Physiological response to incremental stationary cycling using conventional, circular and variable-geared, elliptical Q – chain rings

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Submitted to the School of Medical Sciences, Faculty of Health Sciences, University of KwaZulu-Natal, in partial fulfillment of the requirements for the Degree of Masters of Medical Sciences (Sports Medicine).

November 2008

Declaration

I, Andrew Jones, declare that the work upon which this project is based is original and my own (except where acknowledgements indicate to the contrary) and that neither the whole work or part thereof has, is presently, or is to be submitted for another degree at this or any other university.

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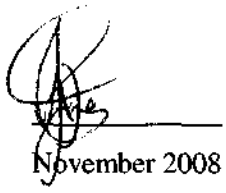

November 2008

Conflict of Interest Statement

I declare that there were no competing interests in this research and that no financial or other support was received from the manufacturers of Rotor Q-rings.

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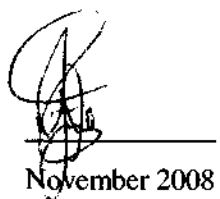

November 2008

Acknowledgements

I would like to thank the following people for their help in completing this research and without whom this work would not have been possible:

1. My research project supervisor, Professor E M Peters-Futre (School of Medical Sciences, Faculty of Health Sciences, UKZN), for all her support, guidance, advice and assistance with this work. More importantly, I would like to thank her for teaching me to be a better research supervisor to my own students.

2. Mrs. Tonya Esterhuizen (Statistician, College of Health Sciences, UKZN) for her help and advice with the statistical analyses.

3. Dr Stuart Rose, for his assistance with the phlebotomy and for his advice as a fellow cyclist.

4. Robin and Geoff Richards, "the bike mechanics", who gave up Friday afternoons and Saturday mornings of their training time to assist us.

5. My receptionist, Julie Buchner, for her editorial assistance and help with the graphic artwork.

6. The cyclists who so freely gave of their time and effort.

7. My wife, Bronwyn, thank-you for listening to my thoughts and plans, being patient with me, for being there to support and understand me.

8. My family and friends for their patience, love and support during my studies and this project.

Abstract

Background: As variable-geared, elliptical Rotor Q-rings may improve pedal dynamics by reducing the effect of the "dead spot" in the pedaling action and altering the mechanical leverage, use of these chain rings is currently gaining popularity among competitive amateur and professional cyclists. There are, however, no randomized, controlled, published studies examining the physiological effect of using Rotor Q-rings vs. standard circular chain rings. In addition, no previous studies comparing circular and noncircular chain rings have included analysis of the markers of exercise induced muscle damage.

Aim: This work was designed to compare physiological response to an incremental cycling protocol when using Rotor Q-rings (QR) with an eccentricity ratio of 1.10 and 74^0 default setting, to that obtained when normal, circular chain rings (NR) are used.

Methods: Twelve trained amateur cyclists (age: 40.67 ± 7.53 years) performed two incremental tests to exhaustion on their own bicycles in a controlled laboratory environment. The subjects were randomized to QR and NR trials which took place seven days apart, within a cross-over design. The type of chain ring attached to the cycle (QR vs. NR) was blinded from the participant. After an eight-minute warm-up at 130 W, the power output was increased by 30 W on the minute. During each trial, heart rate, VE, VO_2 were measured continuously and RPE and blood lactate concentration were measured during the last 15 seconds of each workload. Ventilatory and blood lactate turn- points were determined from serial VE and blood lactate concentrations. Serum lactate dehydrogenase (LDH) concentration was measured before and immediately after each trial. A numerical pain rating scale was used to assess post exercise leg muscle and knee joint soreness 24hr post trial.

Results: There was no statistically significant difference ($p > 0.05$) in mean peak power output (380 ± 29.0 W vs. 385 ± 31.8 W), mean power (194.9 ± 12.7 W vs. 197.2 ± 16.7 W), mean distance covered (9.02 ± 1.29 km vs. 8.89 ± 1.84 km) during the QR and NR trials, respectively. There were no statistically significant differences between trials in submaximal and maximal $V0_2$, VE or RPE, and ventilatory or lactate turnpoints ($p > 0.05$). Knee pain and leg muscle soreness as well as and increment in serum LDH levels did also not differ significantly following the two trials ($p > 0.05$). The difference in peak blood lactate concentrations (12.62 mmol. ℓ^{-1} ± 2.15 on QR vs. 13.84 mmol. ℓ^{-1} ± 1.68 on NR), however, reached borderline significance ($p = 0.055$).

Conclusion: Despite the popularity of non-circular chain rings and the apparent mechanical advantage derived from their use, the findings of this study were unable to provide support for significant physiological advantages when using Rotor Q-rings with an eccentricity ratio of 1.10 and 74^0 default setting, during an incremental cycling test to exhaustion. While the borderline significance of the lower

mean maximal blood lactate concentration following the Q-ring trial requires confirmation in a larger study, the possible roles of training, higher eccentricity ratios and different orientations of the crank to the chain ring in eliciting a physiological advantage, require further investigation.

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List of Abbreviations

$(a - v O_2)$	- difference between arterial and venous oxygen concentration
ACE	- angiotensin converting enzyme
ANOVA	- analysis of variance
AT	- anaerobic threshold
AT4	- anaerobic threshold at a blood lactate level of 4 mmol. ℓ^{-1}
ATP	- adenosine triphosphate
BMI	- body mass index
BP	- blood pressure
Cumsum	- cumulative summation
cm	- centimeter
CO_2	- carbon dioxide
DMAX	- maximum perpendicular distance from the line connecting the start and end of the workload
DNA	- deoxyribonucleic acid
EMG	- electromyograph
F_EV1	- forced expiratory volume in one second
FVC	- forced vital capacity
HCO_3	- hydrogen carbonate
H^+	- hydrogen ion
hr	- hour
km	- kilometer
ℓ	- litre
LDH	- lactate dehydrogenase
LKB1	- serine/threonine protein kinase
MCT	- monocarboxylate transporter
MLSS	- maximal lactate steady state
mmol. ℓ^{-1}	- millimoles per litre
ml. kg^{-1}. min^{-1}	- millilitres per kilogram per minute
MTB	- mountain bike
µL	- microlitre
n	- number
NRS	- numerical pain rating scale
NRT	- normal ring trial

NR	- normal chain ring
O_2	- oxygen
OBLA	- onset of blood lactate accumulation
p	- probability
PGC1A	- peroxisome proliferator activated receptor gamma co-activator 1a
Q-ring	- Rotor Q-ring
QRT	- Q-ring trial
QR	- Rotor Q-ring
RPE	- rate of perceived exertion
rpm	- revolutions per minute
RER	- respiratory exchange ratio
RNA	- ribonucleic acid
s	- seconds
SD	- standard deviation
Tacx	- Tacx Fortius Virtual Reality Trainer
T_{VE}	- ventilatory turnpoint
VCO_2	- carbon dioxide expired
VE/VO_2	- ventilatory equivalent
VE	- pulmonary ventilation/ minute ventilation (L/min)
VE max	- maximum pulmonary ventilation
VO_2	- oxygen uptake
VO_2 max	- maximum oxygen consumption
VO_2 peak	- peak oxygen consumption
w	- watts

Chapter 1

Introduction

1.1 Introduction to the problem:

The bicycle has evolved since the days of the crank-driven velocipede and there have been many developments designed to make the bicycle faster, more efficient and more economical; either through improved aerodynamics or by trying to derive more power through the drive-train mechanism (Burke, 2003). Today cycling is often chosen as a low impact alternative to running and continues to grow both locally and abroad.

The act of pedaling can be divided into two phases – a downstroke extending from the twelve o' clock (0^0) position to the six o'clock (180^0) position and an upstroke starting at the 180^0 and ending at the 0^0 position (Asplund and St. Pierre, 2004). It is only while the cyclist exerts downward pressure on the pedal, that the bicycle is propelled forward (Neptune and Rankin, 2008). Peak torque is developed when the pedal is at 100^0 past the top dead center and torque is low when the pedal is either at the top or the bottom of the pedal stroke (Burke, 2003). The circular chain ring has thus far been the most popular choice in transmitting power from the pedals via the chain to the rear cluster and wheel. Both Burke (2003) and Malfait *et al.* (2006), however, suggest that this may not be the most efficient or economical design and that an eccentric or elliptical chain ring may well improve these dynamics.

When oval shaped Q-rings are used in the place of conventional circular chain rings, the effective downward push phase of the pedal stroke is prolonged and the time spent in positions of low mechanical advantage is reduced making the pedal technique more efficient (Ferrari, 2004).

Several studies have been published on the use of eccentric or non-circular chain rings (Hue *et al.*, 2007; Hull *et al.*, 2007; Ratel *et al.*, 2004; Hue *et al.*, 2001), but only one preliminary report has appeared of work which focused on the Rotor Q- ring (Martinez *et al.*, 2006). In this report some improvements in the physiological response to an exercise program were noted when compared to a circular chain ring, but the results were not statistically analyzed and the improvements noted in terms of power output were not clearly specified (Martinez *et al.*, 2006).

Despite the current popularity of oval Rotor Q-chain rings among both professional and serious recreational cyclists, scientific evidence of their advantages is therefore not available and a carefully controlled laboratory study is required in order to assess the physiological impact of the mechanical adaptations imposed by fitting these non-circular, variable-geared, elliptical chain rings to racing and training bicycles.

1.2 Aim and objectives of study

1.2.1 General aim

To determine the effect of using elliptical, variable-geared Rotor Q-rings when compared to conventional circular chain rings on the physiological response to an incremental exercise protocol in trained male amateur endurance cyclists.

1.2.2 Specific objectives

To compare the following parameters during an incremental exercise test using Rotor Q- rings and conventional circular chain rings:

- Submaximal heart rate, pulmonary ventilation (VE), oxygen consumption (VO_2), blood lactate concentration and rate of perceived exertion (RPE)
- Peak power output, VE, VO_2, heart rate, blood lactate concentration and RPE
- Ventilatory turnpoint (T_{VE}), blood lactate turn- point (T_{lact})and heart rate deflection point
- Serum pre and post exercise lactate dehydrogenase (LDH) concentration difference
- Numerical Pain Rating Scale (NRS) for leg muscle soreness and knee discomfort

1.3 Hypothesis to be tested

As the evidence base of the physiological benefits of using the Rotor Q-rings in preference to circular chain rings is currently limited, the following non-directional null hypothesis was set prior to undertaking the study:

There will be no significant difference in the above mentioned parameters between the trial using conventional circular chain rings and the trial using oval Q-chain rings during an identical incremental exercise test to exhaustion.

1.4 Scope of the study

This randomized, single blind, cross-over trial was restricted to twelve male amateur endurance cyclists who complied with the inclusion and exclusion criteria of the study. These included cycling a minimum of six hours per week during the four months prior to the trials.

Each participant reported to the exercise physiology laboratory on three occasions. Following a baseline assessment and familiarization session, cyclists were randomized to two identical incremental cycling trials to exhaustion. One trial was conducted using a standard circular 53 tooth chain ring and one after an oval, variable-geared Rotor Q-ring had been fitted to the cycle. Blindedness was maintained by covering both chain rings with an opaque plastic disk and with the use of a RavX sweat cloth.

During each incremental trial, heart rate, VO_2, V_E, RPE and blood lactate concentrations were assessed at each power output on the minute, while serum lactate dehydrogenase and blood lactate concentrations were also measured pre and post trial. The degree of muscle soreness/knee discomfort was recorded 24 hours post trial.

In order to eliminate a training effect as a potential confounder in the study, the between-trial wash-out period was restricted to seven days.

Chapter 2

Review of the Related Literature

2.1 Cycling

2.1.1 Introduction

The modern day bicycle has undergone numerous changes since the crank-driven Velocipede made in France in 1855 or the Pennyfarthing designed in England in 1873. It was only in 1880 that the precursor of today's bicycle, the safety bicycle, with wheels of equal size and pedals that were attached to a chain ring through gears and a chain that drove the rear wheel, was developed (www.footprintpress.com). There have subsequently been numerous further developments in making the bicycle faster through aerodynamic changes to the frame or by trying to derive more power via the drive-train mechanism (Burke, 2003).

Cycling has continued to grow in popularity and is often chosen as a low impact alternative to running. It is estimated that approximately five million Americans ride at least 20 days per month (Asplund and St. Pierre, 2004) and up to nine percent of all trips currently made in Europe are made by bicycle (Mozer, 2008). Similar growth has been reported in South Africa, particularly in mountain bike riding and racing (Smith, 2007).

2.1.2 The bicycle drive-train

The bicycle drive-train begins with the pedals which rotate the crank arms which are held in axis by the bottom bracket. Attached to the one crank arm is the chain ring which drives the chain. This then rotates the rear wheel via a cassette. The gearing system, controlled by the derailleur, is used to vary the number of rear wheel revolutions produced by each turn of the pedals. By shifting gears upward on the rear cassette or downward on the front chain rings, the force required to move the same distance is spread over more pedal strokes and this reduces the cyclists fatigue while cycling up a steep hill or against a heavy wind. Cyclists therefore have their preferred rate of pedal turn-over or cadence at which their legs produce optimal power or work more economically (Asplund and St. Pierre, 2004).

2.1.3 Bicycle biomechanics

When the 0^0 crank angle corresponds to the vertical position of the crank arm, the act of driving the pedal around the circle can be divided into downstroke and upstroke phases which occur between 0 and 180^0 and 181 and 360^0, respectively (Burke, 2003). Hillebrecht *et al.* (1997) further subdivided the crank cycle

into four 90^0 power output sectors Figure 2.1), namely, Sector 1 (between 315 and 45^0) and Sector 3 (between 135 and 225^0) which are associated with the top and bottom dead points of the crank cycle, and Sector 2 ($45 - 135^0$) and Sector 4 ($225 - 315^0$) which constitute the active "push-down" and "pull-up" phases, respectively (Rankin and Neptune, 2008; Bertucci *et al.*, 2005; Hillebrecht *et al.*, 1997).

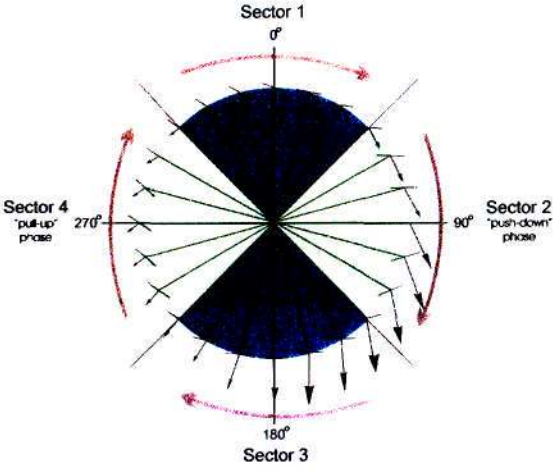


Figure 2.1 Power output sectors and the magnitude of resultant forces as function of crank arm alignment (Adapted from Rankin and Neptune, 2008; Burke, 2003; Hillebrecht *et al.*, 1997)

Forces applied to the pedals have two vector components, an effective tangential component which is perpendicular to the crank arm and an ineffective radial component, which is applied parallel to the force (Figure 2.2). To achieve forward movement (translation) of the bicycle, a downward force is required on the pedal and the crank arm. The propulsive torque is dependant on the product of the length of the crank-arm and the magnitude of the tangential component of the downstroke, as only forces acting perpendicularly to the bicycle crank arm will rotate it. Peak torque on the pedal therefore occurs when the crank arm is forward and almost horizontal, at about 100^0 past top dead center, as in this position, the tangential component of the force is greatest. Conversely, the resultant torque is low when the pedal is at the top or bottom of the pedal cycle, with the largest force component being radial and directed parallel to the crank arm (Burke, 2003).

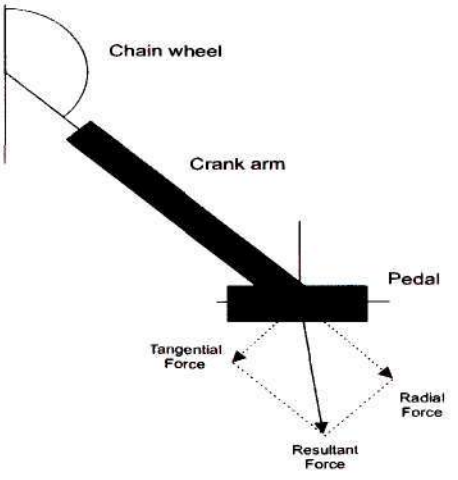


Figure 2.2 Forces generated during pedaling (Adapted from Hillebrecht *et al.*, 1997).

As the pedals are connected through the bottom bracket, the net crank torque is the sum of the forces applied to both pedals and there are two distinct torque peaks corresponding to the right and left pedal downstrokes, respectively. As is shown in Figure 2.3, there are also two distinct low points in torque production as the pedals pass through the top and bottom centers of the pedal arc (Bertucci *et al.*, 2005). These are traditionally known as the dead spots in pedaling action. As biomechanical efficiency is determined by the ratio of the sum of the tangential and resultant forces (Hillebrecht *et al.*, 1997), cycling is more efficient when the ineffective force parallel to the crank arm (radial component) is kept to a minimum and the transition across the dead spots is smooth (Ferrari, 2004; Colson, 2002). A cyclist should therefore aim at prolonging the effective phase or downstroke of the pedal movement and reducing the amplitude of the two torque peaks, in order to optimize efficiency of cycling (Burke, 2003).

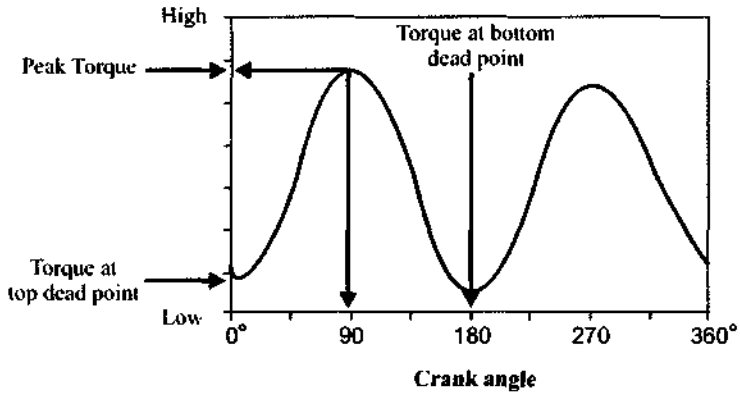


Figure 2.3 Pedal torque oscillation
(Adapted from Bertucci *et al.*, 2005)

Mountain bikers have been reported to pedal more uniformly or smoothly than road cyclists. It has been suggested that they produce smaller oscillations in power magnitude as they pedal in a more circular pattern than road riders (Burke, 2003). Lopes and McCormack (2005) suggest that they may also have adapted to this way of pedaling to minimize rear wheel slippage while pedaling uphill on loose soil.

2.1.4 Muscles of cycling and pedaling technique

In terms of muscular effort, the force generated pependicular to the crank arm, should be optimal to maximise the forward movement of the cycle on the downstroke, while the force of gravity also needs to be overcome on the upstroke. It is also important to pedal in perfect circles to negate the effect of the area of least mechanical advantage i.e. the dead spots in Sectors 1 and 3 of the crank cycle (Hobson *et al.*, 2007; Armstrong and Carmichael, 2006; McCormack, 2005).

Major muscles involved in the pedal movement include the quadriceps which act as hip flexors and knee extensors and the hamstrings which function as knee flexors and hip extensors. The quadriceps muscles, the predominant knee extensors, and the gluteus maximus, primary hip extensors, provide most of the

forward drive for bicycle movement and are predominantly recruited from 0 – 150.^{0} While the involvement of the quadriceps muscles is greatest from 60 - 90^0, the gluteus maximus are primarily recruited in the 70- 150^0 zones (Figure 2.4; Umberger *et al.*, 2006; Asplund and St Pierre, 2004).

As plantar flexors, the gastrocnemius muscles act as accessory muscles in the 60 - 190^0 zone, with greatest recruitment between 120 to 180^0 (Umberger *et al.*, 2006; Lopes and McCormack, 2005). The hamstring muscles, as knee flexors, however, take over the pedal action on the upward movement of the pedal between the 150 to 270^0 positions and contract in opposition to the effects of gravity. They are particularly active at the area of least mechanical advantage i.e. 180^0 (Umberger *et al.*, 2006). The action here is small as the downward force on the opposite pedal outweighs the hamstrings upward pull. Focusing on correcting this upward pull can reduce the quadriceps load, as without this assistance from the hamstring muscles, the quadriceps would have to lift the weight of opposite leg too (Burke, 2003).

