in the general equations of forces and moments in the torque-driven model (see 2.5).*
The only remaining forces/moments in the model are dynamic forces/moments caused by gravity and inertial effects and are subject to examination.

3. Results dynamic joint-moments and dynamic joint-power.

3.1. Curve profile of dynamic joint-moments and dynamic joint-power.

Dynamic joint-moments (-torques) are the moments needed to be developed in the joints, simply and solely to overcome the inertial (-mass) forces/moments and the gravitational forces of the moving legs at different pedaling rates.
Per definition, dynamic joint-moments do not generate any crank power.

The same applies for the dynamic joint-power.

By means of an adapted Matlab® programme for each of the chainrings considered, the curve profile of the dynamic joint-moments, respectively dynamic joint-power were calculated as a function of cycle time and plotted, given a specific pedaling cadence (rpm).

Each graph shows for the circular chainring and for a specific non-circular chainwheel the evolution of the dynamic joint-moments/power versus cycle time in the knee-joint and in the hip-joint.
"Data-tips" indicate the maximum values (**peak-value**).

3.2. Some examples of dynamic joint-moments curves.

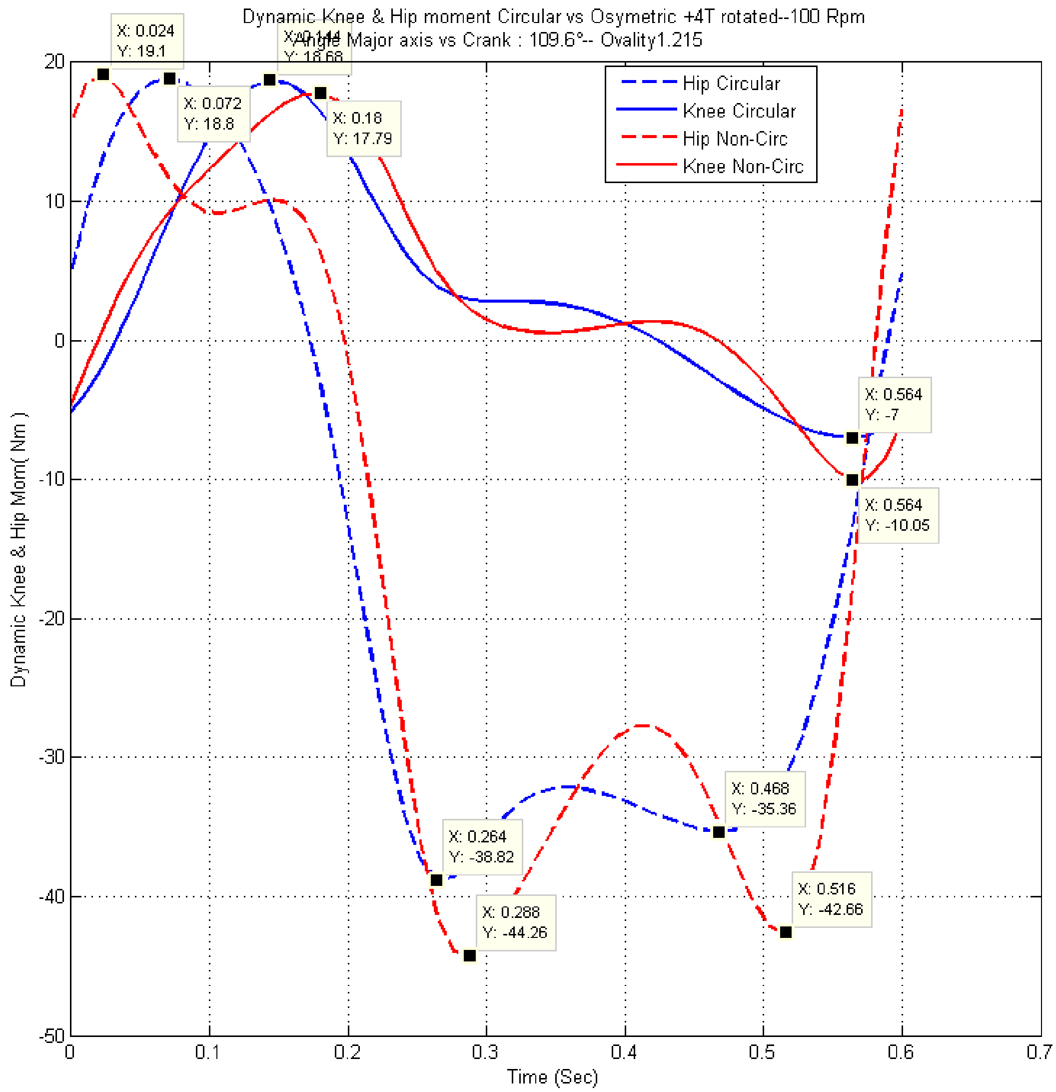


Figure 4: Curve profile of dynamic knee and hip moment - 100 rpm Circular chainring vs Osymetric-crank orientation angle 109.6° - ovality 1.215

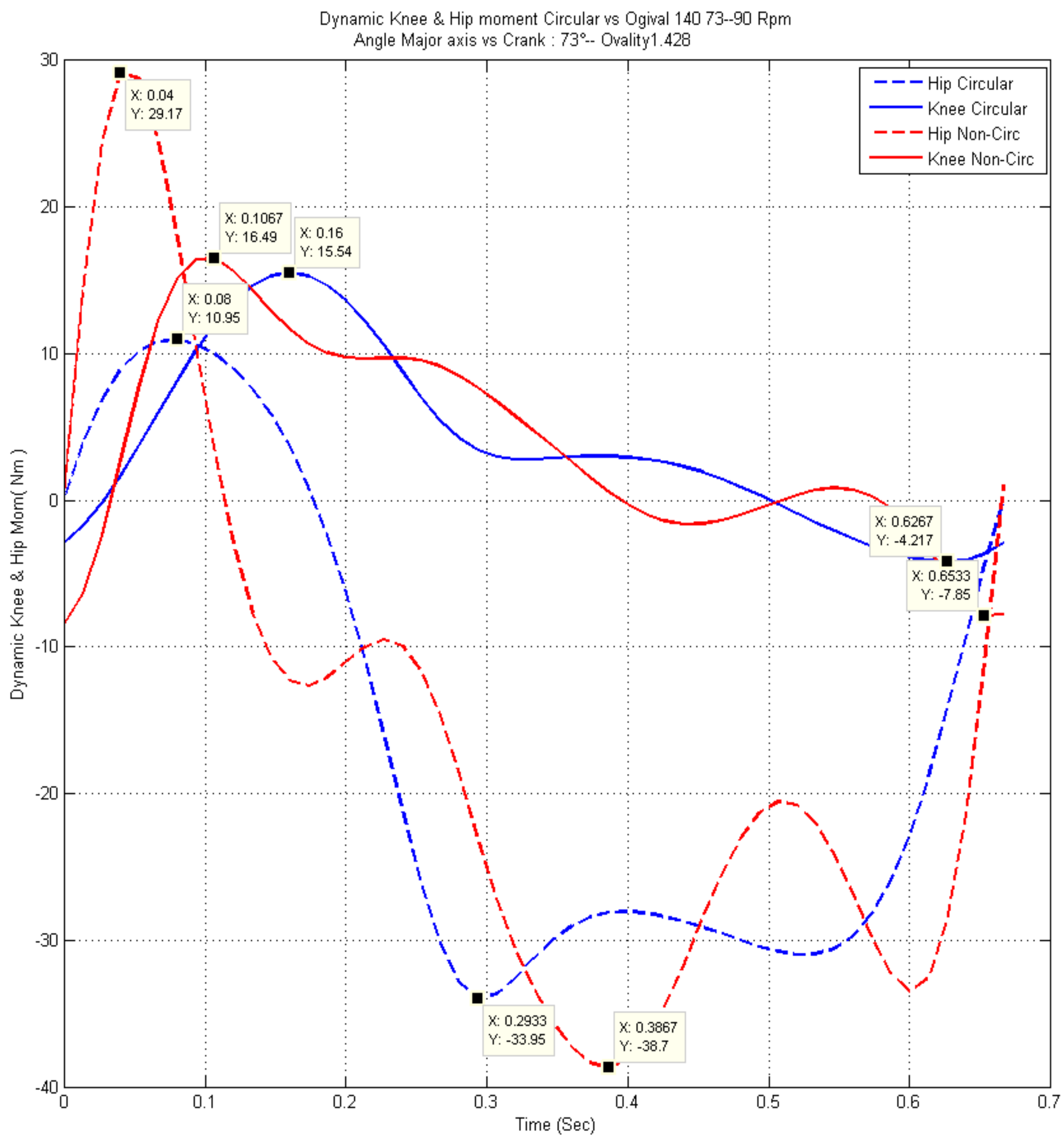


Figure 5: Curve profile of dynamic knee and hip moment - 90 rpm
Circular chainring vs Ogival 140-crank orientation angle 73°
- ovality 1.428

Notice the extremely erratic path of the Ogival curves.

3.3. Some examples of dynamic joint-power curves.

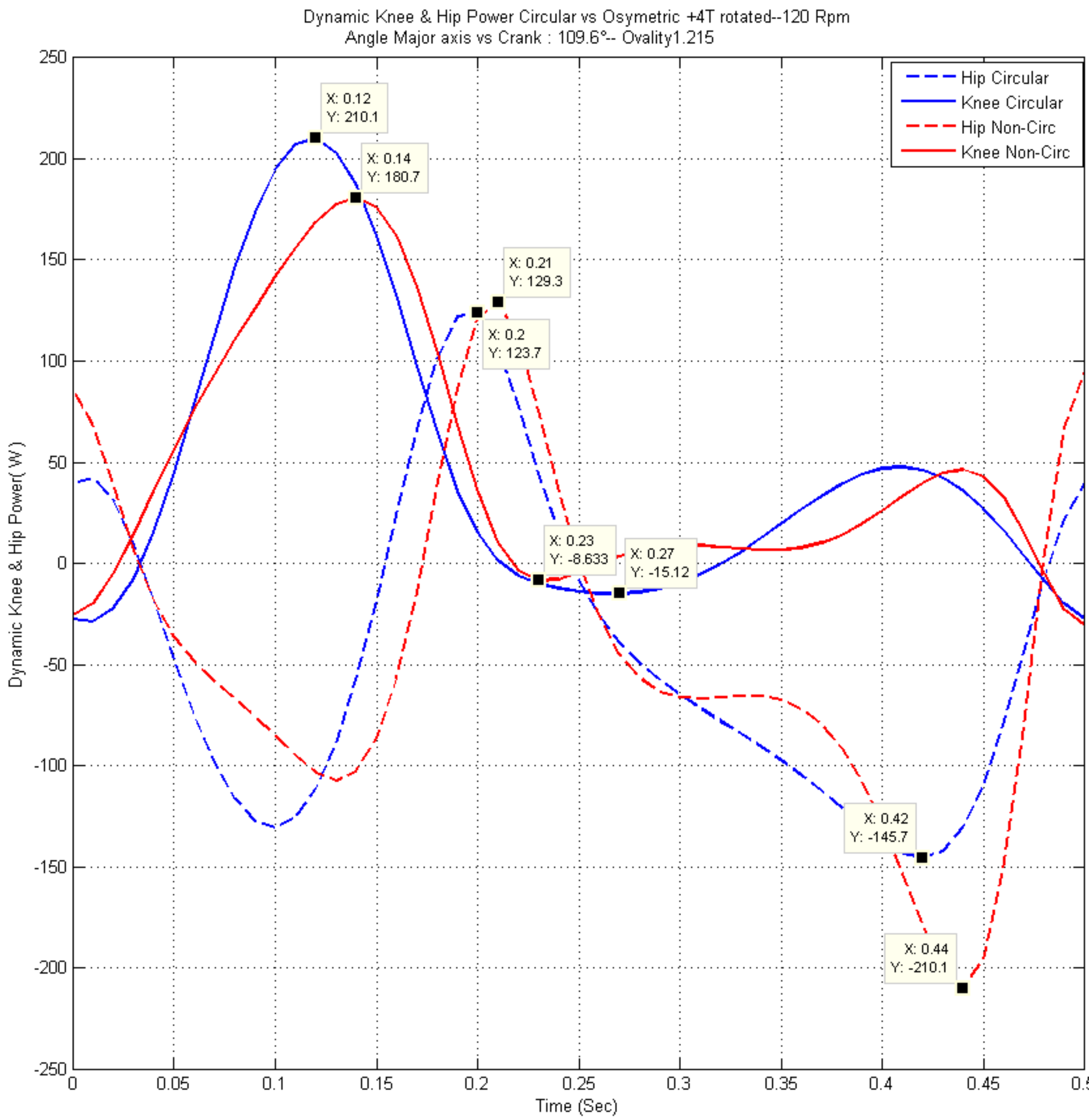


Figure 6: Curve profile of dynamic knee and hip power - 120 rpm
Circular chainring vs Osymetric crank-orientation angle 109.6°
- ovality 1.215

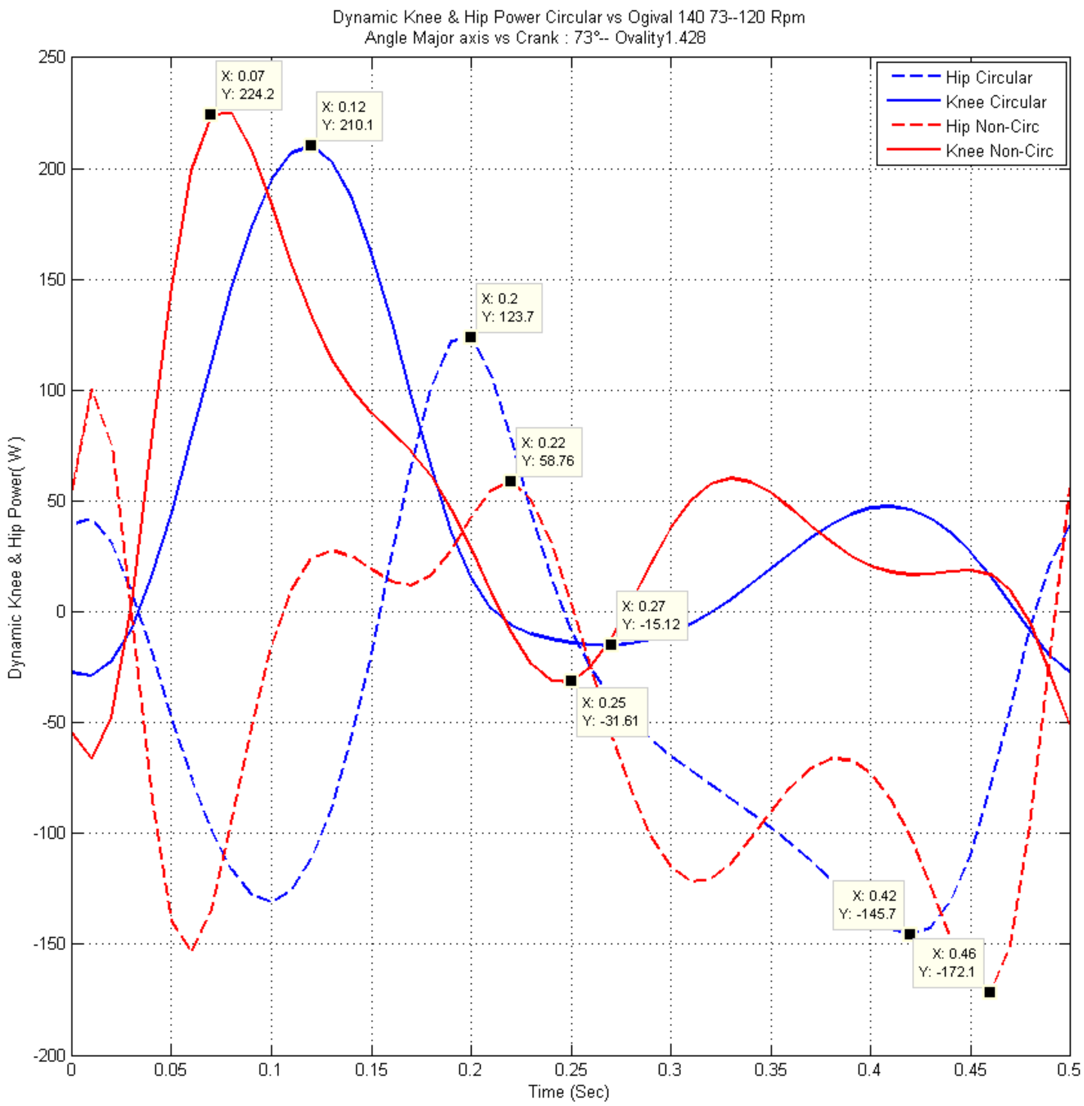


Figure 7: Curve profile of dynamic knee and hip power - 120 rpm
Circular chainring vs Ogival 140 crank-orientation angle 73°
- ovality 1.428

Notice the extremely erratic path of the Ogival curves.

