# MECHANICAL POWER OUTPUT DURING CYCLING

## The efficacy of mobile power meters for monitoring exercise intensity during cycling

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Submitted by Alfred Nimmerichter, to the University of Exeter as a thesis for the degree of

Doctor of Philosophy in Sports and Health Sciences



I certify that all material in this thesis which is not my own work has been identified and that no material has previously been submitted and approved for the award of a degree by this or any other University.

Signature

# Abstract

One of the most meaningful technical innovations in cycling over the past two decades was the development of mobile power meters. With the ability to measure the physical strain under "real world" outdoor conditions, the knowledge of the demand during cycling has improved enormously. Power output has been described as the most direct measure of intensity during cycling and consequently power meters becomes a popular tool to monitor the training and racing of cyclists. However, only limited research data are available on the utilisation of power meters for performance assessment in the field or the analysis of training data. Therefore, the aims of the thesis were to evaluate the ecological validity of a field test, to provide an extensive insight into the longitudinal training strategies of world-class cyclists and to investigate the effects of interval training in the field at difference cadences.

The first study aimed to assess the reproducibility of power output during a 4-min (TT4) and a 20-min (TT20) time-trial and the relationship with performance markers obtained during a laboratory graded exercise test (*GXT*). Ventilatory and lactate thresholds during a *GXT* were measured in competitive male cyclists ($n = 15$; $\dot{V}O_2max$ 67 ± 5 $mL \cdot min^{-1} \cdot kg^{-1}$; $Pmax$ 440 ± 38 $W$). Two 4-min and 20-min time-trials were performed on flat roads. Strong intraclass-correlations for TT4 ($r = 0.98$; 95 % *CL*: 0.92-0.99) and TT20 ($r = 0.98$; 95 % *CL*: 0.95-0.99) were observed. TT4 showed a bias ± random error of − 0.8 ± 23 $W$ or − 0.2 ± 5.5 %. During TT20 the bias ± random error was − 1.8 ± 14 $W$ or 0.6 ± 4.4 %. Both time-trials were strongly correlated with performance measures from the *GXT* ($p < 0.001$). Significant differences were observed between power output during TT4 and *GXT* measures ($p < 0.001$). No significant differences were found between TT20 and power output at the second lactate-turn-point (*LTP 2*) ($p = 0.98$) and respiratory compensation point (*RCP*) ($p = 0.97$). In conclusion, TT4 and TT20 mean power outputs are reliable predictors of endurance performance. TT20 was in agreement with power output at *RCP* and *LTP 2*.

Study two aimed to quantify power output (PO) and heart rate (HR) distributions across a whole season in elite cyclists. Power output and heart rate were monitored for 11 months in ten male (age: 29.1 ± 6.7 y; $\dot{V}O_2max$: 66.5 ± 7.1 $mL \cdot min^{-1} \cdot kg^{-1}$) and one female (age: 23.1y; $\dot{V}O_2max$: 71.5 $mL \cdot min^{-1} \cdot kg^{-1}$) cyclist. In total, 1802 data sets were sampled and divided into workout categories according to training goals. The PO at the *RCP* was used to determine seven intensity zones (Z1-Z7). PO and HR distributions into Z1-Z7 were calculated for all data and workout categories. The ratio of mean PO to *RCP* (intensity factor, *IF*) was assessed for each training session and for each interval during the training sessions ($IF_{INT}$). Variability of PO was calculated as coefficient of variation ($CV$). There was no significant difference in the distribution of PO and HR for the total season ($p = 0.15$), although significant differences between workout categories were observed ($p < 0.001$). Compared with PO, HR distributions showed a shift from low to high intensities. *IF* was

significantly different between categories ($p$ < 0.001). The $IF_{INT}$ was related to performance ($p$ < 0.01), although the overall $IF$ for the session was not. Also, total training time was related to performance ($p < 0.05$). The variability in PO was inversely associated with performance ($p < 0.01$). In conclusion, HR accurately reflects exercise intensity over a total season or low intensity workouts but is limited when applied to high intensity workouts. Better performance by cyclists was characterised by lower variability in PO, greater training volume and the production of higher exercise intensities during intervals.

The third study tested the effects of low-cadence (60 $rev \cdot min^{-1}$) uphill ($\text{Int}_{60}$) or high-cadence (100 $rev \cdot min^{-1}$) flat ($\text{Int}_{100}$) interval training on PO during 20 min uphill ($\text{TT}_{up}$) and flat ($\text{TT}_{flat}$) time-trials. Eighteen male cyclists ($\dot{V}O_2max$: 58.6 ± 5.4 $mL \cdot min^{-1} \cdot kg^{-1}$) were randomly assigned to $\text{Int}_{60}$, $\text{Int}_{100}$ or a control group (Con). The interval training comprised of two training sessions per week over four weeks, which consisted of 6 bouts of 5 min at the PO at $RCP$. For the control group, no interval training was conducted. A two-factor ANOVA revealed significant increases on performance measures obtained from $GXT$ ($Pmax$: 2.8 ± 3.0 %; $p < 0.01$; PO and $\dot{V}O_2$ at $RCP$: 3.6 ± 6.3 % and 4.7 ± 8.2 %, respectively; $p < 0.05$; and $\dot{V}O_2$ at ventilatory threshold: 4.9 ± 5.6 %; $p < 0.01$), with no significant group effects. Significant interactions between group and the uphill and flat time-trials, pre vs. post-training on time-trial PO were observed ($p < 0.05$). $\text{Int}_{60}$ increased PO during both, $\text{TT}_{up}$ (4.4 ± 5.3 %) and $\text{TT}_{flat}$ (1.5 ± 4.5 %), whereas the changes were − 1.3 ± 3.6 %; 2.6 ± 6.0 % for $\text{Int}_{100}$ and 4.0 ± 4.6 %; − 3.5 ± 5.4 % for Con, during $\text{TT}_{up}$ and $\text{TT}_{flat}$, respectively. PO was significantly higher during $\text{TT}_{up}$ than $\text{TT}_{flat}$ (4.4 ± 6.0 %; 6.3 ± 5.6 %; pre and post-training, respectively; $p$ < 0.001). These findings suggest that higher forces during the low-cadence intervals are potentially beneficial to improve performance. In contrast to the $GXT$, the time-trials are ecologically valid to detect specific performance adaptations.

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# List of Abbreviations

| | |
|---|---|
| 3-HAD | 3-hydroxyacyl CoA dehydrogenase |
| $ADP$ | Adenosine diphosphate |
| $AT$ | Anaerobic threshold |
| $ATP$ | Adenosine triphosphate |
| $BL$ | Blood lactate concentration |
| $BL_{max}$ | Maximum blood lactate concentration |
| $CP$ | Critical power |
| CS | Citrate synthase |
| EMG | Electromyography |
| $FAD$ | Flavin adenine dinucleotide |
| $FTP$ | Functional threshold power |
| GEX | Gas exchange |
| $GXT$ | Incremental graded exercise test |
| $HR$ | Heart rate |
| $HRmax$ | Maximum heart rate |
| $IAT$ | Individual anaerobic threshold |
| $IF$ | Intensity factor |
| $IF_{INT}$ | Intensity factor for interval |
| LDH | Lactate dehydrogenase |
| $LT$ | Lactate threshold |
| $LTP\ 1$ | First lactate turn point |
| $LTP\ 2$ | Second lactate turn point |
| MDH | Malate dehydrogenase |
| MLSS | Maximal lactate steady state |

| | |
|---|---|
| $NAD$ | Nicotinamide adenine dinucleotide |
| $N$ | newton |
| $NP$ | Normalized power |
| $O_2$ | Oxygen |
| $OBLA$ | Onset of blood lactate accumulation |
| $PaCO_2$ | Arterial partial pressure of carbon dioxide |
| $PCr$ | Phosphocreatine |
| PFK | Phosphofructokinase |
| $P_i$ | Inorganic phosphate |
| PK | Pyruvatekinase |
| $P$ | power |
| $RCP$ | Respiratory compensation point |
| RM | Repetition maximum |
| RPE | Rating of perceived exertion |
| $rpm$ | Pedaling cadence |
| SDH | Succinate dehydrogenase |
| $T$ | Torque |
| TRIMP | Training impulse |
| TT20 | Twenty minute all-out time-trial |
| TT4 | Four minute all-out time-trial |
| $\text{TT}_{flat}$ | Flat time-trial |
| $\text{TT}_{up}$ | Uphill time-trial |
| $\dot{V}E/\dot{V}CO_2$ | Ventilatory equivalent for carbon dioxide |
| $\dot{V}E/\dot{V}O_2$ | Ventilatory equivalent for oxygen |
| $\dot{V}O_2max$ | Maximal oxygen uptake |

| | |
|---|---|
| $VT$ | Ventilatory threshold |
| $W'$ | Anaerobic work capacity |
| $W$ | watt |

**Declaration**

All the material contained within this thesis is original work conducted and written by the author. The following publications and conference communications are a result of this work.

**Publications**

Nimmerichter, A., Williams, C., Bachl, N., & Eston, R. (2010). Evaluation of a field test to assess performance in elite cyclists. *Int J Sports Med, 31*(3), 160–6.

Nimmerichter, A., Eston, R., Bachl, N., & Williams, C. (2011). Longitudinal monitoring of power output and heart rate profiles in elite cyclists. *J Sports Sci, 29*(8), 831–9.

Nimmerichter, A., Eston, R., Bachl, N., & Williams, C. (2011). Effects of low and high cadence interval training on power output in flat and uphill cycling time-trials. *Eur J Appl Physiol*, (in press). DOI 10.1007/s00421-011-1957-5

**Conference communications**

Nimmerichter, A., Williams, C., & Eston, R. (2009). Evaluation of a field test to assess aerobic endurance and performance in elite cyclists. *European College of Sports Sciences, Oslo.*

Nimmerichter, A., Eston, R., & Williams, C. (2010). Using power output to monitor exercise intensity: a longitudinal study in elite cyclists. *World Congress on Cycling Science, Edinburgh.*

Nimmerichter, A., Eston, R., & Williams, C. (2010). Distributions of power output and heart rate: a longitudinal study in elite cyclists. *European College of Sports Sciences, Antalya.*

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I would like to thank my first supervisor Dr. Craig Williams. When I have sent my research proposal to the University of Exeter in 2007 it landed on his desk at some point and fortunately raised his interest. I was invited for an interview and to present the goals of my "project". I remember the evening when I arrived in Exeter St. Davids. Craig was kindly enough to pick me up from the station and for identification he has worn a blue jacket from British Cycling Federation. We drove around Streatham campus, further down to St. Luke's and finally ended up in "Raddys" where I was introduced to Anni Vanhatalo, Andy Jones, Fred DiMenna and some others, who challenged themselves in a round of pool billiard. I also remember that I had a bad flu, my head felt twice its size and I thought to myself: "perfect time to get ill". However, the next day Craig guided me through the interview and gave me an impression of studying in Exeter. A few weeks later when I was back in Austria, I was really delighted to got the official acceptance letter from the admission office. I would like to thank you Craig, for the chance you gave me as a student of "advanced age" to complete my PhD. Unfortunately I could not spent as much time in Exeter, working along with you, as I like to. However, I have benefited so much from our meetings and discussions during several weeks at St.Luke's but also during our Skype teleconferences. Whenever a question arises you were promptly available with some useful advice. I hope that my work as well as the results of our studies have fulfilled your expectations. Once again, many thanks for being my supervisor and friend.

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*“If power meters preceded heart rate monitors, the latter might have never been sold separately.”*

Charles Howe, US Cycling Coach

## Part I

# Introduction

Cycling is one of the most frequently practised leisure time activities in the world. At the first sight, the technical skills required during cycling seems to be easy *("just turn the cranks")*. Taking a more exact view from the different cycling disciplines, almost all abilities of sports science can be observed. In most events, endurance performance is the dominating performance determinant. However, during uphill climbing, time-trialing or certain track disciplines that requires high power outputs, strength becomes a limiting factor. In mass-start events, technical skills such as exact steering and quick reactions are important to stay in a good position. Also in track events, where bicycles are equipped with fixed gears and without brakes, these skills are a prerequisite to compete successfully. In off-road events, such as mountain-biking and cyclo-cross, rocky, gravel or muddy surface, as well as narrow downhill sections, the technical skills of the rider have a great influence on the results. The knowledge of the versatility in cycling events is a prerequisite for coaches and scientists to set up the appropriate training to reach successfully the individual goals.

Overall cycling performance has multiple influencing factors. In Figure 1 a model of the factors affecting cycling performance is presented. At the bottom line of this model stands training. It is well known that training is the most important environmental stimulus for the improvement of performance (Astrand & Rodahl, 1986; Bassett & Howley, 2000). A high level of performance is the result of several years of training which leads to specific adaptations according to the applied training stimulus, until the highest possible performance level is reached. A training stimulus is adequate as long as it is sufficient to force the body to adapt. In addition, the type of exercise leads to specific adaptations (e.g. endurance, strength) in response to that stimulus (Faria et al., 2005b,a; Hausswirth et al., 2009). The model in Figure 1 shows that the *"main pillar"* of cycling performance is made of "training" which leads to the "physiological ability" to produce "power output". However, this pillar is surrounded by multiple factors which may interact with the central factors and therefore have an influence on cycling performance (Atkinson et al., 2003; Faria et al., 2005b,a). During the last two decades remarkable expansions of scientific knowledge were applied to cycling. One of the most impressive innovations was the introduction of mobile power meters. These devices measures power output directly on the bicycle and offers the opportunity to study the physiological demands during prolonged training and racing over various terrains in the field.

This thesis aimed to investigate the interactions between training ↔ physiological ability ↔ power output and cycling performance. After briefly explaining the basic principles of mechanical power

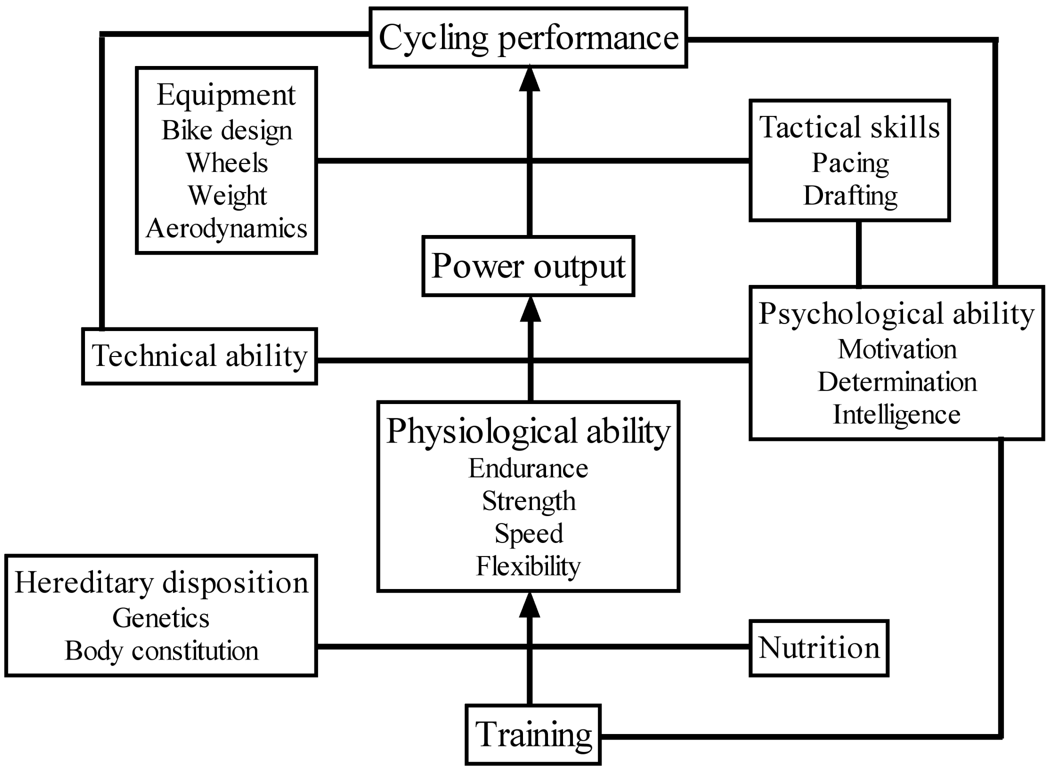



Figure 1: Schematic overview of the factors affecting cycling performance (adopted from Atkinson et al., 2003)

output and exercise metabolism, the current literature will be reviewed with regard to the physiology of cycling, exercise induced adaptations and performance assessment and the practical relevance to training.

# 1 Basic Principles of Mechanical Power Output

Since many decades calculations of power output have been widely used to estimate the efforts of outdoor cycling. In the late 1980s, when commercially available devices which measures power output directly on the bicycle emerges, scientists and trainers were able to study the physiological demands during prolonged training and racing over various terrains. While using mobile power meters, the measured power output is the result of all influencing variables like air resistance, rolling resistance or gradient.

The external power demand ($P$) of cycling performance can be modeled as the product of the net resistive forces ($Fres$) to forward motion and the average rate of ground speed ($V$).

$$P = Fres \times V \tag{1}$$

Where external power is given in watt ($W$), the resistive force is given in newton ($N$) and the velocity in meter per second ($m \cdot s^{-1}$). During outdoor cycling, the resistive forces changes largely due to different conditions in wind direction, rider's position, mass, flat or hilly terrain, road surface and of course traveling speed (Gressmann, 2002). The main forces to overcome can be divided to:

- Rolling resistance ($Froll$)
- Gravitational resistance ($Fslope$)
- Air resistance ($Fair$)

Assuming that the friction in the bearings of the bottom bracket, pedals, hubs and chain requires additional forces of approximately $3 - 5$ % ($DT_{eff}$: drive-train efficiency of $95 - 97$ %) (Kyle, 1986), the total forces to overcome are described as:

$$Fres = (Froll + Fslope + Fair)/DT_{eff} \tag{2}$$

While cycling on flat roads, air resistance and rolling resistance are the only forces impeding the forward motion of the cyclist. During uphill cycling, gravitational force becomes an additional, major part of total force.

Table 1: Coefficients of rolling resistance on different surfaces of 27 inch road tyres with a tyre pressure of 6.0 *bar* (Kyle, 1996)

| Surface | $C_{rr}$ |
|---|---|
| Wooden track | 0.0025 |
| Smooth tarmac | 0.0040 |
| Normal tarmac | 0.0080 |
| Rough tarmac | 0.0085 |
| Cobblestones | 0.0092 |

The rolling resistance depends on the total system mass and the coefficient of rolling resistance ($C_{rr}$). The biggest influence on $C_{rr}$ arises from the tyre pressure and the roughness of the pavement (Kyle, 1996). In Table 1 the coefficients of rolling resistance of different surfaces are shown.

A $C_{rr}$ reduction of 62 % and 24 % occurs with an increase in tyre pressure from 150 $kPa$ to 600 $kPa$ ($1.5 - 6.0$ $bar$) and from 600 $kPa$ to 1200 $kPa$ ($6.0 - 12.0$ $bar$), respectively (Grappe et al., 1999). With a higher total mass the vertical load on the wheels is higher and consequently increase $C_{rr}$. As a result of an increase in total mass from 76 kg to 91 kg, a 12 % higher $C_{rr}$ has been reported (Grappe et al., 1999). In addition to total mass and tyre pressure, the wheel diameter, the construction and material of the tyre and the temperature have a small effect on $C_{rr}$ (Kyle, 1996; Gressmann, 2002).

As well as for the rolling resistance, total mass has a major effect on gravitational resistance. The slope of a gradient is usually given as a percent value. For example, a slope of 10 % means that a vertical displacement of 10 m has to overcome on a horizontal distance of 100 m.

To overcome air resistance is the main requirement during level ground cycling at velocities above 15 $km \cdot h^{-1}$. Air resistance does not exhibit a linear but a quadratic function with an increase of velocity (Kyle, 1996; Gressmann, 2002). Therefore, the doubling of velocity leads to a fourfold increase of $Fair$ and at velocities above 40 $km \cdot h^{-1}$ $80 - 90$ % of the total resistive forces are attributed to air resistance (Figure 2) (Faria et al., 2005b; Heil, 2002).

Air resistance is mainly influenced by the coefficient of drag ($C_d$) and the projected frontal area ($A_p$) and depends on the air density, the square of the velocity, the size and the shape of the body and the inclination of the body to the airstream. Since frontal area is the only variable which can be influenced directly by the rider, mainly by the choice of the position on the bike, several methods have been used to determine $A_p$. The "cut out" method compares the weights of cut out contours of photographs of the cyclist in racing position on the bike and a reference rectangle with a known area (Capelli et al., 1998; Heil, 2001). On digital photographs the frontal area can be measured directly with appropriate software (Figure 3) (Heil, 2001, 2002).

Frontal area has also been estimated (Heil, 2001) as a constant fraction (i.e. 20.25 %) of the body surface area which can be calculated using the equation from Du Bois & Du Bois (1916). And

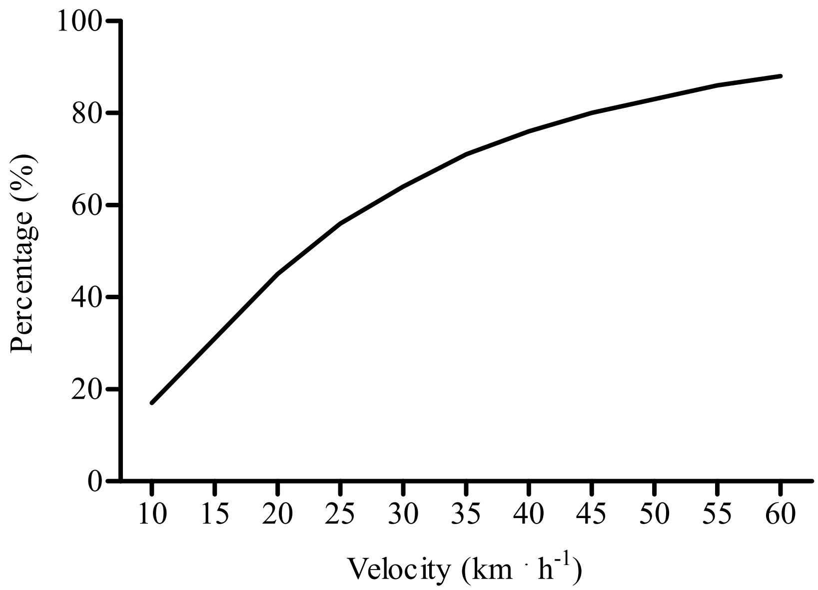



Figure 2: Percentage of air resistance during level ground cycling

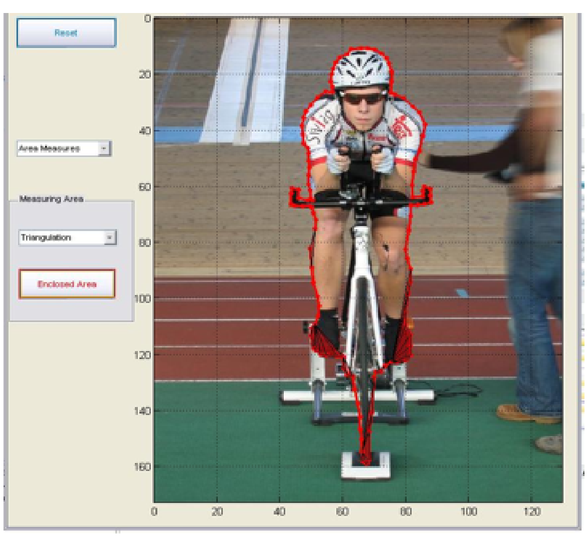



Figure 3: Software supported measurement of projected frontal area (Buchas et al., 2007, personal communication)

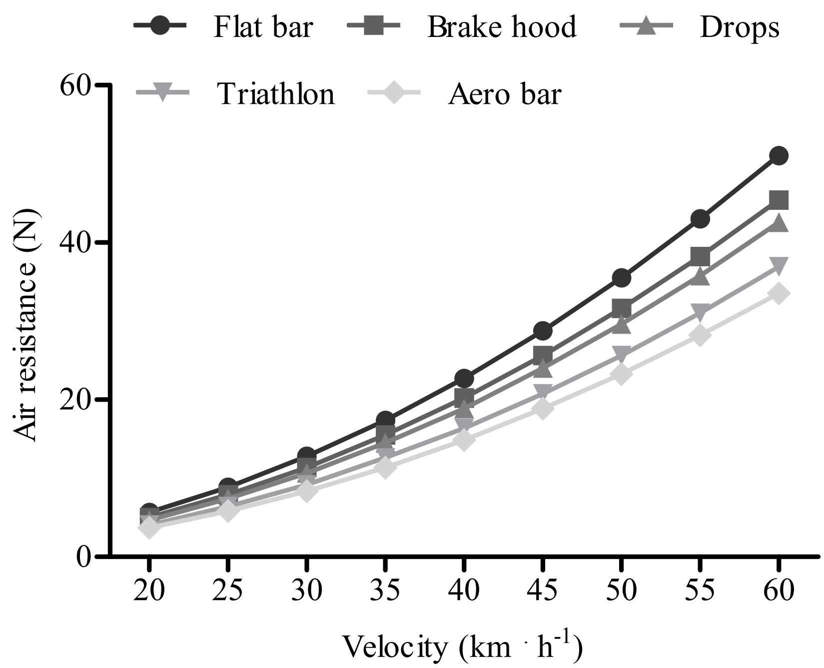



Figure 4: Air resistance as a function of velocity at different handlebar positions

finally the combined term of the coefficient of drag and the frontal area ($C_d A_p$) has been measured with mobile power meters (Grappe et al., 1997). In Figure 4 the changes in air resistance at different velocities and handlebar positions are shown.