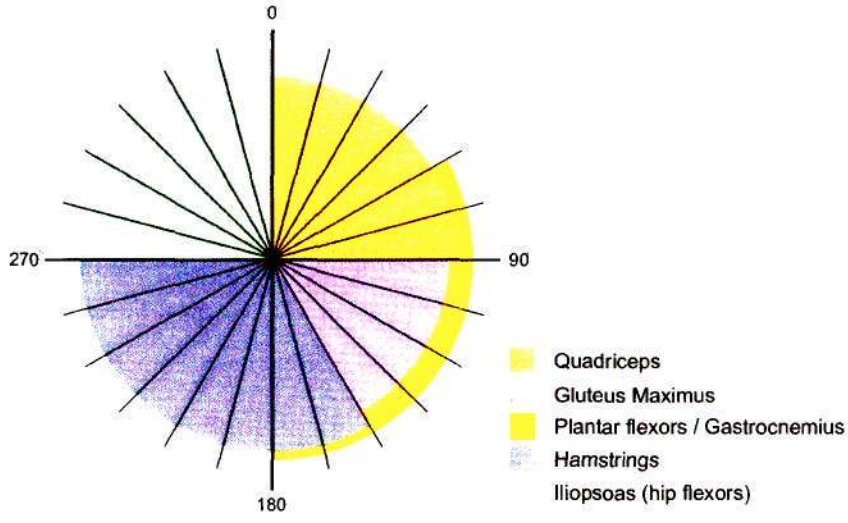


Figure 2.4 Muscle involvement during the pedal trajectory

The psoas and iliacus muscle action complete the remaining zone between 270 and 0^0. It is their action that carries the pedal over the 0^0 dead spot (Umberger *et al.*, 2006; Lopes and McCormack, 2005), but this contribution is small as the quadriceps of the other leg would be driving down creating a force which may help swing the pedal over the 0^0 position (Burke, 2003).

The anterior tibialis and long extensor toe muscles have a very small role to play in the pedal action, but are still involved in lifting the foot and toes as the pedal moves over from the 280 to the 0^0 position (Umberger *et al.*, 2006). According to Ferrari (2004) by encouraging the cyclist to use his ankle more or by pedaling on tip to this can help reduce the ineffective pedal forces and thus reduce the stress on the other muscles involved in pedal movement.

Pedal strokes will vary according to each rider's body type, riding position, saddle height, saddle fore-aft position and preferred cadence (Mooney, 2007). By altering the position in which the cyclist pedals in order to gain more power or increase leg speed, the cyclist can cause injury to the above muscle groups. The riders who have the saddle set too high place greater stress on the hamstring and gastrocnemius groups as the knee is allowed to extend more, which has been reported to contribute to posterior knee pain (Asplund and St. Pierre, 2004). With a saddle in a low position, it places more stress on the quadriceps muscles and can result in anterior knee pain (Asplund and St. Pierre, 2004; Baker, 1998). When the rider moves the saddle forwards, this emphasizes quadriceps contraction and allows for a greater leg speed and a higher cadence, but can also contribute to anterior knee pain. Positioning the saddle backward results in greater hip extension and thus more gluteal contraction, but can cause over emphasis on the hamstring group and associated posterior knee pain/tendonitis (Mooney, 2007; Asplund and St. Pierre, 2004).

2.1.5 Joint movement during the pedal stroke

The hip is kept in a predominantly flexed position dependant on each cyclist's position on the bicycle. At the 0^0 position the hip is at maximum flexion, it will then undergo extension as the quadriceps and gluteal muscles contract until the 180^0 position is reached. With contraction of the hamstring and hip flexor muscles and the effect of the pedal lifting the foot as the opposite leg drives downward, the hip will then undergo flexion again (Burke, 2003).

Depending on the cyclist's position on the bicycle, saddle height and saddle forward or backward movement the knee will go through approximately 75 - 85^0 of motion. At the point of power application and maximum knee flexion, it would be at 110^0 and it would then extend to approximately 25 - 35^0 at the bottom of the pedal stroke (Asplund and St. Pierre, 2004; Krause, 2004). The knee would also translate medially on the downward pedal stroke as a result of the normal valgus orientation of the knee. On the upward movement of the pedal these movements are reversed and the knee then translates laterally and undergoes flexion (Asplund and St. Pierre, 2004; Burke, 2003).

The degree of ankle plantar and dorsiflexion is dependant on saddle height and may be from five degrees dorsiflexion to 12 degrees plantar flexion at the 0^0 position and 20 - 25 degrees plantar flexion at the 180^0 position (Krause, 2004). The foot position on the cleat of the cycle shoe also contributes to the degree of ankle plantar and dorsiflexion as moving the foot posteriorly resulted in less ankle dorsiflexion, but increased muscular activity in the quadriceps and gluteal muscles. Moving the foot anteriorly would result in increased ankle dorsiflexion (Ericson, 1986). Burke (2003) states that moving the foot forward on the pedal reduces the amount of strain on the Achilles tendon and can help those riders wanting to pedal a harder gear, but at a slower leg speed. The ankle movement during the pedal cycle is to plantar

flex on the upstroke until the last 35 - 45^0 at which point it begins to dorsiflex slightly. This continues and increases into the downstroke (Burke, 2003). Individual pedal style also makes a difference as some cyclists will over-emphasise the ankle's movement i.e. the pedal is scooped around the crank arm during the pedal cycle. According to Ferrari (2004), this will make the pedal action smoother and will thus reduce the height of the two force peaks that occur. Other cyclists will attempt to keep the ankle in a neutral position.

As the force is applied to the pedal the foot pronates which causes an internal rotation of the tibia, the degree of pronation is dependant on each cyclist's natural foot biomechanics and the type of shoe that is worn. Many road cycling shoes are made of carbon and may have magnesium, titanium ore steel lasts which may restrict the foot's natural movement to some degree. On the upstroke of the pedaling movement the foot will supinate as it becomes unloaded and this will cause the tibia to rotate externally (Asplund and St. Pierre, 2004).

2.1.6 Cadence and factors contributing to it

Some cyclists will chose a slower cadence while some will 'spin' at a very high cadence. Most will, however, chose to pedal at a rate that works for them. This is possibly affected by their muscle typing and morphology, the size of the bicycle frame or its components, the feeling of exertion while pedaling and their cycling experience. According to Marsh (1996) and Bieuzen *et al.* (2007) the cadence that correlates with the "metabolic optimum" or the cadence that is most economical with the lowest oxygen consumption is around 55-65 rpm, but experienced cyclists consistently use cadences considerably higher (85 - 95 rpm). The reason for this is uncertain. It has been suggested that training status is an important variable (Burke, 2003) as experienced cyclists tend to choose cadences that minimize perceived exertion although these may not be the most economical. Marsh (1996) suggested that using a higher cadence would also result in greater recruitment of Type I fibers, while more Type II muscle fibers would be recruited at a lower cadence. As Type II fibers are less economical, the riders would therefore feel increased strain at these lower cadences (Marsh, 1996).

Marsh (1996) also proposed that smaller muscular forces, implying less muscular effort, repeated more often may result in a feeling of less fatigue at a higher cadence. Ferrari (2003) supports this suggesting that there is greater force on the pedal and hence greater load on the muscle when pedaling at lower cadences. This was confirmed by Deschenes *et al.* (2000) who found that pedaling at a cadence of 40 rpm compared to 80 rpm, produced greater levels of post-exercise cortisol and plasma lactate concentration, heart rate and rate of perceived exertion after 30 minutes of cycling.

Gonzalez and Hull (1989) highlighted the importance of tailoring the bicycle equipment to the individual for optimal results. They found that the optimal crank arm length, seat height and longitudinal foot position on the pedal increases as the size of the rider increases, but cadence and seat tube angle decreases as the riders size increases. According to these authors incorrect bicycle fit could thus negatively affect the rate of pedaling and a smaller cyclist would have a higher rate of cadence than that of a larger cyclist (Gonzalez and Hull, 1989).

Another factor affecting optimal cadence is blood flow to the muscles. In the period of maximum muscle contraction, particularly in the first third of the crank cycle, there is reduced blood flow and thus oxygenation to the muscles (Burke, 2003). This is thought to be the result of the increased intramuscular pressure that occurs in this period. This reduced blood flow is then reversed when the muscle is in its' recovery phase. As the duration of restricted blood flow to the working muscles is shorter at high pedal rates, Burke (2003) advocates the use of a cadence above 90 rpm.

MacIntosh *et al.* (2000), however, favor an optimal cadence that would increase at each wattage, but result in the lowest EMG amplitude at each given power output. This is supported by the finding of Hallen and Foss (2004) that higher cadences are more economical at higher wattages.

Although Umbereger *et al.* (2006) most recently confirmed that low (40 rpm) and high cadences (120 rpm) are substantially less efficient than cadences between 60-100 rpm, regardless of fiber typing, the question of optimal pedaling cadence, has, however, not been resolved conclusively. Few investigations have examined well trained riders on their own bikes and even fewer studies have examined the cadence selection of trained cyclists in open road cycling.

2.1.7 Cycling efficiency

Gross mechanical efficiency has been defined as the ratio of work done to energy expended or the percentage of total energy that is expended that produces external work. This is an estimate of whole body efficiency (Burke, 2003). Gross efficiency is a product of training, with pro-tour riders exhibiting an efficiency of up to 25%, while non-cyclists are 20% efficient at the same intensities (the remaining 80% of the energy produced being burnt off as heat). This is also dependant on the percentage distribution of type I muscle fibers in the cycling muscles. The greater the percentage of type I fibers, the more efficient the cyclist will be (Faria *et al.*, 2005; Burke, 2003).

In addition to the internal factors that influence a rider's efficiency, several external factors are also important. These include poor fit or incorrect bicycle set up which will result in reduced efficiency (Faria

et al., 2005). As mentioned previously, the cyclist's chosen gear ratio and pedaling cadence also directly affects the cycling efficiency (Faria *et al.*, 2005). Other factors include friction within the drive-train, the bottom bracket, chain elements, rear transmission and the type of bearings and lubricant used in the internal bearings (Burke, 2003).

The tyre's casing and tread also make a difference as some have a greater rolling resistance than others, making the cyclist's forward progression less efficient. The surface ridden on, tyre pressure, tyre and wheel diameter (there is less aerodynamic drag in a wheel with a smaller diameter) and tyre temperature (Burke, 2003) also affect cycling efficiency and need to be controlled in scientific studies.

2.1.8 Eccentric and non-round chain ring research

The circular chain ring, which provides a constant radius from the crank centre to the chain driving the rear wheel, has so far been the most popular choice in transmitting the power of the pedal stroke to the rear cluster. Both Burke (2003) and Malfait *et al.* (2006), however, suggest that there is still uncertainty that the circular crank system is the optimal choice and that eccentric or elliptical systems may very well improve the crank/pedal dynamics due to variation on the radius of a non-circular chain ring as a function of the crank angle. Thus, in theory, the advantage offered by these elliptical chain rings would be to improve the mechanical effectiveness of the chain ring by exploiting the positions in the pedal stroke where higher torque is generated or by accelerating either the up or downstroke of the pedal movement which should then translate into improved performance (Ratel *et al.*, 2004). Several laboratory studies have been performed on the use of eccentric, elliptical, skewed ellipses or non-circular chain rings. The results of these studies have, however, not been consistent.

According to Neptune and Herzog (2000) and Ratel *et al.* (2004) when an elliptical chain ring is compared to a circular chain ring in the crank cycle, there will be regions of increased or decreased crank speed and possibly altered muscle contraction velocities. A study was therefore conducted on eight competitive cyclists to determine whether muscles may adapt by increasing the magnitude of contraction, increasing the action of non-primary muscles or changing the muscle contraction timing to include more regions of increased crank speed (Neptune and Herzog, 2000). It was found that adaptation to the two different orientations of an elliptical chain ring occurred very quickly within the first 10-20 cycles of switching to the elliptical chain rings. There was very little difference in muscle activity timing or EMG magnitude, most notably in the regions of crank angle favorable to produce muscle power, between using the different chain rings. These authors suggested that the nervous system adapted and altered the degree of neurological supply to the muscle instead of altering the timing of contraction with the different chain rings. They only found slight differences in the pedal profiles, indicating that the muscles had traveled through the same range of motion (Neptune and Herzog, 2000).

Although Okajima (1983) found that the non-circular *Biopace* chain ring improved cycling efficiency by reducing leg joint torques and muscle EMG when compared to a circular chain ring at a given power output, Hull *et al.* (1992) found that there was no difference in the physiological variables (heart rate, blood lactate, VO_2 max and respiratory data) that were studied when round, *Shimano Biopace* and two custom-made, engineered elliptical designs were compared. The two engineered, skewed, elliptical designs were orientated 80^0 from each other along the major and minor axes. The study was conducted over four consecutive days with the eleven, male, cyclists riding at 80% of VO_2 max and again at 60% VO_2 max with each ring. The order of the chain ring use was randomized, but not controlled.

These findings were confirmed by Cullen *et al.* (1992) when seven competitive cyclists rode their own bike on a wind trainer. The participants were permitted only two gear ratios (5.92 m and 7.33 m) and three pedal cadences (50, 70 and 90 rpm), while examining the same physiological variables, using both the circular chain ring as well as a non-round chain ring No difference was observed in cycling efficiency when using the different rings.

Ratel *et al.* (2004) tested 13 endurance trained, sub-national, cyclists between the ages of 16 and 45, on their own bikes on a simulator using circular and noncircular (*O. symetric Harmonic*) chain rings, but this time altering the speed and the slope every two and a half minutes until exhaustion. The order of the chain ring use was randomized, but not controlled. The physiological variables i.e. VE, VO_2, RER and heart rate were assessed continuously, but blood lactate concentrations were assessed in the last 30 seconds of each two and a half minute period only. Similar results were achieved to those reported by Cullen *et al.* (1992) and Hull *et al.* (1992).

In 2001 Hue *et al.*, in a study involving eleven cyclists over a two week period, while confirming no differences in cardio-respiratory function, found that there was, however, a significant difference in performance, *viz.* faster times, with an eccentric chain ring in a one kilometer all-out laboratory test. The design of this chain ring increased the crank arm length by allowing one of the cranks to slide and revolve around an elliptical cam on the downstroke and reduced crank-arm length on the upstroke. This allowed greater torque on the downstroke which may have translated into greater speed. The crank arm length actually increased from 175 mm to 200 mm on the downstroke and then returned to 175 mm on the upstroke, thus allowing an increased mechanical advantage on the downstroke. The order of the chain rings used in this study were randomized, but not controlled.

The above-mentioned test was repeated using 12 competitive male cyclists with a mean age of 17.4 ± 0.3 years, in a 1000 m time trial around a 333 m banked cycling velodrome, while using the *Pro-race* chain ring (Hue *et al.*, 2007). The use of the chain rings was again randomized, but not controlled. Only one gear ratio was used (8.16 m) and the performance, physiological variables (heart rate and blood lactate concentration measured before and after each trial) and the speeds, did not vary significantly. They did,

however, find a positive correlation between performance when using the eccentric chain ring and lean lower limb muscle volume and calf muscle size and therefore suggested that there may be a benefit to using the eccentric chain ring if the subject has a greater lower limb volume and calf size (Hue *et al.*, 2007).

A study examining the efficiency of a carbon fiber eccentric chain ring versus a standard circular, metallic, chain ring on the same bicycle (Belen *et al.*, 2007) yielded conflicting results. The eccentric chain ring's carbon fiber design was supposed to eliminate the disadvantage of the extra weight of the aluminium model of the same chain ring (*Prorace*). The order of chain ring use was randomized, but not controlled. This eccentric chain ring also emphasized the greater torque achieved on the downward or push phase of the pedal stroke by employing the same elliptical cam and sliding crank arm. These researchers found that using the eccentric chain ring actually significantly lowered maximal speed (39.4 ± 2.5 and 41.5 ± 2.9 km. hr^{-1}) at volitional exhaustion and increased oxygen uptake, carbon dioxide production and heart rate. There was no significant difference in blood lactate concentrations at exhaustion, five and 15 minutes post trial between the two chain rings.

Rankin and Neptune (2008) attempted to identify the force-length-velocity relationships that could maximize average crank power using isokinetic pedaling to optimize chain ring shape by developing an optimization model. They used algorithms to perform these optimizations and concluded that an eccentric chain-ring with a ratio of 1.29 (major to minor axes lengths) and rotated 91.8^0 to the crank arm, would succeed in increasing crank power by three percent at 90 rpm. They found that the increased power was the result of angular velocity of the crank being slower in the power phase of the crank arm movement which would allow the muscles to generate more power for longer, particularly the gluteal, *vastus lateralis* and ankle plantar flexors (Figure 2.4). These authors also state that careful consideration should be given to the subjects' muscle fiber typing as those with slow twitch muscle fibers may benefit more from a chain ring with a less eccentric shape.

Despite the lack of consistent positive findings in terms of physiological responses, consensus among the cycling fraternity that eccentric chain rings provide a mechanical and subsequent performance enhancement appears to prevail.

2.1.9 Rotor Cranks

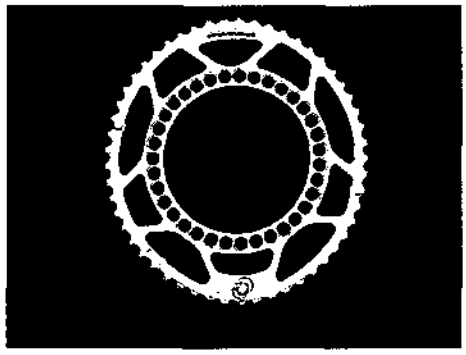
The rotor crank system uses four elliptical gears that are attached to the bottom bracket of the bicycle frame. The system makes each pedal crank independent of the other i.e. the cranks are no longer fixed at 180^0 from each other. This allows the rider to eliminate the dead spots completely as the cranks will not be at the 0^0 and 180^0 positions simultaneously (Santalla *et al.*, 2002; Martinez *et al.*, undated). The leg undergoing the upward phase of pedal movement can therefore assist the downward movement of the other leg in its power phase. The ascending crank moves faster than the descending crank and moves

over the 0^0 position before the descending crank reaches the vertical position. This may help reduce the onset of fatigue in the main muscles of pedaling making the pedal stroke more mechanically efficient. (Burke, 2003) Varied results have thus far been obtained when using rotor cranks. Santalla *et al.* (2002) found that there was an improvement in delta efficiency but, not in terms of VO_2 max or peak power output, when using these cranks. Lucia *et al.* (2004) found no advantage in using the Rotor cranks when physiological variables, economy and efficiency were assessed, but Martinez (undated) did report a reduction in blood lactate concentration and heart rate when using this system.

2.1.10 Rotor Q-Rings

The Rotor Q-ring system, entering the cycling market in 2005, was designed to emulate the gear variations of the Rotor cranks, but allow the cyclist to use the bicycle's own cranks. It was designed as a modified ellipse with circle arcs at the ends of the major axis with an eccentricity ratio of 1.10. Its long axis measures 212 mm while the short axis measures 192 mm. Although there are multiple attachment points that allow for inter-rider variability, the manufacturers recommended that the attachment point is at 74^0 for the long axis against the crank arm (Malfait *et al.*, 2006). The Q-ring's design allows customization as its attachment to the crank bolts can be varied according to the preferences of each cyclist. The system also weighs less than the crank system made by Rotor and is considerably more cost effective.

These variable, more oval-shaped Q-chain rings allow the rider to move through or reduce the spots of poor biomechanical efficiency and in so doing, reduce the physiological and muscular load, but maintain the same speed or power (Malfait *et al.*, 2006). Q-rings change the equivalent chain ring tooth size by decreasing it at 180^0 and 0^0 and increasing it within the power phase (30 -150^0). At 0^0 the Q-ring is equivalent to a 51 tooth chain ring (the normal: 53), while at the maximum power point it is equivalent to a 56 tooth chain ring. By reducing the time spent in the dead spot, the cyclist's performance should improve as well as reduce the occurrence of tendonitis of the knee and other sources of knee discomfort (impressions.co.za; www.rotarcranksusa.com). In addition, it is possible that use of these Q-rings increases the cyclist's efficiency by allowing the legs to remain in the active or power phase of the pedal stroke for longer (impressions.co.za; www.rotarcranksusa.com).



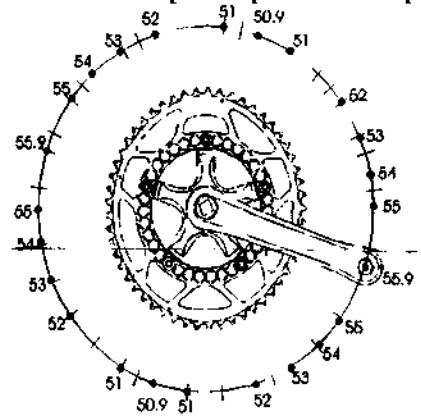


Figure 2.5 The 53 tooth Rotor Q-ring with eccentricity ratio of 1.10 (left) and Q-ring showing equivalent leverage in tooth count when compared to a circular ring (right).

The actual pedal movement remains circular and the crank arms are still orientated 180^0 from each other. It is only the time spent in the different phases of the 360^0 cycle that is different, and as such, the adaptation to the Q-ring occurs very quickly (Pavelka, undated)

Of great interest is the recent, preliminary report (Martinez *et al.*, 2006) of a study performed using the Q-Rings (Rotor Systems) on eight male subjects under the age of 23. The study consisted of three parts: an incremental exercise test, a repetitive maximal sprint test in which each sprint was maintained for 20 seconds followed by 40 seconds of rest and a 90% maintained power test. Martinez *et al.* (2006) reported reduced lactate concentrations for the same effort and a higher peak power output when the cyclists used the Q-rings in a 90% maintained power test (Martinez *et al.*, 2006). In the progressive incremental exercise protocol Martinez *et al.* (2006) found a 3% increase in power and a slightly reduced heart rate (2%), while in the repeated sprint test greater power output was produced in the first, third and fourth sprints only. No difference was noted in heart rates or VO_2 max results (Martinez *et al.*, 2006). Unfortunately the data were not statistically analysed and the statistical significances of the small changes reported, are not available.