3.4 Relative importance of dynamic joint-moments/power

Dynamic joint moments/power are relatively important when being compared to total joint moments/power assuming par example 104 W average crank power per single-leg at 90 rpm (see "basic study").
This is explained in the next two graphs (fig 8 dynamic; fig 9 total)

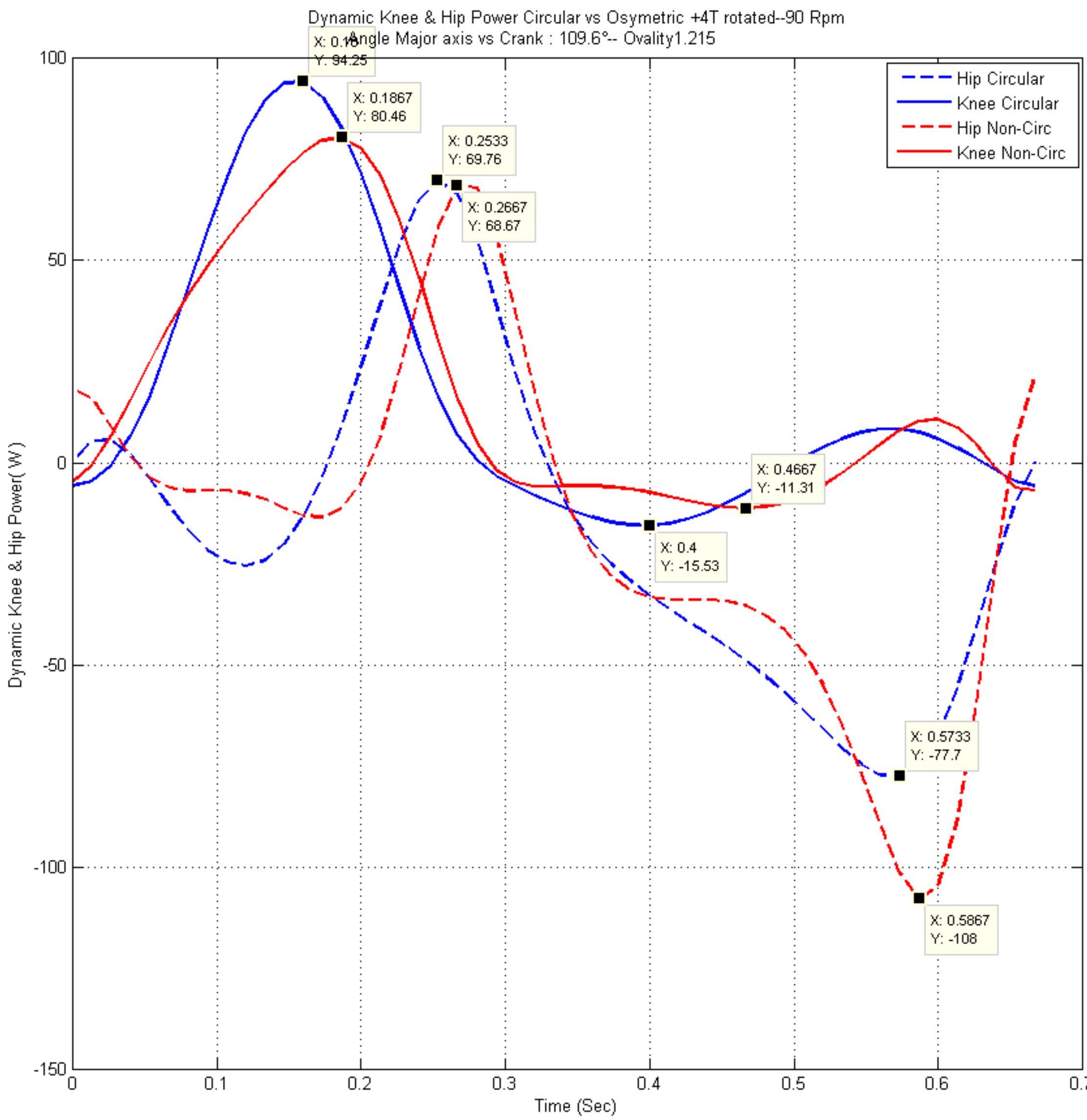


Figure 8: Curve profile of dynamic knee and hip power - 90 rpm
Circular chainring vs Osymetric crank-orientation angle 109.6°
- ovality 1.215

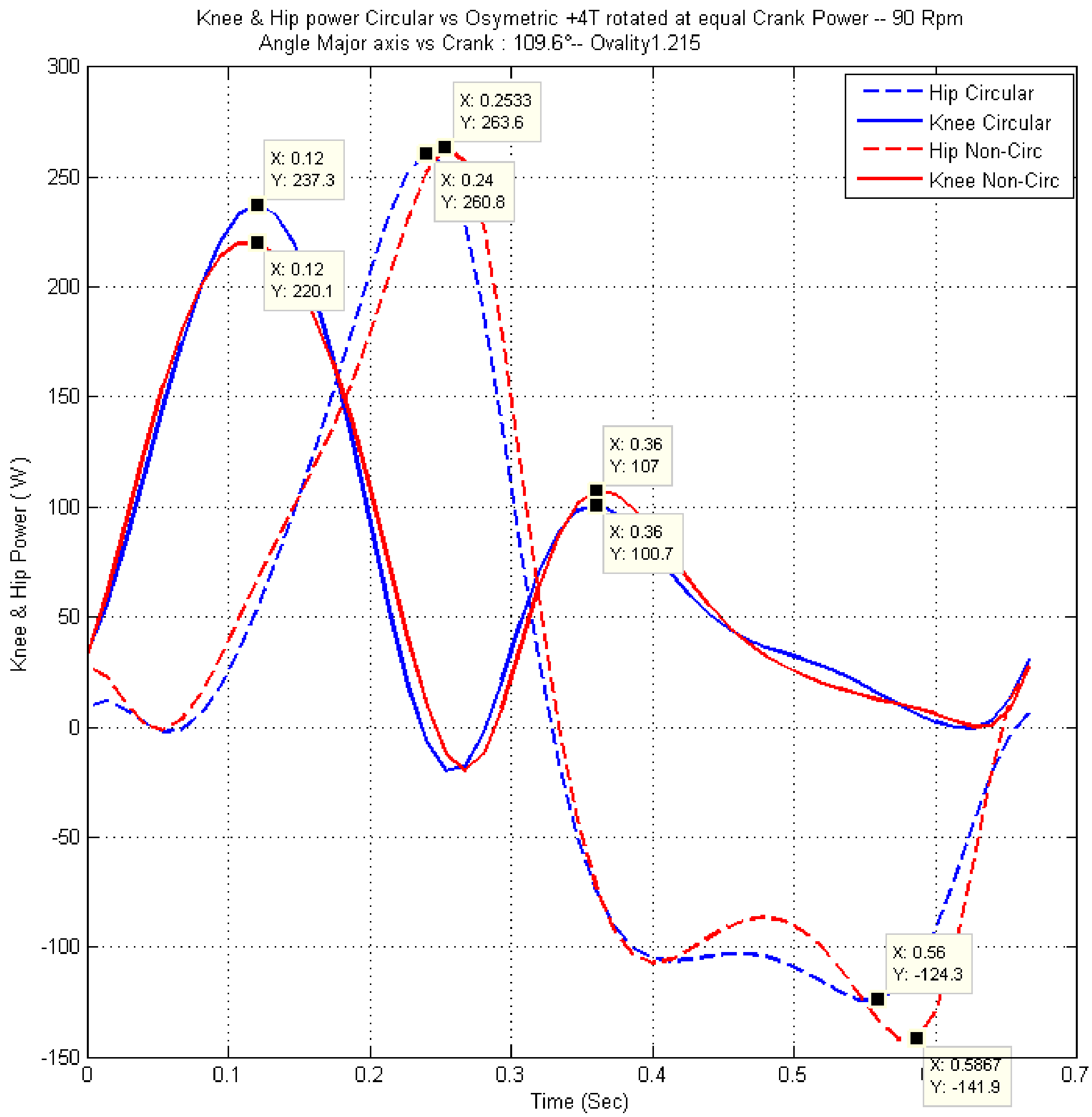


Figure 9: Curve profile of total knee and hip power
Average crank power 104 W per single-leg at 90 rpm ("basic study")
Circular chainring vs Osymetric crank-orientation angle 109.6°
-ovality 1.215

For a circular chainring:
-total knee peak-power extensor muscles equals 237.3 W (hip 260.8 W)
-dynamic knee peak-power extensor muscles equals 94.25 W (hip 69.76 W) being 39.7 % (hip 26.7 %) of total

For the Osymetric non-circular chainring - crank orientation angle 109.6°
-total knee peak-power extensor muscles equals 220.1 W (hip 263.6 W)
-dynamic knee peak-power extensor muscles equals 80.46 W (hip 68.67 W) being 36.6 % (hip 26.1 %) of total
assuming 90 rpm and 104 W average crank power per single-leg.

3.5. Result tables and graphs dynamic peak joint-moments and - power.

The **peak-values** of the dynamic moments/power calculated by the mathematical model are a function of the parameters chainring shape, ovality, crank orientation angle and pedaling cadence.

Calculations were executed for extensor and flexor muscles for both the knee and the hip joint.

All these results are presented below in tables ("spreadsheet") and visualised in graphs by the use of "OpenOffice-Calc", which should make interpretation easier.

3.5.1. Result tables of dynamic peak knee-moments (result table 1).

Dynamic Peak knee moments Nm	Extensors RPM →						
	40	60	80	90	100	120	140
Circular	5,23	8,16	12,72	15,54	18,68	25,97	34,58
Osy-Orig	5,64	7,87	11,46	13,69	16,19	22,16	29,19
Osy+4	5,36	7,50	11,94	14,70	17,79	24,94	33,40
Osy+5	5,32	7,75	12,39	15,21	18,43	25,65	34,64
Q-Ring-Orig	5,44	7,98	12,08	14,66	17,55	24,23	32,12
Q-ring+4	5,34	7,64	11,71	14,25	17,09	23,80	31,72
Optimal	5,52	7,18	11,54	14,13	17,16	24,04	32,23
Optimal+1	5,46	7,50	12,11	14,90	17,92	25,26	33,78
Ogival-140-73	6,18	9,28	13,74	16,49	19,63	26,88	35,46
Ogival-140-107	5,85	7,50	11,49	14,20	17,23	24,25	32,54
Polchlopek-Orig.	5,40	7,30	11,32	13,84	16,70	23,30	31,10
Polchlopek+1	5,33	7,37	11,62	14,29	17,13	23,80	32,14

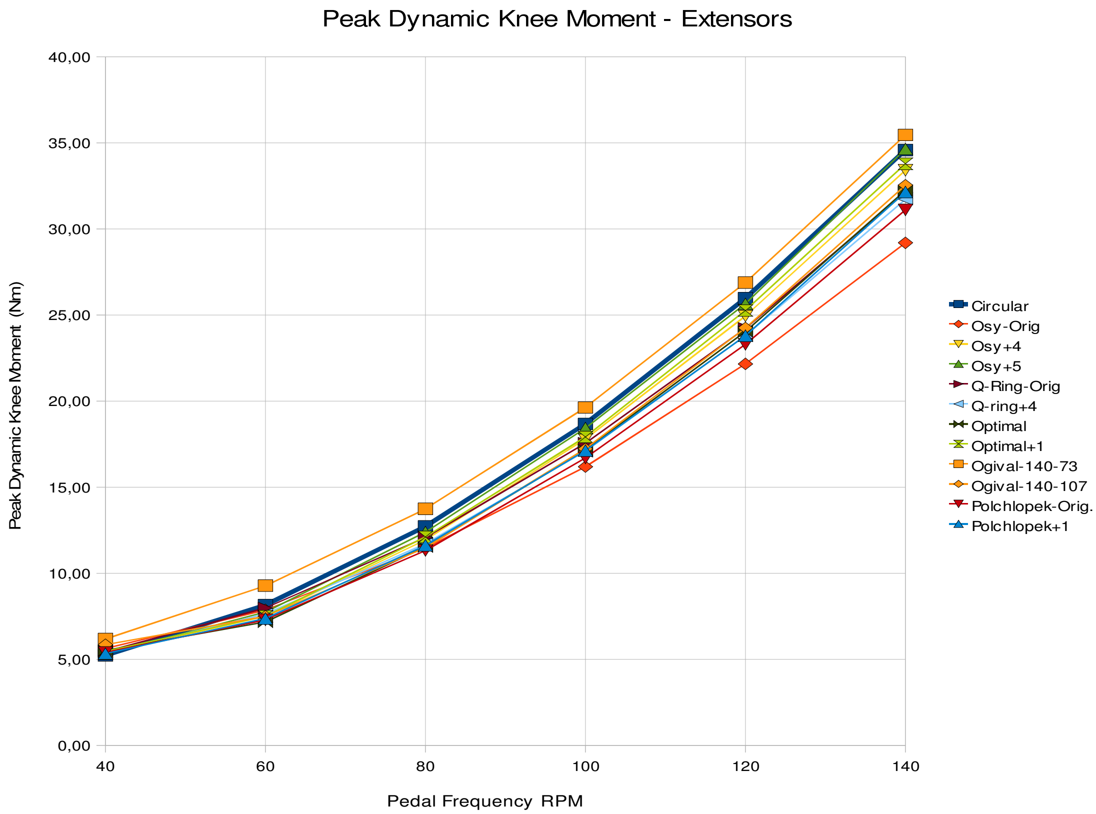
Dynamic Peak knee moments Nm	Flexors RPM →						
	40	60	80	90	100	120	140
Circular	6,11	4,52	-1,73	-4,22	-7,00	-13,45	-21,09
Osy-Orig	6,43	4,59	-3,53	-6,37	-9,55	-16,91	-25,85
Osy+4	6,47	5,07	-3,66	-6,67	-10,05	-17,86	-27,09
Osy+5	6,46	5,19	-3,50	-6,66	-10,02	-17,82	-27,03
Q-Ring-Orig	6,22	4,23	-2,30	-4,84	-7,63	-14,50	-22,23
Q-ring+4	6,30	4,57	-2,65	-5,33	-8,33	-15,27	-23,47
Optimal	6,57	5,19	-4,25	-7,38	-10,86	-19,30	-28,43
Optimal+1	6,57	5,32	-4,19	-7,35	-10,88	-19,50	-28,73
Ogival-140-73	6,62	4,84	-4,69	-7,85	-11,38	-19,80	-29,50
Ogival-140-107	6,84	5,71	-5,53	-8,98	-12,85	-22,20	-32,35
Polchlopek_Orig	6,42	4,78	-3,40	-6,28	-9,51	-16,98	-25,83
Polchlopek+1	6,43	4,91	-3,32	-6,18	-9,50	-17,50	-26,01

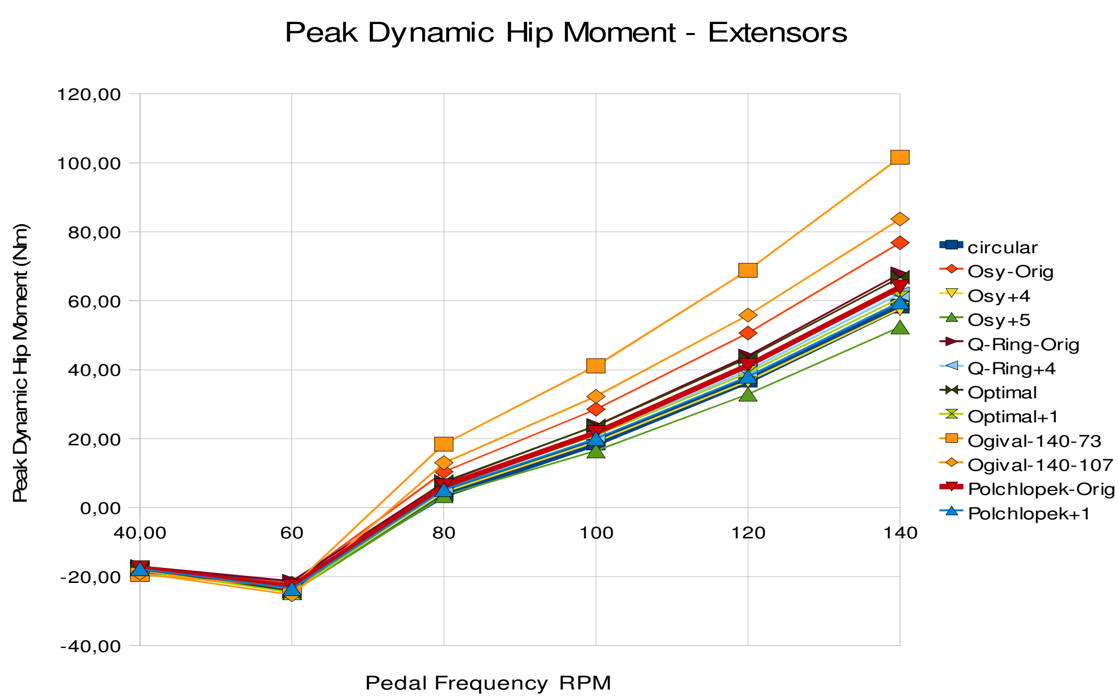
3.5.2. Result tables of dynamic peak hip-moments (result table 2).