Air density is related to air pressure and inversely related to temperature. Therefore, air resistance decreases at higher temperatures and at higher altitudes. As a consequence, many attempts to brake the cycling world hour record have been made at high altitudes (Bassett et al., 1999). For example in Mexico City at 2200 m above sea level, air density is 25 % lower at a temperature of 20° Celsius in comparison to sea level conditions. However, the attempt to reduce air resistance by lowering air density is limited by the fact that endurance performance is reduced at altitude. A $10-15$ % reduction of maximal oxygen uptake at 2500 m above sea level has been reported (Bassett et al., 1999).

With the knowledge of all the resistive forces a cyclist has to overcome, power output can be calculated by multiplying the forces with the velocity as given in Equation 1. It should be noted that the required power output to overcome air resistance increases to the $3^{rd}$ power of velocity whereas an increase in rolling resistance and gravitational resistance leads to a proportional increase of power output. In Figures 5 and 6 the power outputs during level ground and uphill cycling as well as the fractions of *Proll*, *Pair* and *Pslope* to the total power outputs, are shown.

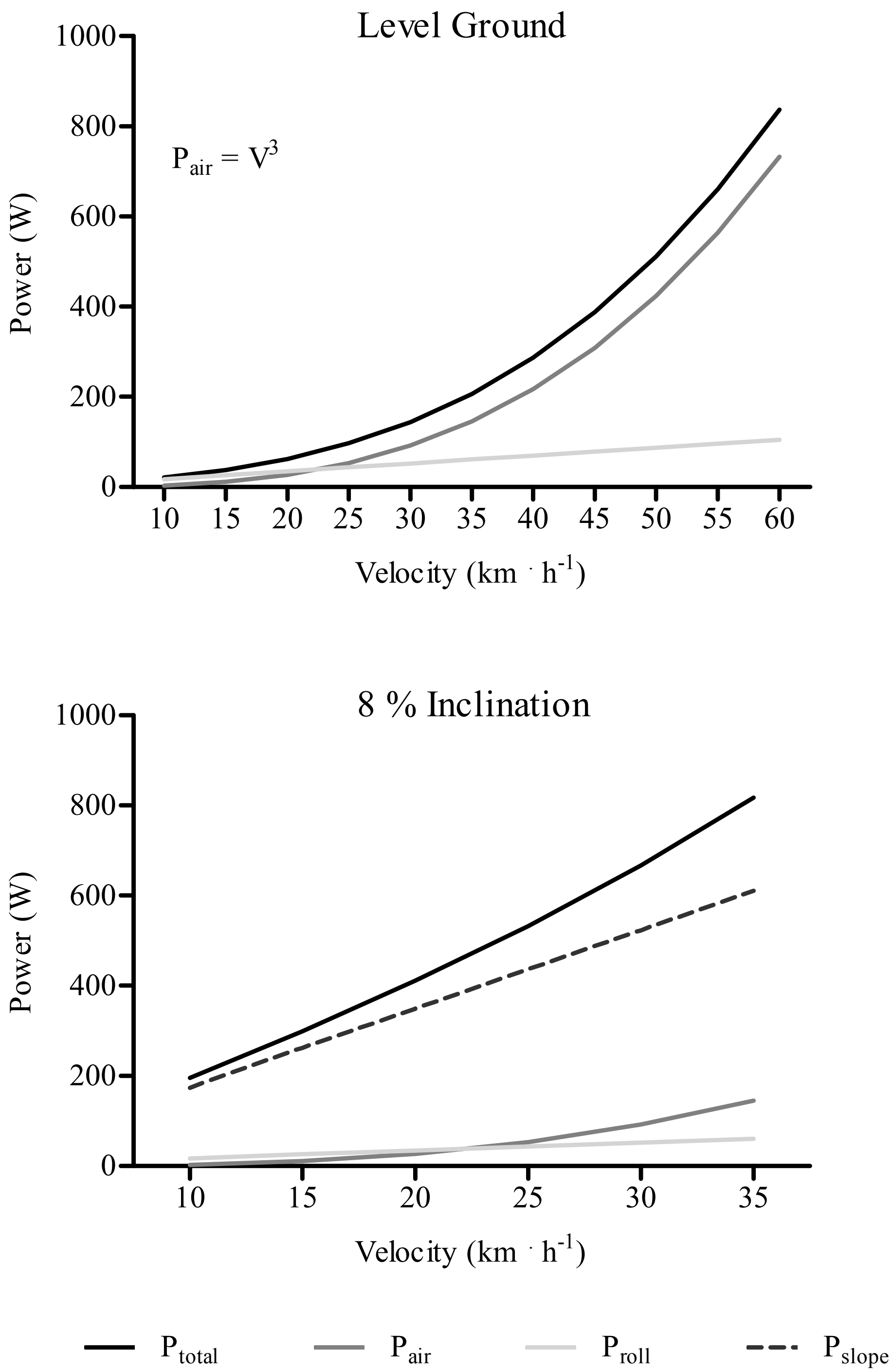



Figure 5: Relationship between power output and velocity during level ground and uphill cycling. See text for detailed explanations.

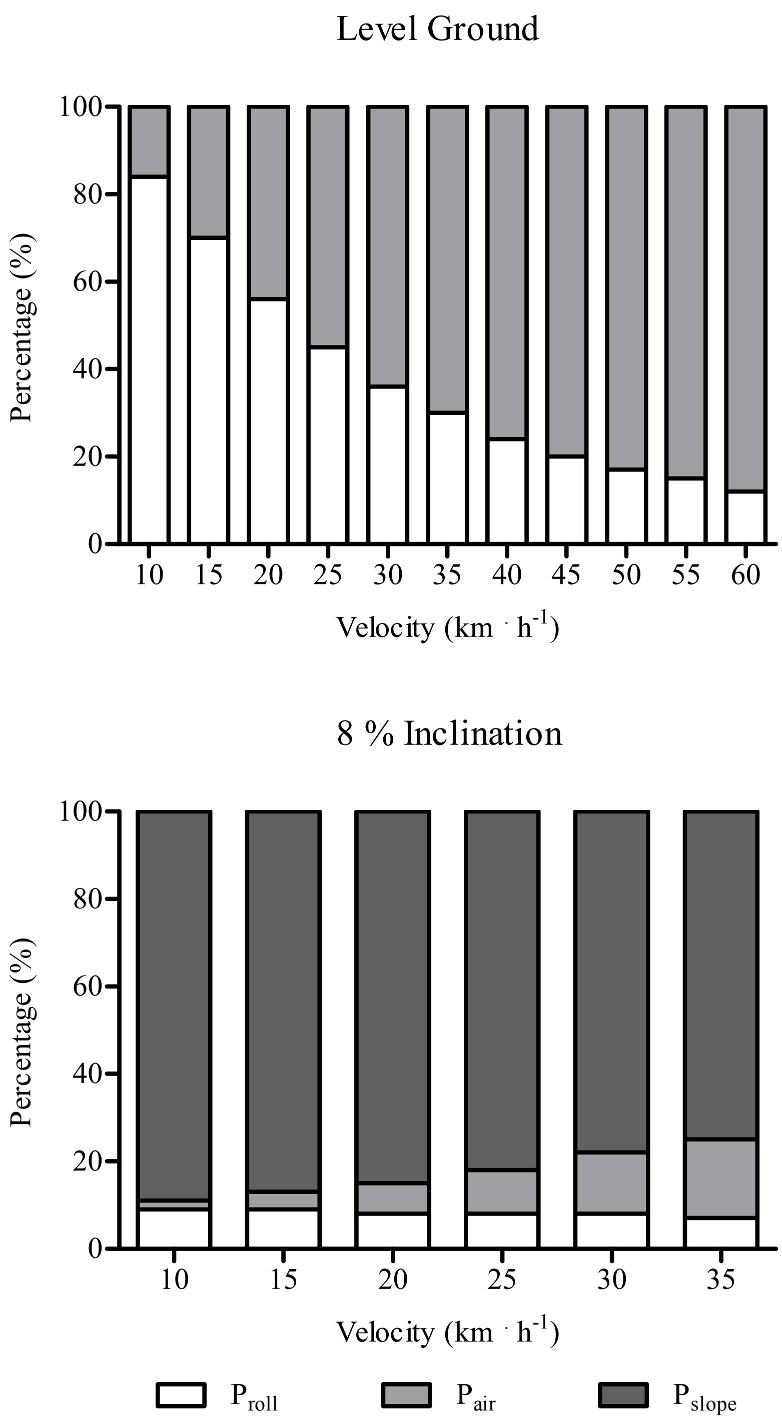



Figure 6: Distribution of rolling resistance, air resistance and gravitational resistance during level ground and uphill cycling at increasing velocities.

## 1.1 Power Measurement with Mobile Devices

The required forces to propel the bike are generated by the muscles, applied on the pedals and transmitted to the rear wheel via the cranks, the chain and the sprockets. Currently there are three devices available that measures these forces in the bottom bracket (Ergomo$^{TM}$), in the rear hub (Power Tap$^{TM}$) or on the cranks (SRM$^{TM}$). The first commercially available device was the SRM mobile power meter (Schoberer Rad Messtechnik – SRM, Juelich, Germany) in the late 1980s. This power meter is the most frequently used device for the purpose of training as well as for research. It has also been used in the present studies and therefore the technical principles are briefly described.

With SRM mobile power meters, the mechanical power output is measured through the multiplication of the torque applied to the cranks and the speed at which they turn (Power output = Torque x Angular velocity). Small deformations of the cranks induced through torque application are measured via strain gauges and converted to an electrical signal which is transmitted to a microcomputer ("Powercontrol") on the handlebar where power output is calculated using the following equation:

$$Power = T \times \omega = (measured\,frequency - zero\,offset\,frequency)/slope \times (2\Pi \times rpm/60) \qquad (3)$$

where:

Power = watt

$T$ = Torque $(N \cdot m^{-1})$

$\omega$ = Angular velocity $(rad \cdot s^{-1})$

Measured frequency = electrical signal through torque application $(Hz)$

Zero offset frequency = unloaded electrical signal $(Hz)$

Slope = calculated slope from the calibration process $(Hz/Nm)$

$rpm$ = cadence $(rev \cdot min^{-1})$

The electrical signal increases linear to the applied torque. During the calibration process in the factory the slope of this linear relationship is determined and important for the correct calculation of power output. The zero offset frequency is the electrical signal when no torque is applied on the crank and is given as the intercept of the linear relationship on the y − axis (Figure 7). As the zero offset frequency is sensitive to changes in temperature, a zero offset calibration must be carried out before each ride to ensure the accurate measurement of power output.

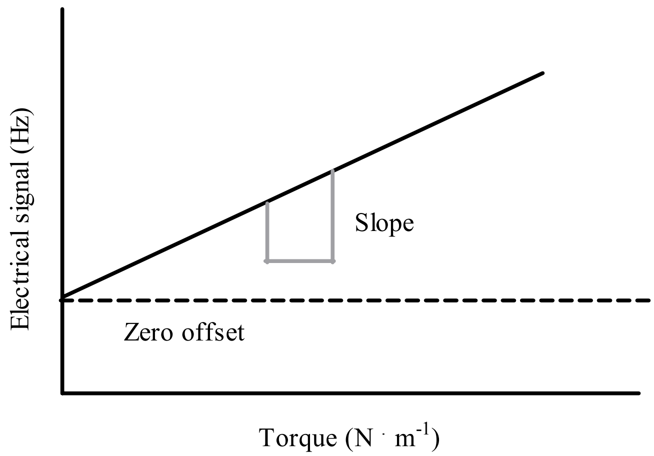



Figure 7: SRM calibration measures: The linear increase of the electrical signal in response to the applied torque on the crank. Zero offset frequency and slope of the linear relationship are important for the calculation of power output.

# 2 Exercise Metabolism

The different disciplines of cycling are characterised by a large variability in physiological demand. Cycling events differ in duration (one minute to several hours), type (single or mass start) and the terrain. Therefore, the metabolic pathways to convert energy from ingested food to chemical energy that is used for muscular contractions during exercise, are briefly described.

The contraction of skeletal muscle during exercise depends on the conversion of chemical energy stored in adenosine triphosphate ($ATP$) to mechanical energy. Since the $ATP$ store in human muscle is limited to provide energy for only a few seconds, it must be replenished immediately by a series of chemical reactions. The first anaerobic or non-oxidative source to immediately re-synthesize $ATP$ is phosphocreatine ($PCr$). The bonding energy stored in $PCr$ is used to phosphorylate $ATP$ from the products of $ATP$ degradation adenosine diphosphate ($ADP$) and inorganic phosphate ($P_i$). The second pathway to replenish $ATP$ is the glycolytic system. Carbohydrates are utilised through a series of chemical reactions to form pyruvic acid regardless of oxygen availability. When the rate of $ATP$ requirement is high and oxidative phosphorylation can not provide the required energy, pyruvic acid is converted to lactic acid (anaerobic glycolysis). However, when the energy turnover is lower and oxygen is sufficiently available, pyruvic acid is converted into acetylcoenzyme A ($acetyl - CoA$) which can enter the tricarboxylic acid cycle ($TCA - cycle$) in the mitochondria. This oxidative pathway can also be supplied via the breakdown of fat, where $acetyl - CoA$ is formed from free fatty acids during $\beta - oxidation$ and to a lesser extent from proteins. In the $TCA - cycle$ nicotinamide adenine dinucleotide ($NAD$) and flavin adenine dinucleotide ($FAD$) are used as hydrogen carriers ($NADH$ and $FADH$) that enters the electron transport chain where their stored energy is used to build $ATP$. In contrast to anaerobic or non-oxidative pathways where energy is provided at high rates for short periods, oxidative phosphorylation replenish $ATP$ over prolonged periods of time.

# Part II

# Literature Review

## 3 Physiology of Cycling

### 3.1 Anthropometry

Considering the broad spectrum of cycling disciplines and events (Table 2), there is also a large range of anthropometric characteristics in cyclists. A mean height of 180 ± 3 cm and a body mass of 86.2 ± 6.1 kg has been reported for Australian male track sprint cyclists (Gardner et al., 2007). In accordance, Dorel et al. (2005) reported a mean height of 180.8 ± 3.9 cm and a body mass of 83 ± 5 kg in a group of French male track sprinters. Craig & Norton (2001) have shown that time-trialists and pursuiters (∼ 184 cm) are usually taller than track sprint cyclists (∼ 178 cm) and that body mass is between 70 − 75 kg in pursuit and points race cyclists in comparison to sprinters and time-trialists (80 − 85 kg).

Table 2: Characteristics of road racing (a) mountain-bike (b) and track cycling (c) events

a

| Discipline | Duration (min) | Distance (km) |
|---|---|---|
| Road races | 120 - 420 | 100 - 300 |
| Criteriums | 45 - 90 | 30 - 60 |
| Time-trials | 5 - 80 | 3 - 60 |

b

| Discipline | Duration (min) | Distance (km) |
|---|---|---|
| Cross Country | 90 - 150 | 25 - 50 |
| Downhill | 3 - 5 | 1 - 4 |
| Marathon | 180 - 360 | 60 - 120 |

c

| Discipline | Duration (min) | Distance (km) |
|---|---|---|
| Sprint | 2 (10 - 13 s) | 0.6 - 0.8 (200m) |
| Time-trials | 0.5 - 1.1 | 0.5 - 1 |
| Pursuit | 4 - 5 | 3 - 4 |
| Points race | 35 - 50 | 25 - 40 |

Road cyclists must perform in a variety of competitive situations like uphill and flat terrain and single or mass-start events. Analyses of the characteristics of professional cyclists revealed that time-trial and flat-terrain specialists are taller (181 − 186 cm) and heavier (71 − 76 kg) in comparison to all-terrain (180 cm; 68 kg) and uphill specialists (175 cm; 62 kg) (Lucia et al., 2000a; Padilla et al., 1999). The mean height and body mass in competitive mountain-bikers have been reported to be 175 − 180 cm and 65 − 70 kg, respectively (Impellizzeri et al., 2005b; Lee et al., 2002; Stapelfeldt et al., 2004; Wilber et al., 1997). Although these studies have shown that body mass is lower for cyclists in events that requires a high level of endurance performance as well as for uphill specialists, the percent body fat is reportedly low ($8 - 10$ %) across all cycling disciplines (Craig & Norton, 2001; Impellizzeri & Marcora, 2007; Lucia et al., 2001b). Thus, indicating the large amount of muscle mass required in track sprinters to produce high forces for short periods of time (Dorel et al., 2005; Gardner et al., 2007; Martin et al., 2007).

Performance measures like oxygen uptake or power output are usually higher for heavier athletes when they are expressed in absolute values (i.e. not related to body mass) suggesting an advantage over lighter athletes. Therefore, these measures can be related to body mass to allow comparisons between athletes. Most studies have used a mass exponent of 1 (i.e. $mL \cdot min^{-1} \cdot kg^{-1}$ for oxygen uptake, or $W \cdot kg^{-1}$ for power output) to express performance measures related to body mass (Lucia et al., 2004a; Padilla et al., 2001; Vogt et al., 2007b). However, a mass exponent of 0.32 has been shown to better predict performance during flat cycling (Padilla et al., 1999; Swain, 1994) and allometric scaling of the relationship between body mass and the energy cost during uphill cycling revealed that performance might be better described with a 0.79 exponent (Heil, 1998; Swain, 1994). Both authors concluded that a mass exponent lower than 1 is necessary to account for the relative advantage of heavier cyclists in relation to cycle mass. However, Swain (1994) also suggested that 0.79 is not as well established as the 0.32 exponent for flat cycling and Heil (1998) reported that 0.89 should be used to predict uphill cycling ability. It should be noted that mass exponents of 0.32 and 0.79 have been used by several authors (Impellizzeri et al., 2005a; Lucia et al., 2004a; Padilla et al., 1999) for power output despite the fact that these exponents are originally derived for oxygen uptake. Recently Nevill et al. (2006) attempted to evaluate whether or not the same exponents could be used to predict uphill and flat performance ability from power output. It was shown that a mass exponent of 0.48 for both, maximum ($Pmax$) and ventilatory threshold power output, explained 69 and 59 % of the variance of flat time-trial cycling speed. In addition, uphill cycling speed was proportional to $Pmax$ with a mass exponent of 0.91, thus supporting the results from Heil (1998).

Although these studies supported the assumption that larger cyclists perform better during level cycling and a lower body mass is an advantage during uphill cycling, it should be noted that the winners of the Tour de France over the last twenty years were exceptionally well time-trialists and climbers, despite considerable differences in anthropometric characteristics.

## 3.2 Endurance Performance

Endurance performance is a major requirement for cyclists and can be described as the ability to re-synthesize $ATP$ via oxidative phosphorylation. It is determined by aerobic power, that is the maximal rate of oxygen used for $ATP$ re-synthesis (i.e. $\dot{V}O_2max$), aerobic capacity, which refers to a high sub-maximal level of oxidative $ATP$ phosphorylation without the accumulation of lactate (e.g. lactate thresholds, ventilatory thresholds) and mechanical efficiency, that is defined as the ratio of work done to energy expended. With the exception of the sprint events of track cycling and the downhill races in mountain-biking, the most outstanding characteristics of cyclists is their aerobic power and capacity.

### 3.2.1 Aerobic Power

Maximal oxygen uptake ($\dot{V}O_2max$) is one of the most frequently used parameters to describe aerobic power. It provides an insight into the functional capacity of the oxygen uptake and transport system as well as the utilisation of oxygen in the muscle tissue (Bassett & Howley, 2000). Oxygen enters the body via the lung, diffuses into the blood, is transported by the heart via arteries and finally diffuses from the capillaries to the mitochondria in the muscles. This oxygen transport pathway can be classified into "central factors" (i.e. capacity of the cardio-respiratory system and the blood) and a "peripheral factor" (i.e. skeletal muscle) (Bassett & Howley, 1997, 2000). Consequently, the potential limiting factors for $\dot{V}O_2max$ lie along this oxygen transport cascade.

**Central Factors** Maximal oxygen uptake is quantitatively related to maximal cardiac output ($\dot{Q}max$) and the maximal arterio-venous oxygen difference ($a-\bar{v}O_2max$) and is described as the Fick-equation:

$$\dot{V}O_2max = \dot{Q}max \times (a - \bar{v}O_2max) \tag{4}$$

Cardiac output is a reflection of the pumping capacity of the heart and is given by the stroke volume and the heart rate. The arterio-venous oxygen difference is indicative of the amount of oxygen being extracted from the blood by the tissues. Although it is possible to directly measure $a - \bar{v}O_2$ in vivo via arterial and venous catheterisation (Krustrup et al., 2009), this approach is limited by the type of exercise and the highly invasive nature. Therefore, $\dot{V}O_2$ is usually measured at the mouth to estimate the oxygen consumption in the muscle (Jones & Poole, 2005).

Several studies have shown that an exercise-induced increase in $\dot{V}O_2max$ is mainly related to an increase in $\dot{Q}max$ (Daussin et al., 2007; Hoogsteen et al., 2004; Pluim et al., 1996). There are small differences in maximal heart rate ($HRmax$) between trained and untrained people and therefore, a higher stroke volume is attributed to the increase in $\dot{Q}max$ (Bassett & Howley, 2000; Giada et al., 1998; Rowlands & Hopkins, 2002). Stroke volume is the difference between the ventricular end-diastolic volume and the end-systolic volume and at rest is approximately 70 $ml$ in the untrained heart and approximately 100 $ml$ in athletes (Astrand & Rodahl, 1986). In the endurance-trained athlete, dilation of all four cardiac chambers and increased left ventricular wall thickness increase the pumping capability of the heart. During maximal exercise the stroke volume in athletes increase to $\sim$ 200 $ml$, compared to untrained subjects ($\sim 120\ ml$) (Astrand & Rodahl, 1986). The increase of stroke volume from rest to exercise is accomplished by the Frank-Starling mechanism to maintain the end-diastolic volume of the left ventricle (i.e. increase of venous return or "preload") thereby increasing left-ventricular contractility and the ejection of the blood (Solaro, 2007).