When using a mathematical model to compare different non-circular chain rings, Malfait *et al.* (2006) found that in terms of total crank power and peak joint power loads, the Q-ring produced greater load on the knee joint muscles than the circular chain ring, but less load on the hip joint muscles. In terms of crank power efficiency, an improvement was found by rotating the long axis of the Q-ring by 122.7^0. It was also calculated that this angle produced less knee strain.

No controlled, cross-over laboratory trial has, however, yet been performed on subjects using circular and non-circular variable-geared Q-chain rings. Most other trials on eccentric, noncircular, elliptical or eccentric chain rings (Hue *et al.*, 2007; Ratel *et al.*, 2004; Hue *et al.*, 2001; Cullen *et al.*, 1992; Hull *et al.*, 1992) have also concentrated only on the physiological markers of exercise, but no trials have, as yet, examined the effect of these chain-rings on markers of exercise-induced muscle damage.

2. 2 Physiological response to incremental exercise

2.2.1 Heart rate

During exercise, cardiac output increases to match the increased metabolic demand of the muscles (Wilmore and Costill, 2005). This is achieved by activating both the chronotropic and inotropic reserves of the heart. As exercise begins, activation of the sympathetic nervous system has an accelerating effect on impulse generation by the sinoatrial node (Ganong, 2005). A linear increase in heart rate which is positively correlated with the increase in metabolic rate and oxygen consumption (VO_2), occurs as workload increases. The rate of this increase is also affected by the internal body temperature via the Q10

effect (Fukuba *et al.*, 2001), medication, ingestion of caffeine and other CNS stimulants, altitude and gender (Wilmore and Costill, 2005; Roberts, 2002).

With improved training status, the increased stroke volume generated at a given power output reduces the rate at which the heart rate increases and also increases the rate with which the heart rate returns to normal after exercise (Roberts, 2002). Endurance training has also been found to be one of the major factors which attenuates the age-related drop in maximum heart rate (Robergs and Landwehr, 2002; Miller *et al.*, 1993). Hence the formula 220-age (Londeree and Moeschberger, 1982), which is based on a one beat per year fall in maximum heart rate, has been found not always to be applicable to trained endurance athletes (Carter *et al.*, 2003).

A heart rate break point at which work intensity increases more than heart rate during an incremental exercise test, also termed the heart rate deflection point, was proposed by Conconi *et al.* in 1982 as correlating with the anaerobic threshold (Wasserman *et al.*, 1967). The degree of heart rate deflection has, however, been found to be highly dependant on the type of protocol used (Ghosh, 2004) and not consistent. This is particularly evident in older subjects and cardiac patients who show a high degree of non-regular heart rate response and often fail to display a heart rate deflection point (Ignjatovic *et al.* 2008, Hoffman *et al.*, 2004).

2.2.2 Oxygen consumption (VO_2): submaximal and maximal

Due to increased metabolic demands of exercise, there is a linear relationship between the VO_2 and the power output which has been shown to correlate strongly with the increments in heart rate (Xu and Rhodes, 1999). As the intensity increases, so the rate of oxygen uptake increases too, until a plateau in VO_2 is reached and no further increase occurs with an increase in work rate.

Maximum oxygen consumption (VO_2 max) has been defined as the maximum rate at which oxygen can be taken up, distributed in the body and used to perform work (Bassett and Howley, 2000), commonly expressed in $\ell . min^{-1}$ or $ml . kg^{-1} . min^{-1}$. Work may continue after reaching this limit, but this depends on the individual's oxygen independent metabolism, maximum power output and motivation (Noakes, 2001; Xu and Rhodes, 1999). The higher work rates can only be maintained for a short period of seconds to minutes as there will be an accumulation of metabolites of non-oxidative metabolism, a slowing of ATP-generation and thus reduced muscle performance (Noakes 2001; Bergh *et al.*, 2000). Should the individual, however, fatigue before this plateau phenomenon is observed, the maximum value recorded is referred to as VO_2 peak (Arngrimsson *et al.*, 2002; Mancini *et al.*, 2000)

Although numerous exercise physiologists continue to maintain that VO_2 max is a measure of "aerobic" metabolism of the body, there is currently much controversy surrounding its value as a predictor of

potential in endurance events (Brooks, 2002; Noakes, 1998; 1997). There is also considerable debate regarding the role of the pulmonary, cardiovascular and muscular systems in determining the uptake of oxygen used or the rate of oxygen delivery during exercise (Grassi 2001; Hughson *et al.*, 2001; Bergh *et al.*, 2000; Richardson *et al.*, 1999).

There is a notable lag of 10-15 seconds between the increase in workload and the increase in VO_2 and the reason for this is also open for debate. While it may be related to the rate of delivery of O_2 to the exercising muscle or to the rate of intramuscular oxidative metabolism, at exercise levels above the lactate threshold, the rate of oxygen delivery to the muscle has been described as the most critical factor in determining the rate of O_2 uptake (Grassi 2001). Proponents of this theory suggest that the rate of VO_2 increase during intensive exercise is limited by central factors which determine the cardiac output, arterial O_2 content and muscle blood flow.

While oxygen delivery to the working muscle is dependant on the capacity of the pulmonary and cardiovascular systems, peripheral factors such as oxygen diffusing capacity and O_2 utilisation have also been suggested as limiting factors (Richardson *et al.*, 1999; Xu and Rhodes, 1999). Mathieu-Costello and Hepple (2002) report that muscle fiber size and capillary density influence the rate of oxygen absorption in the muscle, but according to Hughson *et al.* (2001), the ATP supply and demand is limited by the availability of metabolic substrates and the adaptation of the metabolic pathways without any impact of O_2 on these mechanisms. Skeletal muscle O_2 uptake has also been reported to be affected by the muscles oxidative metabolism related to acetyl group availability in the mitochodria or possibly by the "regulatory effects on intracellular respiration related to phosphocreatine splitting" (Grassi, 2000; Richardson *et al.*, 1999).

A third school of thought (Noakes, 1998) proposes that local muscle factors which are independent of oxygen delivery or uptake, may limit VO_2 max by halting maximal exercise before the O_2 dependant systems are taxed to their maximum. Athletes with superior muscle contractility, either due to greater myosin ATPase activity or enhanced capacity to bind calcium, superior muscle efficiency, elasticity and fatigue resistance, are thought to sustain higher work rates for longer before the maximum pumping capacity of their hearts is reached. These are, in turn, proposed to be dependent on the contractile ability and efficiency of the heart which will produce a greater blood flow to the muscles before coronary flow becomes a limiting factor (Noakes, 1997). According to the central governor theory, the brain's motor cortex is also able to monitor the state of oxygenation of the heart and inhibit further recruitment of additional skeletal muscles once this critical threshold is reached (St. Claire Gibson and Noakes, 2004).

$VO_{2\ max}$ is affected by each person's genetic background and this may account for up to 20-90% of the variance seen between individuals (Hagberg *et al.*, 2001), but few studies have investigated the role that this may have. The related genes that have been identified included the ACE II genotype, skeletal muscle creatine kinase gene and the angiotensin-converting enzyme gene (Hagberg *et al.*, 2001).

The subject's initial level of training also influences each subject's response to an incremental exercise test. Lortie *et al.* (1984) reported a mean 33% increase in VO_2 max when a 20 week training program was given to a group of sedentary subjects. They, however, found considerable variation between individuals with improvement in maximum aerobic power ranging from 5 - 88%. Richardson *et al.* (1999) attribute this primarily to a combination of the increase in size of the capillary-to-fibre interface and mitochondrial volume which follow endurance training. In contrast, age affects VO_2 max negatively and a general decline of about 1% per year after the age of 25 has been reported (Xu and Rhodes, 1999). This may not be solely due to the aging process, but may be due to increased body mass without changes to ventilation values (Xu and Rhodes, 1999). It may also be due to the reduced maximum heart rate, maximal stroke volume and maximal difference between arterial and venous oxygen concentration (a-v O_2; Xu and Rhodes, 1999). The rate of age-related reduction in VO_2 max has been found to be limited in athletes who continue to exercise at previous intensities as both high-intensity resistance and endurance training are known to improve the rate of oxygen uptake by the exercising muscle and the rate of oxygen delivery (Richardson *et al.*, 1999).

When the VO_2 max values of athletes of similar running performances are compared, the inverse relationship between VO_2 max and performance times is not strong (Bassett and Howley, 2000). One of the factors which may explain the frequent observation that individuals with a high VO_2 max do not necessarily out-perform those with lower maximum values VO_2 at a given submaximal workload, is economy of effort (Noakes, 2001). During cycling, this is expressed as the power output generated at a cost of one litre of oxygen per minute of exercise (W/VO_2) or the energy required (VO_2) to maintain a constant power output (Burke, 2003). It has also been reported to be related to the percentage of type I muscle fibers in the active skeletal muscle (Grassi, 2000) and possible neural adaptation (Loveless *et al.*, 2005).

2.2.3 Exercise induced increments in blood lactate and blood lactate transition thresholds

The principal circulating product of carbohydrate digestion is glucose. This is polymerized and stored as glycogen in the muscles and liver (Ganong, 2005). When the demand of working muscles increases, blood glucose diffuses into the active muscle cells and together with glucose molecules derived from intramuscular glycogen stores, is phosphorylated to glucose-6-phosphate and catabolised to pyruvate primarily via cleavage through fructose and the trioses in a series of sequential metabolic reactions known as glycolysis and/or glycogenolysis (Ganong 2005, Noakes, 2001; Figure 2.6).

With increasing exercise intensity and exercise between thirty to ninety seconds in duration, glycogenolysis and glycolysis are the primary contributors to energy production (Noakes, 2001). During high –intensity exercise, the increased glycolytic rate, however, results in the production of more pyruvate

than can be fully oxidized in the mitochondria. This is accompanied by an increase in the NADH: NAD ratio, which activates the lactate dehydrogenase isoenzyme favouring the reduction of pyruvate to lactate (Noakes, 2001; Peters, 1984; Figure 2.6).

As a by-product of glycolysis and glycogenolysis during high intensity exercise, hydrogen ions are produced inside the muscle cell. To prevent hydrogen ion accumulation these ions are co-transported with lactate into the circulation (Noakes, 2001; Robergs, 2001).

Lactate uptake by the mitochondria and the pyruvate – lactate exchange in the peroxisomes are examples of intracellular lactate shuttles (Hashimotto and Brooks, 2008; Brooks, 2002). This has now been confirmed by the discovery of a mitochondrial lactate oxidation complex which is composed of the mitochondrial monocarboxylate transporters, muscle lactate dehydrogenase and cytochrome oxidase (Hashimotto and Brooks, 2008). Increased lactate thus appears in the circulation whenever the glycolytic rate is high (Noakes, 2001).

As the end-metabolite of glycolysis and glycogenolysis in the cytosol, lactate then enters the blood circulation and is shuttled around the body to be used by the heart, the liver or other inactive muscles (Peters-Futre *et al.,* 1987). This process has also been termed the cell-cell lactate shuttle (Hashimotto and Brooks, 2008; Brooks, 2002; 2000) and is of greatest significance during the post-exercise recovery, particularly when it is active (Peters-Futre *et al.*, 1987).

With increased exercise intensity, the lactate concentration in both the muscle and blood will rise and the lactate produced will be transported from the muscle fiber to the extra-cellular fluid and the capillaries (Seiler, 2007; Binzoni, 2005; Noakes, 2001). The rise of the blood lactate concentration is thus a function of exercise intensity (Binzoni, 2005; Noakes, 2001) and according to both Robergs *et al.* (2004) and Hashimotto and Brooks (2008), lactate may be seen as a cell-signaling molecule that is involved in the adaptive response to exercise which activates or up-regulates the monocarboxylase transporter and cytochrome oxidase genes. This also explains the increased capacity for lactate clearance via oxidation with training (Hashimotto and Brooks, 2008).

Athletes and coaches alike currently measure their training status and that of their athletes, by assessing lactate production during exercise training and several terms are used interchangeably. These include lactate threshold, anaerobic threshold, OBLA (onset of blood lactate accumulation) and maximal lactate steady state (MLSS).

An athlete's lactate threshold has been defined as that point during exercise of increasing intensity at which blood lactate begins to accumulate above resting levels (Philp *et al.,* 2005). This point generally occurs at blood lactate levels below 2 mmol. ℓ^{-1} and has been used by swimming coaches to assist in ensuring that athletes train within their zone of maximal aerobic development since the mid 1970's (Peters, 1984; Maglischo *et al.,* 1982). It has also been described as a marker of potential endurance

performance as competitors with lactate thresholds which occur at a higher workload would out-perform others with lower thresholds even if they had the same VO_2 max (Stasiulis *et al,* 2000).

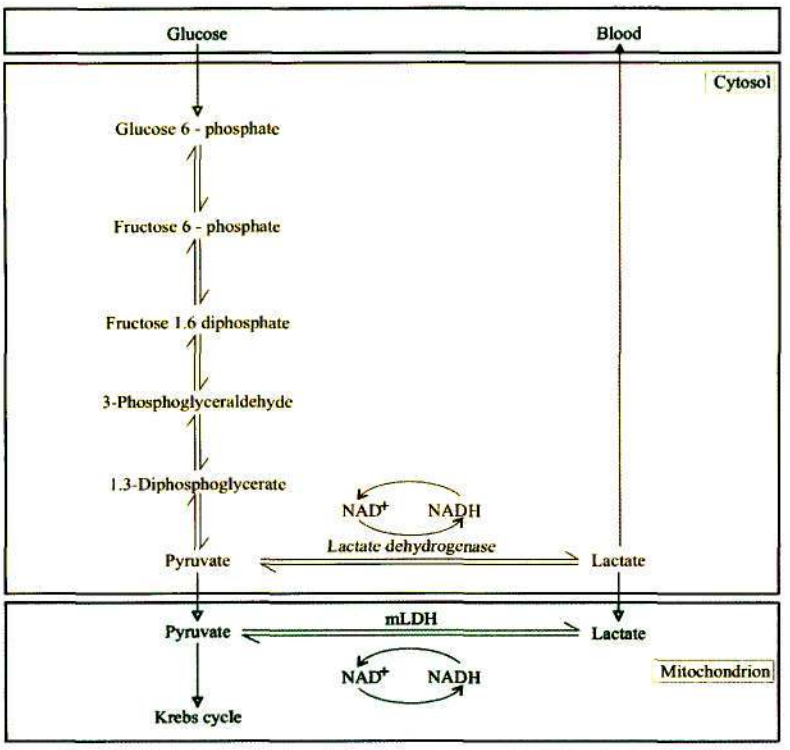


Figure 2.6 The lactate shuttle Adapted from: Hashimotto and Brooks (2008), Brooks (2002; 2000)

Baptista *et al.* (2005) describe the MLSS as the highest power output that the athlete can maintain for an exercise period of 15-20 minutes without an increase in blood lactate accumulation. According to Noakes (2001), this may be the point which gives the most meaningful measure of each athlete's lactate threshold.

As the exercise intensity continues to increase there is a non-linear increment in lactate concentration. This is often referred to as onset of blood lactate accumulation (OBLA), lactate turn-point (T_{lact}) or the lactate anaerobic threshold (AT_{lact}) and generally occurs when the concentration of blood lactate reaches about 4 mmol. ℓ^{-1} (Mader and Heck, 1986). The simple AT4 method of determination of the lactate turn-point therefore purely involves determining the workload at which the blood lactate concentrations reach 4 mmol. ℓ^{-1}. This value has also been generally accepted as the point at which the athlete may begin to recruit Type II muscle fibers (more reliant on glycolytic metabolism/carbohydrate catabolism) and thus prompt a rapid rise in blood lactate concentration (Noakes, 2001; Mader and Heck, 1986).

Cook (2005), however, argues against the use of the fixed blood lactate concentration of 4 mmol. ℓ^{-1} or the AT4 method of determining lactate turnpoint as considerable variation in the levels at which a sudden

increment in the blood lactate concentrations occurs, have been reported between individuals. While Mader and Heck (1986) reported that it may vary from 3.05- 5.5 mmol. ℓ^{-1}, Stasiulis *et al.* (2000) found that it may be as low as 2 mmol. ℓ^{-1} or as high as 5.5 mmol. ℓ^{-1}. Cook (2005) therefore suggests that the use of variable blood lactate concentrations provides a more accurate indication of endurance performance as it allows for individual differences between athletes.

The DMAX or "maximal distance" is a commonly used method of determining the lactate turnpoint. It involves constructing a tendency line through a 3rd degree polynomial function and a straight line connecting the initial and final points of the lactate curve. The longest perpendicular distance to this straight line is considered as the lactate turnpoint (Cheng *et al.*, 1992). This method has been reported to be preferable to the AT4 method as, in addition to accounting for the numerous factors which influence the point at which it occurs (Baptista *et al.*, 2005), it also has been described by Zhou and Weston (1997) as being highly repeatable and reliable with no significant difference in the values obtained when compared to the AT4 method.

Another traditional method for determination of the lactate turnpoint has been the visual inspection method which may, in turn, have several variations (Goodwin *et al.*, 2007). Using this method, two or more investigators evaluate the graphic relationship between blood lactate concentration and work rate to determine the inflection-point in the curve (Goodwin *et al.*, 2007; Martin and Whyte, 2000). Two lines of best fit to the data are drawn and the intersection of the two lines is considered to be the lactate turn-point (Goodwin *et al.*, 2007; Fukuba *et al.*, 1988). A log-log transformation may also be incorporated (Goodwin *et al.*, 2007; Robergs, 2001; Hughson *et al.*, 1987).

The variance in the lactate turnpoint has been shown to be dependent on several different factors. While muscle fibre type (Peters, 1985; 1984), size of muscle mass (Seiler, 2007), body mass and surface area (Buresh *et al.*, 2004) and circadian rhythms (Forsyth and Reilly, 2004) have been reported to affect lactate production at a given workload, age and training status (Seiler, 2007; Priox *et al.*, 2000; Masse-Biron *et al.*, 1992) are factors of most relevance to this investigation. A superior training status would imply a higher mitochondrial volume which would increase the capacity for oxidative metabolism and uptake of pyruvate generated during glycogenolytic/glycolytic metabolism and reduce reliance on non-oxidative catabolism of glucose for ATP production (Seiler, 2007). The rate of blood lactate clearance, capillary density and blood flow or blood volume in the active musculature also have an impact on blood lactate levels as in a trained athlete there is increased capillarization and thus improved tissue oxygenation (Kime, 2003; Peters, 1984). A trained athlete would also have increased removal of blood lactate during exercise as a greater proportion of blood flow would be directed through the kidneys and the liver than in an untrained subject (Peters, 1984).

Although early findings of Reaburn and Mckinnon (1990), Masse-Biron *et al.* (1992) and Priox *et al.* (2000) reported increased lactate production with increased age, this is, however, reduced with training (Priox *et al.*, 2000; Masse-Biron *et al.*, 1992). Reaburn and Mckinnon (1990) confirmed this in their finding of no significant difference in blood lactate parameters studied after maximal sprint swimming in athletes in the 25 - 35, 36 - 45, 46 -55 and 56 plus age groups.

2.2.4 Ventilatory turnpoint

A sudden, non-linear increase in pulmonary ventilation (VE) during an incremental exercise protocol was first termed as the ventilatory anaerobic threshold by Wasserman in 1967. This point at which ventilation rises out of proportion to the uptake of oxygen has subsequently also been referred to as the ventilatory threshold (Cohen *et al.*, 1991). It relies on the identification of an increased ventilatory drive which results from an increase in CO_2 and H^+ production which is associated with an increase in lactate production during exercise. It is also identified by a non-linear increase in CO_2 production and a sudden increase in the respiratory exchange ratio (Solberg *et al.*, 2005).

Several authors have promoted the use of a ventilatory threshold for determining the onset of reliance on anaerobic metabolism as it is less invasive than blood lactate testing (Higa *et al.*, 2007; Kara *et al.*, 1999; James *et al.*, 1989). But according to Yeh *et al.* (1983), detection of this ventilatory turnpoint by non-invasive means is difficult and highly subjective as there was a large reviewer variability when the turnpoint was determined from gas response data.

The V-slope method assesses the linearity of the VCO_2: VO_2 relationship (Solberg *et al.*, 2005). During exercise below anaerobic threshold there is an almost equal increase of VCO_2 and VO_2 and the ventilatory turnpoint occurs when the HCO_3^- in the cell start to buffer the H^+ and the slope of the VCO_2 / VO_2 regression line increases to greater than 45^0 (Higa *et al.*, 2007). The intersection point between the two regression lines is regarded as the V-slope anaerobic threshold (Solberg *et al.*, 2005; Wasserman, 2002). Bischoff and Duffin (1995) found that when the ventilatory threshold was determined by the eye (visual basic method) and compared to the V-slope method, there was similar comparison.

Kara *et al.* (1999) compared the use of the DMAX method which was originally designed for determination of T_{lact} (Cheng *et al.*,1992) and ventilatory thresholds detected by conventional linear regression, and found that there was no statistical difference between these thresholds. They found that when conventional linear regression was used in combination with the DMAX method, the validity of the derived ventilatory turnpoint was improved.