Dynamic Peak hip moments			Extensors				
Nm			RPM →				
	40	60	80	90	100	120	140
Circular	-17,80	-22,43	3,93	10,95	18,80	36,98	58,46
Osy-Orig	-17,98	-21,88	10,44	18,99	28,54	50,66	76,80
Osy+4	-18,01	-24,03	4,55	11,46	19,10	36,79	57,70
Osy+5	-18,26	-24,45	3,50	9,46	16,50	32,91	52,41
Q-Ring-Orig	-17,07	-21,30	7,29	15,09	23,80	43,99	67,84
Q-Ring+4	-17,36	-22,37	5,68	12,94	21,04	39,82	62,01
Optimal	-17,83	-24,09	7,57	15,20	23,72	43,47	66,80
Optimal+1	-18,21	-24,66	6,01	13,06	20,94	39,09	60,78
Ogival-140-73	-19,37	-22,94	18,46	29,17	41,14	68,86	101,60
Ogival-140-107	-18,95	-25,24	13,01	22,11	32,29	55,86	83,71
Polchlopek-Orig	-17,45	-22,89	6,31	13,74	21,75	41,26	63,97
Polchlopek+1	-17,72	-23,42	5,25	12,26	20,08	38,08	59,63

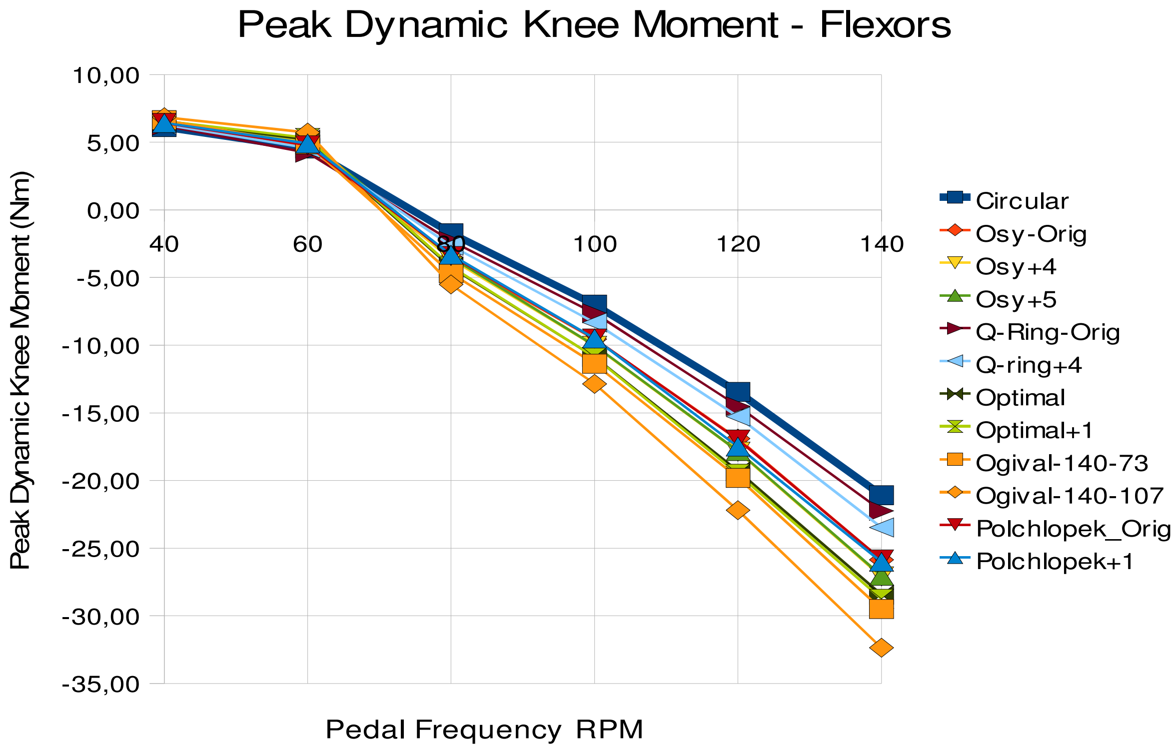
Dynamic Peak hip moments			Flexors				
Nm			RPM →				
	40	60	80	90	100	120	140
Circular	-17,47	-21,00	-29,60	-33,95	-38,82	-50,09	-63,61
Osy-Orig	-18,94	-22,66	-28,79	-34,73	-40,25	-53,02	-68,24
Osy+4	-18,94	-24,32	-32,73	-38,17	-44,26	-58,36	-75,03
Osy+5	-18,91	-24,57	-33,51	-39,01	-45,16	-59,41	-76,26
Q-Ring-Orig	-17,98	-20,80	-28,09	-32,20	-36,98	-47,95	-60,90
Q-Ring+4	-18,24	-22,17	-29,94	-34,48	-39,80	-52,00	-66,41
Optimal	-19,38	-25,13	-33,28	-38,87	-45,10	-59,41	-76,62
Optimal+1	-19,34	-25,39	-34,08	-39,88	-46,36	-61,37	-79,11
Ogival-140-73	-19,75	-23,69	-32,75	-38,70	-45,35	-60,75	-78,96
Ogival-140-107	-20,37	-27,35	-35,89	-42,33	-49,52	-66,18	-85,87
Polchlopek-Orig.	-18,77	-23,33	-31,08	-36,09	-41,70	-54,68	-70,02
Polchlopek+1	-18,71	-23,69	-31,78	-36,98	-42,80	-56,26	-72,18

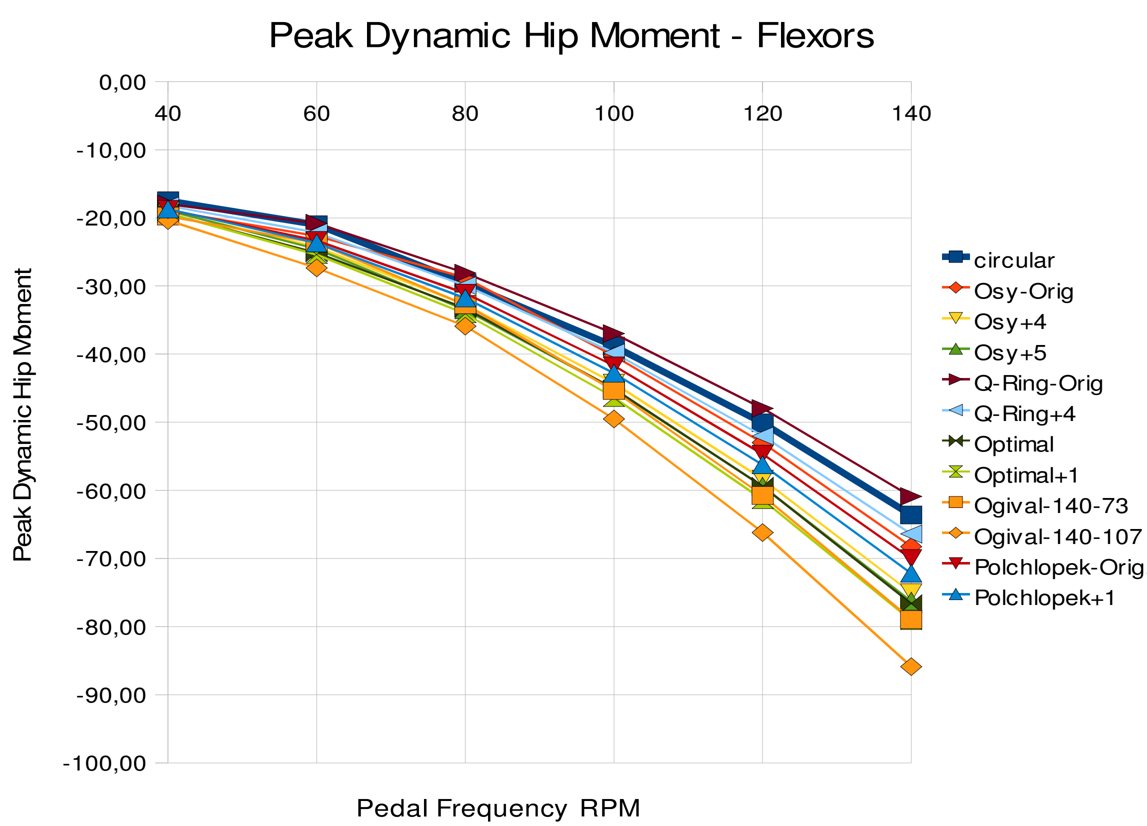
3.5.3. Graphs dynamic peak knee/peak hip-moments of the extensor muscles.
Figure 10





3.5.4. Graphs dynamic peak knee/peak hip-moments of the flexor muscles.
Figure 11





3.5.5. Result tables of dynamic peak knee-power (result table 3).

Dynamic Peak knee Power			Extensors				
W			RPM →				
	40	60	80	90	100	120	140
Circular	14,00	33,40	68,80	94,25	125,90	210,10	326,40
Osy-Orig	14,18	30,43	59,03	79,38	104,30	169,90	260,40
Osy+4	11,78	27,85	58,31	80,46	107,80	180,70	281,40
Osy+5	11,79	29,26	61,81	85,35	114,50	192,00	299,20
Q-Ring-Orig	14,26	32,09	64,75	87,87	116,30	192,40	297,70
Q-ring+4	13,33	27,85	60,33	82,09	109,20	181,40	281,10
Optimal	11,97	25,31	53,47	73,62	98,53	164,70	256,20
Optimal+1	11,40	27,16	57,53	78,89	106,20	178,30	278,40
Ogival-140-73	17,19	39,27	77,54	104,40	137,40	224,20	346,00
Ogival-140-107	12,91	25,47	46,18	65,39	87,96	148,10	231,40
Polchlopek-Orig.	12,76	27,63	55,83	76,21	101,30	168,70	261,90
Polchlopek+1	12,35	27,63	57,13	78,44	104,70	174,60	271,00

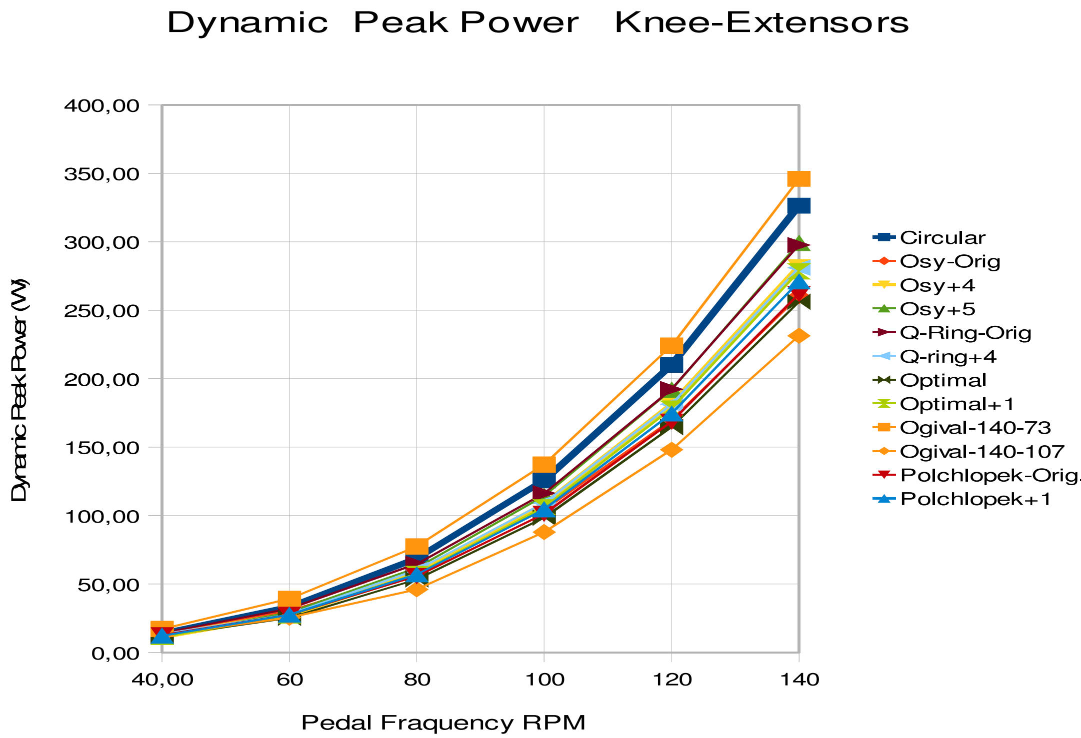
Dynamic Peak knee Power			Flexors				
W			RPM →				
	40	60	80	90	100	120	140
Circular	-13,45	-16,04	-16,00	-15,53	-15,10	-15,12	-16,84
Osy-Orig	-12,54	-13,53	-10,55	-11,54	-13,33	-18,64	-26,22
Osy+4	-12,50	-15,27	-13,94	-11,31	-6,25	-8,64	-12,07
Osy+5	-12,73	-15,85	-15,44	-13,49	-5,07	-6,98	-9,38
Q-Ring-Orig	-13,11	-14,79	-13,20	-13,45	-14,31	-17,99	-23,62
Q-ring+4	-12,90	-15,27	-12,24	-10,35	-10,46	-13,29	-16,79
Optimal	-12,16	-14,73	-13,08	-10,24	-5,70	-10,11	-14,56
Optimal+1	-12,36	-15,46	-14,88	-12,84	-9,41	-8,14	-11,39
Ogival-140-73	-12,49	-11,59	-14,54	-17,69	-21,67	-31,61	-46,16
Ogival-140-107	-11,40	-14,28	-14,03	-12,37	-9,50	-12,10	-17,88
Polchlopek-Orig.	-12,55	-14,59	-11,54	-8,46	-9,27	-12,56	-16,55
Polchlopek+1	-12,59	-15,03	-12,93	-9,68	-7,85	-10,13	-12,80

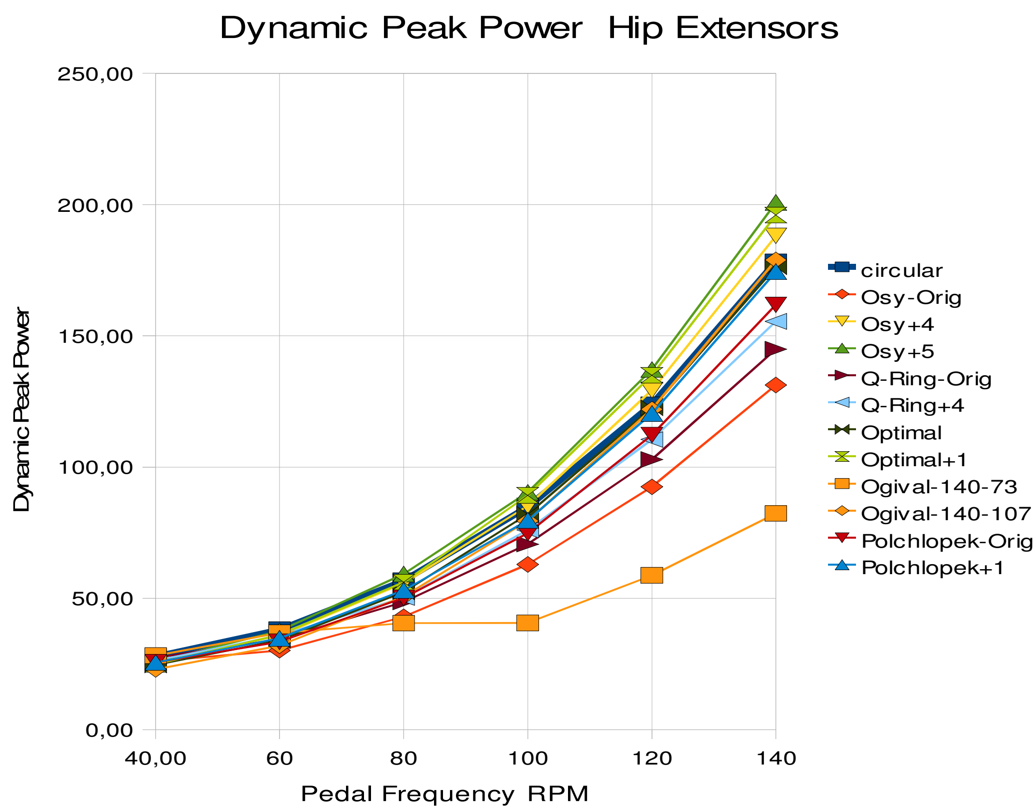
3.5.6. Result tables of dynamic peak hip-power (result table 4).

Dynamic Peak hip Power			Extensors				
W			RPM →				
	40	60	80	90	100	120	140
Circular	27,91	38,11	56,78	69,76	84,82	123,70	178,20
Osy-Orig	26,06	30,19	43,01	51,65	62,94	92,49	131,30
Osy+4	25,51	35,87	55,81	68,67	85,24	129,30	188,10
Osy+5	26,00	37,60	59,27	73,62	90,42	137,20	200,80
Q-Ring-Orig	27,33	34,44	48,64	58,28	70,66	102,90	144,90
Q-Ring+4	26,36	35,87	50,31	62,19	76,03	110,50	155,50
Optimal	24,61	34,06	52,46	66,02	82,04	122,60	176,30
Optimal+1	24,96	36,16	56,15	71,26	89,23	135,00	196,00
Ogival-140-73	28,21	36,87	40,58	39,95	40,68	58,76	82,38
Ogival-140-107	22,96	32,01	50,73	62,98	79,54	122,00	178,90
Polchlopek-Orig.	25,64	33,47	50,20	61,29	74,85	112,20	161,80
Polchlopek+1	25,61	34,78	53,10	65,20	79,73	120,40	174,50

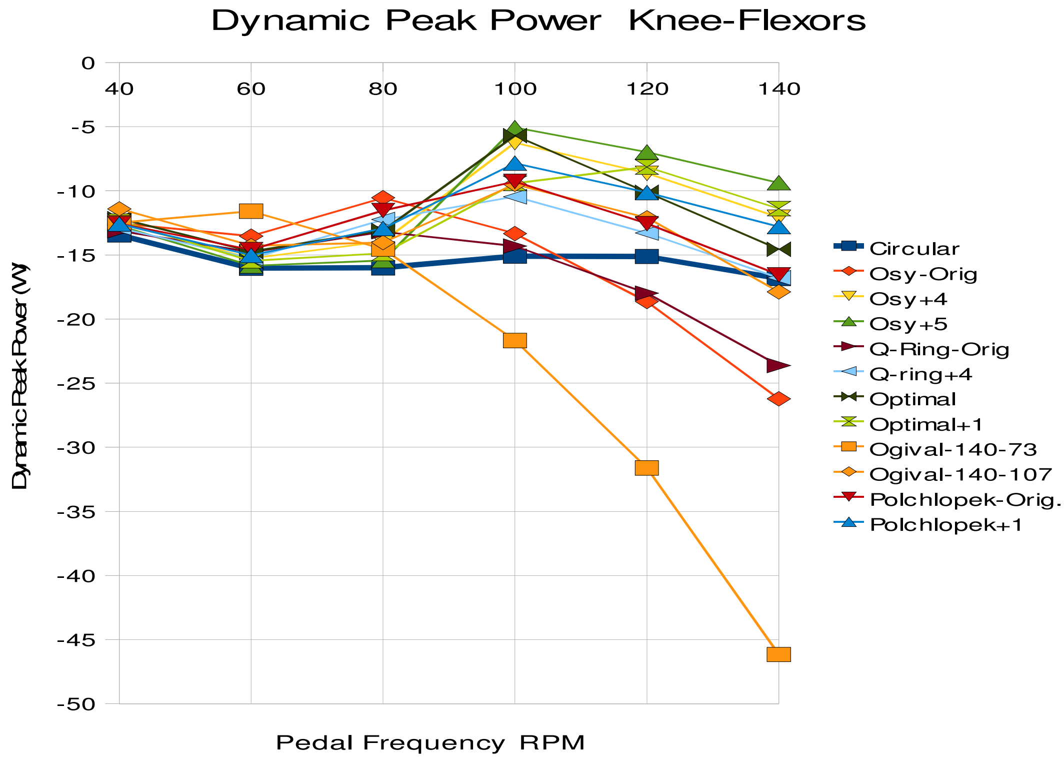
Dynamic Peak hip Power			Flexors				
W			RPM →				
	40	60	80	90	100	120	140
Circular	-22,87	-38,49	-62,10	-77,70	-96,67	-145,70	-210,90
Osy-Orig	-25,70	-44,30	-72,79	-91,38	-113,30	-168,70	-242,00
Osy+4	-27,58	-49,72	-84,16	-108,00	-136,60	-210,10	-308,70
Osy+5	-27,51	-49,61	-86,04	-110,30	-139,40	-213,90	-313,80
Q-Ring-Orig	-23,30	-38,92	-62,10	-77,70	-93,46	-136,70	-210,90
Q-Ring+4	-24,80	-49,72	-69,74	-87,74	-109,00	-162,80	-236,30
Optimal	-28,83	-52,42	-89,79	-114,60	-143,80	-223,30	-330,30
Optimal+1	-28,85	-53,25	-91,53	-118,40	-150,70	-234,00	-346,40
Ogival-140-73	-26,26	-45,30	-74,48	-93,41	-115,70	-172,10	-246,50
Ogival-140-107	-31,82	-59,45	-105,90	-137,30	-175,10	-272,90	-404,90
Polchlopek-Orig.	-28,50	-46,63	-77,01	-97,61	-122,70	-186,90	-272,60
Polchlopek+1	-26,75	-47,59	-79,73	-101,80	-128,20	-195,70	-286,10