Cardiac hypertrophy is a common adaptation to endurance training. Rodriguez Reguero et al. (1995) reported a diastolic ventricular thickness $>$ 13 mm and a mean ventricular mass index of 152 $g \cdot m^2$ in 21 professional cyclists and a mean ventricular mass index of 116 $g \cdot m^2$ in professional cyclists has been reported by Lucia et al. (1999). In a large cohort study of 947 Italian athletes from 25 sports Pelliccia et al. (1991) reported 16 mm as the upper limit of diastolic ventricular thickness in 1.7 % of the athletes. Whyte et al. (2004) investigated 442 British athletes (306 male and 136 female) from 13 sports. The upper limits of diastolic ventricular thickness were 14 mm and 11 mm and the ventricular mass index was 164 $g \cdot m^2$ and 131 $g \cdot m^2$ for males and females, respectively (Whyte et al., 2004). In both studies cyclists were amongst those athletes at the upper limit of the physiological cardiac hypertrophy, together with athletes from rowing, triathlon, canoeing and judo (Pelliccia et al., 1991; Whyte et al., 2004).

There is supporting evidence that the hemodynamic-induced stretch of the muscle fibres occurring during the preload phase and the subsequent enhanced contraction force resulting in an increased protein synthesis that finally leads to cardiac adaptations (Wikman-Coffelt et al., 1979). However, the signalling pathways at cellular level are not entirely clear and recent advances in molecular biology have shown the complexity of the signal-transduction cascade involved in process of cardiac hypertrophy (Heineke & Molkentin, 2006). For example, Wilkins et al. (2004) have shown separate signalling pathways for the up-regulation of pathological (calcineurin/NFAT pathway) vs. physiological (PI3K pathway) cardiac hypertrophy.

**Peripheral Factors** Skeletal muscle is composed of a variety of muscle fibre types. Muscles fibre types were classified as slow-twitch (type I), intermediate (type IIA) and fast-twitch (type IIB) fibres (Brooke & Kaiser, 1970) with different metabolic and contractile properties (Hilber et al., 1997; Talmadge et al., 1993). Different techniques have been used to classify muscle fibre types. The biochemical identification of enzymes related to oxidative or glycolytic metabolic pathways leads to three fibre types: slow-twitch oxidative, fast-twitch oxidative and fast-twitch glycolytic (Pette et al., 1999). The identification of myosin heavy chain (MHC) isoforms result in MHCI, MHCIIa and MHCIIx/d (Hilber et al., 1997). It should be noted that MHCIIx/d was formerly identified as the fastest myosin heavy chain MHCIIb, which was found in rats but is not expressed in humans (Ennion et al., 1995). Most recently classifications using histochemical myosin ATPase staining methods have identified seven different subtypes of human muscle fibre types (Table 3) (Staron, 1997).

Table 3: Comparison of different skeletal muscle fibre type classifications (Scott et al., 2001)

| Myosin ATPase | Myosin heavy chain | Biochemical |
|---|---|---|
| I | MHCI | Slow-twitch oxidative |
| IC | | |
| IIC | | |
| IIAC | | |
| IIA | MHCIIa | Fast-twitch oxidative |
| IIAB | | |
| IIB | MHCIIx/d (formerly IIb) | Fast-twitch glycolytic |

In comparison to type II fibres, type I fibres are characterised by lower

- Intramuscular $ATP$ and $PCr$ stores
- Glycolytic enzyme activity
- Cross-sectional area
- Force production
- Contraction speed

and higher

- Intramuscular triglyceride stores
- Aerobic enzyme activity
- Mitochondrial density
- Capillary density
- Myoglobin content

and therefore, are better adapted to perform aerobic work.

Adaptations of the skeletal muscle in response to endurance exercise have shown a muscle fibre type shift toward type I (Pette, 1998) and severe deconditioning like spinal cord injury or microgravity resulted in a shift from type I to type II fibres and the associated changes in enzyme activity (Criswell et al., 1996; Fitts et al., 1989; Manchester et al., 1990). The distribution of type I and type II fibres in the majority of people is roughly 50 % (Holloszy & Coyle, 1984).

An early study on skeletal muscle characteristics in competitive cyclists found no significant differences in fibre type composition (slow/fast-twitch) of the vastus lateralis muscle between two groups of male cyclists ($\dot{V}O_2max$: 67.1 and 57.1 $mL \cdot min^{-1} \cdot kg^{-1}$), one group of female cyclists ($\dot{V}O_2max$:

50.2 $mL \cdot min^{-1} \cdot kg^{-1}$) and one group of untrained males ($\dot{V}O_2max$: 38.2 $mL \cdot min^{-1} \cdot kg^{-1}$) and active females ($\dot{V}O_2max$: 41.5 $mL \cdot min^{-1} \cdot kg^{-1}$) (% slow-twitch fibres 51 − 57 %) (Burke et al., 1977). The authors found however, increased activities of oxidative enzymes (succinate dehydrogenase [SDH], malate dehydrogenase [MDH]) in both, male and female cyclists compared to untrained or active subjects (Burke et al., 1977). Neumann (1990) reported a significantly higher percentage of slow-twitch fibres in track sprint cyclists (66 %), 1 km track time-trialists (71.6 %), 4 km pursuit cyclists (78.6 %) and road cyclists (79 %) of the German Democratic Republic. In accordance with Burke et al. (1977) significantly higher activities of oxidative enzymes (SDH and citrate synthase [CS]) were found for the group of road cyclists in comparison to the track cyclists. Enzymes involved in anaerobic glycolysis (phosphofructokinase [PFK], pyruvatekinase [PK] and lactate dehydrogenase [LDH]) were reportedly higher for the track cyclists (Neumann, 1990). A group of 15 competitive male cyclists with a $\dot{V}O_2max$ of 69.2 $mL \cdot min^{-1} \cdot kg^{-1}$ was divided into two groups according to their 40-km time-trial performance by Coyle et al. (1991). Oxidative enzyme activity (CS and 3-hydroxyacyl CoA dehydrogenase [3-HAD]) as well as the percentage of type I fibres (66.5 % vs. 52.9 %) and the capillary density (23 %) was significantly higher for the group with better time-trial performance (53.9 min vs. 60.0 min) (Coyle et al., 1991). The authors also reported a strong relationship ($r = 0.75$, $p < 0.001$) between the years of endurance training and the percentage of type I fibres (Coyle et al., 1991). The studies of Neumann (1990) and Coyle et al. (1991) indicate that cyclists with a higher percentage of type I fibres are more competitive in endurance events. However, there are no longitudinal data to show whether the amount of type I fibres is the result of an exercise-induced conversion from type II fibres, or whether these athletes have advanced to elite level because they have a predominance of type I fibres.

In addition to changes in enzymatic profiles, other factors like mitochondrial biogenesis (Befroy et al., 2008; Holloszy & Coyle, 1984; Hood & Saleem, 2007) and capillary density (Burke et al., 1977; Coyle et al., 1988; Rodriguez et al., 2002; Sjøgaard, 1984; Zoladz et al., 2005) have been reported to enhance oxygen extraction in skeletal muscle of endurance trained athletes. Hoppeler et al. (1985) found a 40 % increase in mitochondrial volume density (i.e. volume of mitochondria per volume of muscle fibre) in the vastus lateralis muscle of previously untrained subjects after six weeks (5 x 30 min per week) of cycle ergometer training at 85 % of $HRmax$. The same group (Rösler et al., 1985) reported a 15 % increase in the capillary per fibre ratio after eight weeks of similar intervention. Zoladz et al. (2005) compared the capillary density and capillary per fibre ratio in the vastus lateralis muscle of untrained ($n = 7$), endurance trained ($n = 9$) and sprint-power trained ($n = 8$) subjects. The authors reported 11 % higher capillary per fibre ratios (1.9 ± 0.3; 2.1 ± 0.4; 2.1 ± 0.5 for untrained, endurance and sprint trained, respectively) and a 20 − 25 % higher capillary density (245 ± 44.9, 308 ± 64.5 and 325 ± 74.7 capillaries per $mm^2$) in both of the trained groups in comparison to the untrained group ($p < 0.05$) (Zoladz et al., 2005). Although significant differences were found between untrained and trained subjects, the study failed to identify differences in angiogenesis between endurance and sprint-power trained subjects. This might be explained by the characteristics of their subjects which were classified as national and sub-national level in distance running, cross-country skiing and cycling (endurance group) and a mixture of ski jumping, karate, ice hockey, soccer, modern dance, volleyball and handball (sprint-power group) (Zoladz et al., 2005).

Sjøgaard (1984) has investigated muscular adaptations during a season of amateur ($\dot{V}O_2max$: 56 $mL \cdot min^{-1} \cdot kg^{-1}$) and elite cyclists ($\dot{V}O_2max$: 71 $mL \cdot min^{-1} \cdot kg^{-1}$). Capillary density (30 %) as well as the activities of oxidative enzymes (CS, 3-HAD; $30 - 60$ %) were significantly higher ($p < 0.05$) in elite athletes at the start of the season. After five month elite cyclists increased enzyme activities by $30 - 60$ % without changes in $\dot{V}O_2max$ and capillary density (Sjøgaard, 1984). Unfortunately the amateur cyclists were not re-tested and therefore it is unclear whether this adaptation is related to the (presumably) higher training load of the elite cyclists. However, the author concluded that the changes in muscle enzyme activities may be of importance for the regulation of muscle metabolism enhancing the endurance capacity in elite cyclists (Sjøgaard, 1984).

A cross-sectional study of Rodriguez et al. (2002) compared muscle fibre characteristics between two groups of male road cyclists (ten 21 year old cyclists with a history of three years of sport competition [RC21] and ten 25 year old cyclists with a history of seven years of competition [RC25]) and two subgroups of five non-trained subjects who were matched for age with the cyclists (NT21 and NT25). The cyclists showed an increased percentage of type I fibres (RC25 > RC21 > NT) and decreased percentage of type IIA (RC25 < RC21 < NT) and IIB fibres (RC25 = RC21 < NT), an increased cross-sectional area of all fibre types (RC25 = RC21 > NT) except IIB fibres (RC25 > RC21), an increased mitochondrial volume in all fibre types (RC25 > RC21 > NT) except type IIA fibers (RC25 > RC21 = NT21) and an increased capillary density (RC25 > RC21 > NT) (Rodriguez et al., 2002). These findings indicate that a shift in fibre type distribution toward type I occur in cyclists which is accompanied by an increase in the number of capillaries. These effects, together with a higher cross-sectional area in type IIB fibres, appears to be more accentuated in athletes with a longer time of sport participation.

The studies of Coyle et al. (1991); Sjøgaard (1984) and Rodriguez et al. (2002) have shown that in endurance trained athletes with a high level of $\dot{V}O_2max$ significant changes in skeletal muscle occur in response to their training. As a consequence of the increases in mitochondria and oxidative enzymes there is a decreased lactate production and an enhanced lactate utilisation during exercise (Gladden, 2000). These skeletal muscle adaptations are important in explaining endurance performance at sub-maximal exercise intensities and thus are related to aerobic capacity and efficiency.

### 3.2.2 Aerobic Capacity

Although $\dot{V}O_2max$ is a strong indicator of maximal aerobic power (Balmer et al., 2000a; Bentley et al., 2001b; Lucia et al., 2004a) it has been reported as a poor discriminant in elite endurance athletes, where it remains relatively constant despite further increases in competitive performance (Jones, 2006). Several studies have shown that the tolerance to sustain fatigue without the accumulation of lactate at a high sub-maximal fraction of $\dot{V}O_2max$ is a strong performance predictor (Coyle et al., 1991; Lucia et al., 2004a, 2002b). As a consequence, different models of blood lactate and ventilatory thresholds have been used for the determination of aerobic capacity.

**Lactate and Ventilatory Thresholds** The assessment of the blood lactate profile during an incremental exercise test enables the identification of the lactate threshold or the first lactate turn point (*LTP 1*) (i.e. the first increase of blood lactate concentration above baseline during incremental exercise) and the second lactate turn point (*LTP 2*), which is the second inflection in blood lactate concentration when plotted against power output or velocity (Davis et al., 1983; Spurway & Jones, 2006) (Figure 10).

The measurement of gas exchange during incremental exercise is a non-invasive approach to determine lactate turn points and can be described as follows. As the work rate is increasing, $\dot{V}O_2$, $\dot{V}CO_2$ and $\dot{V}E$ increase linearly. During this phase $\dot{V}CO_2$ output comes entirely from substrate metabolism. When lactate acidosis emerges, $\dot{V}CO_2$ increases more rapidly because $CO_2$ generated by the bicarbonate buffering of blood lactate contributed to the metabolic $CO_2$ production. The increase of $\dot{V}CO_2$ as compared to $\dot{V}O_2$ defines the ventilatory threshold ($VT$), or as originally described as "anaerobic threshold" ($AT$) by Wasserman & McIlroy (1964), and can be determined via the V-slope method (Beaver et al., 1986). In response, $\dot{V}E$ increases in proportion to $\dot{V}CO_2$ to regulate arterial partial pressure of $CO_2$ ($PaCO_2$; phase of "isocapnic buffering"). As a result, an increase of the ventilatory equivalent for oxygen ($\dot{V}E/\dot{V}O_2$) appears. Further increases of work rate causes a more rapidly increase of $\dot{V}E$ than in $\dot{V}CO_2$ and a decrease in $PaCO_2$. Consequently, an increase of the ventilatory equivalent for $CO_2$ ($\dot{V}E/\dot{V}CO_2$) is observed. This phase of "hypocapnic hyperventilation" reflects the compensation for metabolic acidosis (respiratory compensation point; $RCP$) (Beaver et al., 1986; Wasserman et al., 1994). A schematic overview of ventilatory and blood lactate responses to incremental exercise is depicted in Figure 8 - Figure 10.

The exercise intensity at *LTP 1* or $VT$ has been shown to be a valid and reliable predictor of aerobic capacity (Amann et al., 2004; Van Schuylenbergh et al., 2004; Weston & Gabbett, 2001). The effects of a more rapid fatigue and muscle glycogen depletion associated with the increased blood lactate concentrations at exercise intensities above *LTP 1* / $VT$ (Coyle, 2000; Wasserman et al., 1994),

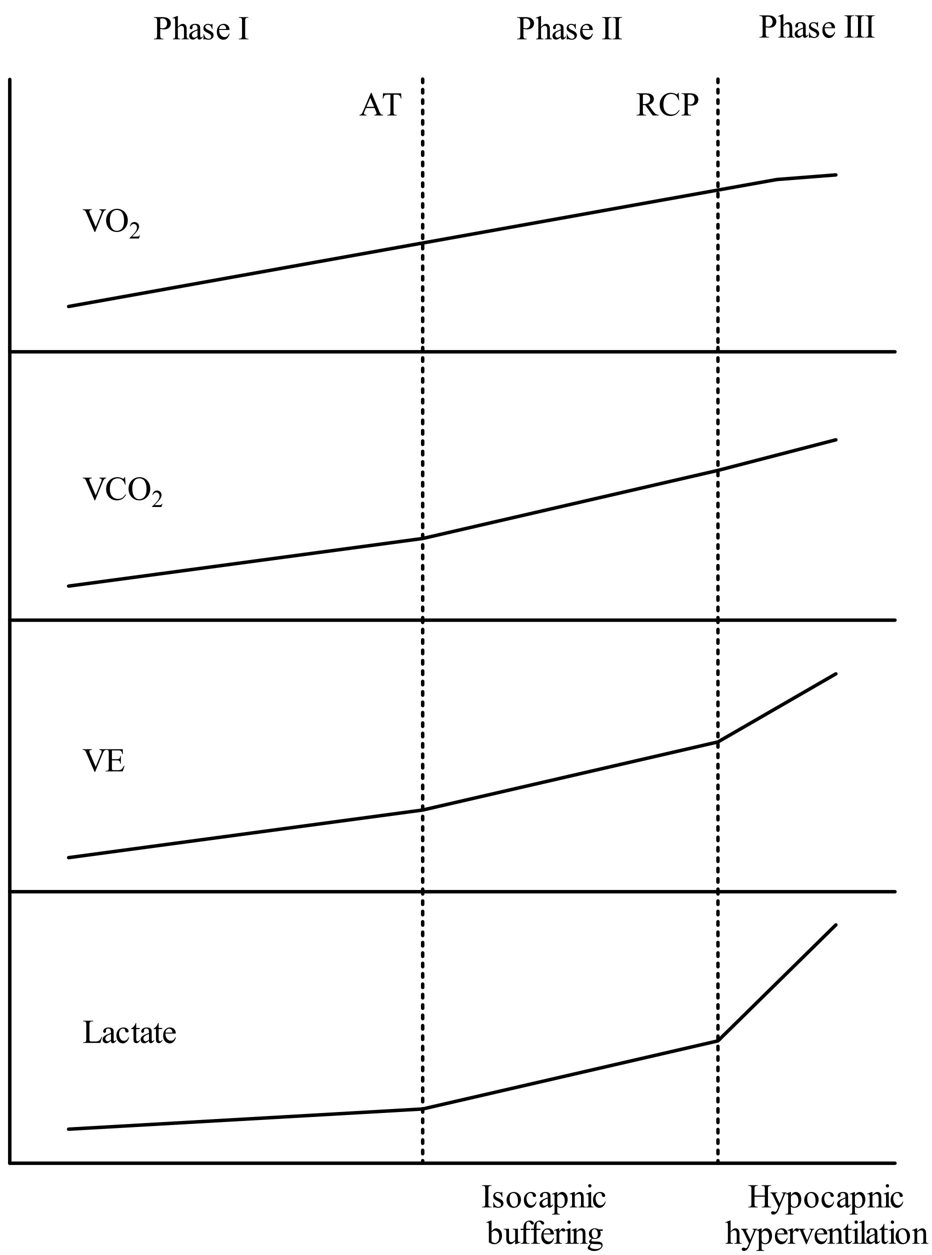



Figure 8: Response of lactate and ventilatory measures to incremental exercise (adapted from Wasserman et al., 1999)

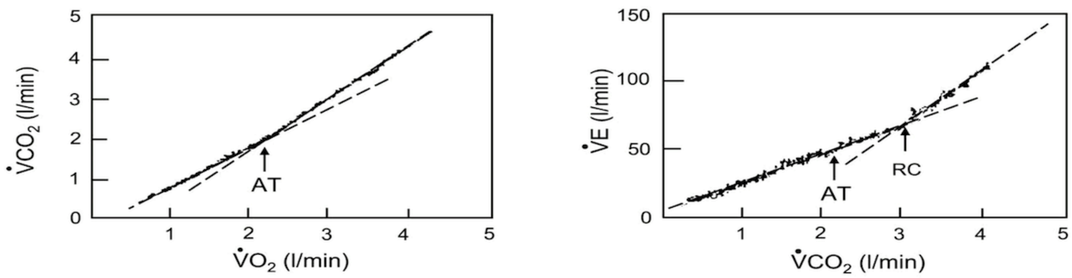



Figure 9: Determination of $VT$ or $AT$ (left panel) and $RCP$ (right panel) (Beaver et al., 1986)

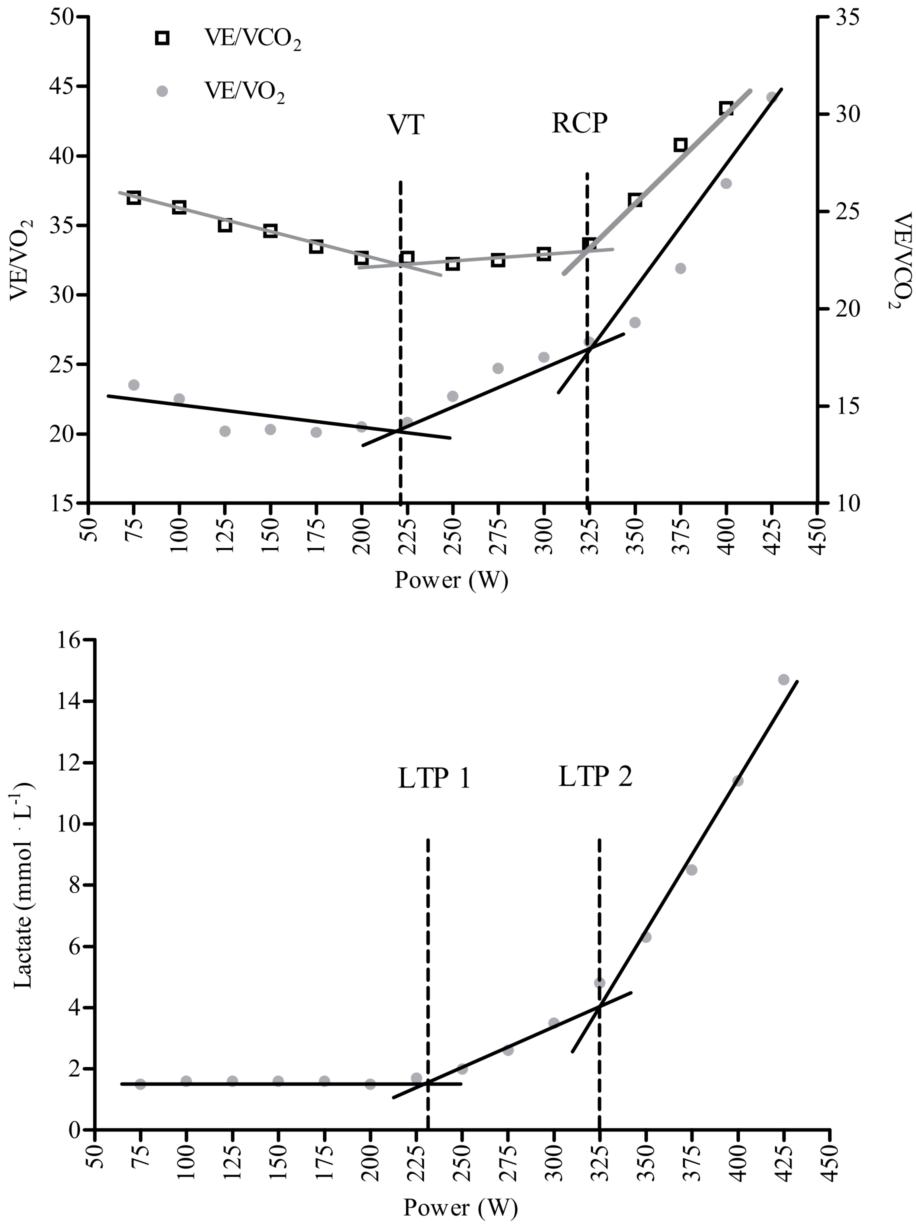



Figure 10: Determination of the ventilatory threshold and respiratory compensation point (upper panel) and the first and second lactate turn point (lower panel)

did not occur below that threshold. Blood lactate remain low at baseline levels and therefore work rates below *LTP 1 / VT* are encountered by athletes during training to improve basic endurance (Esteve-Lanao et al., 2007; Fohrenbach et al., 1987; Seiler & Kjerland, 2006). In addition it is an important indicator for performance in long-lasting endurance events like marathon running or road cycling (Jones, 2006; Lucia et al., 2004a). However, during most forms of endurance events athletes are required to work at higher exercise intensities for prolonged periods (Earnest et al., 2009). The highest exercise intensity where metabolic acidosis can be compensated for is *LTP 2* or *RCP*. Although not identical, this threshold is an approximation of the exercise intensity where blood lactate appearance is matched by its removal (i.e. maximal lactate steady state) (Smith & Jones, 2001; Van Schuylenbergh et al., 2004).

**Maximal Lactate Steady State** The maximal lactate steady state (MLSS) is defined as the highest work rate that can be maintained without continuous blood lactate accumulation (Beneke, 1995). The determination of MLSS requires several constant load tests of 30 min at sub-maximal intensities between 70 % and 90 % of $\dot{V}O_2max$ (Beneke, 2003). As a criterion for a steady state lactate profile an increase of no more than 1.0 $mmol \cdot L^{-1}$ between 10 min and 30 min of constant load exercise is accepted. The work rate associated with MLSS is an important measure for endurance athletes since it represents the boundary above which blood lactate rises inexorably and leads to exhaustion in a finite time. The intensity representing the MLSS has been shown to be highly related to competition performance in endurance events ($r$ = 0.92 with 8-km running and $r$ = 0.84 with 40-km cycling time-trial speed) (Jones & Doust, 1998; Swensen et al., 1999).