In terms of prediction of the ventilatory threshold from more easily obtainable parameters, the Conconi test protocol is commonly used by sports coaches to predict anaerobic threshold from heart rate. This is based on the linear increase in heart rate with an increase in exercise workload and the fact that a point is reached when work intensity increases more than the heart rate. This point is known as the heart rate deflection point and has been shown to correspond with the anaerobic threshold (Ignjatovic *et al.*, 2008).

This protocol has, however, subsequently been found to be unsuitable for reliable assessment of the anaerobic threshold as it failed to determine a reproducible heart rate deviation and in some cases may even fail to produce a detectable defection point (Ignjatovic *et al.*, 2008; Ghosh, 2004). This was recently confirmed by Carey *et al.* (2008) who reported that only 39.1% of the participants demonstrated a heart rate deflection point, while Ignjatovic *et al.*, (2008) found that older subjects and cardiac patients show a high degree of non-regular heart rate response and as a result a heart rate deflection point may not be found. Hoffman *et al.* (2004) also found that there was little significant difference between the heart rate deflection point and lactate turnpoint or lactate threshold

2.2.5 Lactate dehydrogenase

Strenuous exercise can cause microscopic damage to skeletal muscle which is associated with leakage of muscle proteins such as creatine kinase, myoglobin, troponin I, alpha actin and LDH through the disrupted membranes into the circulation (Amat *et al.*, 2007; Clarkson *et al.*, 2006; Maughan, 1989).

Lactate dehydrogenase (LDH) is a hydrogen transfer enzyme found in many body tissues including the heart, brain, red blood cells, kidneys, lung, liver, and in skeletal muscle. It is responsible for converting L-lactate to pyruvate, an essential step in producing cellular energy, the final step in the oxygen-independant glycolysis chain (Drent *et al.*, 1996). There are five sub-units of the LDH enzyme that depend on the organ of origin or predominance. These five isoenzymes have different chemical and physical properties and are thus identifiable as being more or less organ specific. In skeletal muscle the LDH-4 and LDH-5 isoenzymes predominate. Enzyme levels in these tissues are very high when compared to that found in serum and any leakage of the enzyme from even a small mass of injured tissue would result in an increase in serum levels.

When injury affects tissues, the cells release LDH into the extracellular space and thus its presence in the blood stream serves as an indicator of this damage (Drent *et al.*, 1996). Interestingly, Amat *et al.* (2007) reported concentrations as high as 298.3 ± 11.04 IU/L in uninjured sportspersons (n = 33) when compared to 51.3 ± 4.7 IU/L in uninjured non-sportspersons (n = 33).

Peak values of LDH following acute exposure to exercise causing muscle damage are to be expected at 6 hours after exercise (Maughan *et al.*, 1989). This is confirmed by Karamizrak *et al.* (1994) who found

that after performing very short duration, very intense exercise LDH levels were elevated after at 6 hours post test. Peters *et al.* (2005) also reported significantly elevated LDH concentrations in marathoners in the immediate, when compared to 24 hour post-exercise, blood samples after a 90km ultra-marathon.

2.2.6 Rates of perceived exertion (RPE)

The individual's subjective perception of work is based on psychophysical principles which maintain that perception interprets external stimuli. The perceived exertion scale assumes that the sensation of work can be rank ordered in categories from low to high exertion, relative to maximum effort (Scherer and Cassady, 1999). Borg (1982) developed the 15 point scale, ranging from 6 to 20. Each number was to correlate with an exercising heart rate 10 times the number. A high correlation between heart rate and RPE was identified. On test-retest during cycling at progressive workloads reliability was demonstrated at exercise intensities above 70% of maximum heart rate especially when the RPE was taken within the last minute of each stage of exercise (Scherer and Cassady, 1999).

There are several factors that affect this perception of level of exertion. Physiological factors include respiratory and metabolic responses which provide central inputs, while peripheral inputs include those obtained from mechano-, chemo- and thermal receptors and may relate to joint pain, blood glucose concentrations and pH. Psychological factors include mood, motivation and expectation (Chen *et al.* 2002; Scherer and Cassady, 1999), while external factors that affect perception of work include ambient temperature or competitive settings (Myles, 1985).

When used in conjunction to the physiological measurements the RPE scale can give the researcher the ability of the test individual to tolerate the strain imposed during the test. According to Scherer and Cassady (1999), few subjects rate maximum at 20 with 17-19 being selected most often.

Although, in general, the relationship between the VO_2, heart rate and workload and RPE appears to hold true for young to middle aged adults at various levels of fitness and different modes of exercise (Scherer and Cassady, 1999), the findings of Chen *et al.* (2002) suggest that the validity of Borg's RPE scale may not be as high as previously thought as measure of exercise intensity ($r = 0.80 - 0.90$).

2.3 The numerical pain rating scale (NRS)

Pain assessment tools were designed in a clinical setting, to help the patient describe their pain. The pain scale is one tool that is commonly used to describe pain intensity. The three most commonly used scales include the Visual Analogue Scale, the Verbal Rating Scale and the Numerical Rating Scale (NRS). Williamson and Hoggart (2005) found that the NRS was valid and reliable and, in general use, showed good sensitivity generating data that could be statistically analyzed. In this scale, pain intensity is measured on an 11 point scale where 0 is equal to no pain at all and 10 is equal to the worst pain imaginable. Farrar *et al.* (2001) and Salaffi *et al.,* (2004) found that the NRS compared well with other

forms of pain measurement regardless of disease type, age, sex, study result or treatment group in assessment of change in multiple studies of chronic pain. According to these authors a 30% reduction in NRS score would indicate an important clinically significant difference, while a 15% difference would be the minimal change indicating an improvement.

2.4 Local muscle adaptations to exercise training: selected pertinent aspects

It is well known that muscles adapt when exposed to the stress induced by exercise above a minimum threshold intensity and increase their size and strength when they are forced to contract at tensions close to their maximum i.e. when overloaded (Abernethy *et al.*, 1990). This hypertrophy has been reported to be due to decreasing the rate of protein degradation in Type I or slow twitch muscle fibres (Fahey, 1998; Abernethy *et al.*, 1990) and increased rate of protein synthesis in type II or fast twitch fibers (Fahey, 1998; Abernethy *et al.*, 1990). The rate of synthesis has been shown to be dependant on the duration and intensity of tension placed on the muscle which, in turn, affects the rate of amino-acid entry into muscle cells (Fahey, 1998).

According to Abernethy *et al.* (1990) chronic endurance activity may also produce a shift from type IIb fibers to type I fibers or type IIa fibers, while training at levels approximating VO_2 max causes the proliferation of type IIc fibers (Abernethy *et al.*, 1990).

For training to be effective it should be specific. The nature of each contraction will effect the recruitment of motor units within the muscle which is, in-turn, affected by the threshold level of the alpha motor neuron. High repetition, low intensity exercise affect the type I fibers and this endurance training improves the fiber's oxidative capacity (Fahey, 1998).

It is also well accepted that endurance exercise will increase the capillary to muscle fiber interface, capillarization or micro- vascular filtration capacity which results in increased oxygen carrying capacity and diffusion (Charles *et al.*, 2006; Ingjer, 1979). The number and size of the subsarcolemmal mitochondria have also been found to increase following a six week training program of 30 minutes per day on a cycle ergometer (Hoppeler *et al.*, 1985). Other intramuscular adaptations to exercise training involve an increase in the markers of mitochondrial activity i.e. citrate synthase, succinate dehydrogenase and phosphocreatine hydrolysis (Rockl *et al.*, 2007; Phillips *et al.*, 1996). Taylor *et al.* (2005) found that in addition to an increase in hexokinase II and citrate synthase, following endurance and interval training, there was also an increase in LKB1 and PGC-Ia proteins which they attributed to maintaining the training induced increase in mitochondrial mass.

Due to enhanced mitochondrial capacity and greater rates of pyruvate oxidation, there is less accumulation of lactate concentration at a given workload following endurance training (Phillips *et al.*, 1996). This has also been shown to result from the increased muscle content of two monocarboxylate transporter proteins, MCT1 and MCT4, which increase in response to endurance training (Juel *et al.*,

2004). This results in a rightward shift of the lactate turnpoint with endurance training during an incremental exercise protocol (Bloom *et al.*, 1976)

Weston *et al.* (1997) confirmed this in cyclists who trained at 80% of peak sustained power output for 5 minutes in six repetitions reporting that they experienced greater skeletal muscle buffering capacity, improved time to fatigue, and improved 40 km time trial performance, without a change in phosphofructokinase activity after four weeks of training. According to Hamilton and Booth (2000) many of the mechanisms underlying the adaptation of skeletal muscle to exercise, however, still remain to be discovered as little is known about the exercise responsive genetic regulatory factors, trans-acting proteins (DNA and RNA-binding proteins) or signaling pathways.

2.5 Conclusion

Assessment of the potential beneficial effects of a mechanical adaptation to the cycle would therefore ideally involve comprehensive assessment of both physiologic responses to a given exercise protocol and subjective perceptions of the cyclists. These would need to include:

- Submaximal heart rate, VE, VO_2, blood lactate concentration and rate of perceived exertion (RPE)
- Peak power output, VE, VO_2, heart rate, blood lactate concentration and RPE
- Ventilatory turnpoint (T_{VE}), blood lactate turn- point (T_{lact}) and heart rate deflection point
- A systemic marker of muscle damage concentration pre and post exercise
- Muscle soreness/knee discomfort index or NRS following the trials

Chapter Three

Methods and procedures

3.1 Ethical clearance

Approval to conduct the study was obtained from the Biomedical Research Committee of the University of KwaZulu-Natal (Clearance No: BF090/07) and the study was conducted according to the principles of the Declaration of Helsinki (Rickham, 1964).

3.2 Subjects

The twelve volunteer subjects were recruited via an advertisement in local cycling clubs, on the clubs' respective internet web sites, and by word of mouth from the from the Greater Ethekwini municipal area. Applicants were screened telephonically to assess their suitability for the research according to the following preset criteria:

Inclusion criteria

These included the following:

- Male gender
- No history of cardiovascular, /hepatic/ renal/ endocrine or metabolic dysfunction
- Age range between 22 and 55 years
- Road and/or mountain bike cyclists
- Training a minimum of six hours per week - either on the road/off-road, spinning or on a stationery trainer, for the previous four months
- Willingness to take part in the study and consent for all aspects of study protocol e.g. completion of questionnaires, maximal exercise tests, blood tests

Exclusion criteria

These included the following:

- Possessing any medical condition which may place the subject's health at risk
- Use of ergogenic/performance enhancing substances or any medication or supplement that may have influenced physiological markers or subjective perceptions of metabolic stress during the exercise trials
- Change of either their training or becoming ill and requiring medication before either of the trials

3.3 Study Design

The study was designed as a single-blind, randomized, two-period, cross-over laboratory trial which was preceded by a baseline assessment. Following selection, the subjects were randomly placed, by using the random number tables, into Groups A and B. As is shown in Figure 3.1, Group A was assigned to the NR

trial first, while Group B was assigned to the QR trial first. The two trials were separated by a seven day interval.

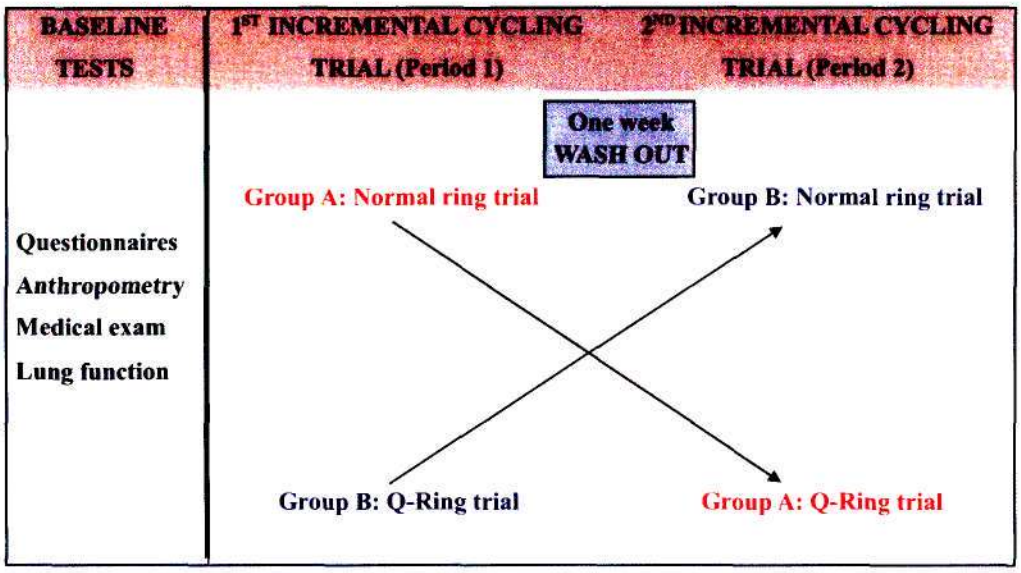


Figure 3.1: Schematic representation of the study design: a two-period cross-over following baseline testing

3.3.1 Pre-study laboratory visit:

During the initial pre-study laboratory visit and baseline assessment, each subject was given an information document (Appendix A), which outlined the purpose of the study, the experimental protocol, and the right to terminate the study at any time, prior to proceeding with the study. They were also asked to sign a letter of consent (Appendix B), and complete medical screening (Appendix C) and training status questionnaires (Appendix D). The latter obtained information regarding both their pedaling style and training status

Assessments of basic anthropometric measures were performed. After measuring height and mass, the subject's body fat percentage was determined from the sum of the biceps, triceps, sub scapular and suprailiac skin folds using the technique described by Durmin and Womersley (1974). Each subject's lung function (F_EV_1, FVC and FVC/F_EV_1) was assessed by using a Flowmate spirometer (Jaeger, Wuerzburg, Germany). In addition to the above, the subject's respiration rate, resting heart rate, blood pressure and oral temperature were recorded. Face masks of different sizes were fitted in order to select the appropriate size for use in the two subsequent exercise trials

Figure 3.2 Selecting a tight-fitting face mask

The subjects were fully familiarized with operation of the Tacx Fortius Virtual Reality Trainer (Serial no: 41071718, TBV, NL-2241, BW Wassenaar, The Netherlands), test equipment and test procedure. Cylists were requested to use their own bicycles and ensure that their normal cycling position was replicated and that they were as comfortable as possible on the trainer. They were also required to use their own pedals and cycling shoes in an attempt to reduce the risk of injury as "cleated" pedals and shoes are less likely to lose contact with the pedal surface during maximal effort.

The subjects were asked to avoid extremes of physical climate and hard physical activity in the 24 hours preceding the two exercise trials and to maintain the same training load in the week prior to each trial (Figure 3.1). They were instructed that foods containing caffeine, alcohol or any other stimulants were not to be consumed prior to the trials.

3.3.2 Cycling trials

3.3.2.1 Exercise protocol and metabolic analyses

Depending on which trial the subject was to complete, either the conventional circular chain ring remained on his bicycle or it was replaced by the Rotor Q-ring (Rotor Componentes Tecnologicos SL, 53-40130mm BCD, Spain). In those subjects who had been assigned to Group A (Figure 3.2), the Q-ring was attached in the optimum chain ring position i.e. position 1, 2, 3, 4 or 5 depending on the cyclists preferred pedaling style and seat position (Figure 3.3). The subjects using the Q-ring had the chain ring fitted according to the results of the riding style questionnaire (Appendix D).

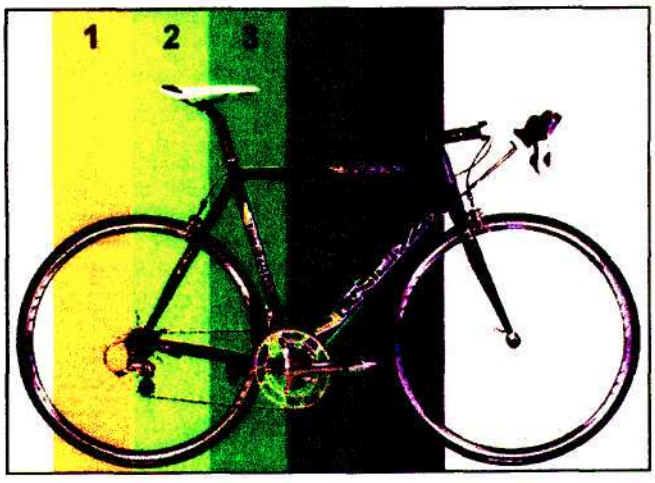


Figure 3.3 Seating position to determine Q-ring attachment point (adapted from www. rotorbike.com/2006/ocp.htm).

The chain ring was then covered by a plastic shield to blind the user and a "RavX Sweat-cloth" was attached from the bicycle handle bar to the seat-post to blind the participant from viewing the chain-ring from above. The fitting of both the Q-ring and plastic cover shield occurred in a separate room to the participant to further ensure blinding. As all of the participants had a neutral riding position, the default

position three (74^0) was selected as per the Q-ring instruction brochure of the manufacturers (www.rotorbike.com).

Figure 3.4 Chain ring blinding disc and RavX sweat cloth

Each participant had an "American Classic 350" rear wheel fitted to their bicycle. The wheel was fitted with a Shimano Ultegra cassette (12 – 27). The tyre pressure was kept constant at 100 psi as measured by an "Avinir" floor pump. Each participant thus had the same gear ratio and wheel set. The researcher positioned and secured the participants bicycle on the Tacx Fortius Trainer, ensuring that the bicycle was secure. Each participant was free to select their own gearing and cadence as the workload was preset by the Tacx Fortius.

Respiratory and metabolic responses were assessed using a MetaMax 3B Portable CPX metabolic testing system (Cortex Biophysik, GMBH, Leipzig, Germany). Prior to the assessments, the gas analyzers were calibrated using ambient air and a gas cylinder containing 5.1% CO_2 and 16.7 % O_2 in nitrogen (Air Products, Durban). A two-litre calibration syringe (Erich Jaeger, GmbH, Hoechberg, Germany) was used to calibrate the flow volume sensors. Expiratory flow volume was measured using a triple V transducer containing a 660nm optical turbine sensor which was connected to a tightly fitting facemask. Oxygen and CO_2 content of the expired air was measured by oxygen and carbon dioxide analysers, using an electro-chemical cell and infrared system, respectively. Expired gases were analyzed on a breath-by-breath basis by Metasoft ® software (Cortex Biophysik, Germany) and the rolling 30s average was used in order to record VO_2 throughout the incremental exercise test.

Environmental conditions were kept within a narrow range (ambient temperature: 19.5 - 21^0C; barometric pressure : 1019 - 1021 Kpa) and constant between the test-trials performed on each individual. Tests

were also conducted at the same time of the day for each individual to exclude any diurnal circadian rhythm variation that may have influenced the results (Forsyth and Reilly, 2004).

Prior to starting the exercise trials, baseline data including heart rate, VE and VO_2 was recorded, while the subject was seated quietly before commencing the exercise test.

As is shown in Figure 3.5, at the start of the exercise test, the subject was asked to warm up for eight minutes. The work output was maintained at 130 watts by the electromagnetic brake on Tacx Fortius Trainer, while the rider used a gear and cadence of personal choice. Thereafter, the power output was automatically adjusted by the Tacx Fortius Catalyst software (Version No: 2.0.0.) and Tacx motor brake (Type T1941.50) to increase by 30 W. min^{-1} until the subject reached exhaustion. In addition to the determination of VE and VO_2 (described above) the heart rate was recorded throughout the test by using a polar heart rate monitor (Polar Electro OY, Finland). The rating of perceived exertion (RPE) was determined according to the 15-point scale described by Borg (1982) during the final 15 seconds of each minute throughout the test.

The test was terminated once the subjects had reached three of the following (i) an RPE score of > 18 (ii) an RER of more than 1.15 (iii) estimated maximal age predicted heart rate (iv) an apparent VO_2 plateau with an increase in power output, (v) inability to maintain a cadence of more than 50 rpm.

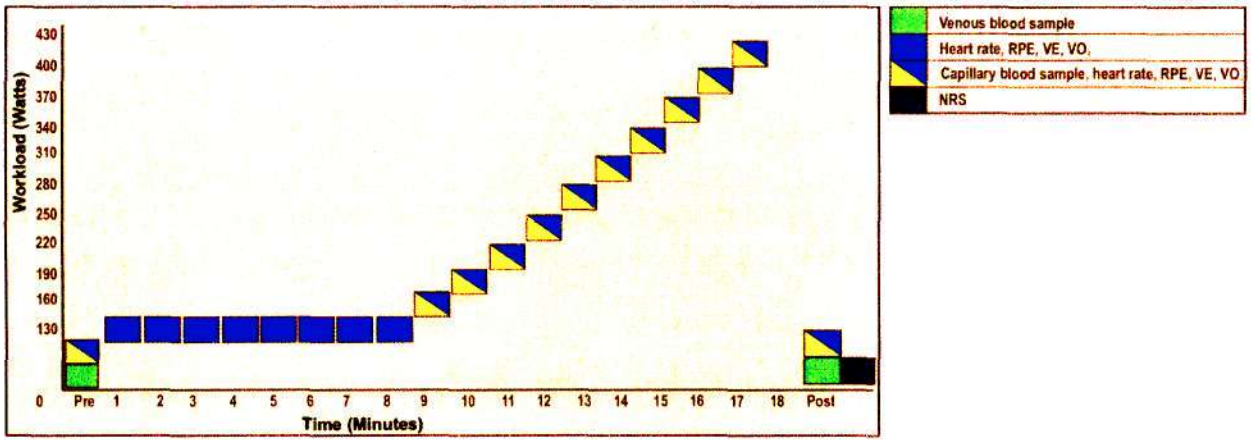


Figure 3.5 Schematic representation of test protocols used for the maximal exercise trials

Following completion of the trial, the bike was taken off the Tacx Trainer, removed to a separate room and the plastic chain ring shield removed. If the Q-ring was used it was then replaced by the owners original circular chain ring. The cyclists were therefore blinded regarding the type of chain ring used for the purpose of the trial.