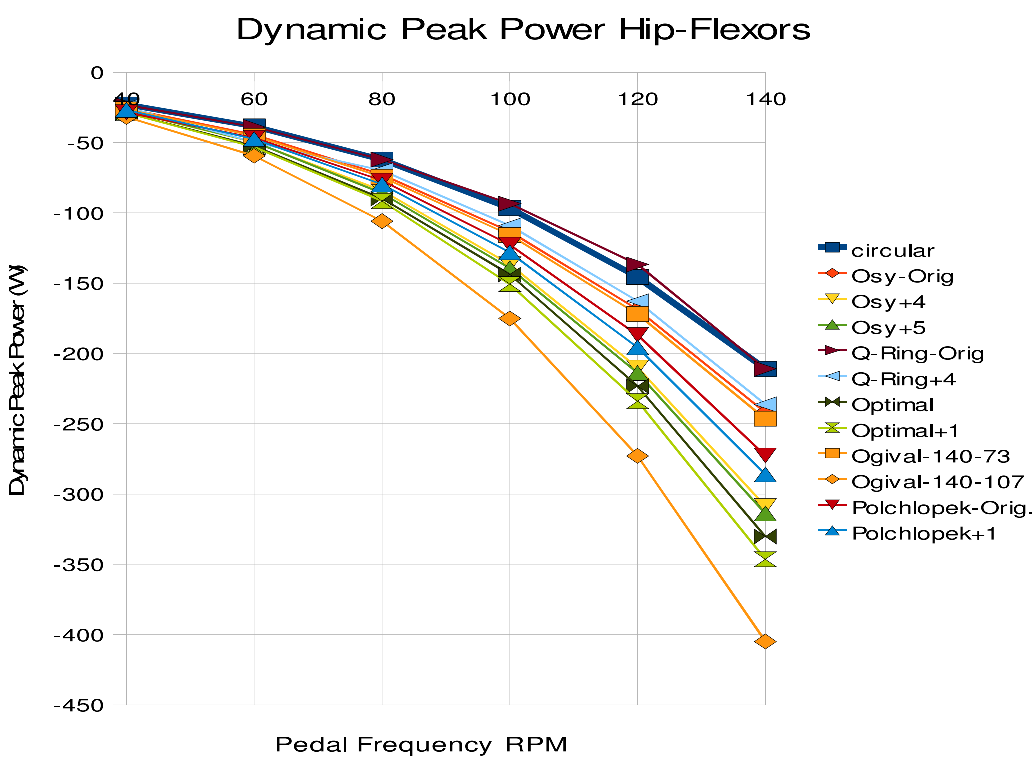
3.5.7. Graphs dynamic peak knee/peak hip-power of the extensor muscles.
Figure 12





3.5.8. Graphs dynamic peak knee/peak hip-power of the flexor muscles.
Figure 13





3.6. Comparison peak values dynamic moments/power of each non-circular chainring versus the conventional circular one.

Differences were calculated between the peak values of the dynamic moments/power of each non-circular chainwheel and the corresponding peak values of the circular chainring, taken as the reference.
This approach makes the analysis much easier and may help to come to conclusions.

3.6.1. Difference tables of dynamic peak knee-moments (result table 5).

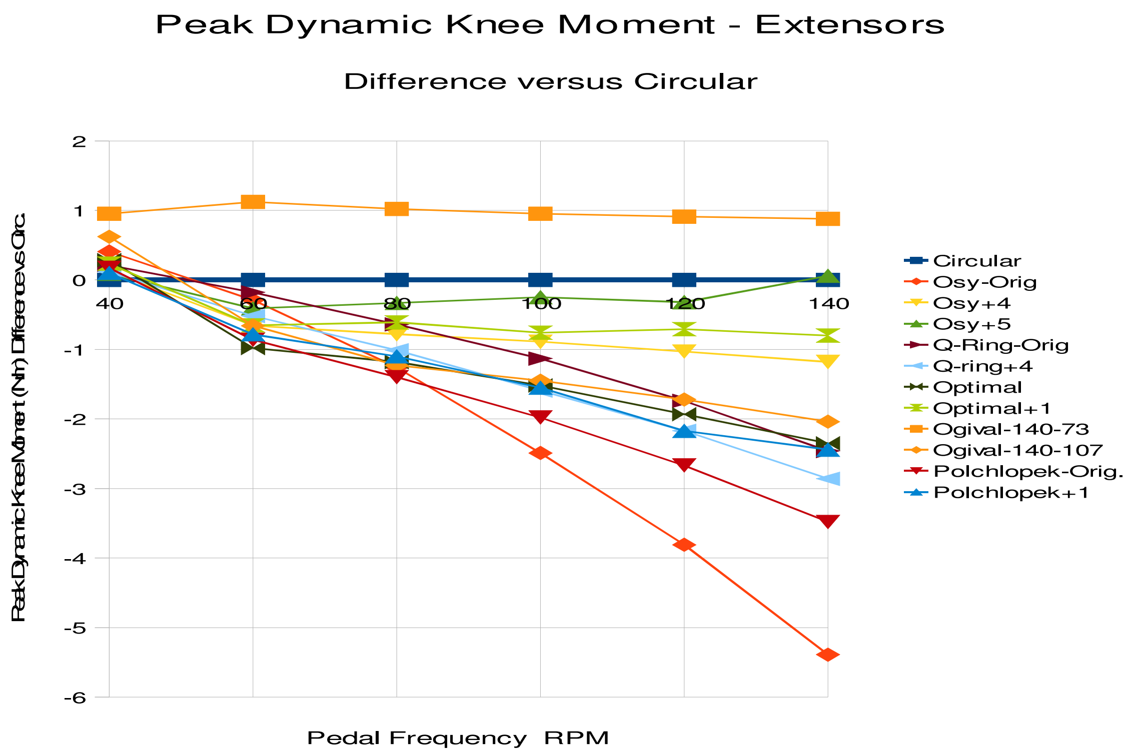
Dynamic Peak knee moments Difference vs. Circular	Nm		Extensors RPM →				
	40	60	80	90	100	120	140
Circular	0,00	0,00	0,00	0,00	0,00	0,00	0,00
Osy-Orig	0,41	-0,29	-1,26	-1,85	-2,49	-3,81	-5,39
Osy+4	0,13	-0,66	-0,78	-0,84	-0,89	-1,03	-1,18
Osy+5	0,09	-0,41	-0,33	-0,33	-0,25	-0,32	0,06
Q-Ring-Orig	0,21	-0,18	-0,64	-0,88	-1,13	-1,74	-2,46
Q-ring+4	0,12	-0,52	-1,01	-1,29	-1,59	-2,17	-2,86
Optimal	0,29	-0,98	-1,18	-1,41	-1,52	-1,93	-2,35
Optimal+1	0,23	-0,65	-0,61	-0,64	-0,76	-0,71	-0,80
Ogival-140-73	0,95	1,12	1,02	0,95	0,95	0,91	0,88
Ogival-140-107	0,62	-0,66	-1,23	-1,34	-1,45	-1,72	-2,04
Polchlopek-Orig.	0,17	-0,86	-1,40	-1,70	-1,98	-2,67	-3,48
Polchlopek+1	0,10	-0,78	-1,10	-1,25	-1,55	-2,17	-2,44

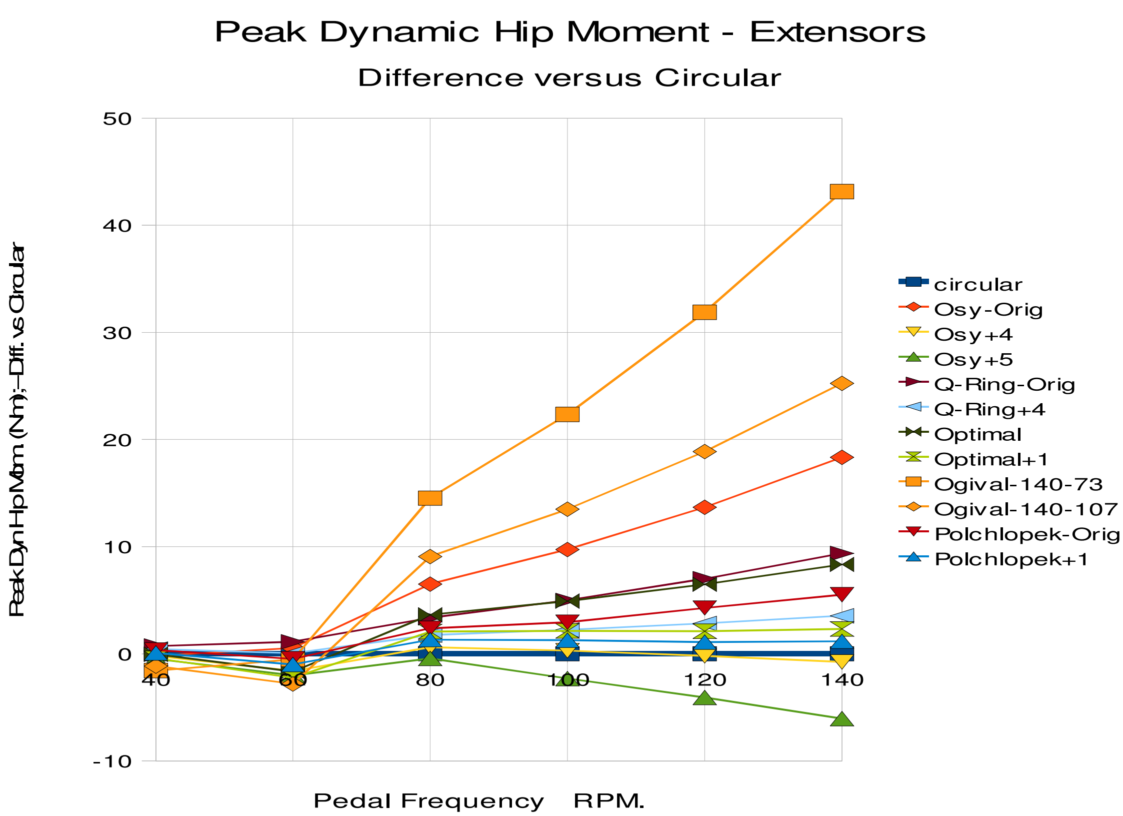
Dynamic Peak knee moments Difference vs. Circular	Nm		Flexors RPM →				
	40	60	80	90	100	120	140
Circular	0,00	0,00	0,00	0,00	0,00	0,00	0,00
Osy-Orig	0,32	0,06	1,80	2,15	2,55	3,46	4,76
Osy+4	0,36	0,55	1,93	2,46	3,05	4,41	6,00
Osy+5	0,35	0,66	1,77	2,44	3,02	4,37	5,94
Q-Ring-Orig	0,11	-0,30	0,58	0,63	0,63	1,05	1,14
Q-ring+4	0,19	0,04	0,92	1,11	1,33	1,82	2,38
Optimal	0,46	0,66	2,53	3,16	3,86	5,85	7,34
Optimal+1	0,47	0,79	2,46	3,13	3,88	6,05	7,64
Ogival-140-73	0,52	0,32	2,96	3,63	4,38	6,35	8,41
Ogival-140-107	0,73	1,19	3,80	4,77	5,85	8,75	11,26
Polchlopek-Orig.	0,31	0,26	1,67	2,06	2,51	3,53	4,74
Polchlopek+1	0,32	0,39	1,59	1,96	2,50	4,05	4,92

3.6.2. Difference tables of dynamic peak hip-moments (result table 6).

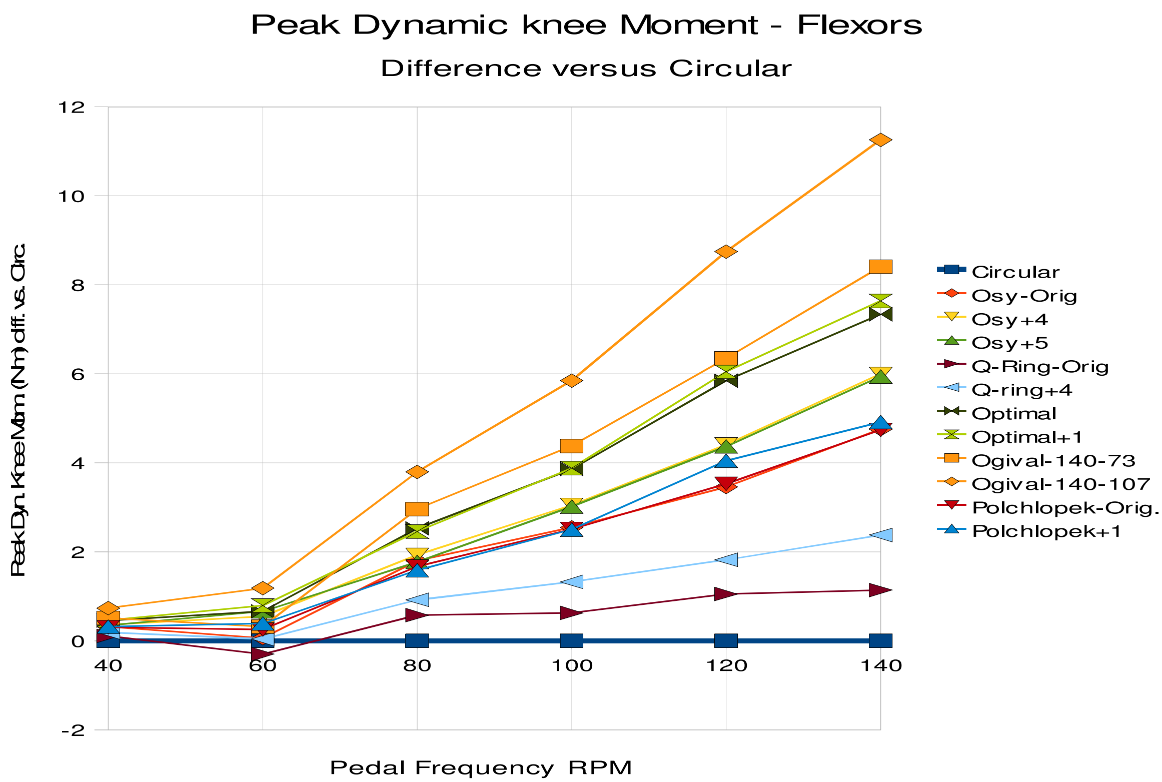
Dynamic Peak hip moments Difference vs. Circular	Nm		Extensors RPM →					Dynamic Peak hip moments Difference vs. Circular	Nm		Flexors RPM →				
	40	60	80	90	100	120	140		40	60	80	90	100	120	140
circular	0,00	0,00	0,00	0,00	0,00	0,00	0,00	circular	0,00	0,00	0,00	0,00	0,00	0,00	0,00
Osy-Orig	-0,18	0,55	6,51	8,04	9,74	13,68	18,34	Osy-Orig	1,47	1,66	-0,81	0,78	1,43	2,93	4,63
Osy+4	-0,21	-1,60	0,62	0,51	0,30	-0,19	-0,76	Osy+4	1,47	3,32	3,13	4,22	5,44	8,27	11,42
Osy+5	-0,46	-2,02	-0,43	-1,49	-2,30	-4,07	-6,05	Osy+5	1,44	3,57	3,91	5,06	6,34	9,32	12,65
Q-Ring-Orig	0,73	1,13	3,36	4,14	5,00	7,01	9,38	Q-Ring-Orig	0,51	-0,20	-1,51	-1,75	-1,84	-2,14	-2,71
Q-Ring+4	0,44	0,06	1,76	1,99	2,24	2,84	3,55	Q-Ring+4	0,77	1,17	0,34	0,53	0,98	1,91	2,80
Optimal	-0,03	-1,66	3,64	4,25	4,92	6,49	8,34	Optimal	1,91	4,13	3,68	4,92	6,28	9,32	13,01
Optimal+1	-0,41	-2,23	2,08	2,11	2,14	2,11	2,32	Optimal+1	1,87	4,39	4,48	5,93	7,54	11,28	15,50
Ogival-140-73	-1,57	-0,51	14,53	18,22	22,34	31,88	43,14	Ogival-140-73	2,28	2,69	3,15	4,75	6,53	10,66	15,35
Ogival-140-107	-1,15	-2,81	9,08	11,16	13,49	18,88	25,25	Ogival-140-107	2,90	6,35	6,29	8,38	10,70	16,09	22,26
Polchlopek-Orig.	0,35	-0,46	2,38	2,79	2,95	4,28	5,51	Polchlopek-Orig.	1,30	2,33	1,48	2,14	2,88	4,59	6,41
Polchlopek+1	0,08	-0,99	1,33	1,31	1,28	1,10	1,17	Polchlopek+1	1,24	2,69	2,18	3,03	3,98	6,17	8,57