The MLSS has been defined by some authors as the "anaerobic threshold" (Beneke, 2003; Heck et al., 1985; Svedahl & MacIntosh, 2003) or the "onset of blood accumulation" (*OBLA*) (Sjodin & Jacobs, 1981), corresponding to the exercise intensity at a fixed blood lactate concentration of 4.0 $mmol \cdot L^{-1}$ and was used in several cycling related studies to evaluate performance capacity (Bentley et al., 2001a; Padilla et al., 2000a, 1999), or to study exercise intensity in competition (Fernandez-Garcia et al., 2000; Impellizzeri et al., 2002; Padilla et al., 2000b, 2001). However, it has been shown that the blood lactate concentration at MLSS varies between athletes. Beneke & von Duvillard (1996) reported significantly lower blood lactate concentrations at MLSS in rowers (3.1 ± 0.5 $mmol \cdot L^{-1}$), than in cyclists (5.4 ± 1.0 $mmol \cdot L^{-1}$) or in speed skaters (6.6 ± 0.9 $mmol \cdot L^{-1}$) and concluded that the blood lactate concentration seems to decrease with the mass of the primarily engaged muscle. Hoogeveen et al. (1997) have shown that endurance trained triathletes and cyclists averaged a blood lactate concentration of 7.4 ± 2.5 $mmol \cdot L^{-1}$ (range $3.2 - 12.2$ $mmol \cdot L^{-1}$) in a 40-km steady state field test. In context of the present thesis it is important to note that several studies have demonstrated steady state blood lactate concentrations of $7.0 - 13.0\ mmol \cdot L^{-1}$ (individual range $5.0 - 16.0\ mmol \cdot L^{-1}$) during self-selected maximal effort time-trials (Mattern et al., 2001; Myburgh et al., 2001; Perrey et al., 2003). These findings indicate that the "constant load" approach to determine MLSS does not reflect competitive situations with the goal to complete a certain distance in the fastest time. The higher variability of the work load during competition can affect the physiological response in comparison with the same average constant work lode (Abbiss & Laursen, 2008; Billat et al., 2001; Suriano et al., 2007). The relationship between distance and the time to complete this distance is linear and the highest velocity for a given distance or the time to exhaustion for a given velocity, is described by the hyperbolic function of the critical power model.

**Critical Power** The concept of critical power ($CP$) proposed a linear relationship between time to exhaustion ($t$) at constant work rate and the total amount of work ($Wtot$) performed at exhaustion (Equation 5 and Figure 11) (Monod & Scherrer, 1965). The slope of the linear relationship represent the power output that can be sustained for a *"long time without fatigue"* (Monod & Scherrer, 1965), and the intercept is a finite amount of work that can be performed above critical power and is referred to as "anaerobic work capacity" ($W'$) (Hill, 1993). For a work rate higher than $CP$, the anaerobic energy store $W'$ is used up and cannot be replenished until the exercise is terminated or power output drops below $CP$ (Hill, 1993; Jones et al., 2010).

$$Wtot = W' + CP \times t \tag{5}$$

Time to exhaustion, power output and anaerobic work capacity can be calculated by rearranging Equation 5 as:

$$t = \frac{W'}{P - CP} \tag{6}$$

or

$$P = \frac{W'}{t} + CP \tag{7}$$

or

$$W' = (P - CP) \times t \tag{8}$$

Figure 11 shows the linear relationship between total work and time to exhaustion as well as the hyperbolic function between power output and time to exhaustion. This hyperbolic function is characterised by two parameters: the asymptote of power output ($CP$) and the curvature constant ($W'$) (Fukuba et al., 2003; Hill, 1993). The power vs. time relationship is constructed by three to five exercise bouts at work rates leading to exhaustion within $1 - 15$ min (Brickley et al., 2002; Hill & Smith, 1993; Moritani et al., 1981; Pringle & Jones, 2002).

Theoretically, the exercise intensity corresponding to $CP$ would be sustainable indefinitely and would finally be limited by fuel supply. It has been shown however, that the time to exhaustion at $CP$ range from $20 - 60$ min (Bishop et al., 1998; Brickley et al., 2002; Jenkins et al., 1998). The studies of Jenkins et al. (1998) and Bishop et al. (1998) have demonstrated that the duration of the exercise bouts used to define the work vs. time relationship influenced the time to exhaustion at $CP$. Using the three shortest durations ($68 - 193$ s) of five predicting trials between $1 - 10$ min result in significantly higher slopes ($CP$) compared with the three longest durations ($193 - 485$ s) and the first, third and fifth trial ($201.0 \pm 37.9$ $W$, $164.0 \pm 22.8$ $W$ and $176.1 \pm 27.6$ $W$, respectively; $p < 0.05$) (Bishop et al., 1998). Jenkins et al. (1998) investigated the effects of these differences on the time to exhaustion. Using predicting trials between $10 - 25$ min the authors found significant differences in $CP$ ($268 \pm 17.5$ $W$, $285 \pm 12.1$ $W$ and $321 \pm 8.8$ $W$; $p < 0.05$) which resulted in significant differences between time to exhaustion ($42.9 \pm 3.9$ min, $39.9 \pm 4.6$ min and $34.4 \pm 2.7$ min, respectively; $p < 0.05$) (Jenkins et al., 1998). Also Brickley et al. (2002) reported exhaustion times between $20 - 40$ min at $CP$ calculated from three predicting trials designed to fatigue their subjects within $1 - 10$ min. In addition, Brickley et al. (2002) found the time to exhaustion to be significantly correlated with $\dot{V}O_2max$ ($r = 0.78$, $p < 0.05$) which suggest that athletes with a higher endurance level can sustain exercise intensities at $CP$ for longer periods.

The study of Brickley et al. (2002) also investigated the physiological response during exercise at $CP$. Oxygen uptake, heart rate and blood lactate concentration significantly increased over time ($p < 0.001$) and $\dot{V}O_2$ reached $91 \pm 2$ % of $\dot{V}O_2max$ at time to exhaustion and it was concluded that the exercise intensity at $CP$ is sustainable between $20 - 40$ min without a physiological steady state (Brickley et al., 2002). In contrast, Poole et al. (1988) found $CP$ to occur at 80 % of $\dot{V}O_2max$ and both oxygen uptake and blood lactate concentration leveled off after an initial increase. However, a slight increase in work rate of 5 % induced a different physiological response with an increase in oxygen uptake and blood lactate concentration until task failure (Poole et al., 1988). It should be noted that the study of Poole et al. (1988) used four predicting trials that leads to exhaustion between $2 - 15$ min. This suggest that high power outputs with exhaustion times below 2 min result in the prediction of higher $CP$ and consequently non-steady state physiological profiles. The steady state response demonstrated by Poole et al. (1988) led to the assumption that $CP$ is coincident to MLSS.

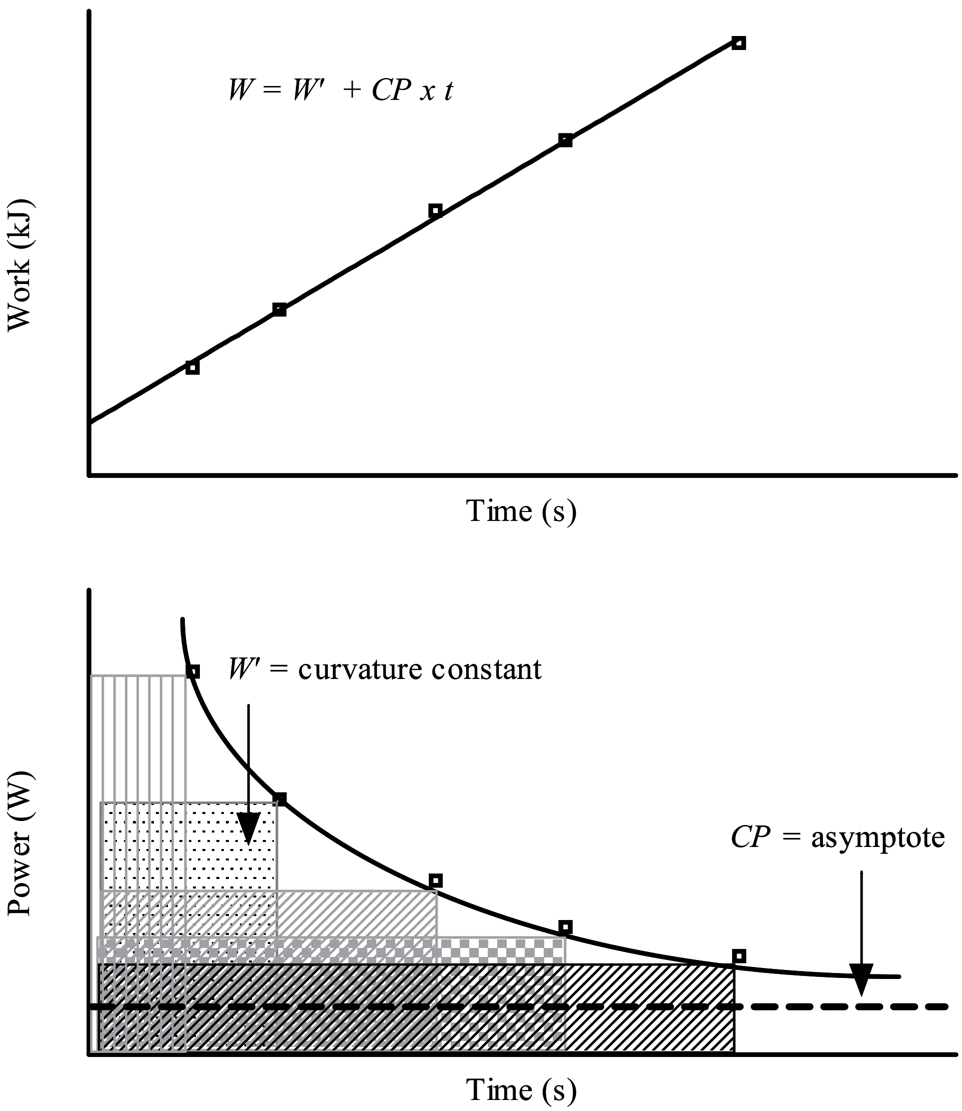



Figure 11: Schematic illustration of the linear work / time relationship (upper panel) and the hyperbolic function of power / time (lower panel) (redrawn from Jones et al. (2010))

Whilst some support this assumption (Sid-Ali et al., 1991; Smith & Jones, 2001) most studies found $CP$ to be higher than MLSS (Dekerle et al., 2003; Jenkins & Quigley, 1990; Pringle & Jones, 2002).

The practical relevance of the critical power concept is that it measures performance in its most "natural" form, that is: measuring the work done per unit of time. This approach is very similar to competitive situations where the completion of a certain distance in the fastest time is the ultimate goal. However, numerous time consuming exhaustive tests are impractical for athletes but also for research. Therefore, attempts have been made to use one single all-out test for the measurement of $CP$ and $W'$. The rational of that approach is that an all-out effort eventually deplete $W'$ and, according to Equation 8 when $W'$ becomes 0, $P = CP$.

Brickley et al. (2007) used a 90 s all-out isokinetic cycling test to test the hypothesis that power output at the end of the test would correspond with $CP$. Although the end power (292 $\pm$ 65 $W$) was related to ($r = 0.89$) it was significantly higher ($p < 0.01$) than $CP$ (264 $\pm$ 50 $W$). In addition, the highest $\dot{V}O_2$ during the 90 s trial was significantly lower than the $\dot{V}O_2max$ obtained during an incremental exercise test (3435 $\pm$ 682 $mL \cdot min^{-1}$ vs. 3929 $\pm$ 784 $mL \cdot min^{-1}$; $p < 0.01$) (Brickley et al., 2007). It was concluded that a 90 s all-out test is too short to determine $CP$ and to allow the attainment of $\dot{V}O_2max$.

In a 3 min all-out test against a fixed resistance Burnley et al. (2006) demonstrated that the $\dot{V}O_2$ during the trial was not significantly different from $\dot{V}O_2max$ (3.78 $\pm$ 0.73 $L \cdot min^{-1}$ vs. 3.84 $\pm$ 0.79 $L \cdot min^{-1}$; $p = 0.75$) can be reached within 60 s and sustained at this level for the remaining test. In addition, a constant work rate 15 $W$ below the end-test power output (EP: mean power output during the last 30 s) applied over 30 min was tolerated in 9 of 11 subjects and of these, 7 subjects achieved a steady state blood lactate (5.6 $\pm$ 1.6 $mmol \cdot L^{-1}$) and $\dot{V}O_2$ response . In contrast, a constant work rate 15 $W$ above the EP leads to exhaustion in all subjects within $\sim$ 13 min (range $2 - 24$ min) (Burnley et al., 2006). In a subsequent study by Vanhatalo et al. (2007a) no significant differences were found between EP and the work above EP (WEP) compared to $CP$ (287 $\pm$ 55 $W$ vs. 287 $\pm$ 56 $W$; $p = 0.37$) and $W'$ (15 $\pm$ 4.7 $kJ$ vs. 16 $\pm$ 3.8 $kJ$; $p = 0.35$). Further studies have shown that the 3 min all-out test is sensitive to track exercise induced changes in EP and WEP (Vanhatalo et al., 2008; Vanhatalo & Jones, 2009) and is robust to pacing and cadence manipulations (Vanhatalo et al., 2007b).

In summary it has been shown that critical power is a functionally valuable performance measure. Together with *LTP 2*, *RCP* and MLSS it represents the upper limit of oxidative metabolism that can be sustained for $20 - 60$ min. Whether or not these concepts could be used interchangeably will be discussed in the next chapter.

**Interchangeability of Thresholds** Considering the three phases of physiological response to incremental exercise (Beaver et al., 1986; Wasserman et al., 1999, 1994), *LTP 2 / RCP* demarcates the transition from the heavy to the severe exercise domain after a phase of bicarbonate buffering and the maximal sustainable intensity at which metabolic acidosis can be compensated. Therefore a coincidence with the maximal lactate steady state seems to be obvious. Several studies have investigated the relationship of MLSS to blood lactate thresholds (Baldari & Guidetti, 2000; Beneke, 1995; Van Schuylenbergh et al., 2004), ventilatory thresholds (Dekerle et al., 2003; Laplaud et al., 2006; Van Schuylenbergh et al., 2004; Yamamoto et al., 1991) and critical power (Dekerle et al., 2003; Pringle & Jones, 2002). Van Schuylenbergh et al. (2004) found no significant differences between MLSS and various lactate and ventilatory thresholds in elite cyclists. The authors reported strong to moderate predictability of MLSS from *Pmax* ($R^2 = 0.72$), individual lactate threshold ($R^2 = 0.72$) and the fixed 4.0 $mmol \cdot L^{-1}$ lactate threshold ($R^2 = 0.5$). In the studies of Dekerle et al. (2003) and Laplaud et al. (2006) MLSS was significantly different from, lies between and was significantly correlated to the first and second ventilatory threshold ($r = 0.64 - 0.71$). In the latter study MLSS was not significantly different and strongly correlated to the power output at a respiratory exchange ratio of 1.0 ($r = 0.97$). The maximal lactate steady state was found to be significantly lower than (Dekerle et al., 2003; Pringle & Jones, 2002) and strongly correlated to critical power ($r = 0.95$) in the study of Pringle & Jones (2002). Blood lactate levels in the cited studies reached approximately 3.5 $mmol \cdot L^{-1}$ to 6.0 $mmol \cdot L^{-1}$. It has been shown however, that inter-individual large differences between 2.5 $mmol \cdot L^{-1}$ and 9.0 $mmol \cdot L^{-1}$ exists (Van Schuylenbergh et al., 2004) and therefore a certain blood lactate level at MLSS can never be a marker of performance ability. In addition the inter-individual variability makes it impossible to associate a fixed blood lactate level obtained from any graded laboratory exercise test to MLSS.

Especially during self-paced high intensity exercise the production of blood lactate at the onset of exercise increases rapidly, with the result of a delayed output of lactate from the muscle into the blood (Gladden, 2000). When exercise is continued on a high sub-maximal level, where lactate production and clearance reach steady state conditions, the initially released lactate must be metabolised to avoid accumulation and as a consequence early exhaustion. During laboratory 30-min self-paced time-trials, blood lactate levels sampled every 5 min ranged from 6.1 $mmol \cdot L^{-1}$ to 15.9 $mmol \cdot L^{-1}$ with an average of $10.6 \pm 1.0$ $mmol \cdot L^{-1}$ (Perrey et al., 2003). Based on the definition of MLSS (see above), nine out of twelve subjects completed the time-trial under steady state conditions despite a considerable high blood lactate concentration. The authors reported no difference between time-trial power output ($234 \pm 11$ $W$) and *RCP* power output ($233 \pm 10$ $W$). Investigations of the starting strategies during 20-km indoor time-trials on an electronic resistance device revealed significant differences of blood lactate levels between a self selected starting strategy (SS TT), an intensity 15 % below the initial 4 min of the self selected time-trial (B TT) and an intensity 15 % above the initial 4 min of the self selected time-trial (A TT) (Mattern et al., 2001). During SS TT and A TT blood lactate levels after 4 min were not significantly different (9.8 $mmol \cdot L^{-1}$ vs. 11.5 $mmol \cdot L^{-1}$), but both were significantly higher than during B TT (4.8 $mmol \cdot L^{-1}$). In all conditions blood lactate increased till minute nine (11.0 $mmol \cdot L^{-1}$, 13.1 $mmol \cdot L^{-1}$ and 8.4 $mmol \cdot L^{-1}$) for SS TT, A TT and B TT, respectively and were significantly different from each other. After nine minutes until the end of the time-trials (30 min − 35 min) blood lactate at SS TT and A TT decreased slightly, whereas B TT remained stable and no significant differences were found. The studies of Perrey et al. (2003) and Mattern et al. (2001) suggest that during self-selected cycling time-trials athletes achieve and more importantly are able to sustain considerable high blood lactate levels. These result were supported by the experiments of Myburgh et al. (2001) and Hoogeveen et al. (1997) as discussed on page 41.

In summary, *LTP 2*, *RCP* and *CP* are sensitive measure of aerobic capacity, leading to exhaustion within 20 − 60 min but not necessarily under steady state conditions. The determination of exercise intensity domains based on the presented threshold concepts will be shown on page 60.

## 3.3 Efficiency

The mechanical efficiency during cycling has been defined as the ratio of mechanical work accomplished to the metabolic energy expenditure required to do that work (Gaesser & Brooks, 1975). Energy expenditure during exercise can be calculated using the caloric equivalent from the measurement of steady state $\dot{V}O_2$ and the respiratory exchange ratio (Péronnet & Massicotte, 1991), or from the measurement of $\dot{V}O_2$ and $\dot{V}CO_2$ (Brouwer (1957) in Moseley & Jeukendrup (2001)). The mechanical efficiency obtained is termed “gross efficiency” (GE) and expressed as percentage of energy expenditure (Equation 9) (Gaesser & Brooks, 1975).

$$GE = \frac{work\ accomplished}{energy\ expenditure} \times 100 \qquad (9)$$

The literature offers other indices of efficiency like work efficiency (i.e. energy expenditure at zero load cycling is subtracted from total energy expenditure), net efficiency (i.e. energy expenditure at rest is subtracted from total energy expenditure) and delta efficiency (i.e. [change in work rate/change in energy expenditure] × 100) (Coyle et al., 1988; Coyle, 2005; Gaesser & Brooks, 1975; Hopker et al., 2009b; Moseley & Jeukendrup, 2001). The aim of the baseline subtraction is to remain with a measure that refers to the required energy expenditure for skeletal muscle contraction. However, it has been criticised that this procedure assumes the baseline to be unaffected by increasing work rates

(Cavanagh & Kram, 1985; Stainbsy et al., 1980). In fact, higher work rates affect the energy needed for e.g. gastrointestinal blood flow or ventilation rate (Cavanagh & Kram, 1985; Stainbsy et al., 1980) and thus will change the baseline energy expenditure. Most studies on cycling have used GE (Hopker et al., 2009a; Leirdal & Ettema, 2011; Lucia et al., 2004b; Mora-Rodriguez & Aguado-Jimenez, 2006) as an index of efficiency. Gross efficiency during cycling has been reported to be in the range of $15 - 25$ % (Coyle et al., 1992; Gaesser & Brooks, 1975).

**Influence of the Test Protocol** As energy expenditure is calculated by indirect calorimetry the accurate measurement of $\dot{V}O_2$ and $\dot{V}CO_2$ under steady state conditions is crucial. The time to achieve a steady state in $\dot{V}O_2$ is $2 - 3$ min at moderate exercise intensities (Whipp & Wasserman, 1972). Higher exercise intensities where a steady state cannot be reached should be excluded for the calculations of GE (Hopker et al., 2009b). Although work stage durations of 2 min (Barbeau et al., 1993) and 3 min (Mora-Rodriguez & Aguado-Jimenez, 2006; Moseley et al., 2004; Samozino et al., 2006) have been found in the literature, Hopker et al. (2009b) suggested the use of longer work stages ($> 5$ min) to be sufficient to reach steady state conditions. Longer work stage durations have been used by Cannon et al. (2007) and Lucia et al. (2004b) (6 min), Hopker et al. (2009a) (8 min) and Hettinga et al. (2007) (20 min). To avoid the occurrence of a non-steady state rise in $\dot{V}O_2$ (Whipp, 1994) only exercise intensities with a respiratory exchange ratio $< 1.0$ should be used to calculate GE.

**Influence of Power Output and Cadence** Several studies have shown that GE is affected by cadence and power output (Chavarren & Calbet, 1999; Gaesser & Brooks, 1975; Samozino et al., 2006; Sidossis et al., 1992). Figure 12 illustrates the increases in GE at any given cadence with increasing power output, and the decreases in GE at any given power output with increasing cadence (Samozino et al., 2006). Based on these findings it has been concluded that the most efficient cadence during cycling is around 50 $rev \cdot min^{-1}$ (Chavarren & Calbet, 1999; Gaesser & Brooks, 1975; Nickleberry & Brooks, 1996). This is in contrast to the observation that professional cyclists prefer cadences around $80 - 100$ $rev \cdot min^{-1}$ in competitions (Lucia et al., 2001c; Rossato et al., 2008; Sassi et al., 2009). It has been shown that the cadence choice during cycling is influenced by numerous factors like age (Sacchetti et al., 2010), cycling experience (Chapman et al., 2008; Marsh & Martin, 1997), exercise duration (Argentin et al., 2006) or terrain (Lucia et al., 2001c; Sassi et al., 2009). Fregly et al. (2000) have shown a quadratic increase of the crank inertia with increasing gear ratio and Sassi et al. (2009) found higher cadences to be used at higher gear ratios (i.e. high velocities on flat terrain) (as observed by Lucia et al., 2001c). Vercruyssen & Brisswalter (2010) assumed that with the choice of higher cadences cyclists trying to reduce the forces applied to the cranks and minimise neuromuscular fatigue instead of riding at an energetically optimal lower cadence. However, the most efficient cadence

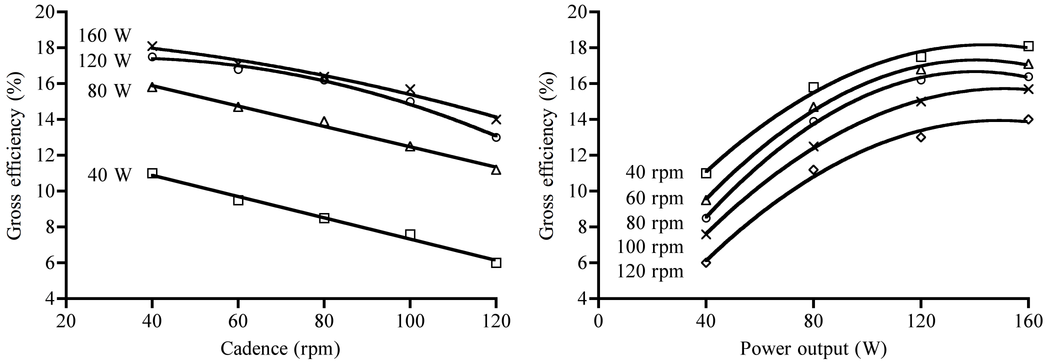



Figure 12: Decrease of GE with increasing cadence (left panel) and increase of GE with increasing power output (right panel) (redrawn from Samozino et al., 2006).

increases with increasing work rates.