The final exercise trial, in which the same protocol and measurements were repeated, was carried out after seven days, at the same time of the day, under the same conditions as in the previous trial, for each participant.

3.3.2.2 Blood sampling and treatment:

A 5 ml pre-trial and immediate post-exercise blood sample was drawn from the antecubital vein, into a vacutainer tube. The serum collection tubes were left to clot for 10 minutes at room temperature, centrifuged @ 3000 rpm, serum extracted, placed into labeled Eppendorf tubes and transferred to a freezer at -20° C until analysis for lactate dehydrogenase.

In addition, during the incremental protocol following the 8 minute warm-up (Figure 3.5), 20 µl blood samples were drawn into end-to-end capillaries which were then immediately deposited into coded 1ml microtest-tubes (EKF- 0209-0100-013) containing a lyzing solution (a heparized phosphate buffered solution, pH 7.2), the samples were gently inverted 10 times and placed in crushed ice. The samples were the analyzed using a table top Biosen C Line Lactate analyzer (EKF Diagnostic, Germany) which was recalibrated after every 10 samples. Each sample measurement was repeated twice to confirm repeatability. The capillary blood samples were drawn from the fingertip before the start of the warm-up period and the during the last 15 seconds of each power output as well as three minutes post exercise (Figure 3.6).

Figure 3.6 Capillary blood sampling from fingertips on the minute

3.3.2.3 Determination of blood lactate turnpoints

Blood lactate concentrations were recorded at 60-second intervals during the 8-12 minute trial (following warm-up) and were plotted against power output during each incremental phase. The lactate turnpoint was expressed as the power output which corresponded to a blood lactate concentration of 4 mmol. ℓ^{-1} (Baptista *et al.*, 2005; Cook 2005; Myburgh *et al.*, 2001) as well as the DMAX method described by Cheng *et al.* (1992) and Zhou and Weston (1997). As is shown in Figure 3.7, when using the DMAX

method, a straight line was constructed connecting the initial and final points of the lactate curve. The longest perpendicular distance from that line to the lactate curve was considered as the lactate turnpoint.

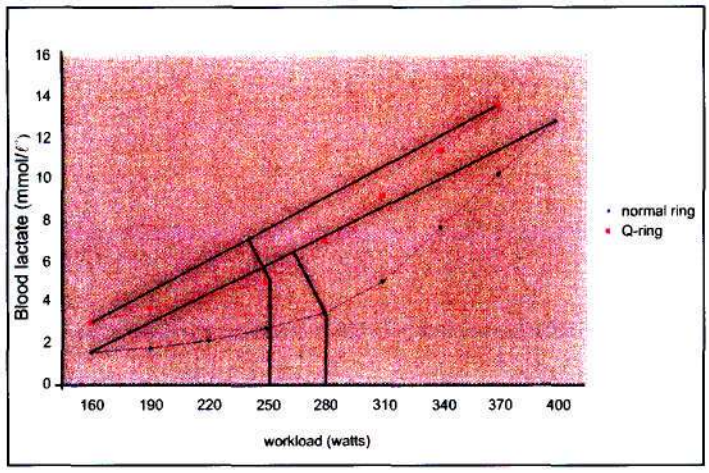


Figure 3.7: Determination of the lactate turnpoint using the DMAX Method. Data from subject no 4.

3.3.2.4 Determination of ventilatory turnpoints

Pulmonary ventilation (VE) was recorded at 60-second intervals during the 8-12 minute trial (following warm-up) and was plotted against power output during each incremental phase of the trial. Ventilatory turnpoint (V_T) was determined using both the visual graphic deflection point of VE (James *et al.*, 1989) as well as by applying the DMAX method to the curve obtained by plotting the VE data. The V_T was taken as that point on the VE curve at maximum perpendicular distance from a straight line connecting mean VE measurement during the last 30 seconds at the starting and finishing work-loads.

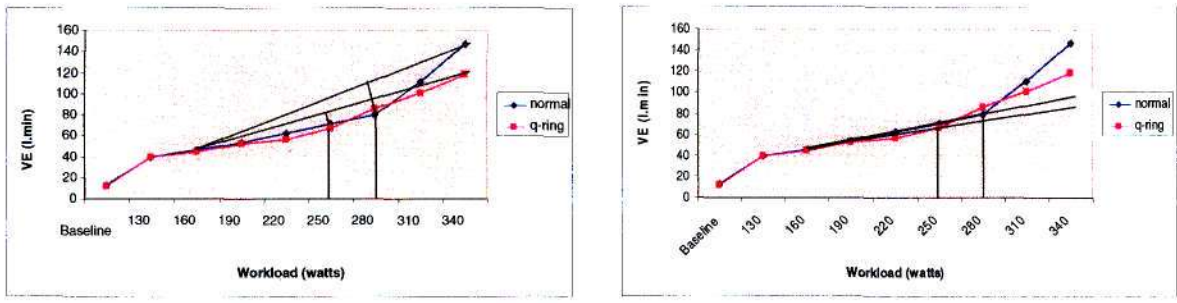


Figure 3.8: Examples of determining ventilatory turnpoint using the visual graphic deflection point (right) and DMAX method (left) Data from subject no 4.

3.3.2.5 Subjective Rating of Perceived Muscle Soreness and Knee Discomfort:

The subject completed the Numerical Rating of Perceived Muscle and Knee Discomfort (Appendix E) on the day following each exercise trial. Subjective ratings of muscular soreness/knee discomfort were determined at the beginning of each day, following trials one and two, with a numerical 0 - 10 scale where 0 = no pain at all to 10 = severe/maximal pain as per the Numerical Pain Rating Scale (Childs *et*

al., 2005; Williamson and Hoggart, 2005). The quadriceps, hamstrings, and calf muscles and knee were assessed under the following four categories: general pain (subject seated and relaxed), daily living (walking /moving), pressure pain (palpation of the muscle area) and stretch pain (stretching the muscle).

3.4 Statistical procedures

Data was be captured in Microsoft Excel and analysed by the statistics package SPSS version 15.0 (SPSS Inc., Chicago, Illinois, USA). Alpha was set at 0.05 and the level of confidence at 95%. Two-tailed tests were used as directionality could not be assumed beforehand.

As the sample is a convenience sample and not truly representative of the cycling population, quantitative data are presented as mean ± standard deviation (SD).

The categorical baseline and demographic data and the group to which the participant was randomized (group A = QRT first, group B = NRT first; Figure 3.1) were compared using Pearson's chi square tests. Quantitative baseline and demographical variables were compared between groups using independent *t*-tests.

There was full compliance in all subjects up to a workrate of 340 watts during the exercise trials, the intention to treat analysis was identical to the per protocol analysis, and participants were analysed in the intervention groups (QRT and NRT) to which they had been assigned There was therefore no need for elimination of bias or preservation of the group randomization advantage (Montori and Guyatt, 2001)

Data were arranged by intervention. Repeated measures analysis of variance (ANOVA) was used for all complete data sets (n = 12; ≤ 340 watts) in order to determine the (i) period (1st vs. 2nd exercise trial), (ii) intervention (1 = QRT, 2 = NRT) and (iii) group (group A vs. group B) effects for quantitative outcomes in this cross-over trial (Figure 3.1) . The intervention*time effect (i.e. the effect of the intervention), intervention *time*group effect (period effect) and time*group effect (the carryover group effect) were determined for each data set. Control for baseline value was achieved by including the baseline value in the model using analytical methods recommended by Dallal (2008). Within periods, the effect of time was analysed using Wilk's Lambda test statistic. This was followed by *post hoc* paired t-tests in order to identify the significance of the intervention effect at each time-point.

Where appropriate, Pearson's correlation analysis was also used to determine relationships between variables which were represented graphically using scattergrams.

Chapter 4

Results

4.1 Subjects' characteristics

The physical characteristics of the 12 subjects who completed this cross-over trial are summarized in Table 4.1. They were amateur male cyclists (mean age: 40.7 ± 7.53 years), who were actively involved in both road (n = 10) and/or mountain bike (MTB; n = 6) races. Some also reported participating in multiday/mutistage races (n = 5) and duathons/triathalons (n = 3) in the preceding year. At an amateur level, the cyclists were able to compete in between four to six "classic events" (about 100 km in road racing and about 45 km in MTB racing) during the year preceding the study.

Table 4.1 Mean (± SD) physical characteristics (n = 12)

Characteristics	Mean (± SD)	Range
Age (years)	40.67 (± 7.53)	24 – 53
Mass (kg)	80.48 (± 13.67)	63.9 - 114.6
Stature (cm)	178.94 (± 5.78)	167 - 189.7
Percentage Body Fat	19.76 (± 4.83)	11.6 - 28.4
Body mass index	22.42 (± 3.18)	18.02 - 30.21
FVC (L)	6.61 (± 0.87)	5.26 – 8.18
F_EV_1 (L)	5.24 (± 0.71)	4.07 – 6.18
FVC/ F_EV_1 Ratio (%)	80.43 (± 24.43)	68.6 - 85.6

4.2 General medical exam and questionnaire

Results of the medical questionnaire did not reveal any prior health related problems, use of performance enhancing substances or smoking in the sample. Abnormalities were also not detected in the baseline medical examination and blood pressure, oral temperature, resting heart rate and respiratory rates were all within normal limits. Lung function data were also within the normal range for their gender, age and stature.

4.3 Cadence and saddle position

Ninety-one percent (n = 11) of participants reported regular use of cadences between 70-90 rpm, with one (8.3%) preferring faster cadences. As is evident in Figure 4.1, the mean cadence did not differ significantly between the two trials ($p > 0.05$) and ranged between 86.05 (± 11.11) for the NRT and 87.10 (± 9.41) for the QRT. There was also no significant difference ($p > 0.05$) in the mean maximum cadence which averaged at 103 (± 14.4) and 107.3 (± 15.3) for the NR and QR trials respectively.

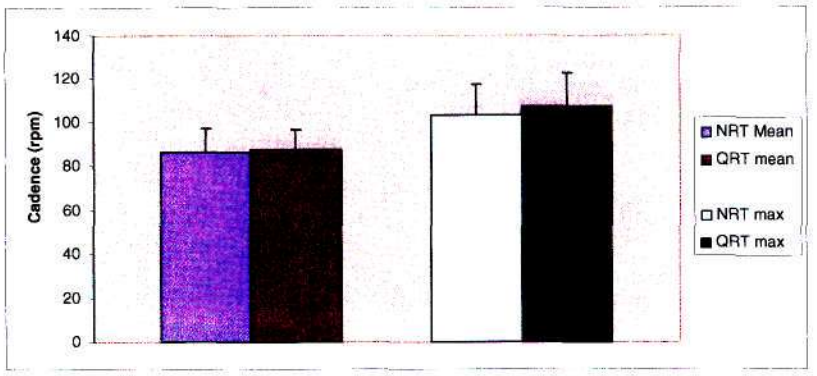


Figure 4.1 Mean (± SD) of mean and maximum cadence during the two trials (n = 11)

The preferred choice of saddle position for all participants was a neutral saddle position (n = 12). Only a minority occasionally sat back 16.6% (n = 2) or forward 33.3% (n = 4) on the saddle.

4.4 Speed, distance and power output

As is evident in Table 4.2 there were no statistically significant differences ($p > 0.05$) in the mean speed and mean maximum speed in either trial. There was also no statistically significant difference ($p > 0.05$) in the distances covered in either trial. The mean peak power output was slightly higher in the NRT than QRT, but the differences were statistically insignificant ($p > 0.05$).

Table 4.2 Mean (± SD) and range of trial speed (km. hr^{-1}), distance covered (km) and peak power output (watts) during the incremental test (n = 12)

Speed (km.h^{-1})	**NRT**	**QRT**
Mean	32.97 (± 6.35)	34.74 (± 8.39)
Range	3.5 - 54.5	2.9 – 53.4
Distance Covered (km)		
Mean	8.89 (± 1.84)	9.02 (± 1.23)
Range	6.29 - 13.52	6.14 - 12.48
Peak Power Output (watts)		
Mean	385 (± 30.81)	380 (± 31.07)
Range	340 - 460	340 - 430

The peak and mean power output for each participant are shown in Figure 4.2. There were no statistically significant differences ($p > 0.05$) between the means (± SD) of the two trials.

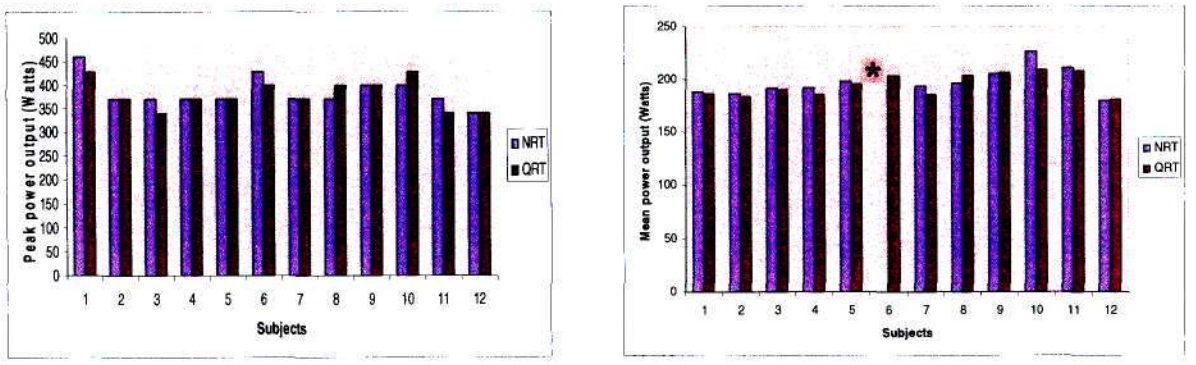


Figure 4.2 Left: Peak power output (watts) for each subject reflected during the two trials (n = 12) Right: Mean power output (watts) for each subject reflected during the two trials (n = 11)
* Technical problem in the Tacx Fortius program recording of the mean power output during NRT.

The peak and mean power output of subjects during the incremental exercise trials in five different categories of mass are shown in Figure 4.3. They do not confirm an increase in peak power output when mass exceeds 100 kg and mean power output when mass exceeds 90 kg.

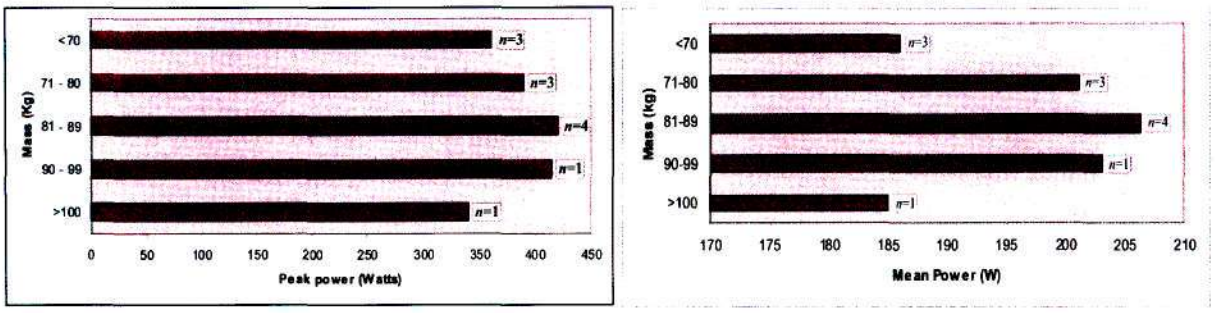


Figure 4.3 Mean peak power (right) and mean power (left) output (watts) as a function of mass

4.5 Heart rate

The mean (± SD) heart rate during the last 10 seconds of each minute of the trial are given in Table 4.3 and depicted graphically in Figure 4.4. This increased linearly with the increase in power output in both trials (time effect: $p = 0.002$). The repeated measures ANOVA used to analyse any possible intra and inter group differences in terms of the time by group (the group effect), intervention/trial by time (the intervention effect) and intervention by time by group (the period effect), revealed statistically insignificant differences in heart rate ($p > 0.05$; Table 4.3). Specifically, the effect of the intervention was not significant ($p = 0.41$).

Post hoc paired t tests revealed that the difference between QRT and NRT was statistically significant at baseline, 130 watts and at 160 watts only. No distinct heart rate deflection point was observed. Mean (± SD) maximum heart achieved by the subjects (n = 12) during the incremental exercise test to exhaustion averaged at 174.67 ± 11.90 in the QRT and 176.92 ± 12.00 in the NRT.

Table 4.3 Mean (± SD) heart rates at each power output during the incremental exercise trials (n = 12)

Watts	NRT	QRT	p value ♣
Baseline	61.2 (± 7.0)	58.9 (± 7.3)	0.028
130	118.6 (± 8.8)	114.1(± 10.5)	0.019
160	126.9 (± 11.5)	122.9 (± 11.8)	0.024
190	133.0 (± 9.7)	129.5 (± 11.4)	0.057
220	140.8 (± 11.2)	138.3 (± 11.4)	0.215
250	147.4 (± 10.5)	146.4 (± 12.4)	0.580
280	153.8 (± 11.9)	153.0 (± 12.2)	0.665
310	161.1 (± 11.7)	160.3 (± 12.2)	0.611
340	167.8 (± 11.9)	167.0 (± 11.7)	0.408
370	171.4 (± 11.4)*	172.4 (± 13)*	0.499
400	178.6 (± 9.7)**	174.3 (± 9.2)**	0.406
430	184.0 (± 11.3)***	174.0 (± 1.4)***	n/a
Intervention*time #			0.410

*n= 11 (NRT), 9 (QRT); **n= 5 (NRT), 4 (QRT) ; ***n=2 (NRT), 2 (QRT); n/a = not applicable
Repeated measures ANOVA, p values based on Wilks' Lambda Test Statistic ♣ *Post hoc* paired t tests

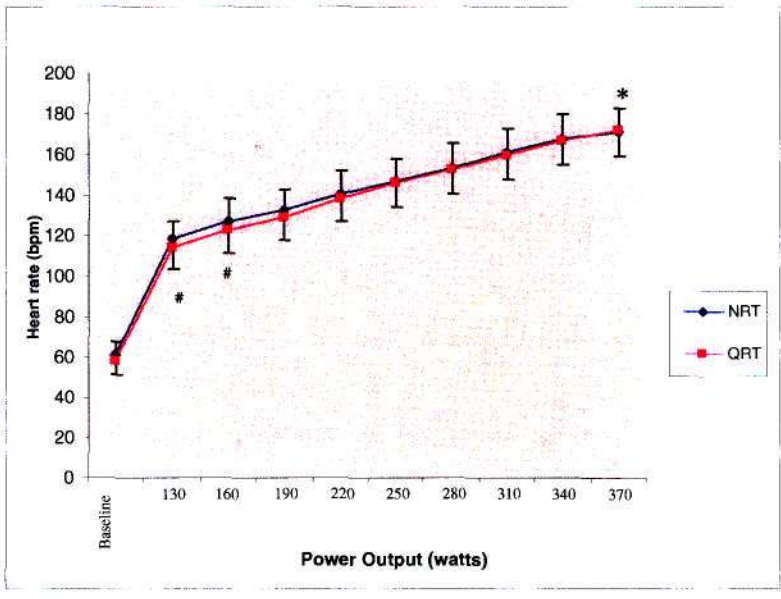


Figure 4.4 Mean (± SD) heart rate during the incremental exercise protocol in NR and QR trials (n = 12) * n = 11 (NRT), 9 (QRT); # $p < 0.05$ *post hoc* paired t tests. Data for when $n > 0.05$ not shown.