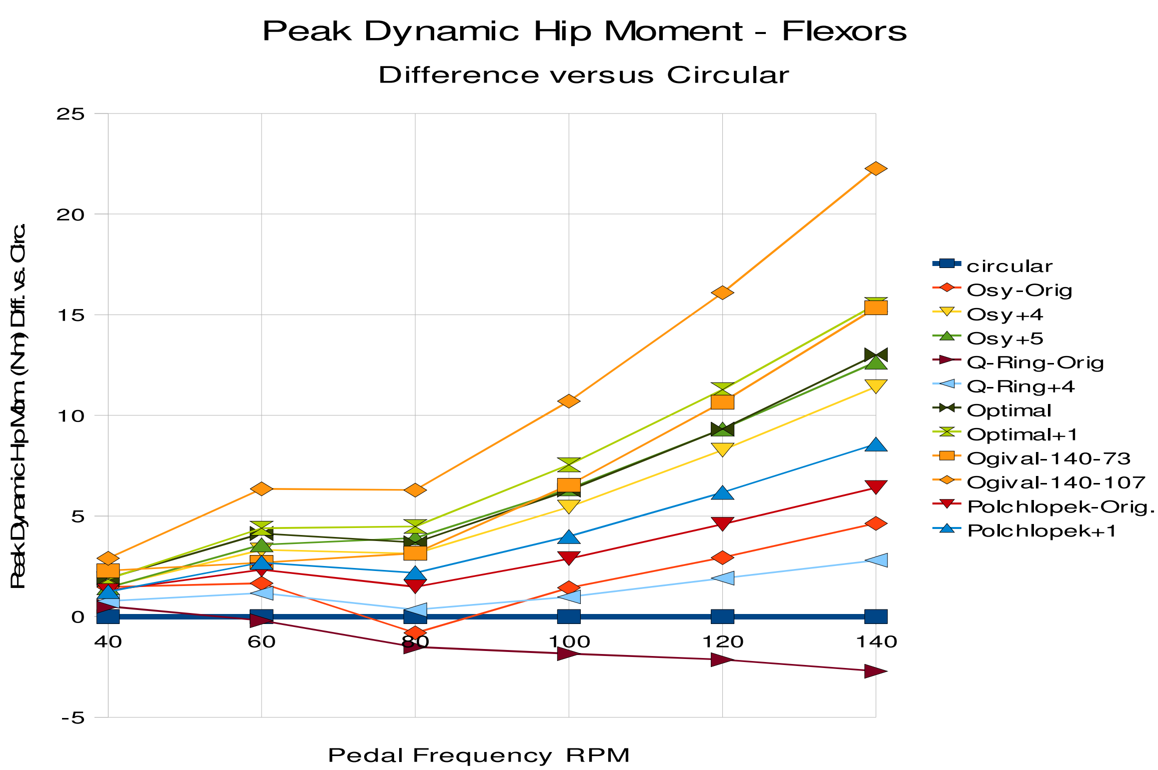
3.6.3. Graphs differences dynamic peak knee/peak hip-moments of the extensor muscles. Figure 14





3.6.4. Graphs differences dynamic peak knee/peak hip-moments of the flexor muscles. Figure 15





3.6.5. Difference tables of dynamic peak knee-power (result table 7).

Dynamic Peak knee Power	W		Extensors				
Diff. Vs. Circ.			RPM →				
	40	60	80	90	100	120	140
Circular	0,00	0,00	0,00	0,00	0,00	0,00	0,00
Osy-Orig	0,18	-2,97	-9,77	-14,87	-21,60	-40,20	-66,00
Osy+4	-2,22	-5,55	-10,49	-13,79	-18,10	-29,40	-45,00
Osy+5	-2,21	-4,14	-6,99	-8,90	-11,40	-18,10	-27,20
Q-Ring-Orig	0,26	-1,31	-4,05	-6,38	-9,60	-17,70	-28,70
Q-ring+4	-0,67	-5,55	-8,47	-12,16	-16,70	-28,70	-45,30
Optimal	-2,03	-8,09	-15,33	-20,63	-27,37	-45,40	-70,20
Optimal+1	-2,60	-6,24	-11,27	-15,36	-19,70	-31,80	-48,00
Ogival-140-73	3,19	5,87	8,74	10,15	11,50	14,10	19,60
Ogival-140-107	-1,09	-7,93	-22,62	-28,86	-37,94	-62,00	-95,00
Polchlopek-Orig	-1,24	-5,77	-12,97	-18,04	-24,60	-41,40	-64,50
Polchlopek+1	-1,65	-5,77	-11,67	-15,81	-21,20	-35,50	-55,40

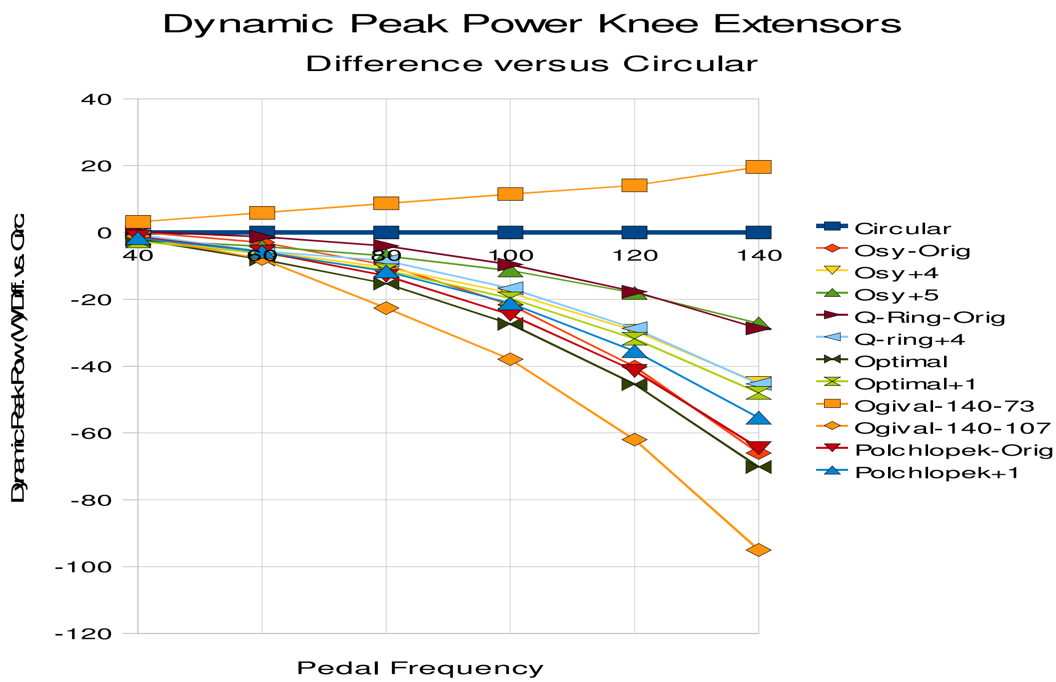
Dynamic Peak knee Power	W		Flexors				
Diff. Vs. Circ.			RPM →				
	40	60	80	90	100	120	140
Circular	0,00	0,00	0,00	0,00	0,00	0,00	0,00
Osy-Orig	0,91	2,51	5,45	3,99	1,77	-3,52	-9,38
Osy+4	0,95	0,77	2,06	4,22	8,85	6,48	4,77
Osy+5	0,72	0,19	0,56	2,04	10,03	8,15	7,46
Q-Ring-Orig	0,34	1,25	2,80	2,08	0,79	-2,87	-6,78
Q-ring+4	0,55	0,77	3,76	5,18	4,64	1,83	0,05
Optimal	1,29	1,31	2,92	5,29	9,40	5,01	2,28
Optimal+1	1,09	0,58	1,12	2,69	5,69	6,98	5,45
Ogival-140-73	0,96	4,45	1,46	-2,16	-6,57	-16,49	-29,32
Ogival-140-107	2,05	1,76	1,97	3,16	5,60	3,02	-1,04
Polchlopek-Orig	0,90	1,45	4,46	7,07	5,83	2,56	0,29
Polchlopek+1	0,86	1,01	3,07	5,85	7,25	4,99	4,04

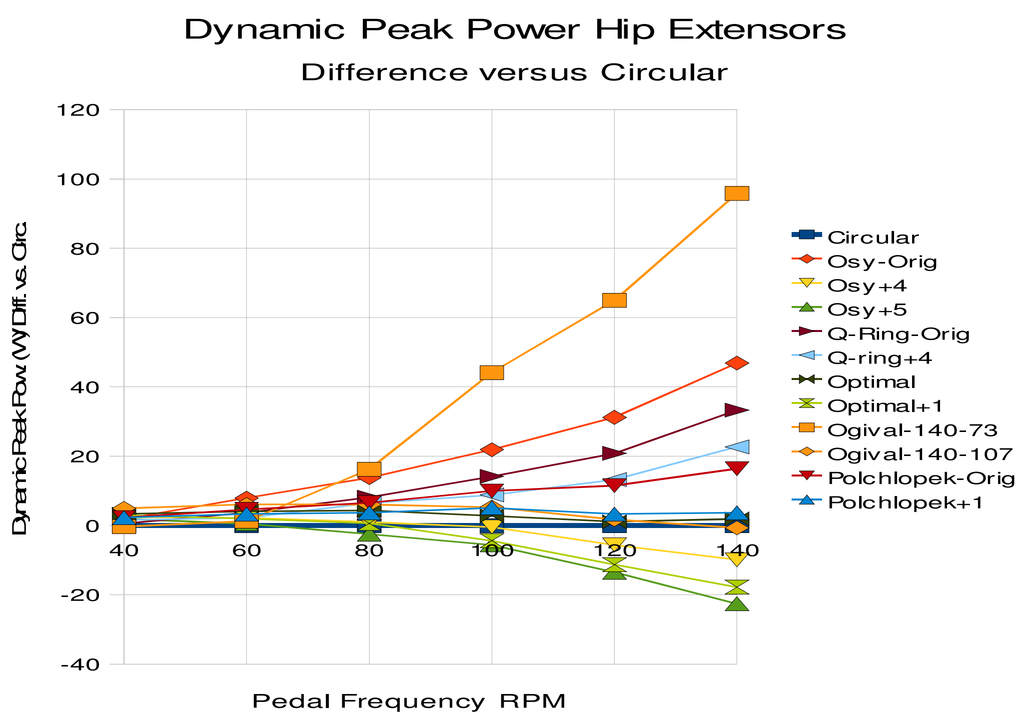
3.6.6. Difference tables of dynamic peak hip-power (result table 8).

Dynamic Peak Hip Power	W		Extensors				
Diff. Vs. Circ.			RPM →				
	40	60	80	90	100	120	140
Circular	0,00	0,00	0,00	0,00	0,00	0,00	0,00
Osy-Orig	1,85	7,92	13,77	18,11	21,88	31,21	46,90
Osy+4	2,40	2,24	0,97	1,09	-0,42	-5,60	-9,90
Osy+5	1,91	0,51	-2,49	-3,86	-5,60	-13,50	-22,60
Q-Ring-Orig	0,58	3,67	8,14	11,48	14,16	20,80	33,30
Q-ring+4	1,55	2,24	6,47	7,57	8,79	13,20	22,70
Optimal	3,30	4,05	4,32	3,74	2,78	1,10	1,90
Optimal+1	2,95	1,95	0,63	-1,50	-4,41	-11,30	-17,80
Ogival-140-73	-0,30	1,24	16,20	29,81	44,14	64,94	95,82
Ogival-140-107	4,95	6,10	6,05	6,78	5,28	1,70	-0,70
Polchlopek-Orig	2,27	4,64	6,58	8,47	9,97	11,50	16,40
Polchlopek+1	2,30	3,33	3,68	4,56	5,09	3,30	3,70

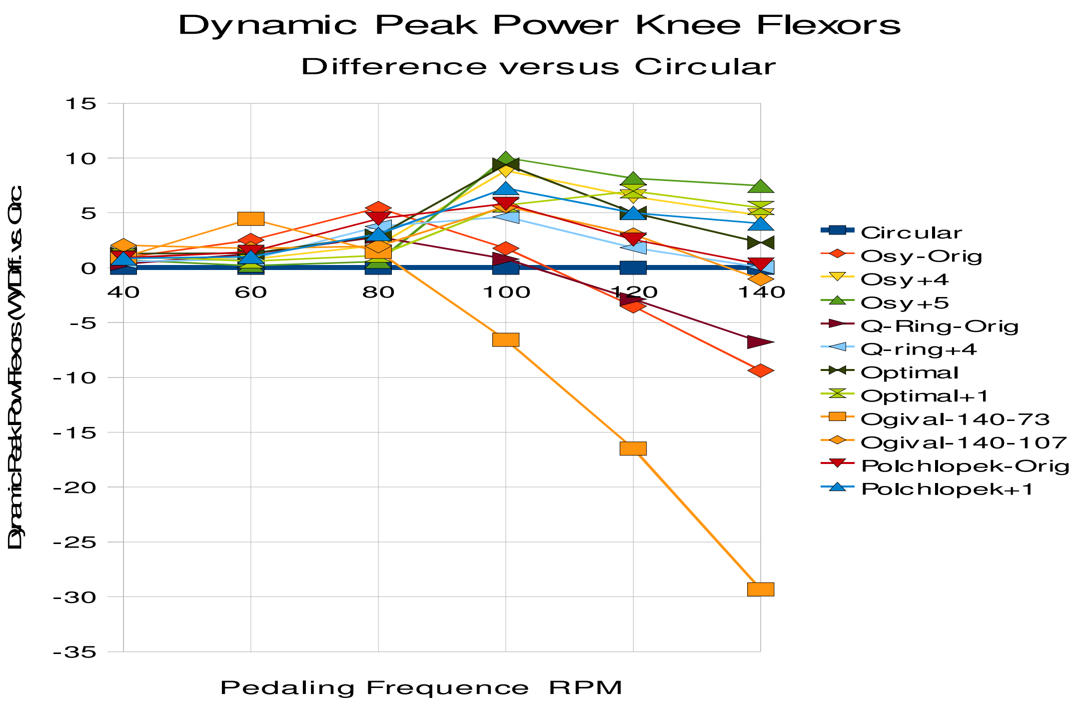
Dynamic Peak Hip Power	W		Flexors				
Diff. Vs. Circ.			RPM →				
	40	60	80	90	100	120	140
Circular	0,00	0,00	0,00	0,00	0,00	0,00	0,00
Osy-Orig	2,83	5,81	10,69	13,68	16,63	23,00	31,10
Osy+4	4,71	11,23	22,06	30,30	39,93	64,40	97,80
Osy+5	4,64	11,12	23,94	32,60	42,73	68,20	102,90
Q-Ring-Orig	0,43	0,43	0,00	0,00	-3,21	-9,00	0,00
Q-ring+4	1,93	11,23	7,64	10,04	12,33	17,10	25,40
Optimal	5,96	13,93	27,69	36,90	47,13	77,60	119,40
Optimal+1	5,98	14,76	29,43	40,70	54,03	88,30	135,50
Ogival-140-73	3,39	6,81	12,38	15,71	19,03	26,40	35,60
Ogival-140-107	8,95	20,96	43,80	59,60	78,43	127,20	194,00
Polchlopek-Orig	5,63	8,14	14,91	19,91	26,03	41,20	61,70
Polclopek+1	3,88	9,10	17,63	24,10	31,53	50,00	75,20

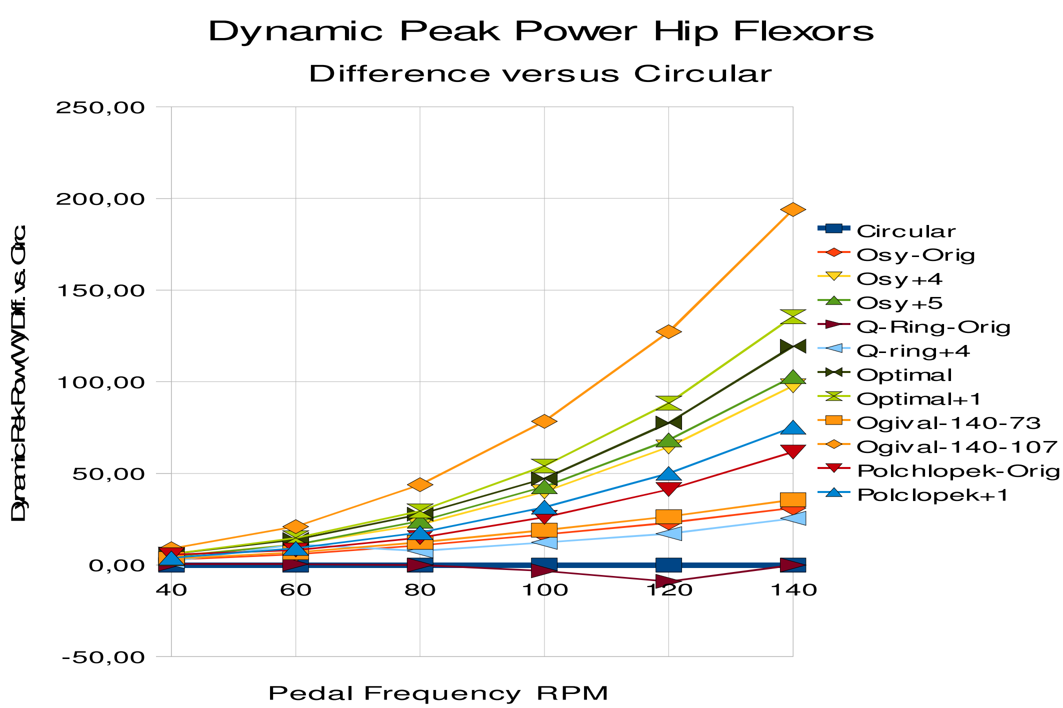
3.6.7. Graphs differences dynamic peak knee/peak hip-power of the extensor muscles. Figure 16





3.6.8. Graphs differences dynamic peak knee/peak hip-power of the flexor muscles.   Figure 17





3.7. Discussion/observations dynamic joint-moments and dynamic joint-power.

3.7.1. Discussion/observations dynamic joint-moments.

The curve profile of the dynamic joint-moments throughout a full crank cycle shows the magnitude and the location of the dynamic peak joint-moments (figure 4; figure 5).
The values of the dynamic **peak** joint-moments are a function of the pedaling frequency, the ovality and the shape of the chainring, the orientation of the crank versus the major axis of the oval, the anthropometric parameters and the bike geometry.

The pedaling frequency.
The absolute values of the dynamic peak-moments which are acting on the joints increase more than linear with increasing pedaling rates.
This is the case for all the chainwheels under examination.
Notice that within the range of 40 to 140 rpm the dynamic peak-moments affecting the knee-extensor muscles increase with a factor 6 and those working on the knee-flexor muscles increase with about the same factor also.
The dynamic peak-moments affecting the extensor and flexor muscles of the hip joint increase with about a factor 4 with increasing pedaling rate.

Figure 10 and figure 11. Result table 1 and result table 2.

Normally, when pedal forces are produced, negative joint moments caused by the flexor muscles and positive moments on the extensors are measured.
However in this study, where no static pedal forces are acting but only dynamic forces/moments are considered to move the lower limbs, we measure positive dynamic peak knee-moments caused by the flexors up to about 70 rpm (figure 11) and negative values beyond.
Likewise the dynamic peak hip-moments caused by the extensor muscles are negative up to about 75 rpm and positive beyond (figure 10).

How to interpret/explain these observations?

The static component equals zero. Only the inertial forces/-moments and the gravity forces acting on the moving lower limbs (dynamic forces/-moments) are taken into account.
At low pedaling frequencies, the accelerations and as a consequence the inertial forces/-moments are relatively small so that the gravity forces are dominant.
When only considering the gravity forces we can examine what the knee- and hip moment should be to keep the gravity force in balance. See figure 18.