Coast & Welch (1985) reported an increase in the most efficient cadence from 50 $rev \cdot min^{-1}$ to 80 $rev \cdot min^{-1}$ with increasing work rates from 100 $W$ to 300 $W$ in trained cyclists. Accordingly, Foss & Hallén (2004) found 60 $rev \cdot min^{-1}$ to be the most efficient cadence at low work rates (i.e. $< 125$ $W$ but at higher power outputs of 350 $W$ all subjects were most efficient at a cadence of 80 $rev \cdot min^{-1}$. In addition Foss & Hallén (2005) investigated the effects of different cadences on time-trial performance. Gross efficiency at a cadence of 80 $rev \cdot min^{-1}$ was significantly higher compared to 60, 100, 120 and the freely chosen cadence (i.e. 90 $rev \cdot min^{-1}$) (2.9, 3.4, 12.3 and 2.3 %, respectively; $p < 0.05$). The finishing time achieved at 80 $rev \cdot min^{-1}$ was not significantly different from that at 90 $rev \cdot min^{-1}$, but at 60 (3.5 %), 100 (1.7 %) and 120 $rev \cdot min^{-1}$ (10.2 %) significantly higher finishing times were observed ($p < 0.05$) (Foss & Hallén, 2005).

In summary these findings indicate that for the determination of GE a standardised cadence should be used over a range of work rates within the functional range of the subjects.

**Influence of Training** Better efficiency is indicated by an increase in GE (i.e. lower $\dot{V}O_2$ at any given work rate) and is associated with a performance advantage in endurance events because it will result in the utilisation of a lower percentage of $\dot{V}O_2max$ at any exercise intensity and consequently a reduction in muscle glycogen utilisation. It has been shown that a low $\dot{V}O_2max$ can be compensated for with a higher GE (Lucia et al., 2002a). Indeed, the authors observed an inverse relationship between $\dot{V}O_2max$ and GE ($r = -0.64$; $p = 0.03$) (Lucia et al., 2002a). Comparisons of GE between trained and untrained subjects are equivocal. Results of previous studies have found no differences between trained and untrained subjects (Moseley et al., 2004; Nickleberry & Brooks, 1996), suggesting that training has no effect on efficiency, whereas Hopker et al. (2007) have shown that in trained cyclists

GE is significantly higher in comparison with recreational cyclists (1.4 %; $p = 0.03$).

The results of Coyle (2005) provided evidence (see section 5 on page 63) that an 8 % improvement in efficiency over seven years in a *Tour de France* winner, was a major factor for the subject's success. The finding from Coyle (2005) was supported by a longitudinal study over five years in an world-class female distance runner (Jones, 1998). The author reported an improvement in running economy over that period (i.e. $\dot{V}O_2$ decreased from 53.0 $mL \cdot min^{-1} \cdot kg^{-1}$ to 47.6 $mL \cdot min^{-1} \cdot kg^{-1}$ at a running speed of 16.0 $km \cdot h^{-1}$).

No significant changes in GE were found over a racing season in competitive cyclists (Barbeau et al., 1993). More recent studies however, have demonstrated longitudinal increases in efficiency (Hopker et al., 2009a; Santalla et al., 2009). In support of the long-term efficiency improvements reported by Coyle (2005) and Jones (1998), Santalla et al. (2009) have shown an increase in delta efficiency from 23.61 ± 2.78 % to 26.97 ± 3.7 % ($p < 0.01$) over a five year period in professional cyclists, whereas $\dot{V}O_2max$ remained unchanged. Significant differences in GE across a season in competitive cyclists have been reported by Hopker et al. (2009a). Gross efficiency was significantly higher in May, July and September than in January and December ($p < 0.05$). The changes across the phases were strongly correlated with total training time and the time spent at higher exercise intensities. The magnitude of a $\sim 1$ % absolute increase in GE reported in that study (corresponding to a $\sim 6$ % relative improvement), can potentially result in a 63 s improvement in a 40-km time-trial (Moseley & Jeukendrup, 2001). The study from Hopker et al. (2009a) indicate that a change in GE is the result of a training induced adaptation across a season. Therefore, it should be noted that longitudinal monitoring of efficiency should be scheduled at the same time of the season.

Increases in efficiency with endurance training might be the result of an improvement in skeletal muscle oxidative capacity. Coyle et al. (1992) demonstrated strong correlations between the percentage of type I muscle fibres and both, delta efficiency ($r = 0.85$; $p < 0.001$) and gross efficiency ($r = 0.75$; $p < 0.001$) in trained cyclists. Exercise induced adaptations in enzymatic profiles (Coyle et al., 1991), mitochondrial biogenesis (Holloszy & Coyle, 1984; Hood & Saleem, 2007) and capillary density (Zoladz et al., 2005) could also enhance the oxygen extraction in skeletal muscle.

The muscular contraction and relaxation during the crank cycle lasts less than 1 s. Therefore, an improvement in neuromuscular activity pattern in response to training is a possible contributor to an increased efficiency (Cannon et al., 2007; Fernández-Peña et al., 2009; Lucia et al., 2000c). Improvements in leg strength through resistance training may reduce the proportion of the maximal force required during each pedalling stroke which delays the recruitment of inefficient type II muscle fibres (Hausswirth et al., 2009; Paton & Hopkins, 2005). Lucía et al. (1999) have demonstrated differences in the breathing pattern between professional and amateur cyclists. Pulmonary ventilation and breathing frequency were significantly lower in professional cyclists at high intensities ($300 - 400\ W$), thus a reduced metabolic demand of the respiratory muscles can decrease the oxygen cost of exercise and thereby increase GE (Lucía et al., 1999).

## 3.4 Anaerobic Performance

The ability to generate high power outputs of brief duration is an essential ability for cyclists. For road cyclists or mountain-bikers the ability to sprint at the end of a race or to attack other riders is decisive and for track cycling sprint disciplines (i.e. $< 1$ km) the generation of energy at a high rate via non-oxidative pathways is the most important performance determinant. As described above, the study of Neumann (1990) has shown that the activity of anaerobic enzymes is higher in track cyclists and thus indicating an exercise induced adaptation.

The relationship of uphill climbing performance with anaerobic capabilities was investigated by Davison et al. (2000). Their volunteers completed an aerobic power test, the traditional Wingate anaerobic power test (i.e. a 30 s all out test) and two simulated hill climbs on a treadmill (1 km & 12 % inclination, and 6 km & 6 % inclination). A strong correlation between performance time and average power achieved during the Wingate test ($W \cdot kg^{-1}$) was found in both time-trials ($r = -0.92$ and $r = -0.90$ for 1 km and 6 km, respectively). Average power during the hill climbs was related to performance time when power was scaled to body mass ($r = -0.92$ and $r = -0.95$ for 1 km and 6 km, respectively). Maximal aerobic power and performance time was related when scaled to total mass (i.e. rider & bike) ($r = -0.89$ and $r = -0.88$ for 1 km and 6 km, respectively). By performing multiple regression analysis using aerobic and anaerobic power Davison et al. (2000) achieved an enhancement of the determination coefficient ($R^2 = -0.98$ and $R^2 = -0.96$ for 1 km and 6 km, respectively). This study highlighted the contribution of anaerobic metabolism during high intensity cycling.

In contrast to road cycling, where the main part of the race is performed at sub-maximal intensities (Jeukendrup et al., 2000; Padilla et al., 2001), the short duration in track cycling events require the rider to maximally tax anaerobic pathways (Craig et al., 1993). For the 4 km pursuit race a contribution of $70 - 80$ % from aerobic and $20 - 30$ % from anaerobic pathways has been estimated (Capelli et al., 1998; Craig et al., 1993), whereas a $50 - 50$ % split was estimated for the 1 km time-trial (Beneke et al., 2002; Craig et al., 1989; Serresse et al., 1988). These relative contributions highlights the importance of a high aerobic power and capacity for track-cycling events and explains the high volumes of endurance training encountered by successful athletes (Schumacher & Mueller, 2002).

Recently the comparisons between field and laboratory tests during short-term sprint cycling have been published (Bertucci et al., 2005b; Gardner et al., 2007). In both studies calculations of the linear relationship between force and velocity as well as the quadratic relationship of power and pedalling rate were performed (for details see Figure 13).

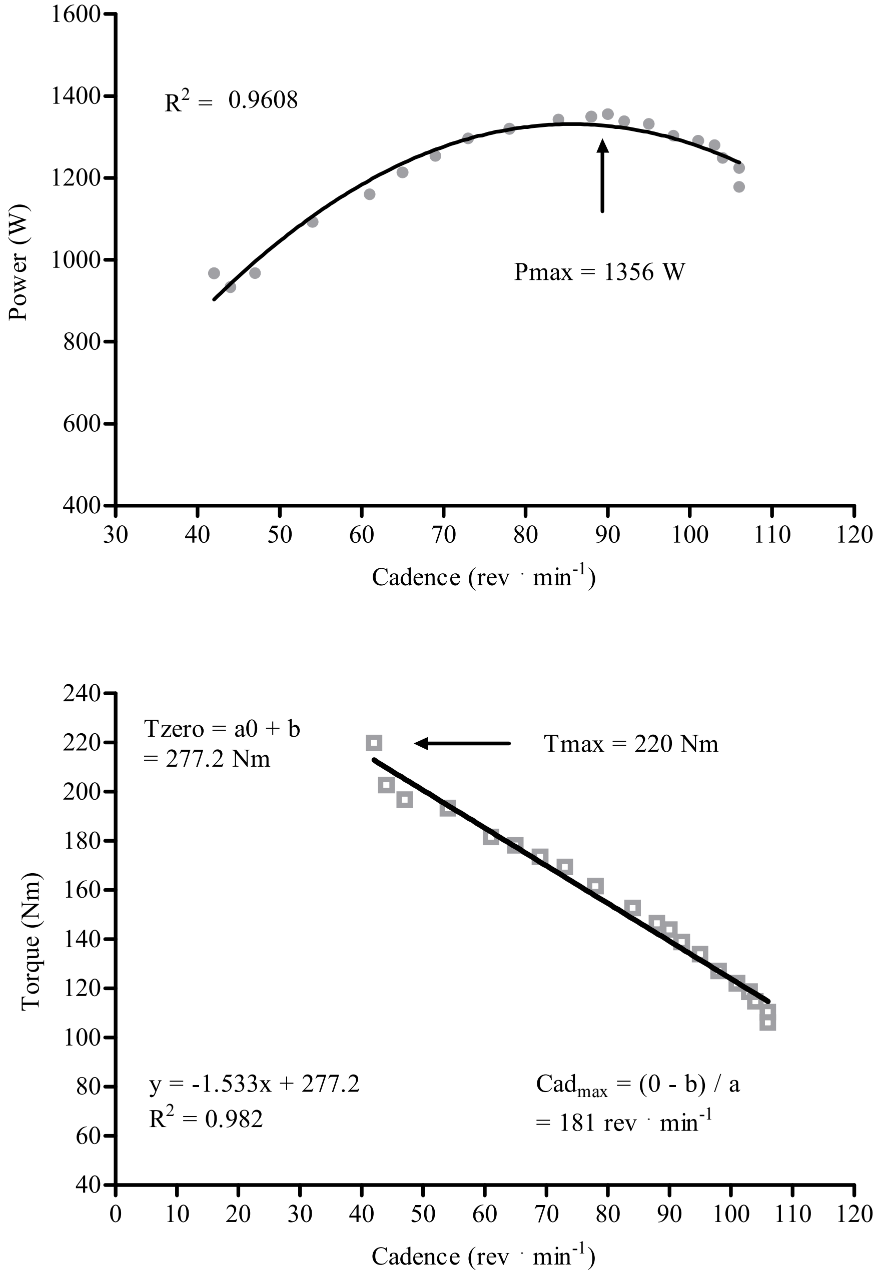



Figure 13: Quadratic relationship (upper panel) of Power ($W$) vs. Cadence ($rev \cdot min^{-1}$) and linear relationship (lower panel) of Torque ($N \cdot m^{-1}$) vs. Cadence ($rev \cdot min^{-1}$) during short term sprint cycling. $Tzero$ ($N \cdot m^{-1}$) and $Cad max$ ($rev \cdot min^{-1}$) are defined by the Y and X interception of the regression line, respectively. $Tmax$ ($N \cdot m^{-1}$) and $Pmax$ ($W$) are highlighted by arrows (A.Nimmerichter, unpublished data)

Bertucci et al. (2005b) found significantly higher values in seated and standing position in the field for maximal pedal force ($Fmax$ [$N$]) and theoretical maximal force ($Fzero$ [$N$]). $Pmax$ ($W$) was higher in standing than in the seated position during outdoor cycling. In contrast, Gardner et al. (2007) reported no significant difference in any variable between field and laboratory sprints. These equivocal results might be caused by the fact that in the first study a roller trainer was used for indoor measurement. In such devices the pressure between the tyre and the roller vary. Especially while riding in a standing position, traction might be reduced and leads to slippage. In addition, in the latter study the participants were experienced sprinters of the Australian track cycling team. These riders are well trained in producing maximal power during short-term efforts.

In the study of Gardner et al. (2007) the maximal power output of 20.8 $W \cdot kg^{-1}$ occurred at a cadence of 129 $rev \cdot min^{-1}$ and the maximum torque ($Tzero$) was 266 $N \cdot m^{-1}$. These findings are in accordance with the results from Dorel et al. (2005) who reported similar values in a group of French track cyclists (19.3 $W \cdot kg^{-1}$, 130 $rev \cdot min^{-1}$ and 236 $N \cdot m^{-1}$). The high anaerobic power of track cyclists are emphasised in comparison to power outputs reported for Austrian national-team mountain-bikers (Baron et al., 1999). The authors found peak power outputs of 15.3 $W \cdot kg^{-1}$ and 14.9 $W \cdot kg^{-1}$ at 115 $rev \cdot min^{-1}$ and 127 $rev \cdot min^{-1}$ during 10 s of isokinetic and non-isokinetic cycling, respectively. Mechanical power output recorded during track-cycling revealed a peak power of 1799 $W$, an average power of 757 $W$ and a minimum power of 399 $W$ at the end of a 1 km time-trial (Craig & Norton, 2001).

In summary this chapter has shown the versatility of different cycling disciplines. The importance of both aerobic and anaerobic characteristics have been emphasised. The next chapter deals with relevant aspects of performance assessment in context of the present thesis.

# 4 Performance Assessment

Since endurance performance is such an important determinant in cycling, performance tests are an integral component for competitive cyclists. Given the importance of exercise tests for the results of the present work, the following sections will discuss procedures, applications and limitations to the methods employed.

## 4.1 General Considerations of Performance Tests

Performance assessment in sports populations is of key interest for exercise scientists. The selection of the test depends on the subjects characteristics like age (e.g. children or elderly), gender, health status (e.g. cardiac patients), or performance level (e.g. untrained or world class). In the case of high-level athletes the tests should meet the specific criteria of the sport. Considering all these factors, it has to be decided whether the chosen test will be performed under laboratory conditions or in the field. The fact that environmental conditions like temperature or humidity, as well as resistive forces can be controlled very well in the laboratory makes them favourable for many researchers. However, assessment under sport specific conditions in the field might increase the ecological validity of the test results.

In modern sports, performance assessment is usually an integral part to training routine. Depending on the sport, tests are carried out several times in the year for different reasons. At the start of the season;

- To assess the initial performance level
- To make comparisons with (sports-specific) normative data
- To identify strengths and weaknesses
- To recommend appropriate training

During the season;

- To monitor progress
- To identify the effectiveness of the applied training
- To predict performance in competition

Before starting any test procedure, coaches and researchers must ensure that the applied testing protocols meet certain criteria.

**Validity** A test is deemed valid, when it measures what it claims to measure. For example, the assessment of endurance performance requires a test duration that is sufficient to tax the aerobic energy pathway. Maximal oxygen uptake is a valid measure because of the relationship with competitive endurance events.

**Reliability** Reliability refers to the reproducibility of a result in repeated measurements. In performance tests variation arises from different sources. The within-subject variation is known as the random variation in a measure when one subject performed the same test several times. The main source of random variation is biological (i.e. physical or mental state, diurnal changes, learning effects, fatigue). Equipment and investigator errors are further contributors to variation (Atkinson & Nevill, 1998; Currell & Jeukendrup, 2008; Hopkins, 2000).

**Accuracy** The level of precision is known as accuracy. High precision in the process of data acquisition corresponds to a low variability and is a prerequisite to detect even small changes.

The standardisation of test conditions increase the reliability and accuracy of the results. It is therefore important to reduce variations in testing procedures. These include measurement equipment, order of tests, warm up procedures or environmental conditions like temperature, humidity or air ventilation. Athletes should be tested at the same time of the day in an adequately rested state and in a sufficiently fluid and nutritional state.

## 4.2 Laboratory Tests

Most of the tests employed to assess the endurance capability of cyclists are performed on a stationary cycle ergometer under laboratory conditions. Generally, ergometers measure power produced against resistive forces. Depending on the ergometer, forces are applied either by a belt sliding around the ergometers flywheel ("friction loaded"), by an electromagnetic brake ("electromagnetically braked"), or by an impeller to create air resistance ("air braked ergometers"). For a technical review and discussion of systematic errors the reader is referred to Paton & Hopkins (2001).

The large number of testing protocols used for performance assessment emphasise the difficulty of identifying a golden standard (see Table 4 for exercise test protocols). The selected method often reflects the preference and the experience of the investigator. However, laboratory tests are commonly applied as continuous incremental exercise, leading to exhaustion after several minutes.

Such tests determine maximal characteristics like $\dot{V}O_2max$, maximal heart rate ($HRmax$) or maximal power output, but also sub-maximal parameters corresponding to set blood lactate concentrations or deflection points as described in chapter 3.2.2 on page 38.

For the studies of the present thesis increments of 25 $W \cdot min^{-1}$ were applied (for a detailed description see chapter 7.1 on page 72) because it is routinely used in our laboratory for exercise tests in elite cyclists. As sub-maximal measures of aerobic capacity lactate turn points and ventilatory thresholds were used (chapter 3.2.2 on page 38). Although the current protocol and the methods of threshold detection have been used in several studies with professional cyclists (Davis et al., 1982; Lucia et al., 2000a, 2004a) and have been shown to be valid and reliable (Amann et al., 2004; Weston & Gabbett, 2001), there are also some limitations that will be briefly discussed.

### 4.2.1 Measures of Aerobic Power

Maximal power output ($Pmax$) and maximal oxygen uptake ($\dot{V}O_2max$) obtained during an incremental graded exercise test ($GXT$) have been shown to be influenced by the test protocol (Bentley et al., 2007; Roffey et al., 2007). Based on a single experimental study by Buchfuhrer et al. (1983) it was

Table 4: Incremental exercise test design and measured physiological variables

| Study | Initial workload / Increment / Stage duration | Physiological variable |
|---|---|---|
| Fernandez-Garcia et al. (2000) | 100 $W/50$ $W/4$ min | GEX ($\dot{V}O_2max$); Lactate ($IAT$) |
| Padilla et al. (2000a) | 110 $W/35$ $W/4$ min/1 min recovery | Lactate ($OBLA$) |
| Bentley et al. (2001b) | 150 $W/30$ $W/1$ min 50 % $\dot{V}O_2max/5$ %/3 min | GEX ($\dot{V}O_2max$) Lactate ($LT$ + $OBLA$) |
| Lucia et al. (2004a) | 20 $W/25$ $W/1$ min | GEX ($\dot{V}O_2max$; $VT$; $RCP$) |
| Ebert et al. (2005) | 125 $W/25$ $W/3$ min | GEX ($\dot{V}O_2max$); Lactate ($LT$ +$AT$) |
| Impellizzeri et al. (2005a) | 100 $W/25$ $W/1$ min | GEX ($\dot{V}O_2max$; $VT$; $RCP$) |
| Impellizzeri et al. (2005b) | 100 $W/40$ $W/4$ min | GEX ($\dot{V}O_2max$); Lactate ($LT$ + $OBLA$) |
| Vogt et al. (2006) | 100 $W/20$ $W/3$ min | Lactate ($LT$) |
| Gregory et al. (2007) | 100 $W/50$ $W/5$ min | GEX ($\dot{V}O_2max$); Lactate ($IAT$) |
| Prins et al. (2007) | 3.33 $W \cdot kg^{-1}/30$ $W/2.5$ min | GEX ($\dot{V}O_2max$); Lactate ($LT$ + $OBLA$) |
| Vanhatalo et al. (2007a) | Unloaded/30 $W/1$ min | GEX ($\dot{V}O_2max$; $VT$) |

GEX = Gas exchange; $IAT$ = Individual anaerobic threshold; $OBLA$ = Onset of blood lactate accumulation; $LT$ = Lactate threshold; $VT$ = Ventilatory threshold; $RCP$ = Respiratory compensation point recommended that a $GXT$ should last $8 - 12$ min to elicit $\dot{V}O_2max$. However, in a recent review by Midgley et al. (2008) the authors have reported several studies where a $\dot{V}O_2max$ occurred during both longer and shorter protocols and it was concluded that cycle ergometer tests could last $7 - 26$ min for the attainment of $\dot{V}O_2max$. Although it has been shown that a $\dot{V}O_2max$ can be reached within 3 min during high intensity exercise (Burnley et al., 2006; Caputo & Denadai, 2008), in most cases additional informations like lactate or ventilatory thresholds are of similar importance and therefore test protocols are applied to determine both maximal and sub-maximal variables. Accordingly, the test durations in the present work were between 15 and 25 min. The advantage of longer increments associated with sub-maximal thresholds will be discussed later. However, such tests have also disadvantages on maximal measures.

As a result of the longer test duration $Pmax$ values of $400 - 450$ $W$ ($6.0 - 6.5$ $W \cdot kg^{-1}$) are reported during tests with four minute increments in professional cyclists (Padilla et al., 1999), whereas $6.5 - 7.5$ $W \cdot kg^{-1}$ have been found when increments of one minute were applied (Lucia et al., 1999a, 2000a, 2001b). As the test duration can be as long as $40 - 60$ min in elite cyclists, the determination of ventilatory measures is not only restricted from a technical point of view (i.e. occlusion of the sampling tube and volume sensor with moisture and saliva), but also by the limited compliance of the athletes. Unpublished observations in our laboratory revealed reduced limits of tolerance during incremental cycling exercise of $45 - 60$ min ($195 \pm 24$ s) in male students wearing a facemask. This discomfort might be exacerbated when instead of a facemask a mouthpiece and noseclip is used.

### 4.2.2 Measures of Aerobic Capacity

Sub-maximal performance measures are sensitive indicators of exercise induced improvements. The responses of blood lactate, heart rate and oxygen uptake to exercise are used to identify adaptations. Especially in highly trained athletes with little or no change in $\dot{V}O_2max$ sub-maximal thresholds have been reportedly sensitive to training (Jones, 2006). For a valid and accurate determination of lactate turn points, as used in the present studies, factors related to blood collection, pre-test preparation, test protocol and data analysis must be considered.

**Pre-test Preparation** Whilst for subjects with a low-activity lifestyle no exercise for 48 h before a test is recommended, this is impractical when testing elite athletes. However, to avoid fatigue and muscular impairment no strenuous (i.e. high-intensity or very long work out) or unaccustomed exercise should be performed. In the present studies the athletes were allowed to train for a maximum of 2 h in their "recovery zone" on the day before a test was planned. Special care has been taken to allow at least three days of recovery after competition.

The blood lactate concentration is decreased at any given work rate when muscle glycogen stores are depleted (McLellan & Gass, 1989; Reilly & Woodbridge, 1999) which leads to a rightward shift in the lactate/power plot and consequently to an overestimation of performance capacity and to a lower limit of tolerance for maximal work rates. Therefore, a carbohydrate rich diet was prescribed the day before and on the test day. In addition, the athletes were advised to refrain from alcohol and caffeine the day before the test. It has been shown that caffeine ingestion potentially enhance performance (Jeukendrup & Martin, 2001; Wiles et al., 2006) but also can increase blood lactate concentration (Doherty et al., 2004) and heart rate (Hunter et al., 2002).