4.6 Oxygen consumption (VO_2)

The mean VO_2 (± SD) during the last 30 seconds of each of the stages of the trial are given in Table 4.4 and graphically depicted in Figure 4.5

Table 4.4 Mean (± SD) VO_2 (ml. kg^{-1}. min^{-1}) during the incremental exercise protocol (n = 12)

Power Output (Watts)	NRT	QRT	p value ♣
Baseline	4.47 (± 0.86)	4.95 (± 0.74)	0.586
130	27.45 (± 4.46)	26.88 (± 3.96)	0.356
160	29.52 (± 5.32)	29.53 (± 5.74)	1.000
190	33.83 (± 6.57)	32.63 (± 5.73)	0.274
220	38.23 (± 6.97)	36.99 (± 6.84)	0.176
250	41.62 (± 7.79)	40.38 (± 6.86)	0.186
280	45.19 (± 8.40)	43.50 (± 8.69)	0.256
310	48.49 (± 7.44)	48.22 (± 9.08)	0.849
340	51.61 (± 8.38)	51.52 (± 9.11)	0.936
370	53.70 (± 7.76)*	55.86 (± 7.76)*	0.628
400	51.70 (± 3.30)**	56.98 (± 6.53)**	0.383
430	51.70 (± 3.11)***	56.10 (± 0)***	n/a
Intervention*time #			0.691

*n = 11 (NRT), 9 (QRT); **n = 3 (NRT), 5 (QRT); ***n = 2 (NRT), 1 (QRT); n/a = not applicable
#Repeated measures ANOVA, p values based on Wilks' Lambda Test Statistic ♣ *Post hoc* paired t tests;

It increased linearly with the increase in power output in both trials (time effect: p = 0.001). The repeated measures ANOVA used to analyse any possible intra and inter-group differences in terms of the group (p = 0.235), intervention (p = 0.691) and period (p = 0.517) effects, revealed statistically insignificant differences in VO_2. *Post hoc* paired t tests revealed that the difference between QRT and NRT was statistically insignificant (p >0.05).

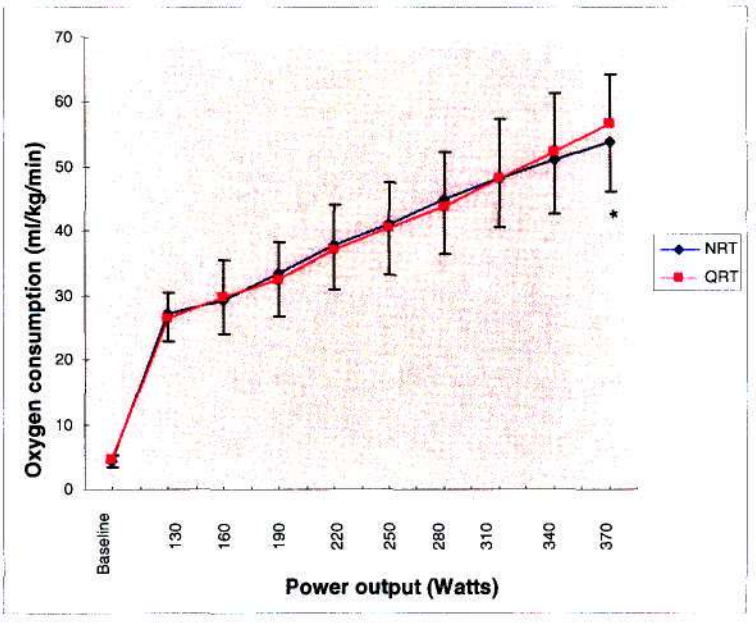


Figure 4.5 Mean (± SD) VO_2 during the incremental exercise protocol (n = 12)
Data from incomplete sample completing work rates > 370W , not shown; * n = 11 (NRT), 9 (QRT).

When individual heart rate and VO_2 data points collected throughout the 24 trials in the study were plotted on a scattergram (Figure 4.6), a statistically significant linear correlation ($r = 0.86$; $p < 0.001$) was confirmed.

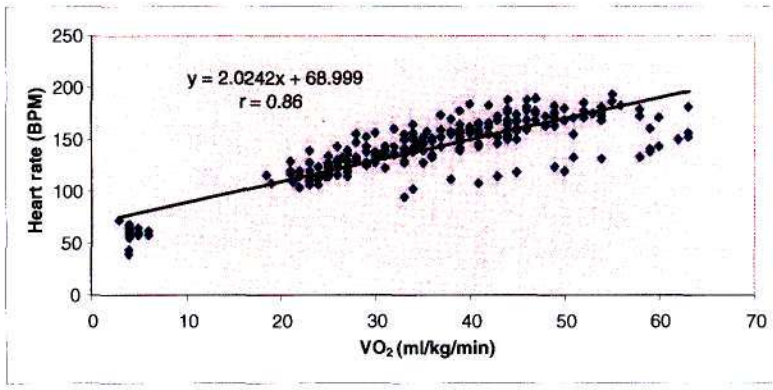


Figure 4.6 Correlation between heart rate and VO_2 ($n = 246$)

The peak VO_2 of subjects at five different peak power outputs are shown in Figure 4.0. They do, however not confirm a higher peak VO_2 when peak power output increased above 400 W.

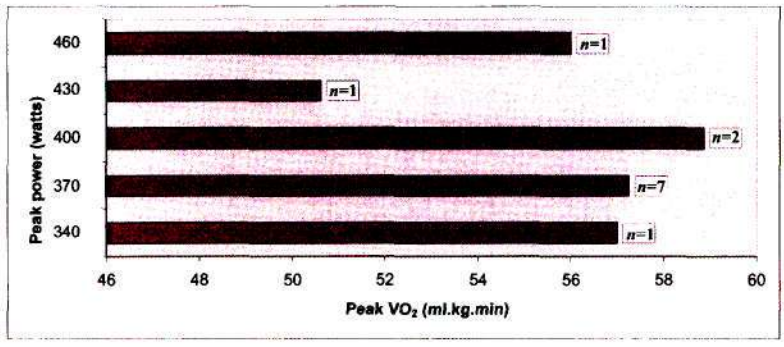


Figure 4.7 Peak VO_2 as a function of five peak power outputs during the incremental cycling trials ($n = 12$)

4.7 Pulmonary ventilation (VE)

The mean (± SD) litres expired per minute at each of the stages of the trial are given in Table 4.5 and depicted graphically in Figure 4.8. The repeated measures ANOVA used to analyse any possible intra and inter group differences in terms of the group effect ($p = 0.152$), the intervention effect ($p = 0.107$) and the period effect ($p = 0.983$), revealed statistically insignificant differences in terms of VE. This increased linearly with the increase in power output in both trials (time effect: $p < 0.001$). *Post hoc* paired *t* tests revealed that the difference between QRT and NRT was only statistically significant at the power output of 370 W ($p = 0.04$).

Table 4.5 Mean (± SD) VE (ℓ. min^{-1}) during the incremental exercise protocol (n = 12)

Power Output	NRT	QRT	p value ♣
Baseline	13.1 (± 2.97)	12.54 (± 4.24)	0.528
130	48.81 (± 7.23)	46.97 (± 10.86)	0.322
160	55.1 (± 9.95)	54.90 (± 11.06)	0.837
190	62.18 (± 11.79)	60.34 (± 12.58)	0.247
220	69.59 (± 11.36)	67.02 (± 14.54)	0.248
250	79.38 (± 13.15)	77.38 (± 14.65)	0.456
280	90.23 (± 12.1)	86.38 (± 16.63)	0.177
310	102.1 (± 12.78)	106.77 (± 20.51)	0.192
340	122.3 (± 16.69)	120.64 (± 16.34)	0.681
370	139.3 (± 15.03) *	131.83 (± 15.98) *#	0.043#
400	146.7 (± 17.58) **	150.20 (± 23.64) **	0.518
430	170.8 (± 20.93) ***	156.5 (± 23.33) ***	n/a
Intervention*time #			0.107

*n = 10 (NRT), 9 (QRT) ; **n = 5 (NRT), 5 (QRT); ***n = 2 (NRT), 2 (QRT); # $p < 0.05$; n/a = not applicable
Repeated measures ANOVA, p values based on Wilks' Lambda Test Statistic ♣ *Post hoc* paired t tests

4.8 Ventilatory turnpoint

The ventilatory turn point (T_{VE}) determined by both Visual Basic and DMAX methods revealed no statistically significant difference ($p > 0.05$) between the two trials. This is shown in Figure 4.8. When using the Visual Basic Method, the turn point occurred at 280.00 W (± 21.21) in the QRT and at 280.00 W (± 24.49) in the NRT. The turn point using the DMAX method occurred at 282.50 W (± 24.91) in the NRT and 277.50 W (± 16.60) in the QRT. There was however, no statistically significant difference ($p >$ 0.05) when the results for the Visual Basic and DMAX methods were compared for the NR or QR trials.

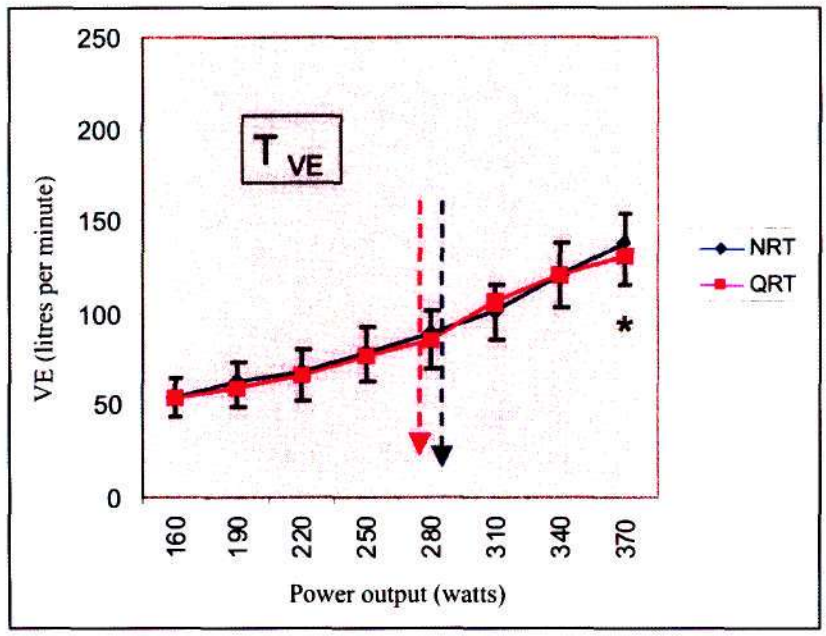


Figure 4.8 Ventilatory response to the incremental exercise protocol
Data from incomplete sample completing work rates > 370W , not shown; T_{VE} determined using DMAX method; * $p < 0.05$ *post hoc* paired *t* tests

4.9 Blood lactate concentrations

The mean blood lactate concentration (± SD) at each of the stages of the trial are given in Table 4.6 and depicted graphically in Figure 4.9. A curvi-linear increase with an increase in power output was confirmed in both trials (time effect; $p = 0.077$). The repeated measures ANOVA used to analyse any possible intra-group differences in terms of the group effect ($p = 0.922$), intervention effect ($p = 0.625$) and period effect ($p = 0.160$), revealed statistically insignificant differences in blood lactate concentration. At no stage during the incremental exercise tests was a statistically significant difference recorded between trials ($p > 0.05$).

4.10 Blood lactate turnpoint

There was no statistically significant difference ($p > 0.05$) in the mean lactate turn point in either trial as determined by either the AT4 method or the DMAX method. The lactate turn point using the AT4 method occurred at 266.36 W (± 26.72) for the NRT and 255.45 W (± 25.00) for the QRT. The lactate turn points, using the DMAX method, for the NRT and QRT were 285.45 W (± 30.86) and 282.73 W (± 29.88) respectively (Figure 4.9).

Table 4.6 Mean (± SD) blood lactate concentration (mmol. ℓ^{-1}) for each power output during the incremental exercise protocol (n = 11)

Watts	NRT	QRT	p value ♣
Baseline	2.39 (± 1.05)	2.31 (± 1.09)	0.861
160	2.62 (± 1.00)	2.86 (± 1.06)	0.519
190	2.86 (± 0.97)	2.82 (± 1.15)	0.925
220	2.99 (± 0.95)	3.17 (± 0.48)	0.670
250	3.46 (± 0.93)	3.89 (± 0.79)	0.269
280	4.43 (± 1.36)	5.00 (± 1.13)	0.350
310	5.60 (± 1.64)	6.13 (± 1.48)	0.403
340	7.96 (± 2.62)	7.85 (± 1.96)	0.888
370	9.61 (± 2.06) *	9.07 (± 2.53) *	0.540
400	11.13 (± 1.95) **	10.32 (± 3.71) **	0.942
430	15.2 (± 0.0) ***	8.31 (± 0.06)***	n/a
3 min post	13.84 (± 1.68)	12.62 (± 2.15)	0.054
Intervention *time #			0.630

*n = 9 (NRT), 9 (QRT); ** n = 6 (NRT), 4 (QRT) ; *** n = 1 (NRT), 2 (QRT); ♣ *Post hoc* paired t tests; n/a = not applicable

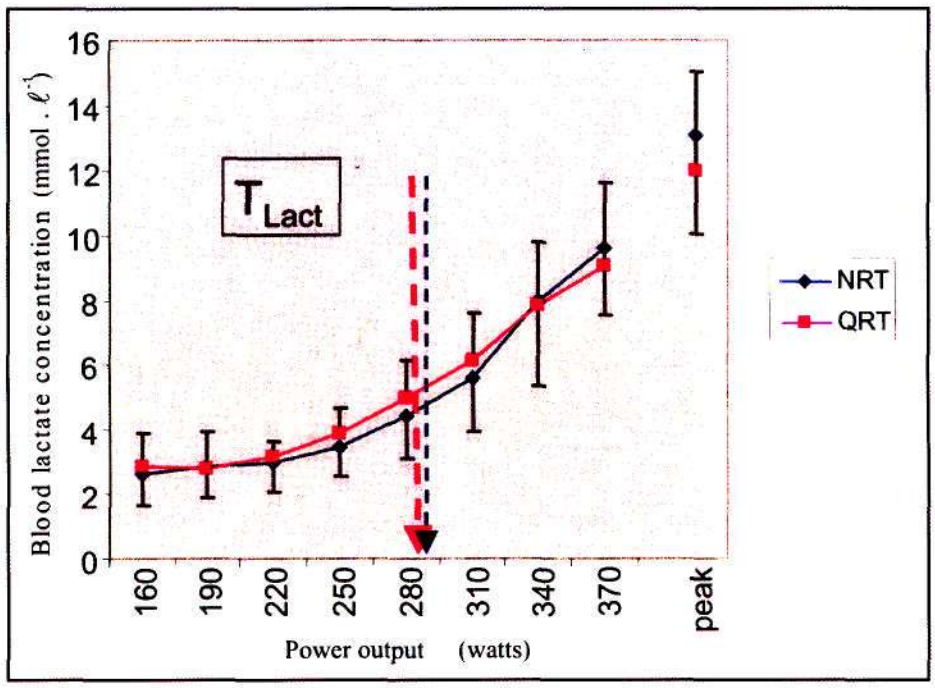


Figure 4.9 Mean (± SD) blood lactate concentration during the incremental exercise protocol (n = 11); Data from incomplete sample completing power outputs > 370W , not shown

The peak blood lactate concentration for each trial are given in Figure 4.10 Borderline statistical significance was reached in the difference between the mean peak blood lactate concentrations (Figure 4.9; $p = 0.055$) with the mean peak blood lactate concentration recorded three minutes post exercise being lower following the QRT in 73 % ($n = 8$) of the subjects.

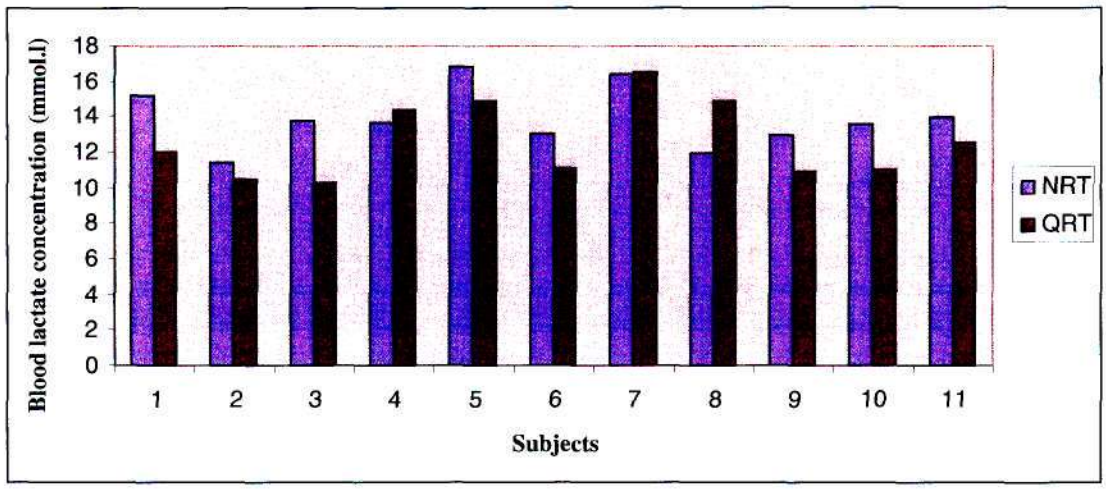


Figure 4.10 Peak blood lactate per participant in the incremental exercise protocol ($n = 11$)

4.11 Rate of perceived exertion

The mean rate of perceived exertion (± SD) at each of the stages of the trial are given in Table 4.7 and depicted graphically in Figure 4.11. At no stage during the incremental trial were the differences between NRT and QRT trials statistically significant ($p > 0.05$). When individualized heart rate and corresponding RPE data obtained during the final 10 seconds of each power output were plotted on a scatter-gram (Figure 4.12) a statistically significant linear association ($r = 0.86$; $p < 0.001$) was confirmed.

The repeated measures ANOVA used to analyse any possible intra and inter-group differences in terms of the group effect ($p = 0.82$), the intervention effect ($p = 0.78$) and the period effect ($p = 0.35$), revealed statistically insignificant differences in terms of RPE (Table 4.7). The RPE increased linearly with the increase in power output in both trials (time effect: $p = 0.002$). *Post hoc* paired t tests revealed that the difference between QRT and NRT was statistically insignificant.

Table 4.7 Mean (± SD) rates of perceived exertion during the incremental exercise protocol (n = 12)

Power Output (watts)	NRT	QRT	p value ♣
130	8.33 (± 1.68)	8.47 (± 1.57)	0.790
160	9.92 (± 1.78)	9.58 (± 1.56)	0.504
190	10.75 (± 1.60)	10.75 (± 1.60)	1.000
220	11.58 (± 1.44)	11.75 (± 1.42)	0.767
250	12.67 (± 1.37)	12.83 (± 1.03)	0.723
280	14.08 (± 1.62)	14.08 (± 0.99)	1.000
310	15.17 (± 1.99)	15.5 (± 1.62)	0.570
340	16.92 (± 1.98)	17 .0 (± 2.13)	0.889
370	17.5 (± 2.22)*	17.9 (± 1.6)*	0.860
400	18.25 (± 0.96)**	18.8 (±1.1)**	0.391
430	18.5 (± 2.12)***	18.5 (± 0.71)***	n/a
Intervention *time #			0.776

n = 10 (NRT), 10 (QRT); ** n = 4 (NRT), 5 (QRT); *** n = 2 (NRT), 2 (QRT); (r = 0.86); n/a = not applicable
Repeated measures ANOVA, p values based on Wilks Lambda Test Statistic ♣ *Post hoc* paired t tests

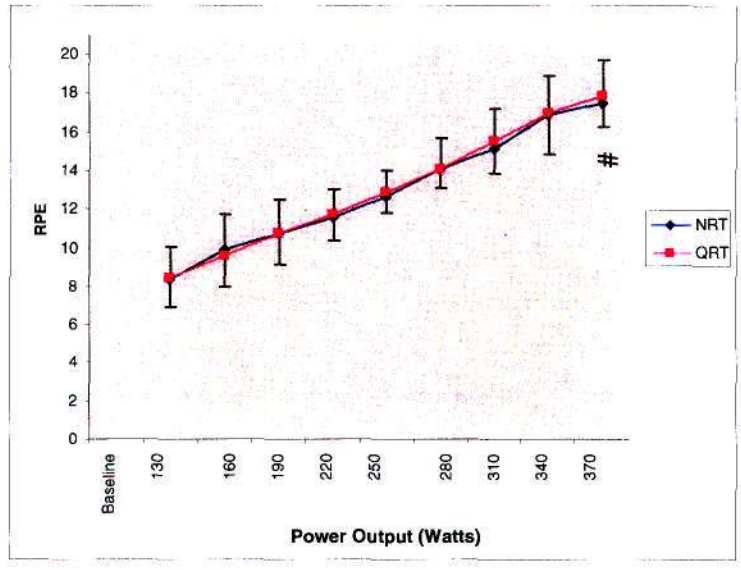


Figure 4.11 Mean (± SD) rate of perceived exertion during the incremental exercise protocol; Data from incomplete sample completing power outputs > 370W , not shown; # n = 10 (NRT), 10 (QRT)

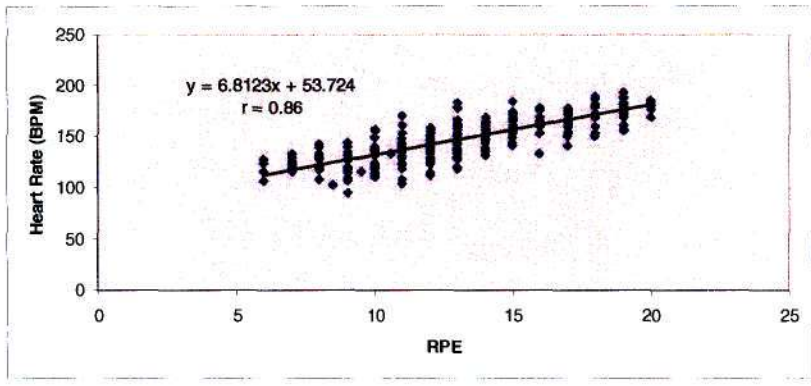


Figure 4.12 Correlation between heart rate and RPE (n = 222; r = 0.86)

4.12 Numerical pain rating scale

The mean numerical pain rating scale results, completed 24 hours post trial, for pain when relaxed, pain on general movement during the day, pain on pressure and pain on stretching are given in Table 4.9 and then depicted graphically in Figure 4.13 There was no statistically significant difference ($p > 0.05$) between the two trials.