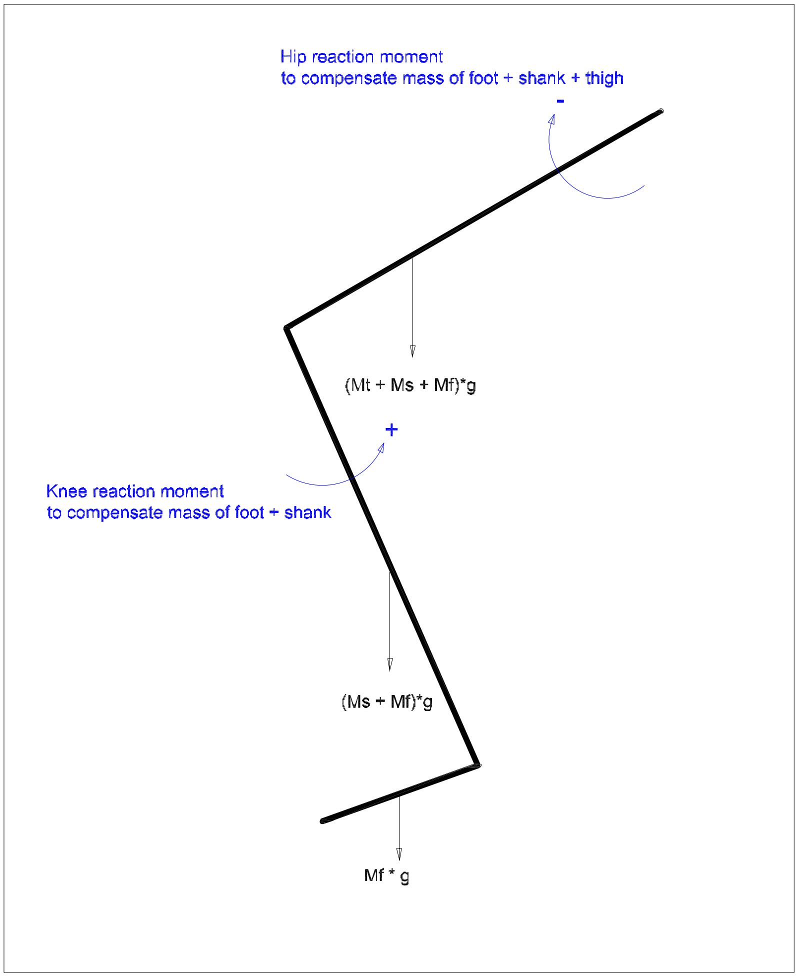


Figure 18: "Moments to balance the gravity forces" (simplified diagram).

We conclude:
-to balance in the knee joint the gravity forces of the foot and the shank, a positive moment has to be realised in the knee joint during the whole crank cycle.
-to balance in the hip joint the gravity forces of the foot, the shank and the thigh, a negative moment has to be realised in the hip joint during the whole crank cycle.
Of course, this situation is only valid in case no inertial forces/-moments are occurring. This theoretically happens at a pedaling rate equal to zero, in practical terms at low pedaling frequencies.

Apparently the inertial forces/-moments are sufficiently small up to 70 or 75 rpm. From 75 rpm and more the inertial forces/-moments dominate the gravity forces and the situation changes. Indeed the gravity forces are independent from the pedaling rate.

This analysis also reveals that in the knee and in the hip, because of the gravity forces, the flexors are more and the extensors are less loaded. This is independent of the kind of chainring and independent of the pedaling rate.

3.7.2. Comparison dynamic peak joint-moments with non-circular chainrings versus circular ones. See result tables 5 & 6 and figures 14 & 15.

Negative differences reveal that smaller peak-moments occur in the joints with the considered non-circular chainwheel compared to the round chainring taken as a reference. *Consequently negative differences are favourable, positive differences are unfavourable.*

The pedaling frequency.
From about 50 rpm on, all the non-circular chainwheels examined (except: Ogival 140-73°) have smaller dynamic peak moments caused by the knee extensor muscles compared to a circular chainring. This favourable difference increases with increasing pedaling rate.

The dynamic peak moments caused by the knee flexors, the hip extensors (from 60 rpm on, except. Osy +4/5) and the hip flexors (except. Q-ring orig) are less favourable compared to the traditional round chainwheel. Also in this case the (unfavourable) difference increases with increasing pedaling cadence.

Crank orientation angle.
By changing the crank orientation angle towards the "optimal" angle, the dynamic peak moment differences are also changing.
-for the extensor muscles (both knee and hip): mostly a favourable change of the differences (except: unfavourable for the knee-extensors with Osy, Optimal, Polchlopek)
-for the knee-flexors: a small worsening compared to circular
-for the hip-flexors: differences versus round becoming more unfavourable too.

Ovality and shape.
Assume the crank oriented in "optimal" position.
We focus on the pedaling rate range of 80 rpm up to 140 rpm.
Ovality: Q-ring (10%), Osy and Polchlopek (21.5%), Optimal (31%) and Ogival 140 (42.8%).
The differences in dynamic peak joint-moments versus round:
-for the knee extensors: the favourable differences are quasi independent of the increasing ovality (only a weak unfavourable effect).
-for the hip extensors: the unfavourable differences increase significantly with increasing ovality.
-for the knee flexors: unfavourable differences increase with increasing ovality
-for the hip flexors: unfavourable differences increase substantially with increasing ovality.

3.7.3. Discussion/observations dynamic joint-power.

The curve profile of the dynamic joint-power throughout a full crank cycle shows the magnitude and the location of the dynamic peak joint-power (figure 6; figure 7).
The values of the dynamic **peak** joint-power are a function of the pedaling frequency, the ovality and the shape of the chainring, the orientation of the crank versus the major axis of the oval, the anthropometric parameters and the bike geometry.

The pedaling frequency.
The absolute value of the dynamic peak-power which is acting on the joints increases with increasing pedaling rates.
This is the case for all the chainwheels under examination.
Notice that within the range of 40 to 140 rpm the dynamic peak-power affecting the knee-extensor muscles increases more than linear and this with a factor of more than 20.
The dynamic peak-power affecting the knee-flexors remains roughly unchanged (except: Ogival 140-73°, Osy orig and Q-ring orig).
The impact of the pedaling cadence on the dynamic peak-power affecting the hip-extensors is far more moderate (about a factor 7) compared to the knee-extensors.
The dynamic peak-power on the hip-flexors increases with a factor well over 10.

The largest dynamic peak-power is developed on both the knee-extensors and the hip-flexors. Their absolute values are in the same order of magnitude, especially in the higher pedaling rates.
Figure 12 and figure 13. Result table 3 and result table 4.

3.7.4. Comparison dynamic peak joint-power with non-circular chainrings versus circular ones. See result tables 7 & 8 and figures 16 & 17.

Negative differences reveal that smaller peak-power occurs in the joints with the considered non-circular chainwheel compared to the round chainring taken as a reference.
Consequently negative differences are favourable, positive differences are unfavourable.

Difference table of dynamic peak power in the knee, affecting the knee-extensors (result table 7):

-all non-circular chainrings give lower dynamic peak power affecting the extensor muscles of the knee joint compared to circular. These favourable differences increase with increasing pedaling rate (except Ogival 140-73°, unfavourable and increasing unfavourable difference).
-an optimal crank orientation angle decreases the advantage versus round with an exception for Q-ring and Ogival. Unfavourable Ogival even overturns into most favourable compared to all other chainwheels.

-with optimal crank orientation angle and e.g. in the pedaling range 80-100 rpm we notice a favourable effect of an increasing ovality: Q-ring (10% ovality), Osy and Polchlopek (21.5%), Optimal (31%) and Ogival-140 (42.8%).

Difference table of dynamic peak power affecting the hip-extensors (result table 8):

-all non-circular chainrings, with the crank oriented in the original position, have higher dynamic peak power affecting the hip-extensor muscles compared to a circular chainwheel. Higher pedaling frequencies have further increased these unfavourable differences.
-with the crank positioned "optimal" the unfavourable differences decrease with increasing pedaling rate and even change to favourable for Osy+4, Osy+5, Optimal, Optimal+1 and Ogival 140-107°.
Unfavourable differences still increase with higher pedaling frequency for Q-ring+4 but at a substantially lower pace than Q-ring orig.
-assuming crank orientation angle optimal and pedaling rate 80-100 rpm, we notice a favourable effect because of the increasing ovality (Q-ring (10%), Osy en Polchlopek (21.5%), Optimal (31%), with exception of Ogival-140 (42.8%)).

We may conclude that for the extensor muscles of the knee and hip, an optimal crank orientation angle and an increasing ovality have an improving impact on the dynamic joint power differences.

Difference table of dynamic peak power affecting the knee-flexors (result table 7):

-all non-circular chainwheels show higher dynamic peak joint power affecting the knee-flexors compared to circular when crank oriented in original position. These unfavourable differences increase up to about 90-100 rpm but further decrease with higher pedaling cadences and even change to favourable differences.
-a rotation of the crank towards "optimal" improves the unfavourable figures in the lower pedaling range up to about 80 rpm (except Q-ring and Ogival). From 90 rpm on, the differences with circular are increasing (more unfavourable).
-at optimal crank orientation angle and in the lower pedaling frequency range (< 80 rpm) we notice a negative effect of an increasing ovality (Q-ring (10%), Osy en Polchlopek (21.5%), Optimal (31%), with exception of Ogival-140 (42.8%)). From 80 rpm up to 100 rpm a rather positive effect. At still higher pedaling rates again an unfavourable impact by increasing ovality.

Difference table of dynamic peak power affecting the hip-flexors (result table 8):

-all non-circular chainwheels have higher dynamic peak joint power affecting the hip-flexors

compared to circular at original crank orientation angle (except: Q-ring). These unfavourable differences increase over the complete pedaling frequency range with exception for the Q-ring.
- a rotation of the crank towards "optimal" shows a substantial deterioration in these already unfavourable figures.
-at optimal crank orientation and over the complete pedaling frequency range we notice a distinct negative effect of increasing ovality.

We may conclude that, grosso modo, the optimal crank orientation angle and an increasing ovality deteriorate further the unfavourable dynamic differences versus round for the flexor muscles of the knee (to a lesser extent) and the hip (to a higher extent).

4. Results dynamic crank power.

When assuming that **only** dynamic moments are acting on the joints (to move the legs), in this case the pedal forces are equal to zero at any time, as well as for the conventional circular chainring as for any non-circular one.
As a consequence, no crank power is generated for both chainwheels: pedal forces equal zero and the dynamic power is needed to move the lower limbs.

We learn from the examination of the dynamic joint-moments (see 3.) that the curve of the dynamic joint-moments is a function of the ovality and the shape of the non-circular chainwheel, the crank orientation angle and the pedaling frequency.

When applying at any moment of the crank cycle, the instanteneous dynamic joint-moments of the circular chainring on a specific non-circular chainring, we will find either an average dynamic crank power gain or an average dynamic crank power loss compared to circular (= dynamic crank power difference).

By designing an **appropriate** ("good") non-circular chainring (ovality, shape, crank orientation angle and cadence) the dynamic component of the joint-load will be altered (optimized) compared to circular and leads to a measurable crank power gain when applying the dynamic joint-moments of the circular on this *appropriate* non-circular chainring.
Indeed, when applying the dynamic joint-moments of a circular on an *appropriate* non-circular chainring,
1. the dynamic joint-power needed to move the lower limbs with the *appropriate* non-circular is delivered and on top of this
2. a dynamic crank power is measured (is available) with the *appropriate* non-circular chainwheel.

This examination was executed with the non-circular chainring types described

in paragraph 2.7. which gives the opportunity to see the impact of ovality, shape and crank orientation angle on the dynamic crank power.
Pedaling cadences of 40, 60, 80, 90, 100, 120 and 140 revolutions per minute are applied.
The results of this analysis should be considered in the design process of an *appropriate* non-circular chainring.

4.1. Dynamic crank power difference non-circular chainring versus circular. Some examples.

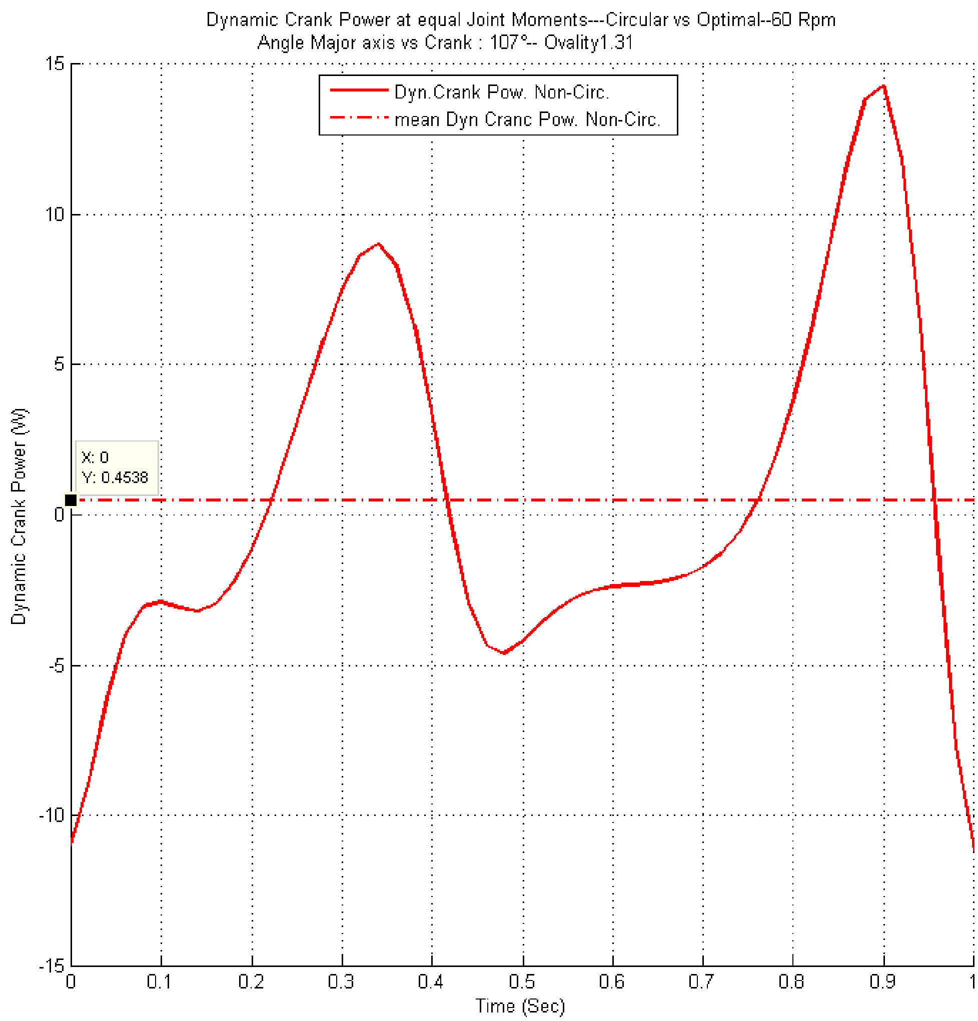


Figure 19: Dynamic crank power difference at equal joint moments
Non-circular Optimal- ovality 1.31 - crank orientation angle 107° - compared to circular chainring.
Pedal cadence 60 rpm.

Average dynamic crank power gain equals 0.4538 W **per single-leg** versus a conventional round chainwheel.

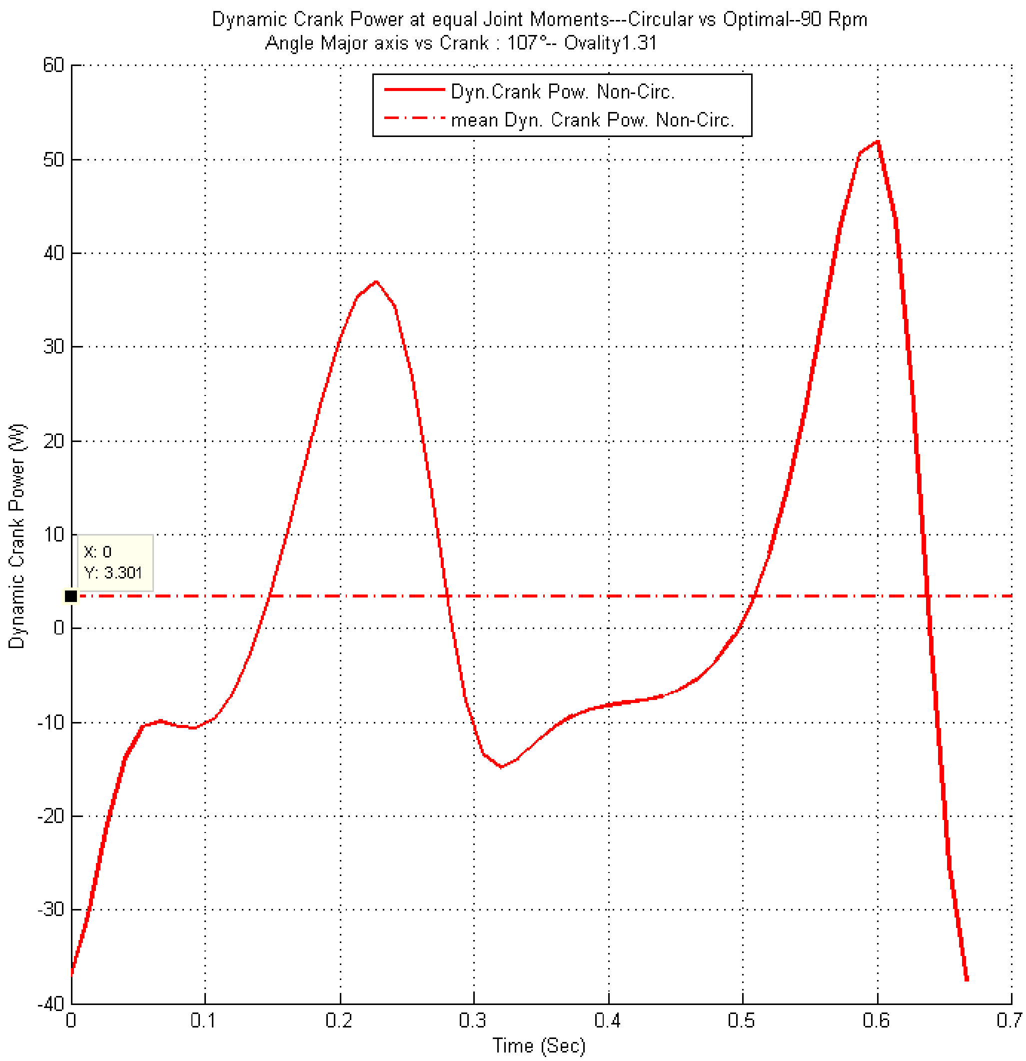


Figure 20: Dynamic crank power difference at equal joint moments
Non-circular Optimal- ovality 1.31 - crank orientation angle 107°- compared to circular chainring.
Pedal cadence 90 rpm.