Since high ambient temperatures have been shown to impair performance (Chan et al., 2008; Tyka et al., 2009) the laboratory conditions should be kept constant at $20 - 22°$.

**Test Protocol** Different durations of the work rate increments leads to different blood lactate responses which affects the determination of lactate thresholds and the associated exercise intensity zones. It is widely accepted that longer increment durations are more likely to reflect steady state blood lactate concentrations during exercise tests. Some studies have reported that durations between $3 - 5$ min are adequate (Bentley et al., 2001a; McNaughton et al., 2006; Urhausen et al., 1993) whereas others recommend at least $5 - 8$ min (Foxdal et al., 1994, 1996). The recommended number of increments ($5 - 9$) leads to long test durations and the associated drawbacks on maximal measures as described above. A number of studies have used 1 min increments to determine both ventilatory and lactate thresholds as well as maximal measures within a single incremental test (Amann et al., 2006; Davis et al., 1982; Lucia et al., 2000a, 2004a; Weston & Gabbett, 2001). Anderson & Rhodes (1991) and Smith et al. (1997) found no differences in lactate thresholds when blood samples were taken at 1 min or 4 min increments. It should be noted that blood lactate measures are usually lower at 1 min increments which result in a rightward shift in the lactate/power plot. However, lactate turn points occur at the same work rate despite higher blood lactate concentrations in longer protocols (Figure 14). Therefore, this finding would suggest a lower performance at any fixed blood lactate thresholds.

**Blood Collection and Analysis** Different methods and blood sampling sites have been shown to affect the measurement of blood lactate concentration (el Sayed et al., 1993a,b; Feliu et al., 1999; Foxdal et al., 1994, 1996). These studies reported higher values in samples obtained from the fingertip in comparison to the vein and the earlobe. Although venous puncture of a cubital vein is a standard laboratory procedure where large volumes of blood are required, capillary blood sampling is the main procedure in exercise science for analysis of blood lactate concentration where a small volume of $< 30\ \mu L$ is sufficient. Capillary puncture during exercise typically uses a fingertip or earlobe and after adequate hyperemisation (i.e. hot water or rubefacient cream for fingertip and earlobe, respectively)

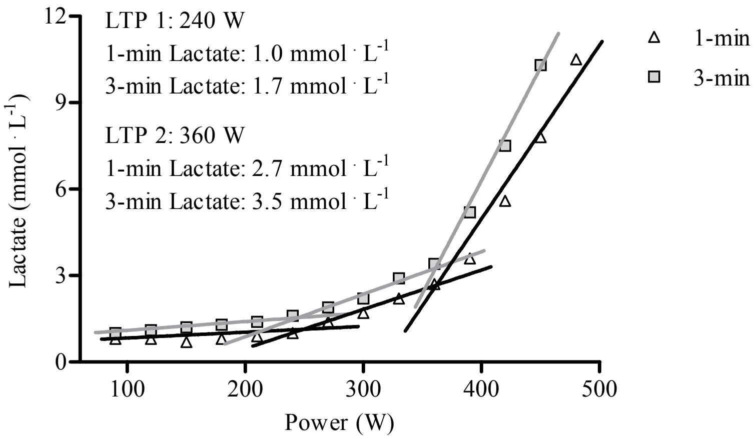



Figure 14: Example of an incremental exercise test with 1 min and 3 min increments and the influence on lactate thresholds. Lactate turn points occur at the same work rates during both protocols whereas fixed lactate thresholds would suppose higher performance for the shorter stages.

it is expected that both sites provide blood of similar composition for at least 30 min.

In the present studies a 20 $\mu L$ capillary blood sample was obtained from the hyperemic ear lobe in the last 10 s of each stage and diluted immediately in 1000 $\mu L$ glucose system-solution to stop glycolysis.

Important implications for valid measures are:

- To wipe away the first drop of blood with a clean pad to avoid contamination of the sample with sweat
- To apply moderate pressure for adequate blood flow to avoid an excess of interstitial fluid in the sample
- To collect the exact amount of blood in the capillary tube to ensure the exact ratio of blood/system-solution of 1:50

In addition to the sampling procedures it has been shown that different blood analysers had an influence on lactate measures (Baldari et al., 2009; Bishop, 2001; Buckley et al., 2003; McNaughton et al., 2002). Regardless of the analyser in use it is a prerequisite to verify the accuracy of any laboratory device. The accuracy of the analyser used for the present thesis (chapter 7.1 on page 72) across one year revealed coefficients of variation of 6.1 %, 5.2 % and 4.1 % for low (1.6 $mmol \cdot L^{-1}$), medium (3.4 $mmol \cdot L^{-1}$) and high (10.0 $mmol \cdot L^{-1}$) control solutions, respectively.

In summary, to allow comparisons in the longitudinal monitoring of athletes or in research it is crucial to apply identical procedures.

**Data Analysis** The final step after data collection is the determination of lactate and ventilatory thresholds. Given the abundance of "individual" threshold concepts (reviewed by Faude et al., 2009) some authors have used work rates associated with fixed blood lactate concentrations to describe aerobic capacity (Fohrenbach et al., 1987; Heck et al., 1985; Sjodin & Jacobs, 1981). However, the influence of nutrition and the applied test protocol on blood lactate levels has been discussed above. The physiological bases of the blood lactate and ventilatory responses to incremental exercise tests (chapter 3.2.2 on page 38) and the distinctive breakpoints are well described in the literature (Beaver et al., 1986; Davis et al., 1983; Spurway & Jones, 2006; Wasserman et al., 1999). The visual inspection of these breakpoints has been criticised for showing poor reliability (Fukuba et al., 1988; Garrard & Das, 1987; Gladden et al., 1985) and therefore computerised methods have gained popularity. However, none of the automated computerised methods seems to provide satisfactory results (Ekkekakis et al., 2008; Gaskill et al., 2001) and thus most studies rely on the visual evaluation of two or more experienced researchers (Amann et al., 2006; Chicharro et al., 2000; Dekerle et al., 2003; Lucia et al., 1999b). Weston & Gabbett (2001) have demonstrated high test-retest ($r = 0.86 - 0.98$; $p < 0.001$), and intra-rater reliability ($r = 0.91 - 0.97$; $p < 0.001$) of ventilatory thresholds.

The methods employed in the present studies used a custom written application which allows the user to shift three linear regression lines in 5 s segments over five graphic plots simultaneously. With this approach the criteria used for threshold determination (see chapter 7.1 on page 72) can be evaluated in a fast and convenient way. The intraclass correlation coefficients in our laboratory were $r = 0.94 - 0.99$ for intra-rater reliability and $r = 0.91 - 0.97$ for inter-rater reliability.

It should be noted however, that during the evaluation of thresholds some data does not show discernible changes in linearity. This is most likely to occur in the first loss of linearity in pulmonary ventilation ($\dot{V}E$) and carbon dioxide ventilation ($\dot{V}CO_2$) (personal experience of the author) which makes an adequate determination of the ventilatory threshold based on one single criterion difficult. Thus, the combined use of criteria will result in far fewer rejections than any individual method.

#### 4.2.3 Exercise Intensity Zones

One goal of exercise tests is the prescription of intensity zones for appropriate training. Since lactate and ventilatory thresholds (i.e. *LTP 1 / VT* and *LTP 2 / RCP*) demarcates three distinctively different physiological responses to exercise, they are crucial to the determination of intensity zones or domains. *LTP 1 / VT* demarcate the boundary between the moderate and heavy exercise zone (Gaesser & Poole, 1996; Whipp & Wasserman, 1972). At the onset of exercise in the moderate-intensity zone a steady state in $\dot{V}O_2$ is reached after $2 - 3$ min and blood lactate concentration is not elevated above baseline (Whipp & Wasserman, 1972). Exercise in the moderate zone can be sustained for several hours and is likely limited by central fatigue but also by glycogen depletion in long sessions.

During exercise above *LTP 1 / VT* but below *LTP 2 / RCP* (i.e. heavy-intensity zone) there is a delayed attainment of the $\dot{V}O_2$ steady state at a higher level as expected for the given power output or velocity due to the $\dot{V}O_2$ slow component and blood lactate concentration reach a steady state at an elevated level (Gaesser & Poole, 1996; Poole et al., 1994; Whipp, 1994; Whipp & Wasserman, 1972). Exercise in the heavy zone has to be maintained in many endurance events like the marathon or cross-country mountain-bike. Glycogen depletion and muscular fatigue are related limiting factors.

The exercise intensity at *LTP 2* or *RCP* demarcate the boundary between the heavy and the severe zone. Exercise at severe intensity can only be maintained for a limited duration since $\dot{V}O_2$ does not reach a steady state and the slow component will drive $\dot{V}O_2$ to its maximum (Hill et al., 2002; Poole et al., 1994). Exercise in this zone covers a broad time range of tolerance. While exercise intensities close to the lower boundary are encountered during 10 km running or $30 - 40$ km cycling time-trials, intensities at the upper boundary are typically found in 1500 m running or the 4 km pursuit event in track cycling.

Exercise intensities above $\dot{V}O_2max$ cannot be sustained for sufficient durations and will be terminated before the attainment of $\dot{V}O_2max$ (extreme-intensity zone) (Hill et al., 2002). Fatigue is likely to occur after $1 - 2$ min (800 m running or 1 km time-trial in track cycling).

It should be noted that this model has been used to describe the physiological demands during both training and racing in elite athletes based on heart rate monitoring (Esteve-Lanao et al., 2005; Lucia et al., 1999a, 2003; Padilla et al., 2001; Seiler & Kjerland, 2006). In contrast to the slow response of heart rate, power output can change immediately from $0 - 1000$ $W$ within a few seconds and therefore it seems to be appropriate to use more intensity zones when power output is used as the primary measure. In the present studies a power model with seven intensity zones will be used to cover the whole spectrum of power output (see chapter 9.2.4 on page 87).

## 4.3 Field Tests

The use of laboratory derived values to assess performance and regulate training is common practice. Although workload during training or competition is usually estimated from the relationship between heart rate and power output observed in laboratory tests, such estimations have limited accuracy due to the so-called “cardiac drift” (Achten & Jeukendrup, 2003; Crisafulli et al., 2006; Heaps et al., 1994; Jeukendrup & Van Diemen, 2001). Recent research suggest that especially in elite athletes the specificity of field tests enhance the practical significance (Bertucci et al., 2005b, 2007; Davison et al., 2009; Jobson et al., 2007, 2008a). Since external factors like wind, equipment, position on the bike, road gradient or tactics have a major influence on propulsion, cycling speed is a poor indicator

Table 5: Different race types and their performance correlates assessed from laboratory measurement

| Study | Race type | Physiological variable | Correlation |
|---|---|---|---|
| Anton et al. (2007) | 14 km flat | $Pmax\ (W)$ | $r = -\,0.90$; $p < 0.001$ |
| | 6.7 km uphill | $Pmax\ (W \cdot kg^{-1})$ | $r = -\,0.66$; $p < 0.001$ |
| Impellizzeri et al. (2005a) | 33.6 km mountain-bike cross country | $P$ at $RCP\ (W \cdot kg^{-1})$ | $r = -\,0.63$; $p < 0.05$ |
| | | $\dot{V}O_2$ at $RCP$ $(mL \cdot min^{-1} \cdot kg^{-1})$ | $r = -\,0.66$; $p < 0.05$ |
| Impellizzeri et al. (2005b) | Mountain-bike cross country | $P$ and $\dot{V}O_2$ at $RCP$ $(body\,mass^{0.79})$ | $r = -\,0.68$ to $-\,0.94$; $p < 0.05$ |
| Lucia et al. (2004a) | 58 km | $P$ at $VT$ $(\dot{V}E/\dot{V}O_2)$ | $r = -\,0.864$; $p = 0.026$ |
| | 56.5 km | | $r = -\,0.77$; $p = 0.27$ |
| | 57 km | | $r = -\,0.923$; $p = 0.025$ |
| Smith et al. (1999) | 40 km | Critical power $(W)$ | $r = -\,0.91$; $p < 0.001$ |
| | 17 km | | $r = -\,0.77$; $p < 0.001$ |

of real effort (Jeukendrup & Van Diemen, 2001). Nevertheless, studies aimed to assess performance during outdoor cycling often used time to complete a certain distance or average speed as performance parameter (Table 5) (Anton et al., 2007; Impellizzeri et al., 2005a,b; Lucia et al., 2004a; Smith et al., 1999).

Two studies have used an incremental protocol based on speed on a velodrome to perform under standardised environmental conditions (Padilla et al., 1996; Gonzalez-Haro et al., 2007). Padilla et al. (1996) described a field test where the speed was increased progressively by 1.5 $km \cdot h^{-1}$ every 2280 meters until exhaustion. Power output and oxygen uptake was estimated from the rider's speed using the formula of di Prampero et al. (1979). Padilla et al. (1996) found no difference between maximal laboratory and field test data concerning power output, heart rate and oxygen uptake. Blood lactate was significantly higher in the velodrome at maximal and sub-maximal levels (60 %, 70 % and 80 % of $\dot{V}O_2max$), as well as sub-maximal heart rates at (40 %, 50 % and 60 % of $\dot{V}O_2max$). $\dot{V}O_2max$ related to body weight $(mL \cdot min^{-1} \cdot kg^{-1})$ was the laboratory parameter with the highest correlation to maximal cycling speed.

In the study of Gonzalez-Haro et al. (2007) power output was measured during an incremental field test on a velodrome. The test was dictated by speed imposed via acoustic signals in increments of 0.7 $km \cdot h^{-1}$ every minute. The authors reported the bias and random error of the field test ($-\,8.1 \pm 52.6\ W$ or $2.0 \pm 12.9$ %) and considered the test protocol as repeatable. Significant differences were reported between the laboratory and field test for maximum power output ($354.7 \pm 41.3\ W$ vs. $407.8 \pm 61.9\ W$; $p < 0.001$), maximum blood lactate concentration ($8.4 \pm 2.6\ mmol \cdot L^{-1}$ vs. $6.9 \pm 1.6\ mmol \cdot L^{-1}$; $p < 0.01$) and maximum cadence ($87.7 \pm 10.0\ rev \cdot min^{-1}$ vs. $99.7 \pm 3.9\ rev \cdot min^{-1}$; $p < 0.001$) (Gonzalez-Haro et al., 2007).

Given the lack of research data on valid and reliable field tests for cyclists it seems to be reasonable to adopt such a specific field test based on power output.

# 5 Endurance Training in Cyclists

The cardiovascular, neuromuscular and metabolic adaptations observed in cyclists are remarkable and probably affect endurance performance. As discussed in the "physiology of cycling" chapter cyclists are amongst those athletes with the biggest hearts (Whyte et al., 2004), the highest percentages of type I muscle fibres (Coyle et al., 1991) and the highest activities of oxidative enzymes (Sjøgaard, 1984). Although these findings indicate that the exercise encountered by cyclists induce these adaptations, the present scientific knowledge of the effects of specific training interventions on adaptive responses is limited. The magnitude of these adaptations depends on numerous factors and includes, apart from genetic endowment, the duration of the total training programme and the volume, intensity and frequency of the individual training sessions (Busso et al., 2002; Esteve-Lanao et al., 2005; Mujika et al., 1996). However, the most effective mixture of these key components is currently unknown.

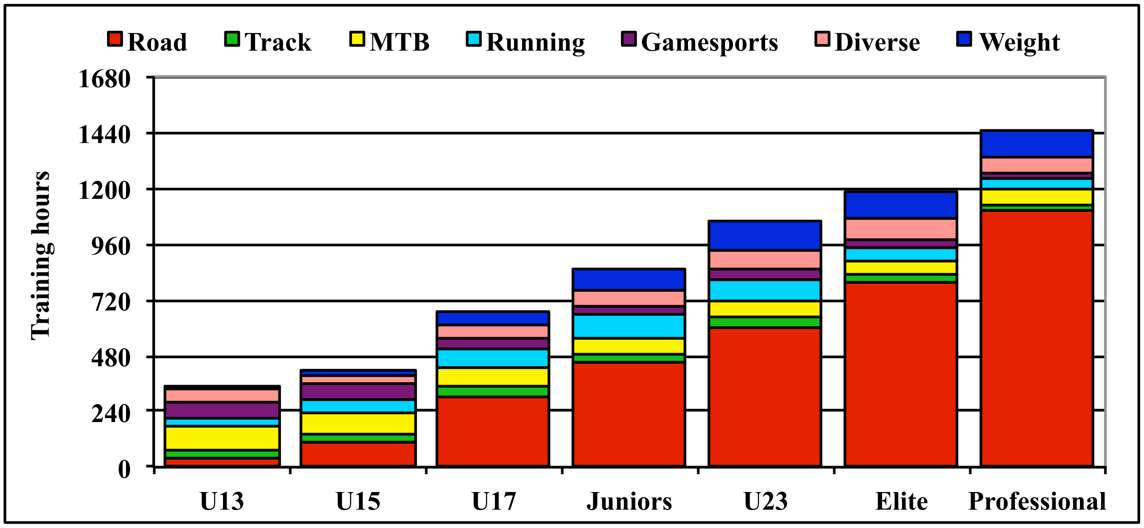
The majority of studies with professional cyclists involved reported volumes of $\sim$ 30000 km or $\sim$ 1000 h per year with the main portion covered in the moderate intensity zone ($\sim$ 70 %) (Lucia et al., 1999a, 2000d; Padilla et al., 2001). The development of world-class performance and the tolerance to train for $20 - 30$ $h \cdot wk^{-1}$ during most parts of the year requires several years of training. One of the few longitudinal reports in the scientific literature shows the development over a seven-year period between the age of $21 - 28$ years of the seven-time winner of the *Tour de France*, Lance Armstrong (Coyle, 2005). It was reported that his $\dot{V}O_2max$ ($\sim$ 6 $L \cdot min^{-1}$ or $\sim$ 80 $mL \cdot min^{-1} \cdot kg^{-1}$) and the occurrence of his lactate threshold ($76 - 85$ % $\dot{V}O_2max$) remained relatively stable across this period. The most remarkable observation was an 8 % improvement in muscular efficiency which enables Armstrong to increase the power output at a given $\dot{V}O_2$ of 5 $L \cdot min^{-1}$ from 374 $W$ to 404 $W$ (Coyle, 2005). The author hypothesised that this improvement could be the result of a shift from type II to type I muscle fibres in the vastus lateralis as a result of training intensely for $3 - 6$ h on most days for several years (Coyle, 2005). It should be noted that Armstrong was already a world-class rider at the age of 22 (world champion) before he achieved his victories at the *Tour de France* after he was diagnosed and treated for testicular cancer at the age of 25.

Although this case study has been criticised for its *"poor methodology"* (Martin et al., 2005), it is the only one that reported the physiological development of a world-class cyclist. Moreover, the case study of Coyle (2005) was strengthened by a study from Santalla et al. (2009), where an improvement of delta efficiency over five years in professional cyclists was observed. Unfortunately, no informations on training data were presented that could elucidate the possible underlying mechanism. Especially longitudinal data of key training components could foster an athletes career from the junior category to professional status. Given the scarcity of such data, in Figure 15 an example of a long-term concept to develop elite performance in Austrian cyclists is presented. The figures show the progressive increase of training volume over a period of approximately 12 years. The lower panel indicates that in the early stages of a cycling career (under 13 and 15 category) about 50 % of the training time comprise non-cycling activities to avoid early specialisation and that the main part of cycling training could be done on the mountain-bike to gain a high level of technical skills. As the career progresses the training becomes more specific and almost all of the training time is spent on the road bike.

This theoretical model of a cycling career gives a rough estimation of the required training volumes of different categories. However, an example of the performance development of a world-class mountain-biker is given in Figure 16. The rider started his career in 1995 at the age of 15. He participated at the Olympic games in Athens and Beijing where he finished in sixth place. In addition he was in the top five at world championships as well as in the world ranking. In Figure 16 the increase of the training hours and the performance improvement over 10 years spanning the age of $18 - 28$ years, are shown. The high level of endurance performance was still evident in 1999 and continuously improved until 2008. The number of incremental exercise tests also shows the seasonal performance changes. In accordance with observations from professional road cyclists (Lucia et al., 1999a, 2000d; Padilla et al., 2001) the training volume recorded for this athlete is $\sim$ 1100 h per year. A temporarily performance reduction as a result of the large increase in training during the seasons 2006 and 2007 was compensated for by lowering the volume in the Olympic season ($\sim$ 960 h) which leads to a pronounced performance improvement in 2008 (Figure 16).

The periodization and the concomitant performance changes in the Olympic season are given in Figure 17. During the first preparatory phase of $\sim$ 20 weeks, the total amount of training covered was $\sim$ 500 h. The main time of training was spent at road cycling (60 %), mountain-biking (22 %) and weight training (9 %). The major part of cycling training (85 %) was used for long steady rides to improve basic endurance. The following competition period of 8 weeks comprised 50 % road cycling and 38 % mountain-biking and the portion of higher exercise intensities increased to 25 %. The changes in power output from the beginning of the season in November 2007 until August 2008 of 6 %, 9 % and 5 % for $VT$, $RCP$ and $Pmax$, respectively highlights the effectivity of the applied training.