The repeated measures ANOVA used to analyse any possible intra and inter-group differences in terms of the group effect (p = 0.22) and the treatment effect (p = 0.22) revealed statistically insignificant differences in terms of NRS. *Post hoc* paired t tests revealed that the difference between QRT and NRT was statistically insignificant.

Table 4.8 Mean (± SD) numerical pain rating scale, 24 hours post trial (n = 12)

Category	NRT	QRT	p value ♣
Relaxed	1.23 (± 1.98)	0.50 (± 0.82)	0.235
Daily Living	1.42 (± 1.98)	0.81 (± 1.05)	0.333
Pressure	1.88 (± 2.02)	1.10 (± 1.16)	0.220
Stretch	2.10 (± 1.97)	1.52 (± 1.51)	0.361

(n = 12); ♣ *post hoc* paired t tests

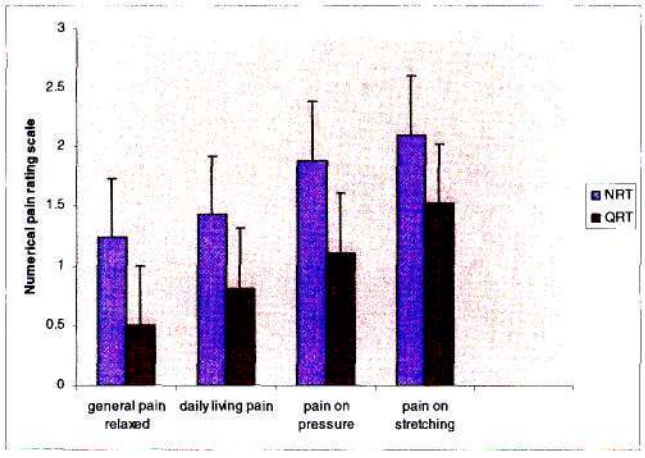


Figure 4.13 Mean (± SD) numerical pain rating 24 hours post trial

4.13 Lactate dehydrogenase concentration

The mean (± SD) LDH concentration (IU/ℓ) pre-trial, immediately post- trial and the differences between the two are given in Table 4.9 and the data are then depicted graphically in Figure 4.14. The maximal exercise test did not result in a significant difference in the LDH concentrations in either of the two trials ($p > 0.05$) and the pre-post trial differences were also not significant ($p > 0.05$).

Table 4.9 Mean (± SD) lactate dehydrogenase concentration pre, post and difference (n = 11)

Lactate dehydrogenase	NRT	QRT	p value ♣
Pre- test	373.0 (± 50.10)	381.7 (± 48.46)	0.37
Post-test	434.0 (± 44.67)	423.7 (± 59.35)	0.32
Difference	61.0 (± 26.42)	42.0 (± 20.41)	0.12
Time effect			0.001

(n = 11); ♣ Paired t tests

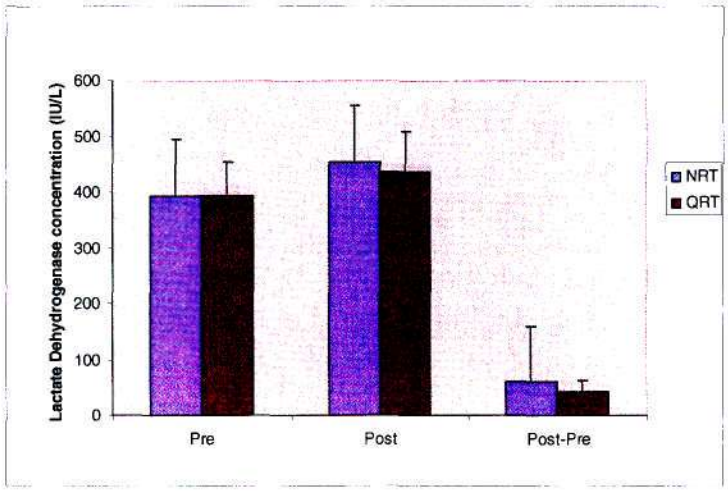


Figure 4.14 Mean (± SD) lactate dehydrogenase response to the incremental exercise protocol (n = 12)

4.14 Conclusion

There was no significant difference in terms of peak and mean power output and speed, distance covered or cadence used during the two trials.

There are also few statistically significant differences between the trials in this study in terms of the physiological response of the participants to the incremental exercise protocol. Significant results ($p <$ 0.05) were only found in the heart rate below 190 W, the VE at 370 W and the difference between the peak blood lactate concentrations following the two trials reached borderline significance ($p = 0.055$).

Chapter 5

Discussion

5.1 Introduction

The Q-ring's diameter at the dead spots is the equivalent of using a 50 tooth chain ring instead of the traditional 53 tooth chain ring. It has been calculated that less time is spent in the areas of least mechanical advantage and that the pedal leg accelerates through these zones (Burke, 2003; Pavelka, undated). The primary purpose of this first controlled, randomized trial to be conducted on the Rotor Q-ring system, was therefore to establish whether this proposed mechanical advantage would translate into a measurable physiological difference and greater cycling economy and/or peak power output

As lack of proper control in cycling trials has been cited as a shortcoming in the data that is currently available (Faria *et al.*, 2005), an attempt was made to blind the cyclists to the chain ring use. Subjects were also randomly allocated to either NR or QR trials in a cross-over design to avoid a possible learning/training effect after the first trial. Use of appropriate statistical techniques reinforced this cross-over design.

Further strengths of the study included the fact that the tests were performed in an exercise physiology laboratory in which the ambient temperature was kept constant and trials were conducted at the same time of the day for each participant. This avoided the possible confounding effect of temperature and fluctuating diurnal rhythms on the physiological variables.

5.2 Subjects

The twelve subjects taking part in the study were competitive, amateur cyclists, which is reflected by the number and type of races in which they competed per annum. The mean age (40.7 ± 7.5 years) also appears to be representative of the age of a large proportion of amateur road and mountain bike racers in South Africa (Rose *et al.*, 2007). A possible reason for this is that the sport of cycling is relatively expensive in terms of equipment costs and training time and requires a degree of independence which is usually only acquired in the "over-thirty" age group in South Africa.

The majority of the subjects who participated in the study fall into the competitive sub-veteran and veteran age groups in South African cycling (Rose *et al.*, 2007). Interestingly, in the only other study analyzing the physiological effects of using Rotor Q-rings (Martinez *et al.*, 2006), the mean age of the sample was, however, 21.1 (± 2.1) years. The age of the subjects in this study does therefore need to be

taken into account when interpreting the physiological response to the maximal exercise trials and may have exacerbated response to the recruitment of untrained muscle fibers during the QR trials.

5.3 Physical characteristics

The mean ± SD stature of the participants in this study (178.9 ± 5.8 cm), falls between those described in the study of Martinez *et al.* (2006) at 175.8 ± 5.9 cm and Rose and Peters (2008) at 182 ± 2.0cm. In terms of the subject's mean mass (80.5 ± 13.7 kg), this sample compares well with those of Rose and Peters (2008; 81.8 ± 2.2 kg) who focused on MBT cyclists, but was considerably heavier than those used by Martinez (2006) who had a mean mass of 69.3 ± 8.4 kg.

The anthropometrical characteristics measured in this study did unfortunately not include somatotyping or measurement of lower limb size and volume. It was therefore not possible to examine the suggestion of Hue *et al.* (2007) that there may be a benefit to using the eccentric chain ring if the subject has a greater lower limb volume and calf size.

5.4 Pedaling style, training status and Q-ring orientation

The majority of the participants in this study were active in both road races (n = 10) and/or mountain bike races (n = 6). This may be due to overlapping seasons for road cycling (September to April) and for mountain biking (March to November) in the South African cycling calendar, so road cyclists could turn to mountain biking in the "off-season" or *visa versa*. As cyclists who mountain bike have been described as having a smoother pedal stroke and power transfer to the pedals (Burke, 2003), they could therefore benefit less from the use of Q-rings. No clear pattern confirming this was, however, evident in the findings of this study.

The Q-ring has numerous possible settings for individual customization, but as all the participants fitted the criteria for the default setting recommended by the manufacturers (position three or 74^0) on the Q-ring, this setting was selected. According to Malfait *et al.* (2006), this position may, however, not be the optimum and in their mathematical model, these researchers determined that rotating the Q-ring and thus re-orientating the main axis of the ring to the crank arm at 107.5^0 instead of 74^0, would optimize performance when using the Q-ring. As this is contrary to the instructions described by the Q-ring manufacturers, a possible solution to this would be to perform a Compu-trainer "spinscan" analysis on each participant (Martinez *et al.*, 2006) when using the normal circular chain ring in order to record the pedal position of maximum power production. This could then be applied to the Q-ring fitting in a future study.

It is possible that a different result would also have been obtained if the Q-ring had been more oval-shaped, with an eccentricity ratio of greater than 1.10, as advocated by Malfait *et al.* (2006) and closer to

1.29 as specified by Rankin and Neptune (2008). These authors also recommended an orientation in which the major axis was rotated 91.8^0 to the crank arm (Rankin and Neptune, 2008). As this was, however, the first randomized controlled study to be undertaken on the Rotor Q-rings, it was necessary to first conduct a study using the manufacturer's recommendation of a 74^0 setting and eccentricity ratio of 1.10, particularly in view of the possibility of inducing knee strain if exceeding these (Malfait *et al.*, 2006).

5.5 Trial data

5.5.1 Cycles used and cycling technique

Each cyclist was able to use their own bicycle for the tests. This ensured that altered bottom brackets, chain make-up, or crank arm length (Burke, 2003) did not affect cycling efficiency. It also controlled for the possible effects of seat height and longitudinal foot position on the pedal and the possibility that incorrect bicycle fit could negatively affect the rate of pedaling. As each cyclist was responsible for selecting his own personal preferred seat position and the Q-ring was attached to the existing crank bolts of each cyclist's bicycle, this variable was unaltered for each subject between trials. There was also no alteration in crank arm length and the knee, hip and ankle joints did not need to adapt to a different pattern of movement (Rankin and Neptune, 2008; Gonzalez and Hull, 1989).

The Tacx Fortius Trainer used an electromagnetic brake as well as tyre friction to provide resistance to the pedal power. There is however, no guarantee that the results obtained would be valid for outdoor cycling in which the road surface, as well as wind speed and direction, vary. There are also frequent changes in saddle position during normal road/MTB cycling on ascending and descending hills or when the subject wishes to relieve saddle pressure, which did not occur during the trials as they were of short duration and the actual bike inclination did not change. This inability to precisely simulate outdoor cycling, is therefore a shortcoming of a laboratory study of this nature.

None of the participants elected to stand and pedal during the trial. This would have changed the relationship between orientation of the chain-ring and the body and resulted in a greater power output (Burke, 2003). It may also have increased the VO_2 peaks recorded as with standing a greater muscle mass would have been used.

The subjects in this study reported not being aware of the type of chain ring that was used in each trial. This may be attributed to the findings of Neptune and Herzog (2000) that there is very little difference in muscle activity timing or EMG magnitude between using different chain rings and that adaptation to the elliptical chain rings occurred within the first 10 - 20 cycles of switching from circular to elliptical chain rings. It therefore appears that the blinding procedure used in this study was effective.

5.5.2 Cadence

Each participant was permitted to select their own cadence and the mean and maximal data confirm preferred cadences documented by the cyclists in the riding style questionnaire (Appendix D). They also support the previous findings of Marsh and Martin (1997) and Bieuzen *et al.* (2007), amongst others.

Most participants settled into a fairly steady cadence that did not alter much during the step-wise incremental trial, selecting instead to move from a higher gear ratio to a lower gear ratio as the work rate intensified. The maximum cadence (QRT: 107.3 ± 15.3 vs. NRT: 103 ± 14.4 rpm) usually occurred in the early part of the trial or during the warm-up period as the participants became accustomed to pedaling on the Tacx Trainer and to the resistance imposed by the electromagnetic brake.

The use of the Q-ring did not appear to influence the cyclist's choice of cadence as no statistically significant difference ($p > 0.05$) was obtained in the two trials in terms of the mean cadence (QRT: 87.10 ± 9.41 vs. NRT: 86.05 ± 11.11 rpm).

5.5.3 Speed during the trial

As the trials were incremental in nature, the feeling for the participant was similar to that when ascending a hill of increasing inclination. As a result the faster speeds occurred at lower-moderate work rates where the participant was able to pedal using a higher gear ratio. The speeds then decreased as the power output increased and the participant chose to shift to an easier gear ratio. As both the normal chain ring and the Q-ring have the same amount of teeth per ring, each pedal revolution revolves the wheel the same distance, but if the feeling of pedaling was easier with either ring it could allow the participant to pedal a harder (smaller) gear on the rear cassette and thus travel further per pedal stroke and at a greater speed.

As the mean and maximum speed were not significantly different between trials ($p > 0.05$), it can be concluded that the proposed mechanical advantage derived from using the Q-ring in the specified settings, did not appear to be large enough to affect cycling performance in this trial.

5.5.4 Power output

When using the Q-ring and the normal chain ring there were also no statistically significant results in either the mean peak power (380 ± 31.1 W vs. 385 ± 30.8 W) or mean power (194.87 ± 12.71 vs. 197.21 ± 16.07) during the two trials. These are higher than the 358.6 ± 34.4 W obtained by Beneke and von Duvillard (1996) in a maximal cycling test and the mean peak power obtained by Martinez *et al.* (2006) which was recorded as 361 (± 29.6) W when the Q-rings were used and 349 (± 28.8) with the normal chain ring. Interestingly, the mean mass of the subjects in this study which is considerably higher than that of the cyclists used by Martinez *et al.* (2006), may, however, have accounted for the higher mean

peak power output in this study. When the subjects were categorized according to body mass and the mean peak power for each category was determined, a clear pattern between mass and peak power was evident, except in the heaviest subject (Figure 4.3). The skinfold measurements and percent body fat (28.4) of this subject, however, explain this discrepancy in the power to mass relationships of this outlier.

The mean power output achieved in the current study was also very similar between the two trials at 194.9 ± 12.71 W (QRT) and 197.2 ± 16.07 W (NRT), respectively. This was also only approximately 11 % lower than that that achieved by professional road racers during a six stage road race competition (220 ± 22 W; Vogt *et al.*, 2006)

It is, however, important to emphasise that almost all of the subjects in this study (n = 11) had no prior experience of using Q-rings in their training. It is therefore also possible that a greater difference may have occurred had each participant been given six weeks or 400 km of training on the Q-ring in order to adapt physiologically prior to the Q-ring trial. This is a possible direction for future research.

5.5.5 Distance

As previously stated, the number of teeth in the two respective rings were equal, but if the participant did feel more comfortable and thus did not trigger a subconscious fatigue avoidance mechanism on one ring versus the other (Faria *et al.*, 2005), the subject would have been able to pedal harder gear on the rear cluster and thus also go further.

On average, the participants covered a slightly greater distance (1.44%) in the QRT than the NRT. Due to large inter-subject variation and standard deviations of the mean within the group, the differences between trials are, however, not significant. These results therefore do not support those of Hue *et al.* (2001), who reported significantly faster completion times with the eccentric chain ring in a one kilometer all-out laboratory test.

5.6 Physiological variables

5.6.1 Heart rate

The heart rate response to both incremental exercise trials displayed a typical linear relationship between heart rate and work rate as reported in the literature (Wilmore and Costill, 2005). The mean heart rates at the 130 W and 160 W were significantly different (p = 0.02; 0.02) between the QR and NR trials. The score at the 190 W workload, although not quite significant (p = 0.06), is also noteworthy in view of the possibility of a Type II error in this relatively small sample. As this lower heart rate response at lower work rates, was, however, not confirmed by the VO_2 data despite the strong correlation between heart rate

and $V0_2$ in the study data (Figure 4.6), greater cycling economy can therefore not be assumed at these low power outputs.

The difference between trials at work rates greater than 190 W was not statistically significant ($p > 0.05$). This appears to indicate that although the subjects appeared to have been more efficient when using the Q-ring at lower workloads, this possible advantage was lost as the power output increased. It is possible that lack of prior adaptation to the Q-ring, as the participants had not had any training period to get used to the Q-ring, may have been a factor which contributed to this finding.

The maximum heart rates at the highest power output achieved in the two trials (QRT: 174 ± 1.4 vs. NRT: 184 ± 11.3) were unfortunately only recorded on the two subjects who were able to achieve 430 W. When the peak heart rate for each subject irrespective of individual peak power output, is, however, analysed and compared, there is also no statistically significant difference between the two trials (QRT: 174.7 ± 11.9 vs. NRT:176.9 ± 12.0).

The failure to identify a definite heart rate deflection point in the mean heart rate response to the incremental exercise trials is not unexpected. It also supports the findings of Carey *et al.* (2008) that only 39.7% of their subjects demonstrated a heart rate deflection point and the previously described non-regular heart rate response in older subjects (Ignjatovic *et al.*, 2008; Hoffman *et al.*, 2004). This absence of a heart rate deflection point in the presence of definite ventilatory and lactate turnpoints, adds to the data which does not support the use of the Conconi test for the prediction of an anaerobic threshold from heart rate response to incremental exercise (Ignjatovic *et al.*, 2008; Hoffman *et al.*, 2004).

5.6.2 Oxygen consumption

The findings of the current study firstly confirm the linear relationship between VO_2 and work-rate during the incremental exercise trials. As the trials needed to be terminated due to fatique and inability to maintain a cadence of > 50 rpm before a plateau in VO_2 was apparent in all subjects, the maximum value achieved has been referred to as VO_2 peak and not VO_2 max.

The lack of significance between the two trials in terms of both submaximal VO_2 at given worloads and peak VO_2 appear to support those of Cullen *et al.* (1992) and Hull *et al.* (1992), who found that there was no difference in the physiological variables that were studied when the round, *Shimano Biopace* and two custom-made, engineered elliptical designs were compared. They also support the findings of Ratel *et al.* (2004) who tested 13 subjects on their own bikes on a simulator, using a circular chain ring and the elliptical chain ring (*Shimano Harmonic*), but this time altering the speed and the slope until exhaustion, with similar results to the above studies.

The lack of significant differences in the VO_2 : power output relationship between the two trials confirms the trend found in the heart rate data (Figure 4.6). The previously well described correlation between VO_2 and heart rate (Wilmore and Costill, 2005) is also confirmed when all data obtained during these two trials are pooled (n = 246; Figure 4.6)

In the current study the peak mean VO_2 was 55.86 (± 7.76) ml. kg^{-1}. min^{-1} in the QRT and 53.70 (± 7.76) ml. kg^{-1}. min^{-1} in the NRT. Although below what might be regarded an elite level for VO_2 max, the mean age of the subjects taking part in the study (40.67 ± 7.53 years), is an important consideration. When the previously reported decrement per year after the age of 25 (Richardson *et al.*, 1999) and the possible attenuation thereof due to the endurance training status of the subjects are taken into account, this would comfortably place these cyclists into the VO_2 max category of above 60 ml. kg^{-1}. min^{-1}, for individuals aged 25 years.

5.6.3 Pulmonary ventilation

There was no significant difference between the two trials in the ventilatory response to the incremental exercise protocol at the sequential time points, except at the work rate of 370 W (p = 0.04).

The linear increase in VE during the early stages of the incremental exercise protocol confirms an increased ventilatory drive with the increase in power output. The peak VE which exceeded 150 litres per minute in six of the subjects, is however, interesting in view of the age of the cyclists and their relatively low peak VO_2.

The sudden non-linear increase in VE which is attributed to an increase in CO_2 and H^+ production and is associated with an increased reliance on carbohydrate metabolism during exercise (Solberg *et al.* 2005), was identified during both exercise trials. When the visual method was used the turnpoint occurred at (280.± 24.49) in the QRT and 280 W (±21.21) in the NRT. Although the difference was greater when DMAX was used, the lack of statistically significant difference (p > 0.05) between the two trials, was confirmed.

The discrepancy between the DMAX method and the more subjective visual graphic method of determining the ventilatory turnpoint is of interest and requires further examination. The lack of significant difference (p > 0.05) between the lactate and ventilatory turnpoints in both trials, however, concurs with the findings of Kara *et al.* (1999) and Bischoff and Duffin (1995). These findings also support those of Cullen *et al.* (1992) and Hull *et al.* (1992) who found that there was no difference in the physiological respiratory variables that were studied when the round, *Shimano Biopace* and two custom-made, engineered elliptical designs were compared.

5.6.4 Submaximal blood lactate concentrations and blood lactate turnpoint

In the current study the baseline resting blood lactate concentrations of 2.31 (± 1.09) for the QRT and 2.39 mmol.ℓ^{-1} (± 1.05) for the NRT, were above the lactate threshold described by Philp *et al.* (2005). It is possible that this may have been due to pre-test anxiety and associated elevated stress hormone levels (Stupnicki *et al.*, 1995) as baseline heart rates (Figure 4.3) were also elevated when compared to early morning basal heart rates (data not shown).