Average dynamic crank power gain equals 3.301 W **per single-leg** versus conventional round chainwheel.

4.2. Result table and graphs average dynamic crank power differences.

All the results are presented in a table ("spreadsheet") and illustrated in graphs by the use of "OpenOffice-Calc", which should make interpretation easier.
For each of the studied oval chainwheels, average dynamic crank power differences versus conventional round are presented for both, original and optimal crank orientation angle and for the successive pedaling rates.

The model assumption of constant bicycle velocity (isokinetic pedaling) effectively **decouples the dynamics and kinematics of the two legs** and allows us to study the dynamic power differences of one isolated leg. Consequently **total dynamic crank power differences equals twice the single-leg figures** (van den Bogert, A.J., 1994).

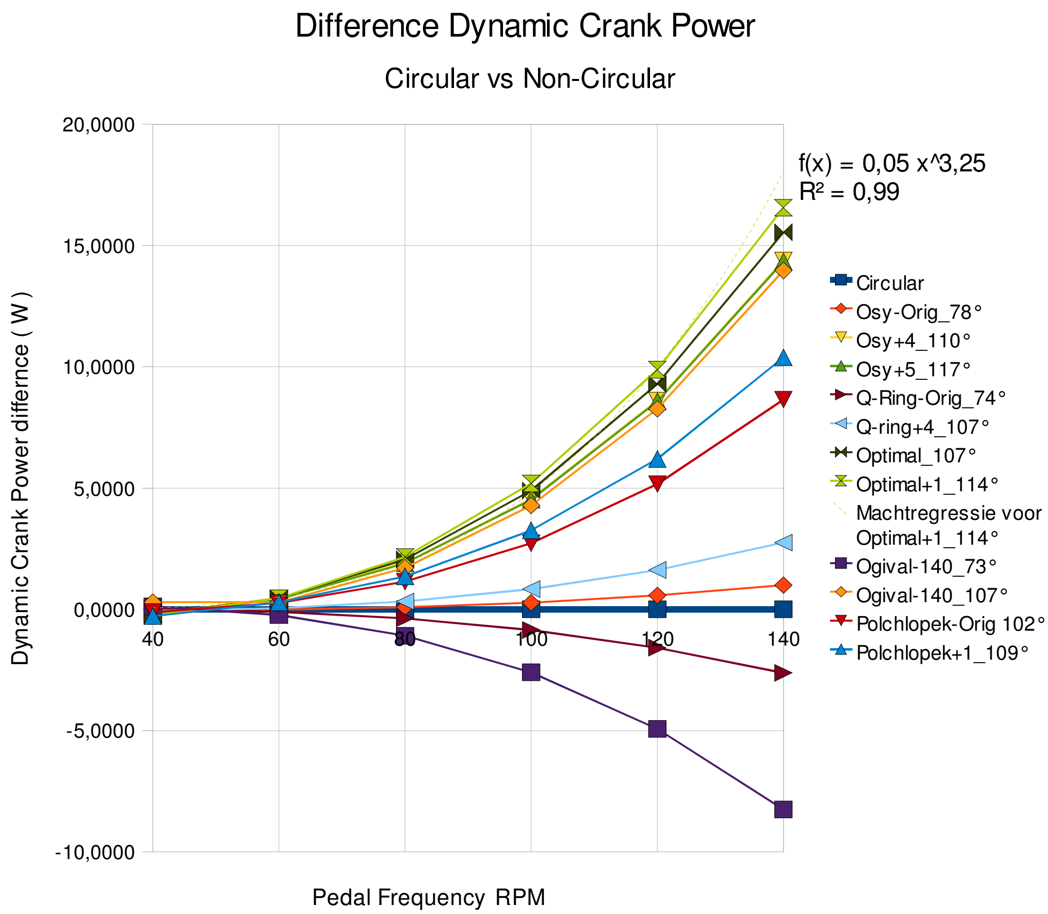
The dynamic crank power gain or loss is an absolute value expressed in Watt.
Gain or loss is independent from any pedal load performed.
This means that the relative dynamic crank power gain or loss is lower with higher pedal load than with lower pedal load.

4.2.1. Result table average dynamic crank power differences vs circular.
Watt per **single-leg**. (result table 9)

Dynamic Crank Power							
Difference			trm				
	40	60	80	90	100	120	140
Circular	0	0	0	0	0	0	0
Osy-Orig_78°	-0,0449	-0,0123	0,086	0,167	0,273	0,569	0,997
Osy+4_110°	-0,1791	0,4458	1,928	3,080	4,553	8,607	14,380
Osy+5_117°	-0,1966	0,4208	1,897	3,047	4,519	8,571	14,340
Q-Ring-Orig_74°	0,0150	-0,1050	-0,378	-0,588	-0,855	-1,587	-2,625
Q-ring+4_107°	-0,0646	0,0448	0,324	0,546	0,831	1,620	2,750
Optimal_107°	-0,2150	0,4538	2,054	3,301	4,897	9,292	15,550
Optimal+1_114°	-0,2483	0,4577	2,160	3,488	5,190	9,881	16,560
Ogival-140_73°	0,1148	-0,2402	-1,090	-1,752	-2,600	-4,934	-8,258
Ogival-140_107°	0,2844	0,2859	1,711	2,834	4,28	8,267	13,97
Polchlopek-Orig 102°	-0,1202	0,2514	1,1410	1,8340	2,722	5,166	8,646
Polchlopek+1_109°	-0,2844	0,2869	1,3550	2,189	3,257	6,200	10,390
OVUM 124 +2_106°	-0,1886	0,2484	1,323	2,166	3,248	6,235	10,500

A positive difference means an average dynamic crank power gain for the non-circular chainring compared to the conventional round one.

4.2.2. Graphs average dynamic crank power differences vs circular.
Watt per **single-leg**. Figure 21



4.2.3. Result table average dynamic crank power differences vs circular.
Watt per **double-leg**.

It is obvious that the total (double leg) dynamic crank power difference or crank power gain of a specific non-circular chainwheel versus the conventional circular one can be calculated by doubling the figures of the single leg result table 9.

4.3. Discussion/observations average dynamic crank power differences versus circular. Result table 9. Figure 21.

The result tables and graphs indicate that, for a given non-circular chainring (ovality and shape), the dynamic crank power difference versus the conventional round chainring is a function of the pedaling frequency and the crank orientation versus the major axis of the oval.

4.3.1 Impact pedaling frequency.

The average dynamic crank power difference compared to the circular chainwheel (gain as well as loss) increases with increasing pedaling rate.
This increase/decrease with raising pedaling cadence is not linear but is a power function of the form f(x) = A*x^n .
As an example for the oval Optimal +1, the function behaves like f(x) = 0.05*x^3.25 with x (grid number) as depiction of the pedaling frequency.

At lower pedaling rates (up to 60 rpm), the average dynamic crank power gains/losses versus round are relatively small, even negligible. This is the case for all the non-circular chainring combinations investigated.

At the normal pedaling cadences of competition cycling, the best performing non-circular chainrings generate dynamic crank power gains of more than 4 Watt (at 80 rpm), up to even more than 10 Watt (at 100 rpm) "double leg".
At 110 rpm about 15 Watt crank power gain is available.

These results are also in line with the results published in the "basic study": isokinetic pedaling at 90 rpm with 104 Watt crank power per single leg.
Indeed, in the "basic study", the crank power efficiency gain with the Osy+5 117° was 2.5% versus round (with identical joint moments on circular and on non-circular).
The dynamic crank power gain of 3.047 Watt per leg at 90 rpm for the Osy+5 117° equates to 2.9% relative the 104 Watt per leg.

The dynamic advantage/disadvantage is an absolute value expressed in Watt. Consequently the dynamic crank power gains/losses compared to the conventional round chainwheel are **independent** from any external pedaling load. This means that the **relative** dynamic crank power gain/loss is smaller with higher pedal loading than with lower pedal loading.

Q-Ring 74° and Ogival_140_73° (both having original crank orientation angle) yield negative dynamic crank power performances over the complete pedaling frequency range 40-140 rpm. Even with an optimal crank orientation angle the Q-ring performance remains (positively) weak.
Osy 78° (original) develops small positive dynamic crank power gains whereas the Osy+4 110° and the Ogival 140 107° are ranking among the best ones.
Polchlopek+1 109° shows rather good figures comparable to OVUM+2 106°.
Optimal 107° and Optimal+1_114° are "best in class".

For all the non-circular chainrings under examination we can conclude that, except for the combinations yielding negative values, an increasing pedaling cadence has a positive impact on the dynamic crank power gain versus circular.

4.3.2. The apparent paradox regarding high pedaling rates. **See appendix 4.6.1**

4.3.3. Impact of ovality and shape.

Impact of ovality:
-assume: non-circular chainrings with crank orientation angle "optimal" versus major axis
-ranking of the non-circular chainrings according to increasing ovality
We calculate the sum and the mean of the dynamic crank power gains in the pedaling range 80-120 rpm. These pedaling cadences are typically used by competition cyclists.

Result table 10

Ovality %	Chainring (crank orientation angle optimal)	Sum and mean dynamic crank power gain vs. round rpm 80 - 120 Watt (single-leg)		Comments
0.0	Round	0	0	Ellipse
10.0	Q-Ring	3.321	0.83	modified ellipse
21.4	Polchlopek	13.001	3.25	bi-axis-symm
21.5	Osymetric	18.168	4.54	point symm
24.0	OVUM	12.972	3.24	Ellipse
31.0	Optimal	20.719	5.18	point symm
42.8	Ogival	17.092	4.27	bi-axis-symm
		sum rpm 80-120	mean	

The dynamic crank power gains compared to round (both the sum and the mean) increase more than proportional to the ovality.
The chainwheels "round", "Q-ring" and "OVUM" are mathematical ellipses and as a consequence perfectly comparable (no impact of shape differences). The ovality of the OVUM increases with a factor 2.4 versus Q-ring whereas the dynamic crank power gain increases with a factor 3.9.
The Optimal with similar shape compared to the Osymetric but with 9.5% more ovality yields 14% more dynamic crank power gain versus Osy.

Impact of shape:
The Polchlopek oval has approximately the same dynamic crank power gains as the OVUM but with 2.6% less ovality, most probably due to its specific shape. Osymetric with quasi identical ovality as Polchlopek reveals about 40% more dynamic crank power gain versus the last one. This can only be explained by its specific point-symmetric shape.
Ogival, notwithstanding a very high ovality of 42.8%, develops lower dynamic power gain compared to Optimal and Osymetric, without a doubt because of its extreme shape which apparently works out adversely.

4.3.4. Impact of the crank orientation angle versus major axis.

For all the non-circular chainwheels under examination, the re-orientation of the crank in the "optimal crank orientation angle position" i.e. in the range 110°-120° (see paragraph 2.7., definition 3. and also the "basic study") improves substantially the dynamic crank power gains compared to the original crank orientation angle of the designers/manufacturer.

We notice also **the same "optimal crank orientation angle"** in the publication of **Miller N.R. and Ross D.** (1980) who developed a non-circular chainring design (with crank at 120°, scientific definition) to maximize the average power for one cycle produced by the pedaling movement.

The dynamic crank power losses of Q-Ring-orig_74° and Ogival-140_73° are even transformed into dynamic crank power gains by re-orienting the crank versus the major axis. The original Polclopek-102° has its crank quite close to the optimal crank position.

It is remarkable that, for the pedaling frequency range of 40 rpm to 140 rpm, a crank orientation angle of 73° (Ogival) and 74° (Q-ring) yields dynamic crank power losses and that with 78° (Osymetric) only negligible dynamic crank power gains are noticed.
A possible physiological explanation of this is given in **appendix 4.6.2**.

4.3.5. Consistency of results calculated by means of the bio-mechanical model with experimentally measured results.

In scientific literature many publications are available reporting the results of comparative laboratory and field testing of the conventional circular chainring and non-circular ones.
These studies try to effectively measure the theoretical advantages of the elliptical chainwheel in both sub and supra maximal cycling conditions.

As already noted above, these test results (mechanical, physiological and muscular data) are for various reasons not always consistent.

Ratel et al. (2004) investigated the original Osymetric-Harmonic for physiological parameters (13 test subjects) and were not able to identify statistical significant benefits in sub and max test circumstances.
Horvais et al. (2007) studied the original Osymetric on physiological, mechanical and muscular parameters, sub and supra maximal (12 test subjects). The average crank power measured with the Wingate-test (predetermined fixed moment/torque, pedaling rate to maximize) did not reveal any advantages for the Osymetric.
Results of both studies are in contradiction with the unlikely (!) high power gains in the "treshold zone" (6 up to 18% according to the criterion) as reported in the publication of Barani et al. (1994) (19 test subjects).
Our torque-driven biomechanical model calculates negligible dynamic crank power gains for the original Osymetric throughout the complete pedaling frequency domain and is actually confirming (is consistent with) the findings of Ratel and Horvais.

In late 2010, comparative tests between the Optimal oval and a conventional round chainring were carried out (with 18 "well trained test subjects") in the biomechanical laboratory of the department "Kinesiology" at the University of Leuven, Belgium (Van Hoovels et al., 2010). Maximal crank power output was measured during a series of short intermittent sprints on a isokinetic (predetermined fixed pedaling rate, moment/torque to maximize) bicycle ergometer. For **all** pedaling cadences between 40 rpm to 120 rpm (included) the Optimal oval showed crank power gains compared to round. These experimentally measured figures (e.g. 5.0 Watt at 80 rpm and 10.6 Watt at 100 rpm) **confirm** and even surpass slightly the dynamic crank power gains calculated with the bio-mechanical model (e.g. 4.3 Watt at 80 rpm and 10.4 Watt at 100 rpm). The pedaling frequency range of 80 rpm till 100 rpm is normally used by elite cyclists in competition. This study has not been published yet.

In a preliminary report (8 test subjects) on Q-rings commercialized by Rotor Cy, Martinez et al., (2006) analysed physiological and biomechanical effects.
Some physiological improvements were reported and also crank power gains (+3 à 4%) compared to the conventional circular chainring. But the results were not statistically analyzed and the improvements in terms of power output were not clearly specified.

Jones et al., (2008) investigated with an excellent documented test protocol, in a carefully controlled laboratory environment, randomized, single blind, in 2-

period cross-over trials (incremental tests to exhaustion with 12 test subjects) physiological, mechanical and muscular parameters of the Q-ring, compared to a circular chainwheel. Neither the mean crank peak-power output, nor the mean crank power, nor the mean distance covered showed statistically significant differences among the chainrings.
Mateo et al., (2010) compare in sprint tests (14 test subjects) the Q-ring to the conventional round chainring. No statistically significant differences were measured for the variables average speed and time to cover the sprint distance.
The above mentioned lab tests are completely in line with the figures calculated with our bio-mechanical model, namely the absence of crank power gains with the original Q-ring. This is most probably explained firstly by its lack of ovality (the oval behaves like a circular ring) and secondly by the crank orientation angle.

No experimental data are available for Ogival.

The original Polchlopek oval (crank orientation angle 102°) was advertised by the designer/manufacturer as the non-circular yielding about 4% crank power gain. It is not clear how this power gain has been measured.
Our bio-mechanical model calculates 3.6 Watt dynamic crank power gain at 90 rpm and 5.4 Watt at 100 rpm for the original Polchlopek. Assuming 200 to 250 Watt at 90 rpm for standard endurance cycling for experienced cyclists (Hull et al., 1992) corresponds to about 2% dynamic crank power gain with the Polchlopek chainring.

The Biopace-oval was tested by Hull et al., (1992). Not any advantage over round was measured. In our "basic study", our bio-mechanical model did not show any advantage over circular either. Obvious reasons are the very low ovality (4%) and the totally wrong crank orientation angle (crank arm oriented nearly parallel to the major axis). The Biopace was not studied in this paper, also because Shimano withdrew the Biopace from market in 1992.

Koninckx et al., (2008) examined (22 well-trained cyclists) a novel pedal design (Vista Pedal) and compared its power output and mechanical efficiency with the conventional pedal. At 80 rpm a crank power gain of 2.5% (SD=0.6%) and at 100 rpm a crank power gain of 1.8% (SD=0.7%) is registered.
In our Project 002 (see website www.noncircularchainring.be), our torque-driven biomechanical model calculates the crank power output and the joint loading of the Vista Pedal and compares the results with the conventional pedal. Our mathematical model shows a crank power gain of 2.7% at 90 rpm.
Thus the lab tests confirm (are matching) completely the results of the model.

Without doubt we may conclude that the figures generated by the torque-driven bicycle-rider musculoskeletal model are consistent with the available experimental results from designer/manufacturer independent experimental research.

4.4. Internal work (-power), MMEE and total dynamic joint power.

In cycling research, **internal work** (internal power) is used to indicate the work done (or the power developed) to move the cyclists legs through each crank revolution (to accelerate and to decelerate the leg segments) and is defined as "the sum of absolute changes in the total mechanical energy of the cyclists legs" (Winter, D.A.,(1979); Welss, R., et al., (1986) and other...).

Muscular **m**echanical **e**nergy **e**xpenditure, **MMEE,** is defined as "the time integral of the sum of the individual joint powers" (Aleshinsky, S.Y.,(1986), Ingen Schenau et al., (1990) and other...)

Aleshinsky (1986) analysed mechanical energy expenditure and internal work and concluded that mechanical energy expenditure does not equal to the sum of internal and external work. Therefore, reduced internal work does not necessarily correlate with reduced muscular mechanical energy expenditure.
Hull et al., (1992) tested the hypothesis (11 test subjects) that reducing internal work would increase efficiency. They designed a crank angular velocity profile (a non circular chainring) that reduced internal work by a minimum of 48% relative to constant angular velocity cycling (circular chainring) over the range of cadences generally preferred by endurance cyclists (80-100 rpm). The experiment did not reveal advantages of the non-circular design over the circular.
Kautz et al., (1994) also concluded that MMEE need not to be equal to the sum of internal and external work and that reducing internal work in cycling does not correlate with reduced MMEE.
Neptune et al., (1998) clearly demonstrated that **internal work is not a valid measure for the energy associated with moving the limbs** and that the internal work method is theoretically flawed and should not be used in cycling analysis.
Kautz et al., (2002) concluded that the internal work hypothesis is invalid as a direct measure of the mechanical energy cost of moving the legs in pedaling.