Longitudinal monitoring of training and performance data over several years as shown in the case studies above, would enhance the current knowledge of training. More specifically, our understanding of the interaction of training methods (i.e. continuous or interval) and exercise intensities and the implications on performance adaptations is limited. Although there is supporting evidence (Coyle, 2005; Esteve-Lanao et al., 2005; Lucia et al., 1999a, 2000d; Padilla et al., 2001) that a high volume of



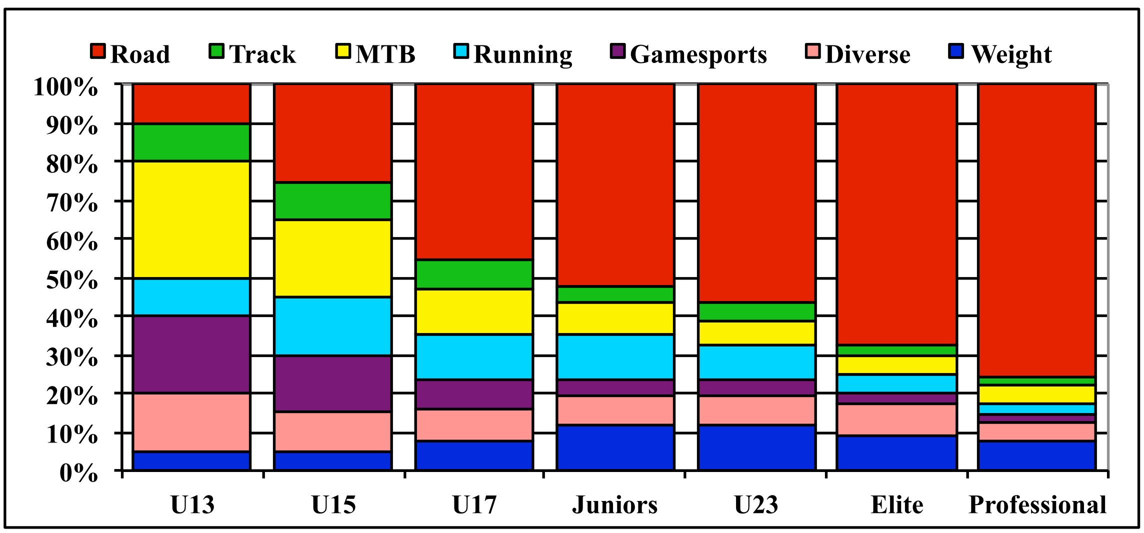




Figure 15: Illustration of the increase in training volume (time) and the distribution of exercise modalities across different categories. (Personal data from the author for presentations at the National Cycling Federation, Austria)

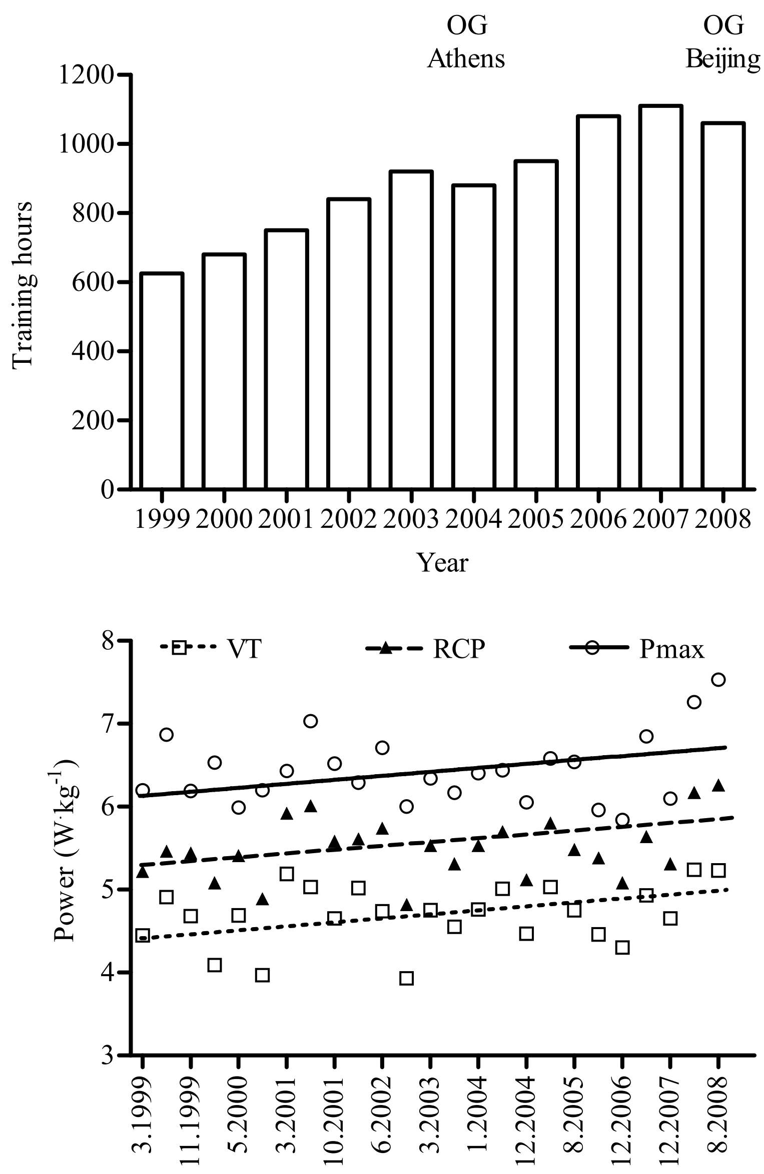



Figure 16: Longitudinal increase of training volume (time) and the associated performance development of a world-class mountain-biker (unpublished data)

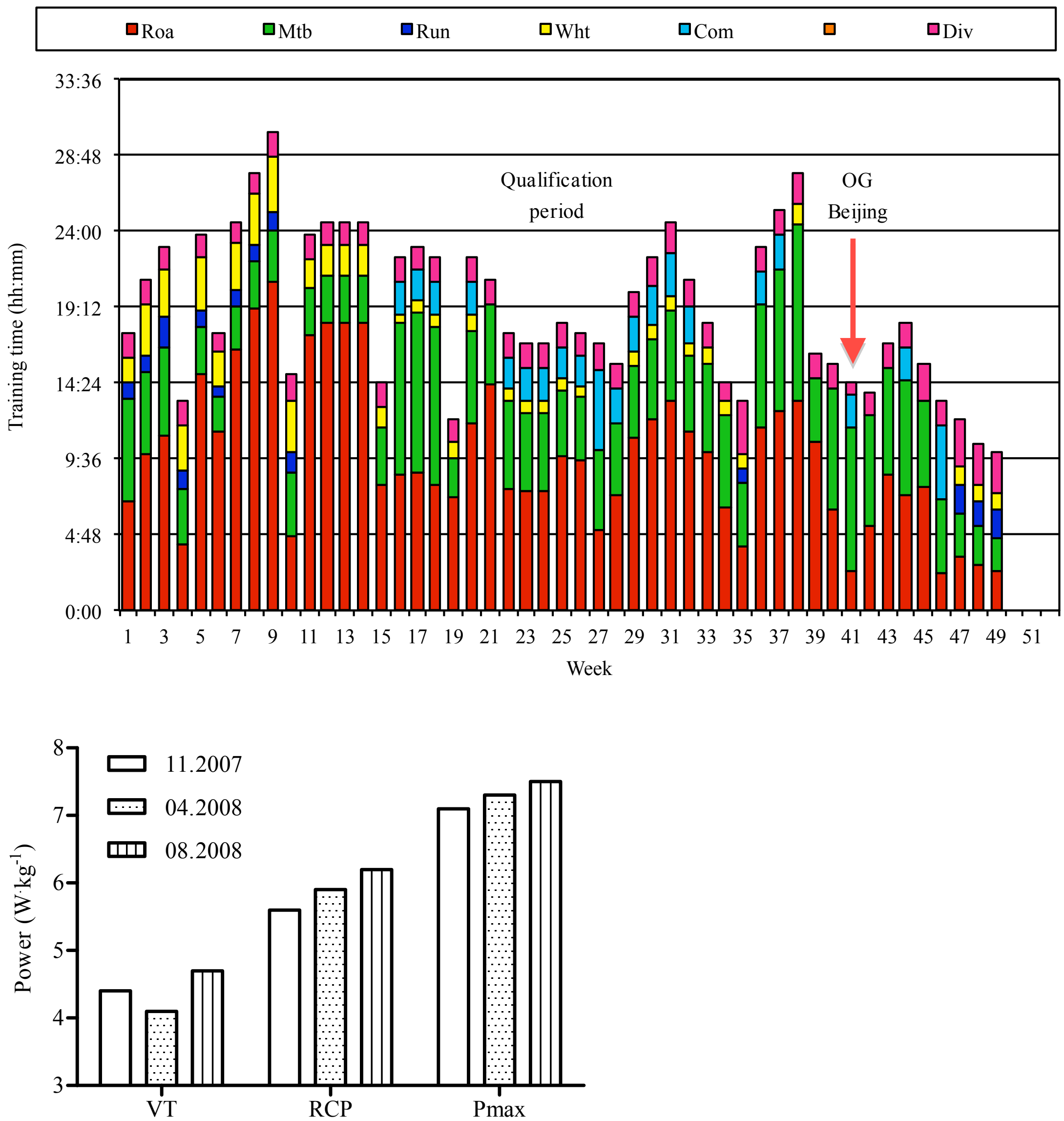



Figure 17: Weekly training in preparation to the Olympic games 2008 and the performance changes across the season (unpublished data)

moderate-intensity exercise is necessary for successful endurance athletes, recent studies have promised similar performance gains with low-volume high-intensity interval training (HIT) (Burgomaster et al., 2008; Gibala et al., 2006; McKay et al., 2009; Wang et al., 2009). These studies suggest that a number of adaptations usually associated with continuous endurance training can be induced with a small volume of HIT. Gibala et al. (2006) reported similar increases in muscle oxidative capacity and muscle buffering capacity after three sessions of four to six repetitions of 30 s all-out cycling with 4 min recovery performed over two weeks in comparison to $90 - 120$ min continuous endurance training sessions. In addition, both groups improved time-trial performance ($p < 0.05$) with no significant difference between groups (Gibala et al., 2006). The same HIT over six weeks compared to five continuous endurance training sessions per week of $40 - 60$ min has been found to induce similar adaptations of carbohydrate and fat metabolism during exercise (Burgomaster et al., 2008). The authors found reduced glycogen and phosphocreatine utilisation during exercise after training and rates of carbohydrate and lipid oxidation were decreased and increased, respectively ($p < 0.05$) in both groups (Burgomaster et al., 2008). Despite the differences in weekly training time ( $\sim 1.5$ and 4.5 h for HIT and continuous training, respectively) and mechanical work ($\sim 300$ and 3200 $kJ \cdot wk^{-1}$ (Gibala et al., 2006); $\sim 225$ and 2250 $kJ \cdot wk^{-1}$ (Burgomaster et al., 2008)), the two diverse training interventions induced remarkably similar adaptations in performance and skeletal muscle oxidative capacity.

Berger et al. (2006) have shown that continuous endurance training (3 sessions per week, 30 min at 60 % $\dot{V}O_2max$) and interval training (3 sessions per week, $20 \times 1$ min at 90 % $\dot{V}O_2max$) results in similar reductions of the phase II time constant and the amplitude of the $\dot{V}O_2$ slow component following transition to moderate and severe exercise after six weeks of training. In accordance McKay et al. (2009) reported a 20 % reduction of the phase II time constant after only two training sessions and a 40 % reduction after eight sessions with no differences between the continuous training group (8 sessions in 19 days, $90 - 120$ min at 65 % $\dot{V}O_2max$) and the interval training group (8 sessions in 19 days, $8 - 12 \times 1$ min at 120 % $\dot{V}O_2max$).

These studies have shown that both, HIT and continuous endurance training elicit rapid changes in previously untrained subjects. However, studies on trained cyclists also revealed the effectiveness of interval training. Stepto et al. (1999) have investigated the effect of different exercise intensities of interval training on 40-km time-trial performance in endurance cyclists. The authors compared five types of interval training sessions: $12 \times 30$ s at 175 % $Pmax$, $12 \times 60$ s at 100 % $Pmax$, 12 $\times$ 2 min at 90 % $Pmax$, $8 \times 4$ min at 85 % $Pmax$, or $4 \times 8$ min at 80 % $Pmax$. The cyclists completed six sessions over three weeks, in addition to their usual continuous endurance training. The greatest performance improvements were observed for the intervals performed at 85 % $Pmax$

(2.8 %) and at 175 % *Pmax* (2.4 %) (both at $p < 0.05$), whereas the other interventions did not result in significant performance enhancements (Stepto et al., 1999). In the study of Weston et al. (1997) muscle buffering capacity, which is associated with short-term sprint activities as applied by Burgomaster et al. (2008) and Gibala et al. (2006), has also been shown to be elevated after six sessions of six to eight repetitions of 5-min intervals at 80 % of *Pmax* in well trained cyclists. In contrast, the activity of citrate synthase and phosphofructokinase remained unchanged. The authors reported strong correlations ($r = -0.85$; $p < 0.05$) between muscle buffering capacity and time to complete a 40-km time-trial and it was concluded that muscle buffering capacity might play a role in sustained, high-intensity exercise (Weston et al., 1997). After twelve sessions of six to nine 5-min intervals at 80 % of *Pmax*, Westgarth-Taylor et al. (1997) found significant improvements in 40-km time-trial power output (from 291 ± 43 $W$ to 327 ± 51 $W$; $p < 0.05$). In addition, carbohydrate oxidation, blood lactate concentration and ventilation were decreased at the same absolute work rates of 60, 70 and 80 % of pre-training *Pmax* ($p < 0.05$), but not at the same relative work rates of post-training *Pmax* (Westgarth-Taylor et al., 1997).

With regard to interval training in cyclists it should be noted that the effects of cadence on performance adaptations are unknown. The force/velocity relationship at any given work rate can change dramatically by the use of different cadences and therefore can change the neuromuscular contraction patterns. Only one study has compared low-cadence ($60 - 70\ rev \cdot min^{-1}$) and high-cadence ($110 - 120\ rev \cdot min^{-1}$) interval training and it was found that the low-cadence strategy results in significantly higher performance improvements (Paton et al., 2009).

Although the potential of interval training to increase the oxidative capacity in skeletal muscle has been shown, the underlying mechanisms are unclear. Recent advances in molecular physiology have identified the peroxisome proliferator-activated receptor-$\gamma$ coactivator 1 alpha (PGC-1$\alpha$) as a potential key regulator of oxidative enzyme expression in a number of cell types (Gibala, 2009; Hood et al., 2006; Hood & Saleem, 2007). An increase in PGC-1$\alpha$ activity was observed with continuous and interval training (Burgomaster et al., 2008; Psilander et al., 2010; Wang et al., 2009) and has been associated with a fast to slow fibre-type conversion (Lin et al., 2002).

It should be noted that in the studies on trained athletes the interval training has been applied concurrently to continuous training in contrast to the research conducted on untrained subjects. It is currently unknown whether or not interval training *alone*, as suggested from the results of Burgomaster et al. (2008) and Gibala et al. (2006) is sufficient to improve or maintain performance in endurance trained subjects. It is very unlikely that the muscular strain, the tolerance to fatigue and the pronounced metabolic adaptations associated with continuous endurance training can be compensated for with interval training over a prolonged period. Even in untrained subjects the effects of long-term interval training (> 1 year) remains to be shown. A recent study over twelve weeks tested the effects of interval training and continuous training on performance and health-related measures (Nybo et al., 2010). In accordance with previous findings the interval training resulted in a significantly higher improvement in $\dot{V}O_2max$ (14 ± 2 %) compared to continuous training (7 ± 2 %) ($p < 0.05$), but was less efficient for lowering the subjects' resting heart rate, percentage of body fat, body mass and for reducing the ratio between total and HDL plasma cholesterol (all $p < 0.05$) (Nybo et al., 2010)

# 6 Summary and Purpose

This review has summarised the physiological requirements of different cycling disciplines as well as the methods and concepts employed to determine endurance performance in cyclists. It has been shown that training data of elite athletes are rarely found in the literature. Longitudinal monitoring of performance and training is required to enhance our understanding of long-term adaptive responses to exercise but also to precisely plan peak performance in elite athletes. Results from laboratory performance tests are important for monitoring the exercise-induced progress and for the prescription of further training. However, a valid field test could further improve the specificity and the implications for training.

The general aim of the thesis was to investigate the efficacy and applicability of power output in field conditions. More specifically, during study one a field test to assess endurance performance in elite cyclists was evaluated. The test-retest correlation and the comparison with well established laboratory performance markers have been addressed. The longitudinal monitoring of exercise intensity during training and racing was the aim of study two. Data were sampled over a whole season in elite athletes to provide a comprehensive insight into the training strategies of elite cyclists. Power output and heart rate profiles, as well as a training dairy was analysed. And in study three the influence of interval training at different cadences during level ground and uphill cycling on flat and uphill time-trial performance was investigated.

The following hypotheses have been addressed:

1. Power output during a 4-min and 20-min time-trial will be reproducible
2. Power output during a 4-min and 20-min time-trial will correspond to *Pmax* and *LTP 2 / RCP* obtained during a laboratory incremental exercise test
3. There will be no significant difference in power output during 20-min uphill and flat time-trials
4. Power output during a 20-min time-trial is sensitive to track exercise induced performance changes

5. There will be a significant difference between the distributions of power output and heart rate exercise intensity zones

6. There will be a significant difference in average exercise intensity in training sessions with different goals

7. There will be a significant positive correlation between performance level and relative exercise intensities during training

8. Uphill and flat interval training will specifically increase power output during 20-min uphill and flat time-trials

9. Performance improvements during a laboratory incremental exercise test will be greater for the uphill-training group

# Part III

# Experimental Procedures

## 7 General Methods

This section describes the materials, methodologies and procedures that have been used for all studies unless stated otherwise.

### 7.1 Laboratory Incremental Graded Exercise Tests

The riders were asked to refrain from strenuous exercise and from alcohol and caffeine the day before the test. To ensure sufficiently high glycogen stores and euhydration, athletes were instructed to follow a carbohydrate rich diet that elicited $\sim 70\%$ of the total caloric intake during the last 24 hours before the test and to drink at least 4 litres. No test was scheduled for 72 h after a competition.

After a medical examination the graded exercise tests ($GXT$) were performed on an electromagnetically braked ergometer (Lode Excalibur, Groningen, The Netherlands). The calibration report for power outputs between $25-1000$ $W$ revealed a coefficient of variation ($CV$) $< 1$ % which is in accordance with the suggestions of Hopkins et al. (2001). The ergometer was equipped with a racing saddle and drop handlebars and with the riders own pedals. After a 5 minute warm up at 50 $W$ the work rate was increased by 25 $W \cdot min^{-1}$ until exhaustion. If the last work rate was not completed, maximal power was calculated according to Kuipers et al. (1985):

$$Pmax = PL + (t/60 \times 25) \tag{10}$$

where PL is the last completed work rate ($W$) and t is the time for the incomplete work rate (s).

Oxygen uptake was measured continuously throughout the test via breath-by-breath open circuit spirometry (Master Screen CPX, VIASYS Healthcare, Hoechberg, Germany). Before each test, flow and volume were calibrated with the integrated system according to the manufacturer's guidelines. Gas analysers were calibrated with gases of known concentrations (4.99 Vol% $CO_2$, 15.99 Vol% $O_2$, VIASYS Healthcare, Hoechberg, Germany). Achievement of maximal oxygen uptake ($\dot{V}O_2max$) was assumed when at least two of the following criteria were observed: a plateau (i.e. increase of less than 2.1 $mL \cdot min^{-1} \cdot kg^{-1}$ over two or more consecutive 1 min $\dot{V}O_2$ samples) in $\dot{V}O_2$ despite an increase in work rate (Howley et al., 1995; Taylor et al., 1955), a respiratory exchange ratio above 1.10 (Duncan et al., 1997), a heart rate within $\pm$ 10 $b \cdot min^{-1}$ of age predicted maximum ($220 - 0.7 \times$ age) (Gellish et al., 2007).

Ventilatory threshold ($VT$) was determined using the criteria of an increase of the ventilatory equivalent of $O_2$ ($\dot{V}E/\dot{V}O_2$) without a concomitant increase of the ventilatory equivalent of $CO_2$ ($\dot{V}E/\dot{V}CO_2$), the first loss of linearity in pulmonary ventilation ($\dot{V}E$) and carbon dioxide ventilation ($\dot{V}CO_2$) (Beaver et al., 1986). Respiratory compensation point ($RCP$) was determined using the criteria of an increase in both $\dot{V}E/\dot{V}O_2$ and $\dot{V}E/\dot{V}CO_2$, and the second loss of linearity in $\dot{V}E$ and in $\dot{V}CO_2$ (Wasserman et al., 1999). The current protocol and the methods of $VT$ and $RCP$ detection have been used in several studies with professional cyclists (Davis et al., 1982; Lucia et al., 2000a, 2004a) and have been shown to be valid and reliable (Amann et al., 2004; Weston & Gabbett, 2001). The methods used for the detection of sub-maximal thresholds in our laboratory revealed intraclass correlation coefficients ($ICC$) of $r = 0.94 - 0.99$ for intra-rater reliability and $r = 0.91 - 0.97$ for inter-rater reliability (unpublished data).

Blood samples were taken every minute (Anderson & Rhodes, 1991; Smith et al., 1997) from the hyperemic earlobe for the measurement of blood lactate concentrations using an automated lactate analyser (Biosen S – line, EKF Diagnostic, Barleben, Germany). The analyser was calibrated with a standard solution of 12.0 $mmol \cdot L^{-1}$ and accuracy was verified by using control solutions with known concentrations of 1.6 $mmol \cdot L^{-1}$, 3.4 $mmol \cdot L^{-1}$ and 10.0 $mmol \cdot L^{-1}$ (Precinorm – U, Precipath – U, Roche Diagnostics, Mannheim, Germany). Lactate turn points were determined as the intensity corresponding to the first (*LTP 1*) and second (*LTP 2*) nonlinear increase in the lactate vs. power output plot (Davis et al., 1983; Spurway & Jones, 2006). Determinations of gas exchange as well as lactate thresholds were conducted by two observers using a custom written application (Figure 10) (Microsoft Excel 2003, Microsoft Corporation, Redmond, USA) (see Appendix 12.5 for an example of a result sheet). In case of disagreement, a third investigator was consulted.

Heart rate was monitored continuously throughout the test with a 12 lead electrocardiograph (Cardiovit AT 104 PC, Schiller, Baar, Switzerland).

## 7.2 Mobile Power Meters

The riders bicycles were equipped with a mobile SRM professional power meter (Schoberer Rad Messtechnik – SRM, Juelich, Germany) for the measurement of mechanical power output and heart rate. The technical informations and principles of measurement are described in chapter 1.1 on page 28.

To ensure accurate measures a static calibration procedure was applied before the studies (Wooles et al., 2005). Before each test or training ride the zero offset frequency of the power meter was adjusted by the supervisor according to the manufacturer's instruction. This device has been shown to provide valid measures in laboratory and field conditions (Balmer et al., 2000b; Smith et al., 2001) and to provide comparable power values to the Lode Excalibur ergometer (Reiser et al., 2000). It has been shown that the accuracy of SRM power meters over a range of $50-1000$ $W$ was $2.3 \pm 4.9$ % (Gardner et al., 2004). Data were sampled at 1 $Hz$ throughout the rides.

## 7.3 Data Analyses

All statistical analyses were performed with the statistical software package PASW Statistics 18 for Mac OS X (SPSS Inc., Chicago, IL). The graphics were generated with the software GraphPad Prism 4.0 for Mac OS X (GraphPad Software Inc., San Diego, CA).

# 8 Evaluation of a Field Test to Assess Performance in Elite Cyclists

## 8.1 Introduction

Endurance is one of the main physical abilities required for many sports. Therefore the measurement of aerobic fitness is an essential requirement to determine training intensities and to evaluate changes in performance. This especially applies to endurance athletes such as road cyclists. Several studies have investigated the relationship between physiological variables obtained during laboratory tests and cycling performance (Amann et al., 2006; Balmer et al., 2000a; Bentley et al., 2001b; Lucia et al., 2004a). Correlations have been found between flat time-trial performance and maximal power output reached during incremental exercise (Anton et al., 2007; Balmer et al., 2000a; Bentley et al., 2001b) as well as with maximum oxygen uptake ($\dot{V}O_2max$) (Bentley et al., 2001b). Sub-maximal thresholds are also highly correlated with flat time-trial performance (Amann et al., 2006; Lucia et al., 2004a). Studies that compare laboratory measurements with outdoor measurements often use time to complete a certain distance or average speed as performance measures (Impellizzeri et al., 2005b; Lucia et al., 2004a). However, external conditions like wind, road surface and gradient, as well as body mass and size have a large influence on these performance variables (Jobson et al., 2007, 2008b). Power output is independent of external influences like wind or gradient and therefore it is more appropriate to use power output as a valid parameter in field test conditions.

To evaluate the performance of elite athletes the specificity of field tests is an important consideration. The validation of an incremental field test performed in a velodrome and based on power output has recently been reported (Gonzalez-Haro et al., 2007). Few studies have analysed the advantages of mobile power meters to investigate the physiological demands of road race cycling (Ebert et al., 2005; Jobson et al., 2008a; Vogt et al., 2006, 2007b) and mountain-bike racing (Stapelfeldt et al., 2004), or to study the biomechanical aspects of pedalling (Bertucci et al., 2007). While exercise tests in the laboratory might be time consuming, expensive and sometimes invasive, the application of power meters for performance assessment under specific field conditions should be considered. A field test can be easily integrated into the training routine of athletes. However, beside the practical application a field test should provide valid and reliable results and detect accurately small performance changes.