There was a further increase in blood lactate concentration as exercise intensity continued to increase. The mean lactate curves are almost identical (Figure 4.9) and results of the multivariate analyses confirmed no statistical significance between trials ($n = 11$; $p > 0.05$). Post hoc analysis also confirmed no differences between trials at each of the individual time points ($p > 0.05$)

In the current study the lactate turnpoint based on the 4 mmol. ℓ^{-1} method of determination described by Mader and Heck (1986), occurred at 255.45 W ± 25.00 in the QRT and at 266.36W (± 26.72) in the NRT. Although this value has generally been accepted as the point at which the athlete may begin to recruit fast twitch muscle fibers which are more reliant on oxygen-independant metabolism and thus prompt a rapid rise in blood lactate concentration (Mader and Heck, 1986), considerable variation in the concentrations at which a sudden increment in the blood lactate concentrations occurred, have been reported between individuals (Cook 2005; Stasiulis *et al.* 2000; Mader and Heck, 1986).

The DMAX method which is based on variable blood lactate concentration and allows for individual physiological differences was thus selected for this study in addition to the AT4 method. Interestingly, a higher lactate turnpoint was however confirmed in both trials when using the DMAX method and the findings of Zhou and Weston (1997) were confirmed. While the rightward shift of the blood lactate turnpoint in well trained individuals is well described (Philp *et al.* 2005), the mean occurrence of the lactate turnpoint above 4 mmol. ℓ^{-1} when using the DMAX method appears to reflect greater tolerance to exercise induced H^+ and CO_2 production in trained individuals and confirms the findings of Stasiulis *et al.* (2000).

Irrespective of the method used, there was, however, no significant difference between the two trials in terms of blood lactate turnpoint. It is possible that there may, however, have been a difference if the study subjects had a 400 km habituation period on the Q-rings as this would have allowed the muscle groups involved to adapt to the altered muscle fibre recruitment and thus possibly improve the efficiency (Neptune and Herzog, 2000).

5.6.5 Maximal Blood Lactate Concentrations

Previous work by our group (Peters 1985; 1987) has shown that blood lactate concentrations peak between 2 and 3 minutes post exercise. This delay was attributed to the diffusion time taken to move from the intracellular site of production into the bloodstream (Peters, 1985; Philp *et al.*, 2005). As in the study of Ratel *et al.* (2004), post-exercise blood samples were therefore taken at 3 minutes post exercise in this study and did peak at this time point during both the QR and NR trials (12.62 ±2.15; 13.84 ± 1.68 mmol. ℓ^{-1}). The peak values were also comparable with previously reported peak concentrations following high intensity interval training on a cycle ergometer (Peters *et al.*, 1987) and with those achieved in an outdoor 1000m track cycling effort (Hue *et al.*, 2007).

Borderline significance ($p = 0.055$) was evident when the lower peak blood lactate concentrations at the conclusion of the QR trials were compared to those following the NR trials. This is an unexpected finding, particularly as (i) 11 of the 12 cyclists (92%) had not had prior training on Q-Rings and (ii) the peak work output achieved during the two trials (QRT: 380 ± 31.07 W; NRT: 385 ± 30.81 W), was not statistically different ($p > 0.05$). Although these findings support those of Ratel *et al.* (2004) and Martinez *et al.* (2006), the latter studies did not confirm the lower mean concentrations reported with statistical significance. A lower peak blood lactate concentration would suggest lesser reliance on oxygen-independent metabolism at given maximal workloads and perhaps lesser recruitment of fast twitch muscle fibres during the final stages of the QRT (Mader and Heck, 1986). Another possible reason could be that cyclists pedalled the chosen gear more easily as a result of the increased mechanical leverage allowed by the Q-ring and that this would imply less muscle effort and less subsequent muscle damage.

As the difference did not quite reach statistical significance ($p = 0.055$) and this may have been due to the low power of the study, these findings do, however, require confirmation in a future study involving larger sample sizes.

5.6.6 RPE

Multivariate analyses confirmed no significant intervention effects between the two trials in terms of RPE. This can be attributed to both physiological (lactate production, VO_2, VE and heart rate) and psychological (mood, motivation, expectation, and fatigue) factors being not differing significantly between trials.

Although there were statistically significant differences in the initial heart rates in the two trials, it is thought that the workload at this intensity was too light to cause a significant change in RPE. Interestingly, the lower maximal blood lactate concentrations recorded in the QR trial, did also not correspond with lower peak RPE scores.

5.6.7 NRS

Q-ring advertisements claim a possible reduction of knee strain with their use due to smoothing out the pedal movement and less jerkiness (www.impressions.co.za; www.rotorcrankusa.com). This has, however, not been assessed scientifically. According to Asplund and St. Pierre (2004), the position in which the cyclist pedals in order to gain more power or increase leg speed may cause injury to the muscle groups involved in cycling. As the Q-ring was reported to increase leg speed over the 0 and 180^0 positions and then increase the power by increasing the leverage in Sector 2 (30 to 150^0) it could have had an influence in increased knee pain. In their mathematical analysis, Malfait *et al.* (2006) hypothesized that the use of the Q-ring actually increased the strain on the knee when in the default (74^0), but reduced the hip strain on pedal movement.

Although there was no statistically significant difference between the two trials, an important finding was that the Q-rings did not increase knee or muscle pain with the mean being less in the trial involving Q-ring use than with the use of the normal circular chain rings. This difference may have been greater if each athlete had been able to adapt to the Q-rings for the recommended 400 km habituation period. The lack of difference between the two trials in terms of perceived muscle soreness, appear to be confirmed by the lack of difference found in LDH concentrations.

5.6.8 Serum LDH concentration

As these muscle protein concentrations are thought to rise following leakage from the previously active muscle fibers, their concentration in the blood reflects the degree of muscle damage incurred during the two incremental trials. In this study there was, however, no statistically significant difference between the two trials ($p > 0.05$) Despite similar baseline concentrations (QRT: 381.7 ± 48.5 IU/ ℓ and NRT: 373.0 ± 50.1 IU/ℓ) there were lower mean blood LDH concentrations in the NR trial (QRT: 423.7 ± 59.4 IU/ ℓ; NRT: 434.0 ± 44.7 IU/ ℓ; 3.8%), but the difference remained statistically insignificant ($p > 0.05$), probably as a result of the large intra-group variance.

According to several anecdotal reports (www.impressions.co.za) when using the Q-ring, it feels smoother and less "jerky" when at the top and bottom of the pedal stroke. If this is true, then it could mean that there is less muscle strain in these positions which would result in less muscle damage. Another possible reason could be the ability of the cyclist to pedal the chosen gear more easily as a result of the increased mechanical leverage allowed by the Q-ring, this would imply less muscle effort and as a result less damage. This is substantiated by Rankin and Neptune (2008) who found that more work is done by the vastus lateralis, gluteus maximus, soleus and gastrocnemius muscles in the 10 to 135^0 zone as well by the psoas and tibialis anterior in the 225 to 0^0 zone but, the work done in the "dead spot" areas were notably less. These authors proposed that as the elliptical chain ring allows the angular crank velocity to slow in the active phase of pedaling, it allows the muscles to generate power for longer, but then requiring less power in the inactive phase of the pedal stroke. As LDH may be one of the factors that influences the

subconscious fatigue avoidance mechanism (Faria *et al.*, 2005), the ability to pedal at the same intensity with less muscle damage could be of benefit in longer rides or trials.

5.7 Conclusion

Although this study was based on a convenience sample of only twelve subjects and there is a possibility of a Type II error due to the low power of the study, the fact that there was no trend of a difference between trials in most physiological parameters assessed within this relatively homogenous sample of well trained recreational cyclists, is an important finding.

On the one hand, it could indicate that additional confounders which possibly relate to the specific training status of the subjects with respect to the use of the two types of chain rings and the appropriateness of the exercise testing protocol, may have influenced the results. On the other hand, the mechanical advantage derived from utilizing the 74^0 default setting and a 1.10 eccentricity ratio in the QR trial may not translate into a significant physiological benefit. Future research in this area should therefore focus on examining the potential effect of modifications of the crank arm orientation of the chain ring and ovality of the chain ring.

The tendency towards lower mean maximal blood lactate concentrations following the QR trials, which only reached borderline statistical significance, requires further investigation.

Chapter 6

Conclusions and Recommendations for Further Research

This is the first randomized, controlled study to have investigated the possibility of performance and physiological benefits related to the use of the Rotor Q-rings by amateur cyclists.

Although there was no statistically significant difference in the response to the two trials in terms of work output, VO_2, RPE, sub-maximal blood lactate concentrations or changes in blood LDH concentrations, peak blood lactate concentrations reached borderline significance ($p = 0.055$) and sub maximal heart rate at work loads below 190 W, were significantly different ($p < 0.05$).

Despite the shortcomings of this study design which included the limited statistical power of the study due to the relatively small sample size and the fact that it was restricted to an incremental cycling protocol on a stationary cyclosimulator in a laboratory setting, important guidelines and directions for future research, emanated from this work.

The blinding process which had never before been attempted was found to be possible and was, in the researcher's opinion, successful.

The possibility of lower peak blood lactate concentrations despite insignificant differences in peak workload output (380 ± 31.07 W vs. 385 ± 30.81 W) and maximum heart rates (174 ± 1.4 vs. 184 ± 11.3), require further verification in a larger study. Investigation into the possibility of lower peak blood lactate concentrations being the result of less reliance on non-oxidative metabolism or lesser recruitment of fast twitch fibers due to greater mechanical leverage and less muscle effort when using a Q-ring, would be a logical progression.

The lower heart rate response recorded which perhaps points to enhanced cycling economy at workloads below 190 W, also requires further investigation. A study dedicated to investigating submaximal cycling economy which should ideally be conducted as an outdoor field study (road/ mountain biking/track cycling), is recommended.

As the Tacx Fortius Trainer used an electromagnetic brake and tyre friction and the resistance was controlled by the computer, the road surface, wind speed and direction and frequent changes in saddle position encountered in outdoor cycling and which would vary from minute to minute, were not taken into account in this laboratory study. Further field trials in the form of a simulated time trial of 20-30 km,

available on the Tacx Fortius Trainer, with simulated hill climbs, descents and even simulated changes in wind direction, would therefore be recommended as this would give a more realistic outcome for cyclists involved in outdoor riding. It would then also be possible for the cyclist to alter their body position more i.e. standing on short up-hill sections and thus potentially derive more power from the Q-ring.

As is suggested in the mathematical model of Malfait *et al.* (2006), rotating the Q-ring to 107^0 may produce even more leverage and thus greater changes in mean and peak workloads when compared to the normal chain ring. Further work is therefore required in order to establish an optimal crank arm chain ring alignment. These authors suggest that an increased eccentricity ratio would also provide greater benefit; this also requires investigation.

There may be merit in pursuing the measurement of blood borne concentrations of LDH or other muscle proteins which have been shown to leak through the disrupted membranes at the muscle/blood interface pre and post trial, as well as the RPE and knee discomfort post trial in a field or a laboratory trial in order to determine tissue microtrauma induced by the elliptical chain rings.

The efficacy of the Q-ring should also be assessed in a mountain bike setting as the theory that the smoother pedal stroke with the Q-rings is an advantage as it promotes better traction in rough conditions (Burke, 2003), requires further examination.

In subjects who were unaccustomed to riding with a Q-ring, the greater time spent in the active phase of the pedal stroke in the QR trial and alteration in the muscular contraction timing during the pedal stroke, may have resulted in recruitment of a larger percentage of untrained fibers. Overcoming training as a possible confounder in this study, would, however, require a longitudinal study which extends over a few months and allowes for a training period on both rings, or larger sample sizes with stratification of the subjects into those who had prior training on Q-rings or normal chain rings.

Further research could also attempt to stratify the sample group into those participants who only mountain bike, those who only ride on the road and those who do both. In addition, stratification could also be based on anthropometrical characteristics e.g. calf muscle measurements and/or somatotyping and muscle typing.

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Appendix A

Study Title: A comparison of the physiological response to incremental stationary cycling using conventional, circular and elliptical, variable-geared Q –chain rings.

SUBJECT INFORMATION SHEET

Greeting:
Welcome to the Exercise Laboratory of the Division of Physiology at UKZN. Thank-you for taking the time to take part in this study.

Introduction: There has been much debate in cycling magazines about the advantages and disadvantages of fitting Q-rings or elliptical chain rings to replace other conventional circular chain rings. There is, however, no scientific evidence to prove whether these do in fact, improve cycling performance or not.

We, Dr Andrew Jones and Professor Edith Peters-Futre would like to determine the effect of elliptical chain rings on cycling performance in trained cyclists. In this study we want to learn whether the use of an eccentric Q-chain ring influences how your body responds to a progressive exercise session. This study is for a Masters degree in sports medicine.

What is involved in the study? – You will be required to visit the laboratory on three occasions:

Visit 1: You will be asked to fill in questionnaires providing us with information regarding your medical history and cycling training habits. We will also measure your height, weight, skinfold thicknesses, lung function, respiration rate, heart rate, temperature and blood pressure and introduce you to cycling on a stationary Tacx Trainer.

Visit 2: You will be asked to bring your own cycle into the laboratory.

A 5ml blood sample will be taken from a vein in your arm by a medical doctor before and after the cycle test. You will be expected to ride your bicycle on a stationary Tacx Trainer for 15 minutes at 125 Watts (warm-up). Thereafter the workrate will be increased by 30 Watts per minute until your heart rate and other physiological variables indicate that you have reached maximum oxygen consumption. Throughout the test we will ask you to indicate your level of exertion on a 20 point scale. In addition,

- the air that you breathe out will be collected by means of an air collection face mask that will be attached to a small analyzer that measures the amount of oxygen that you use and the amount of carbon dioxide you breathe out.

- a finger prick will be used to extract a small sample of blood every 60 seconds. These blood samples will then be analysed so that we can determine how your muscles respond to approximately 20 minutes of exercise of increasing intensity.

Visit 3: One week later, the exact same procedure as is described above, will be repeated.

You will, however, not be able to see which chainrings are on your bike during the two trials. During both trials the chain rings will be covered. This will make the study a blinded study. In one of the two trials, Q-rings will have been fitted to your bike, in the other your usual chain rings will remain on the bike.

You will be given the results of the study after both trials have been completed and be told how your body responded to the two types of chain rings.

There will be ten subjects taking part in the study from the greater Ethekwini Municipal area.

Risks of being involved in the study: There are very few risks in taking part in the study as many of you will be familiar with all of the bicycle related equipment already – the blood samples will be obtained by a very experienced general practitioner who is used to doing this and is a specialist in emergency care should anything go wrong during the test.

Benefits of being in the study: You would receive feedback regarding how your body responds to the two different chain rings on your cycle while cycling at different power outputs as well as your VO_2max and lactate threshold. These will help you choose the most appropriate type of chain ring for your bike, ascertain your current exercise fitness level and, indirectly, how effective your training methods are.

Participation is voluntary, refusal to participate will involve no penalty or loss of benefits to which you are otherwise entitled, and that you may discontinue participation at any time without penalty loss of benefits.

Reimbursements for "out of pocket" expenses. Your traveling expenses to the Laboratory will be reimbursed should you so wish.

Any additional costs that may result from participation in the research. This should not apply as you will be riding on your own bicycles

Confidentiality: Efforts will be made to keep personal information confidential by coding all your data according to your trial subject number and not name. Absolute confidentiality cannot, however, be guaranteed. Personal information may be disclosed if required by law.

Contact details of researcher/s: **For further information / reporting of study related adverse events.**
Dr Andrew Jones : 031-9034467;Cell: 0834098371

Contact details of BREC administrator and chair:
MRS S BUCCAS, Nelson R Mandela School of Medicine, Private Bag 7, Congella 4013
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Appendix B

UNIVERSITY OF
KWAZULU-NATAL

Study Title: A comparison of the physiological response to incremental stationary cycling using conventional, circular and elliptical, variable-geared Q –chain rings.

INFORMED CONSENT DOCUMENT

You have been asked to participate in a Masters research study.
You have been informed about the study by Dr Andrew Jones.
You have been informed about any available compensation or medical treatment if injury occurs as a result of study-related procedures.

You may contact Dr Andrew Jones any time if you have questions about the research or if you are injured as a result of the research. (031-9034467/ 0834098371)

You may contact the Biomedical Research Office at the Nelson R Mandela School of Medicine at 031-260 4769 if you have questions about your rights as a research subject.
Your participation in this research is voluntary, and you will not be penalized or lose benefits if you refuse to participate or decide to stop.

If you agree to participate, you will be given a signed copy of this document and the participant information sheet which is a written summary of the research.

.....

I herewith declare that the research study, including the above information, has been described to me orally. I understand what my involvement in the study means and I voluntarily agree to participate.

_____ _____

Signature of Participant **Date**

_____ _____

Signature of Witness **Date**
(Principal investigator)

_____ _____

Signature of the study supervisor **Date**

Appendix C

UNIVERSITY OF
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Study Title: A comparison of the physiological response to incremental stationary cycling using conventional, circular and elliptical, variable-geared Q –chain rings.

MEDICAL QUESTIONNAIRE

PLEASE ANSWER ALL QUESTIONS

1 Subject No./ Code: .....

2. Do you suffer from any allergies?.....

3. Are you currently in good health? (i.e. no illness within the last 3 months) Yes □ No □
If no, please specify .....

4. Do you suffer from any chronic medical conditions? (i.e. conditions diagnosed more than 3 months ago which affect your everyday life) e.g. diabetes, high blood pressure, asthma. Yes □ No □. If yes, please list .....

5. Are you currently taking any medication? Yes □ No □. If yes, please list below .....
.....

6. Do you suffer from a bleeding disorder (e.g. Haemophilia)? Yes □ No □. If yes, please list
.....

7. Have you been admitted to hospital within the last year? Yes □ No □ If yes, please specify
.....

8. Do you smoke? Yes □ No □
If yes, please specify amount per day and for how many years
.....

9. Are you presently or have you ever used performance enhancing drugs? (e.g. Erthropoeitin, anabolic steroids) Yes □ No □. If yes, please list .....
.....

Thank you for your participation

Dr. Andrew Jones – Principal Investigator

Appendix D

Study Title: A comparison of the physiological response to incremental stationary cycling using conventional, circular and elliptical, variable-geared Q –chain rings.

TRAINING STATUS & RIDING STYLE QUESTIONNAIRE

Please answer all questions. Tick one or more of the following answers per question.

CODE:.....

1. YEAR OF BIRTH:..... AGE:..... GENDER: MALE ☐

2. HOW MANY HOURS DO YOU GENERALLY RIDE PER WEEK?

- ☐ < 5
- ☐ 6 - 10
- ☐ 11 - 15
- ☐ 16 – 20
- ☐ > 21

3. HOW WOULD YOU CLASSIFY YOUR RIDING ABILITY?

- ☐ Weekend warrior (only ride on weekends)
- ☐ Serious amateur (> 5 races per year)
- ☐ Elite (regular top 10% finisher)
- ☐ Professional (paid to ride)
- ☐ Other - specify .....

4. HOW WOULD YOU DESCRIBE YOUR RACING EXPERIENCE WITHIN LAST YEAR?

- ☐ None
- ☐ Fun rider
- ☐ < 5 classics(35-75 km MTB races) /80-100km road races per year
- ☐ > 6 classics(35-75 km MTB races) /80-100km road races per year
- ☐ Multistage/Multiday races e.g. Cape Epic, Sani2c
- ☐ Other -specify.....

5. HOW WOULD YOU APPROACH IMPROVING PEDALING TECHNIQUE AND CADENCE ?

- ☐ Advice from friends
- ☐ Magazine articles
- ☐ Personal experience/trial and error
- ☐ Official sport specific guidelines
- ☐ Other –
  SPECIFY.....

6. WHAT KIND OF RIDING DO YOU DO?

Road riding	☐	☐
Mountain biking	☐	☐
Track cycling	☐	☐
BMX riding	☐	☐
Freestyle/north-shore riding	☐	☐

7. IN TERMS OF YOUR RIDING STYLE,

	Yes	No
do you prefer sprinting?	☐	☐
do you prefer hill climbing?	☐	☐
do you prefer cadences over 100 rpm?	☐	☐
do you prefer cadences below 60 rpm?	☐	☐
do you prefer to sit far back on your saddle?	☐	☐
do you sit neutrally on the saddle?	☐	☐
do you sit forward on your saddle?	☐	☐

THANK YOU FOR YOUR PARTICIPATION
DR. ANDREW JONES
PRINCIPAL INVESTIGATOR

Appendix E

UNIVERSITY OF
KWAZULU-NATAL

Study Title: A comparison of the physiological response to incremental stationary cycling using conventional, circular and elliptical, variable-geared Q –chain rings.

MUSCLE SORENESS/KNEE DISCOMFORT QUESTIONNAIRE

Please rate your muscular soreness/knee discomfort at the beginning of the first day following trials one and two, with a Numerical Pain Rating Scale (0 - 10 scale) where 0 = no pain at all, 5 = moderate, 10 = severe/maximal pain.

Subject No/Code.....

Categories	General pain relaxed	Daily living pain	Pain on pressure	Pain on stretching
Quadriceps				
Hamstrings				
Calves				
Knees				