Muscular mechanical energy expenditure is closely matching the definition of **total dynamic joint power**. MMEE however is "energy" but conversion to "power" is easily done. Moreover, MMEE includes pedal forces (external work) whereas, per definition, in total dynamic joint power pedal forces are set to zero. Only dynamic forces/moments caused by gravity and inertial effects are taken into account.

*Therefore "**dynamic** MMEE per unit of time" (i.e. pedal forces **ex**cluded) is identical to "average (absolute values) total dynamic joint power".*

4.4.1. Average (absolute values) total dynamic joint power over a full crank cycle (90 rpm). Single leg.

Result table 11

Average absolute dynamic joint power		full pedaling cycle
Single leg	90 RPM	Watt

	Osy-Orig	Osy+4	Optimal+1
Ankle Circ.	1,728		
Ankle Non-Circ.	1,736	1,747	1,757
Knee Circ.	23,93		
Knee Non-Circ.	22,42	23,02	23,07
Hip Circ.	34,82		
Hip Non-Circ.	34,38	34,29	34,81
Total Circ.	60,478		
Total non_Circ.	58,536	59,057	59,637

The average (absolute values) total dynamic joint power needed to move the legs over a full crank cycle is roughly equal for both the circular and the non-circular chainrings considered.
The small differences have most probably to do with minor system errors such as conversion of CAD drawings to crank angles, polynomial conversion, assumed pedal angle etc...
This conclusion is logical because in a cyclical movement, having advantages in a specific sector leads undeniably to disadvantages in the remaining sector and vice versa.

4.4.2. Curve profile of the dynamic joint power (absolute values), single leg.

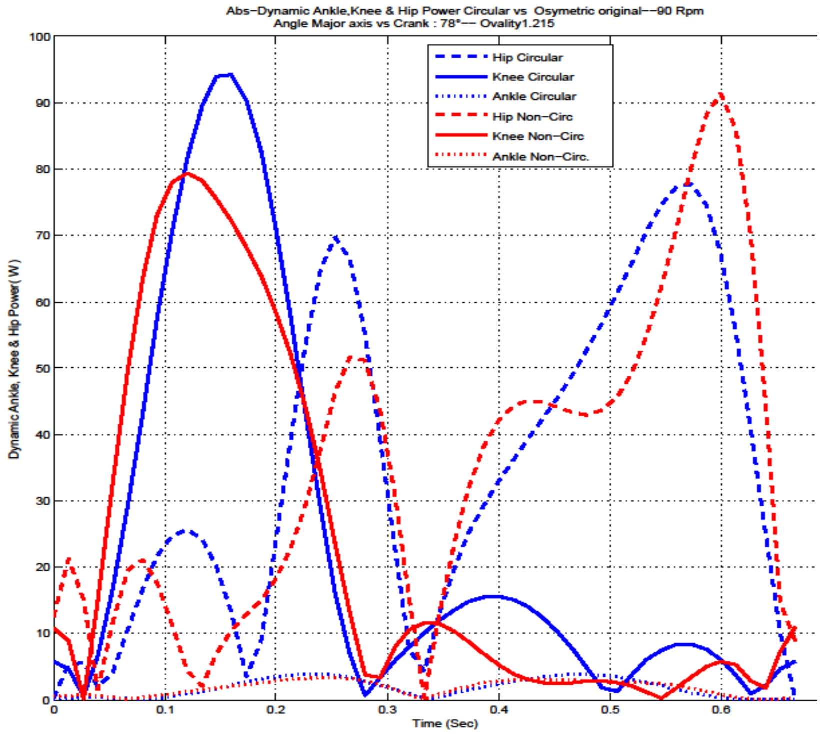


Figure 22: Single leg absolute dynamic joint power Osy original at 90rpm.

Notwithstanding the average (absolute values) total dynamic joint power over a complete crank cycle is the same for both, circular and non-circular, there is a *significant difference in the curve profile of the instantaneous absolute dynamic power of the joints.*

Our attention is drawn to the favourable results (curve profiles) for the non-circular chainring in the "power stroke" (Top-Dead-Centre 0° to Bottom-Dead-Centre 180°, cycle time 0 to 0.33 sec at 90 rpm) and will be further explored.

4.4.3. Average (absolute values) total dynamic joint power over the "power phase" (90 rpm).
Single leg.

Result table 12

Average absolute dynamic joint power	Power stroke	
90 RPM	Watt	Single leg

	Osy-Orig	Osy+4	Optimal+1	Ogival 140/73	Ogival 140/107	Q-Ring Orig.	Q-Ring+4
Ankle Circ.	1,633						
Ankle non-Circ.	1,608	1,546	1,523	1,695	1,512	1,630	1,596
Knee Circ.	39,170						
Knee non-Circ.	39,670	38,170	38,130	42,620	39,170	39,720	39,020
Hip Circ.	24,330						
Hip Non-Circ.	20,380	20,090	19,810	25,920	18,760	22,460	20,640
Totaal Circ.	65,133						
Totaal non_Circ.	61,658	59,806	59,463	70,235	59,442	63,810	61,256
Difference vs Circular (W)	-3,475	-5,327	-5,670	+5,102	-5,691	-1,323	-3,877

Negative differences are favourable, positive differences are unfavourable.

The average (absolute values) total dynamic joint power needed to move the legs during the "power stroke" (0°-180° or cycle time 0 to 0.33 sec at 90 rpm) is significantly different between the circular and the non-circular chainrings considered.
A comparison of the differences in average absolute dynamic joint power (differences in dynamic MMEE per unit of time) as computed in result table 12 and the earlier computed dynamic crank power differences in result table 9 (at 90 rpm) shows a very **similar results pattern (differences)** for both calculations.
Both these findings provide interesting information for explaining the crank power gain with appropriate non-circular chainrings.

4.4.4. Dynamic crank power differences and average total absolute dynamic joint power differences.

During the "power stroke" and **assuming external loading**, the extensor muscles are predominantly recruited and provide most of the forward drive (external crank power) for the bicycle movement.
If during the "power stroke" the average total absolute dynamic joint power is lower with an appropriate non-circular chainwheel than with a circular one, there is a possibility for the extensors to generate more external crank power compared to circular**.** Any **"unloading" of the extensors** by an objectively demonstrable (measurable) dynamic advantage may only **be favourable regarding extensor muscle fatigue and performance.**
Maximum performance is related to fatigue of lower limb muscles (Hull and Gonzales, 1988).
Muscle fatigue is related to muscle stress to a power between 1.5 to 5 (Crowninshield and Brand, 1981). In pedaling activity the lower limb muscle stress may be determined with good accuracy directly from the joint moments developed by hip, knee and ankle (Redfield and Hull, 1986b).
Minimizing the stress would lead to reduced fatigue and hence improved performance (Hull and Gonzales, 1988). This is most probably the case when cycling with appropriate chainrings (lower dynamic joint moments and lower dynamic joint powers) during the "power stroke".

As noted above, the average (absolute values) total dynamic joint power needed to move the legs over a full crank cycle is roughly the same for both the circular and the non-circular chainrings considered.
Having the average (absolute values) total dynamic joint power lower in the "power stroke" for appropriate non-circular chainrings, leads inevitably to higher total dynamic joint power during the "upstroke" (recovery phase, BDC 180° to TDC 360°), compared to circular.
Consequently during the "upstroke", the flexor muscles (not so much loaded indeed) are charged more compared to circular but nearly no external crank power must /may be provided in that sector.

When applying at any moment of the crank cycle, the instantaneous dynamic joint-moments of the circular chainring on an appropriate non-circular chainring, we find an average dynamic crank power gain (see earlier i.e. **4.2.1.**)
As **an example** taking the Optimal+1 114°, at 90 rpm, 3.488 Watt (single leg) dynamic crank power gain versus round has been computed (full crank cycle).
The favourable difference versus circular in average (absolute values) total dynamic joint power at 90 rpm over the "power stroke" is 5.670 Watt (single leg) for the non-circular, giving the possibility to the extensor muscles to generate crank power with the instantaneous dynamic joint-moments of the

circular. However, this "unloading" of the extensors in the "power stroke" is partly lost by an "overloading" of the flexors in the "upstroke" resulting in the mentioned average dynamic crank power gain over the full crank cycle.

Same observations are valid for all the non-circular chainrings studied.
The "overloading loss" in the "upstroke" counts for about (single leg) 2 to 3 Watt (rounded) at 90 rpm, depending on the oval considered.

4.5. Concluding remarks

The results of the study undeniable suggest that an optimization of the dynamic component of the joint loading in cycling, by the design of an appropriate non-circular chainring, provides **objectively demonstrable** advantages to the non-circular chainring compared to the conventional circular one. "Objectively demonstrable" means: correctly computable according to the physical laws of the kinematics and dynamics (kinetics).

The optimization of the dynamic component of the joint loading is obtained by a good choice of the geometric parameters of the non-circular chainwheel namely a sufficiently large ovality, the right shape and the "optimal" crank angle orientation versus the major axis.

An important conclusion is that with an appropriate non-circular chainring the dynamic peak joint moment and the dynamic peak joint power in the knee extensor muscles are lower than with the circular chainring and that the advantages increase with increasing pedaling rate.
For the knee joints, experience shows that the extensor muscles are an important restricting factor. Overloading the knee extensor muscles frequently leads to knee injuries. The appropriate non-circular chainring may provide a lower potential for knee injuries.
The peak values on the knee flexor and the hip extensor/flexor muscles are not systematically lower or higher compared to the conventional circular chainwheel but each specific individual combination has to be examined.

We also learn that dynamic joint moments/-power are relatively important when being compared to the total joint moments/power developed during standard endurance cycling for experienced/competition cyclists.

Another important conclusion is that the appropriate non-circular chainring yields a measurable average crank power gain compared to circular. This dynamic crank power gain, generated by favourable kinematic/dynamic effects on the moving masses of the lower limbs is rather modest but increases "exponentially" with increasing pedaling frequency and is independent from any external pedaling load. Consequently this crank power gain is becoming relatively smaller with higher external pedal load.

The dynamic crank power gains of appropriate non-circular chainrings are computable by means of adequate bio-mechanical musculoskeletal models but are also measurable with lab experiments. This however is dependent on condition of a good "design of experiment", a sufficiently large and homogeneous test sample and multiple measurements. These conditions are not always met in literature.
Osymetric is the best performing commercially available oval chainring, followed by Ogival but for both only if the crank arm is oriented in the optimal position. However the largest crank power gain versus circular is reached by the Optimal (LM-Super) chainring.

Summarizing the line of thought:
-In the study, an ***objective*** *difference is shown in the curving and the peak values of the dynamic (kinetic) joint moments and dynamic (kinetic) joint powers throughout the pedaling cycle for circular and non-circular chainwheels. It is proven that this objective difference is a function of ovality, shape and crank orientation angle. Also the impact of the pedaling rate is demonstrated.*
-From this, it is already possible to distinguish good from less good geometric combinations but this can not be quantified in terms of dynamic (kinetic) crank power gain or loss.
-To make it quantifiable the method of equalization of the joint moments (circular versus non-circular) is developed. The rationale behind this is: in case the joint moments are identical, the lower limb muscle stress is equal too and leads to the same muscle fatigue.
-When working out this hypothesis, a quantified dynamic (kinetic) crank power gain/loss is shown for the different combinations of chainring geometry and pedaling rate. A ranking of the non-circular chainrings is possible.

Notice that, keeping the joint moments identical, the joint angular velocities are different. Possible physiological effects of this are not taken into account in the model.

4.6. Appendix

As mentioned before, physiological aspects are, in first order, not taken into account in this paper because they are not the field of speciality of the authors. "Outside the paper", this appendix is an attempt to explain two remarkable findings, by means of physiological considerations.

4.6.1. The apparent paradox regarding high pedaling rates.

As appears from the graphs, dynamic joint moments and dynamic joint powers increase "more than linear" with increasing pedaling rate, although not so strongly as the dynamic crank power gain.
Besides, the increase of the dynamic joint moments/-powers with the "appropriate ovals" is far less distinct compared to the circular chainwheel.
This suggest that the "internal power" (which is in fact a "dynamic loss", the power needed to move the lower limbs without producing any crank power) increases "more than linear" with higher pedaling rates.
At first glance we may conclude that cycling at high pedaling frequency yields no advantage. Nevertheless a.o. the best Time Trial performances are put up at higher pedaling cadences (e.g. 100 rpm and more).
This has most probably to do with consequences (aspects) of the "force-velocity" relationship of working skeletal muscles and the deduced relationship "power-velocity". See figure 23 below.
Probably at the higher pedaling rates the cyclist is still on the ascending limb of the muscle power curve resulting from the force-velocity relationship because optimal power output occurs at much higher pedaling frequency (120 rpm),(van Soest et al., 2000).
This would mean that, notwithstanding a higher internal power (higher "dynamic loss") it still remains possible to develop even more muscle power.

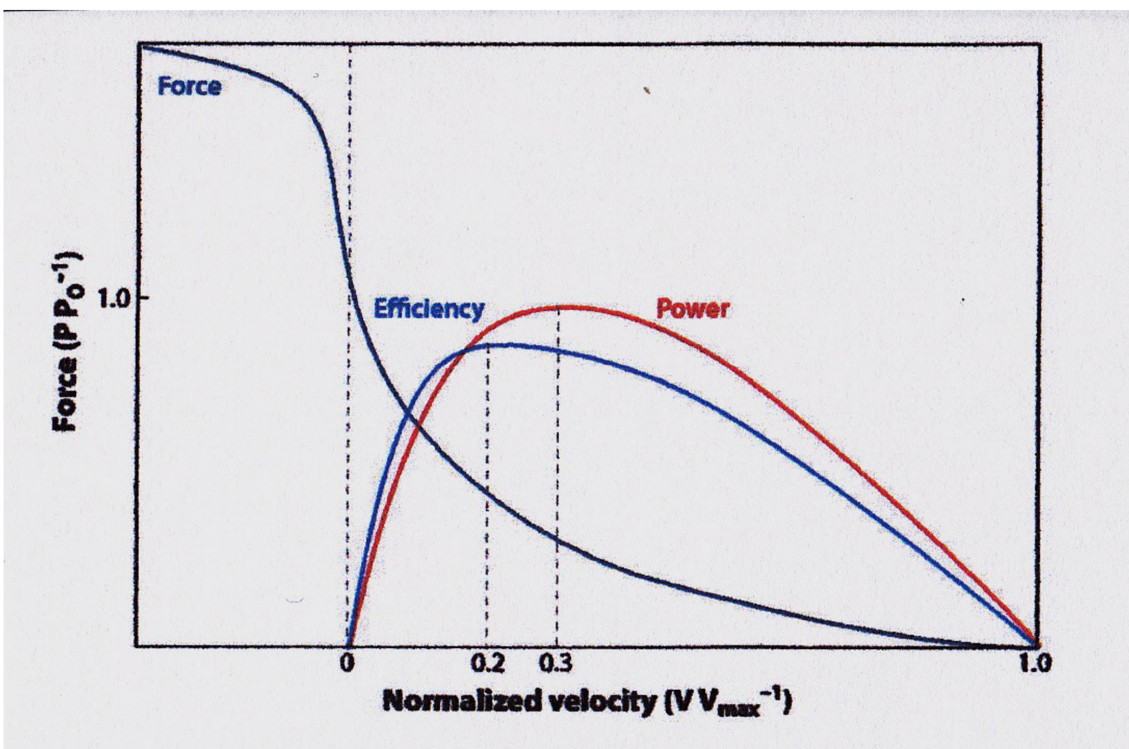


Figure 23: Force-velocity-power-efficiency relationship for skeletal muscle

Since for the same pedaling rate, with appropriate ovals, the maximal and average contraction (shortening) speed of the extensor muscles is lower than with a circular chainring, it is expected that with these ovals a higher pedaling rate can be reached and can (would) be advised.
This assumes (is on condition) that the indeed less loaded flexors are able "to follow".

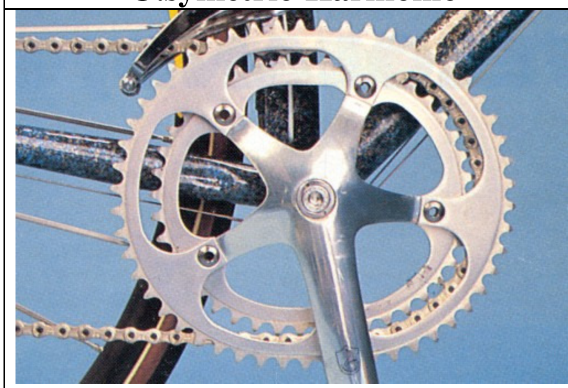
4.6.2. A conceivable explanation for the "optimal crank orientation angle".

It is remarkable that, over the pedaling frequency range 40 rpm up to 140 rpm, a crank angle versus major axis of 73° (Ogival) and 74° (Q-ring) generates increasing dynamic crank power losses and that with 78° (Osymetric) only negligible crank power gains are recorded.

One possible explanation for this is that, with increasing pedaling rates, the muscle coordination (electromyografical onset and offset) is altered.
Thus the crank angles corresponding to muscle force response (the delay between the neural excitation arriving at the muscle and the muscle developing force) increase significantly with pedaling cadence.
Consequently the force production of lower limb extensor muscles is shifted later in the crank cycle. Hence, force is produced on pedals during less effective crank cycle sectors of the "power stroke" and even during the beginning of the "upstroke" (Samozino et al., 2007).

With crank orientation angles of 73°, 74° and 78° and putting the major axis of the oval vertical, the crank arm is relatively low positioned in the down stroke and is already located close to or in the less effective sectors of the pedaling cycle. This also means that the above mentioned non-circulars have their largest gears close to these less effective pedaling sectors. At increasing and higher pedaling rates these ineffective positions become more distinctive.
Consequently, the larger gears are less efficiently exploited which is reflected in the weaker performances.
Most probably the conclusions of Samozino et al., are a logical explanation why, when looking for an "optimal crank orientation angle", having the major axis of the oval chainring vertical, the crank arm must be positioned rather high in the pedaling cycle.

Overview of the studied non-circular chainrings

 **O.symetric-Harmonic**	 **Q-Ring (Rotor)**
 **Polchlopek oval**	 **Ovum**
 **Ogival**	 **LM-Super**

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