Since maximal and sub-maximal power outputs during incremental exercise tests are correlated with time-trial performance, a field test for the assessment of these measures of endurance performance would provide a valuable tool for athlete development. Times to exhaustion at the velocity and power output at $\dot{V}O_2max$ have been found to be $321 \pm 84$ s and $222 \pm 91$ s in running and cycling, respectively (Billat et al., 1996; Billat, 2001), compared to a time to exhaustion of 17 min being reported at 90 %

Table 6: Performance characteristics of the riders

| No | Discipline | Category | Results, Victories |
|---|---|---|---|
| 1 | Road | World Class | Track: WC winner, OG $5^{th}$ place, WCH runner up |
| 2 | MTB | World Class | Winner of UCI Cat.2 MTB races, UCI ranking $<$ 150 |
| 3 | MTB | World Class | Winner of UCI Cat.1 MTB races, OG $6^{th}$ place, WC Top 10, WCH $6^{th}$ place, ECH runner up, UCI ranking $<$ 10 |
| 4 | Road | U23 | NCH Track: runner up Madison Elite |
| 5 | Road | U23 | NCH Juniors Track: runner up Pursuit and TT |
| 6 | Road | U23 | NCH Juniors road, $3^{rd}$ place TT Elite |
| 7 | Road | U23 | NCH Track: runner up TT Elite |
| 8-15 | Road | Elite | Successful in national events |

WC = World Cup; OG = Olympic Games; WCH = World Championships; ECH = European Championships; NCH = National Championships; TT = Time-trial; UCI = International Cycling Federation

of the velocity at $\dot{V}O_2max$ (Billat et al., 1998). Previous studies have shown that the respiratory compensation point ($RCP$) as a measure of anaerobic threshold, occurred at $\sim$ 90 % of $\dot{V}O_2max$ in professional cyclists (Lucia et al., 2004a) and that the average power output during a 20-min time-trial approximated 90 % of maximal power output (Bentley et al., 2001b). Based on these findings it was hypothesised that power output during a 4-min and a 20-min maximal power time-trial would be equal to maximal and threshold powers, respectively. Therefore, the aim of the study was to investigate the test-retest reliability of power output during a 4-min and a 20-min time-trial. Validity was assessed by comparison with maximal and sub-maximal performance measures obtained during a laboratory incremental exercise test.

## 8.2 Materials and Methods

### 8.2.1 Participants

Fifteen competitive male cyclists (mean ± $SD$; age: 25.6 ± 5.2 years; stature: 180.6 ± 4.5 cm; body mass: 70.6 ± 4.4 kg) participated in this study. The riders followed a regular training regimen and participated in races throughout the season. Characteristics of the riders are presented in Table 6. All athletes underwent a medical examination prior to participation and were informed of the experimental procedures. The study was conducted in accordance to the ethical principles of the Declaration of Helsinki (Harris & Atkinson, 2009) and was approved by the institutional ethics committee. All participants provided written informed consent to participate in the study.

### 8.2.2 Study Design

The participants completed one laboratory incremental graded exercise test and two maximal power field tests in randomised order within 20 days. The riders were asked to refrain from strenuous exercise and from alcohol and caffeine ingestion in the 24 h preceding each test. To ensure sufficiently high glycogen stores and euhydration, athletes were instructed to follow a carbohydrate rich diet that elicited $\sim 70$ % of the total caloric intake during the last 24 h before the tests and to drink at least 4 litres. All tests were separated by at least 48 h. Experimental trials were scheduled at least 72 h after competition.

### 8.2.3 Laboratory Incremental Graded Exercise Tests

The incremental graded exercise tests ($GXT$) were performed as described in section 7.1 on page 72.

### 8.2.4 Field Tests

On separate occasions two field tests were performed between 10−14 h. Each field test consisted of a 4-min (TT4) and a 20-min (TT20) maximal power time-trial, separated by a 30 min easy recovery phase. Athletes were advised to choose almost flat or slightly undulating roads with the right of way and without traffic lights. It was expected that at least 2.5 km and 11 km would be covered during the 4-min and 20-min time-trial, respectively. To keep the average gradient below 0.5 % a difference in altitude $<$ 10 m for the 4-min time-trial and $<$ 50 m for the 20-min time-trial was allowed. In total ten different courses were used and evaluated by the first investigator before the time-trials (see Appendix 12.3 on page 146 for the instruction sheet issued to the riders). Data were collected on separate occasions for every cyclist between April and June and therefore environmental conditions were not standardised (Balmer et al., 2000a). All time-trials were supervised and the participants were asked to produce the highest possible power output during the tests. Elapsed time was the only information participants received during the self-paced time-trials. Data were sampled at 1 $Hz$ throughout the tests (see Appendix 12.4 on page 147 for an example of a result sheet).

### 8.2.5 Data Analyses

All descriptive results are reported as mean ± standard deviation ($SD$). The assumption of normality was verified using Kolmogorov-Smirnov's test and Liliefors probability. Statistical differences between laboratory and field test measures were assessed using repeated measures ANOVA. Tukey's post-hoc test was applied to identify differences revealed by the ANOVA. The relationship between field tests and laboratory variables was verified using Pearson's product moment correlation coefficient. Bland Altman Plot's and 95 % limits of agreement were applied to assess the agreement between field tests

Table 7: Maximal and sub-maximal characteristics obtained during *GXT* (mean ± *SD*)

| Measure | *LTP 1* | *LTP 2* | *VT* | *RCP* | *Pmax* |
|---|---|---|---|---|---|
| Power ($W$) | 263 ± 37 | 344 ± 38 | 243 ± 27 | 344 ± 37 | 440 ± 38 |
| Power ($W \cdot kg^{-1}$) | 3.7 ± 0.4 | 4.9 ± 0.5 | 3.5 ± 0.3 | 4.9 ± 0.5 | 6.2 ± 0.5 |
| $\dot{V}O_2$ ($mL \cdot min^{-1} \cdot kg^{-1}$) | 47 ± 4.6 | 57 ± 4.6 | 43 ± 4.2 | 58 ± 4.7 | 67 ± 5.0 |
| $HR$ ($b \cdot min^{-1}$) | 146 ± 14 | 166 ± 13 | 141 ± 13 | 166 ± 12 | 186 ± 12 |
| Lactate ($mmol \cdot L^{-1}$) | 1.5 ± 0.3 | 3.6 ± 0.4 | | | 11.9 ± 1.8 |

$\dot{V}O_2$ = oxygen uptake; *HR* = heart rate; *LTP* = lactate turn point; *VT* = ventilatory threshold; *RCP* = respiratory compensation point

and laboratory measures (Atkinson & Nevill, 1998; Bland & Altman, 1986). Mean values from the field tests (i.e. trial 1 and trial 2) were used for all calculations.

For the assessment of test-retest reliability, systematic bias and random error was calculated by the methods of Bland & Altman (1986). Repeated measures ANOVA was used to assess whether a difference occurred between the field tests and to calculate the intraclass correlation coefficient (*ICC*) (Vincent, 2005). No heteroscedasticity was present in the data using the examinations described previously (Atkinson & Nevill, 1998). The 95 % confidence limits (*CL*) are provided for all reliability measures. Statistical significance was accepted at $p < 0.05$.

## 8.3 Results

The maximal and sub-maximal physiological measures from the laboratory test are presented in Table 7. Mean power output and heart rate during TT4 and TT20 were 412 ± 53 $W$ vs. 347 ± 42 $W$ and 174 ± 13 $b \cdot min^{-1}$ vs. 174 ± 10 $b \cdot min^{-1}$, respectively. In the last minute of the field tests, heart rate reached 180 ± 13 $b \cdot min^{-1}$ and 180 ± 9 $b \cdot min^{-1}$ during TT4 and TT20, respectively. In Figure 18 mean power outputs over 30 s and 60 s intervals are presented for TT4 and TT20, respectively.

Strong correlations were observed between the 4-min and 20-min time-trials for both power output ($r = 0.93$, $p < 0.001$) and heart rate ($r = 0.94$, $p < 0.001$). Power output was significantly higher during TT4 ($p < 0.001$), whereas no significant differences were found for mean heart rate ($p = 0.58$) and maximal heart rate ($p = 0.76$). Power output during the 4-min and the 20-min time-trial was significantly correlated with power output at maximal and sub-maximal measures from the graded exercise test (Table 8). Repeated measures ANOVA revealed significant differences between TT4 and *GXT* measures (Table 8). No significant differences were observed between TT20 and power output at *LTP 2* and *RCP*, whereas power outputs at *LTP 1*, *VT* and *Pmax* were significantly different from TT20 (Table 8).

Bland Altman plots of TT4 and *Pmax* showed a bias ± random error of − 30 ± 58 $W$ or − 7.4 ± 14 % (Figure 19). The bias ± random error of TT20 and *LTP 2* was 0.5 ± 44 $W$ or 0.02 ± 13 %

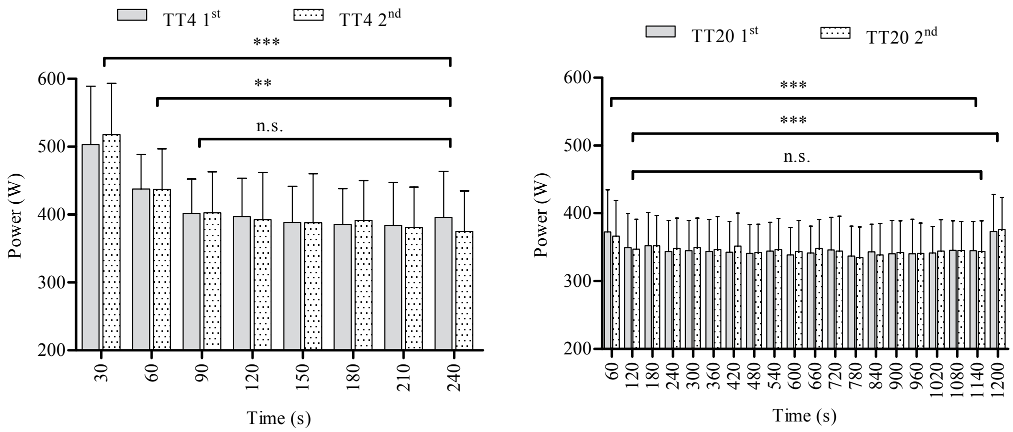



Figure 18: Mean power outputs for 30 s intervals (TT4; left panel) and 60 s intervals (TT20; right panel). ANOVA was calculated as mean of the repeated trials in every time interval. ** Significant at $p < 0.01$; *** Significant at $p < 0.001$; n.s. = Not significant

Table 8: Comparative statistics of power output at maximal and sub-maximal measures between *GXT* and field-tests

| | *LTP 1* | *LTP 2* | *VT* | *RCP* | *Pmax* |
|---|---|---|---|---|---|
| TT4 | | | | | |
| Pearson's ($r$) | 0.90 *** | 0.87 *** | 0.77 ** | 0.78 ** | 0.84 *** |
| 95 % *CL* | 0.65 − 0.96 | 0.60 − 0.95 | 0.38 − 0.92 | 0.45 − 0.93 | 0.54 − 0.95 |
| ANOVA | *** | *** | *** | *** | *** |
| *SEE* ($W$) | 16.9 | 18.6 | 16.7 | 20.8 | 20.0 |
| TT20 | | | | | |
| Pearson's ($r$) | 0.86 *** | 0.84 *** | 0.75 ** | 0.80 *** | 0.82 *** |
| 95 % *CL* | 0.62 − 0.96 | 0.56 − 0.95 | 0.35 − 0.91 | 0.46 − 0.93 | 0.51 − 0.94 |
| ANOVA | *** | 0.98 n.s. | *** | 0.97 n.s. | *** |
| *SEE* ($W$) | 17.8 | 19.6 | 17.3 | 20.6 | 20.9 |

** Significant at $p < 0.01$; *** Significant at $p < 0.001$; n.s. = not significant; *CL* = Confidence limit; *SEE* = Standard error of estimate

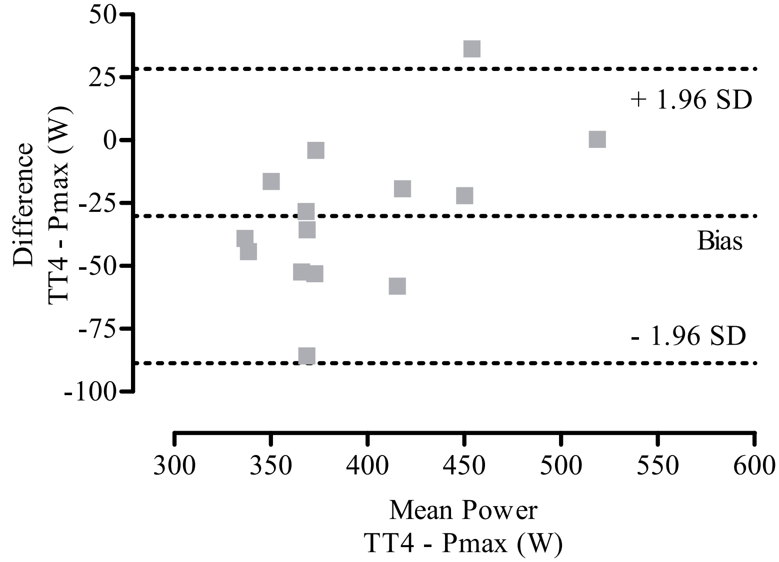



Figure 19: Bland Altman plot of the absolute difference between TT4 and *Pmax* vs. the mean power of TT4 and *Pmax*

(Figure 20). For TT20 and *RCP* the bias ± random error was − 0.4 ± 49 *W* or − 0.3 ± 14.3 % (Figure 20). The heart rate during the field tests was significantly different from the heart rate at *LTP 1*, *LTP 2*, *VT*, *RCP* and from maximal heart rate measured during *GXT* ($p < 0.001$).

Strong test-retest correlations during the 4-min and 20-min time-trials were observed for both power output and heart rate. For power output during TT4 and TT20 *ICC* was 0.98 (95 % *CL* 0.92 − 0.99) and 0.98 (95 % *CL* 0.95 − 0.99), respectively. *ICC* was 0.94 (95 % *CL* 0.8 − 0.98) for heart rate during both, TT4 and TT20. Bland Altman plot's of power output during the two 4-min time-trials showed a bias ± random error of − 0.8 ± 23 *W* or − 0.2 ± 5.5 % (Figure 21). The bias ± random error of power output during the two 20-min time-trials was − 1.8 ± 14 *W* or 0.6 ± 4.4 % (Figure 21).

## 8.4 Discussion

The main findings of this study were that the applied field tests had very high test-retest reproducibility and that power output during the 20-min time-trial correlated with power output at the second lactate turn point (*LTP 2*) and the respiratory compensation point (*RCP*).

It should be noted that the field test in the present study was designed to be used on self-selected flat courses as an easy to use tool for cyclists and coaches. Nevertheless the high reliability of mean power output during the field test was in agreement with the *CV* of 1.3 − 4.3 % for mean power output during a 40-km outdoor time-trial (Smith et al., 2001). An improvement of reliability following

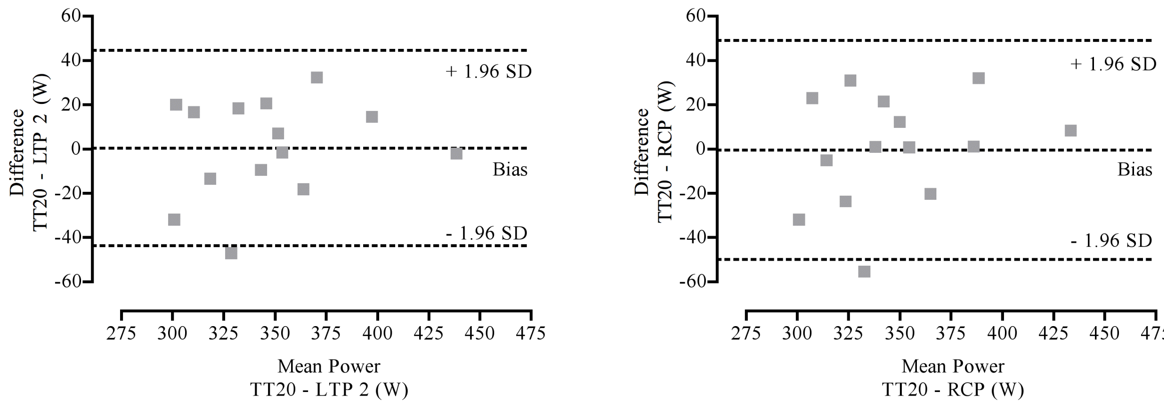



Figure 20: Bland Altman plot of the absolute difference between TT20 and *LTP 2* (left panel) and between TT20 and *RCP* (right panel) vs. their respective mean power outputs

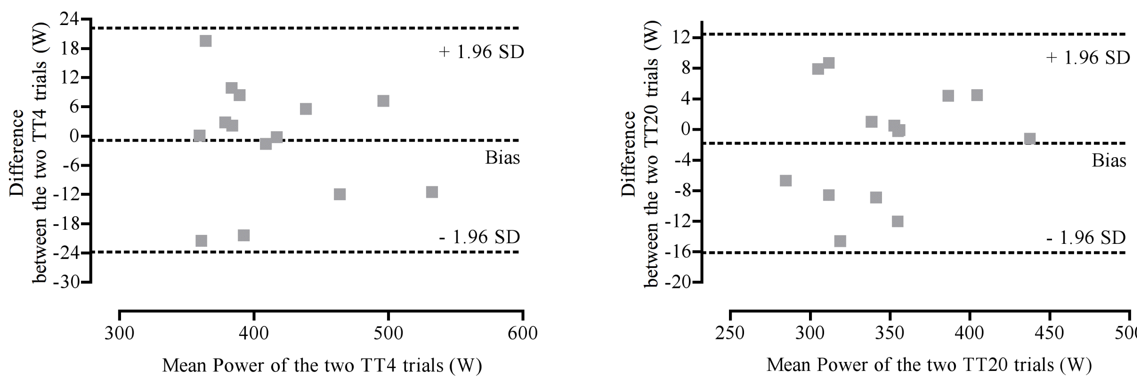



Figure 21: Bland Altman plot of the absolute difference between the two 4-min time-trials (left panel) and the two 20-min time-trials (right panel) vs. their respective mean power outputs

a familiarisation trial has been shown by Laursen et al. (2003). The highly trained cyclists used in that study ($\dot{V}O_2max$ 64.8 $\pm$ 5.2 $mL \cdot min^{-1} \cdot kg^{-1}$) performed three 40-km time-trials on a stationary wind trainer. A $CV$ of 2.0 $\pm$ 1.8 %, 2.3 $\pm$ 1.8 % and 1.2 $\pm$ 1.3 % for trials 1 vs. 2, 1 vs. 3 and 2 vs. 3, was reported, respectively. In the present study all participants were experienced time-trial cyclists. This may explain the small amount of bias between repeated trials.

The lengths of the field tests in this study were shorter than the 40 km ($\sim$ 55 min) reported in the studies of Smith et al. (2001) and Laursen et al. (2003). Since the training load in cycling is between $20 - 30$ h per week there is limited compliance of athletes to perform a $50 - 60$ min time-trial for testing purposes. The field tests performed in the present study could be easily integrated into the training routine of athletes and therefore can be recommended for regular use.

In the present study correlations between power output during the 4-min and 20-min time-trials were found with power output and oxygen uptake at maximal and sub-maximal performance markers obtained from the laboratory graded exercise test. However, the strongest correlation was found between TT4 and TT20 ($r = 0.93$, $p < 0.001$). Amann et al. (2006) have reported a correlation between the power output during a 40-km and a 5-km time-trial on an electrically braked ergometer ($r = 0.76$, $p < 0.01$). In the study of Bentley et al. (2001b), no correlation was found between 20-min and 90-min time-trial power output ($r = 0.66$, $p = 0.54$). The ratio of the power outputs during the 20-min and the 4-min time-trial was 84 %. A similar ratio of 85 % was reported in the study of Amann et al. (2006), whereas Bentley et al. (2001b) found a slightly higher ratio of 88 %. Despite the different test durations in these studies it is suggested that power output obtained during short time-trials is valid to predict the performance of longer time-trials lasting up to one hour. During time-trials lasting more than one hour the utilisation of free fat acids and intramyocellular lipid stores as well as the depletion of glycogen stores may influence the performance outcome and therefore their predictability from short time-trials (Coyle, 1995; Zehnder et al., 2006).

It has been shown that high level athletes are able to tolerate exercise intensities of 95 % − 105 % over 4 to 15 min (Billat, 2001). In accordance the two most successful athletes (i.e. world-class) who participated in the present study performed the 4-min time-trial at 99 % and 108 % of $Pmax$, whereas a fractional use of 91 % of $Pmax$ was observed for the remaining athletes. This ability could be a prerequisite for world-class endurance athletes. Nevertheless, it has been shown that performance during high intensity exercise between 3 to 5 min is strongly correlated to aerobic power but a high anaerobic effort is required during the start phase. These results are supported by Davison et al. (2000). The authors reported a strong negative correlation between maximal aerobic power and performance time during 1 km ($r = -0.89$) and 6 km ($r = -0.88$) uphill cycling. When they included the results of the Wingate anaerobic test into multiple regression analysis, an enhancement of the determination coefficient ($R^2 = -0.98$ and $R^2 = -0.96$ for 1 km and 6 km, respectively) was found.

As well as for the 4-min time-trial, strong correlations between the power output during the 20-min time-trial and aerobic performance markers were observed. Power output and oxygen uptake during the incremental graded exercise test explained 63 % − 75 % and 73 % − 78 % of the variance of 20-min time-trial power. The most important finding was that power output during TT20 ($347.1 \pm 41.6\ W$) was similar to power output at $LTP\ 2$ ($343.6 \pm 38.0\ W$) and $RCP$ ($343.5 \pm 37.3\ W$). The average exercise intensity during the 20-min time-trial was 79 % of $Pmax$, $RCP$ occurred at 86 % of $\dot{V}O_2max$ and blood lactate was $3.6 \pm 0.4\ mmol \cdot L^{-1}$ at $LTP\ 2$. It has been shown that $RCP$ in professional cyclists occurred at 80 % − 86 % of $Pmax$ or at 86 % − 90 % of $\dot{V}O_2max$ (Chicharro et al., 2000; Lucia et al., 2000b, 2003). These results are in accordance with the present study, whereas others reported slightly higher ratios (84 % − 90 %) of the power output at the onset of blood lactate accumulation ($OBLA$) and $Pmax$ (Padilla et al., 1999, 2000b). These differences can be mainly attributed to the longer increments of 4 min during the incremental exercise test and the fact that a friction loaded ergometer has been used in the studies of Padilla et al. (1999, 2000b). It has been shown that power output could be 2 % − 8 % lower under these conditions (Davis et al., 1982; Maxwell et al., 1998). However, all of these studies described the high endurance capacity of professional cyclists. Based on heart rate measurement, exercise intensities between 89 % and 77 % during time-trials lasting between 10 min and 90 min have been found (Fernandez-Garcia et al., 2000; Padilla et al., 2000b). Padilla et al. (2000a) estimated an average power output of 509.53 $W$ from the average speed of 53.04 $km \cdot h^{-1}$ during the one hour cycling world record. The reported power output was very similar to their subject's $OBLA$ (505 $W$) and corresponds to 89 % of the laboratory $Pmax$ (572 $W$). During the nineteen days preceding the world record attempt, several velodrome tests at the target speed were performed. Blood lactate concentrations during the tests were between 4.5 and 7.7 $mmol \cdot L^{-1}$ and at 3 min and 5 min after completion of the world record, blood lactate was 5.2 and 5.1 $mmol \cdot L^{-1}$, respectively. The capacity of professional cyclists to perform at high work rates of about 90 % $\dot{V}O_2max$ over prolonged periods of time (> 60 min) has also been described by Lucia et al. (1999a). The same authors investigated the response of ventilatory parameters during a sub-maximal constant load test in a group of professional cyclists (Lucia et al., 2000b). When their subjects completed a 20-min workout at an exercise intensity of 50 % between the first and second ventilatory threshold (400.4 ± 11.8 $W$), which corresponded to about 80 % of $\dot{V}O_2max$, significant increases from the third to the last minute of exercise were reported for $\dot{V}O_2$, $HR$, $\dot{V}E$, $\dot{V}E/\dot{V}O_2$, $VE/\dot{V}CO_2$ and blood lactate. The increase of $\dot{V}O_2$ during constant load exercise, that is known as the "slow component of oxygen uptake", was 130 $mL$ in 17 min or 7.6 $mL \cdot min^{-1}$ and was significantly lower than previously reported values of 22 $mL \cdot min^{-1}$ (Hagberg et al., 1978) or 60 $mL \cdot min^{-1}$ (Jacobsen et al., 1998). Blood lactate levels remained relatively low at 2 − 3 $mmol \cdot L^{-1}$. The authors concluded that the efficiency and the ability to sustain high work rates over prolonged periods in professional cyclists are mainly responsible for these findings (Lucia et al., 2000b). It was also stated however, that higher work rates at $RCP$ or about 90 % of $\dot{V}O_2max$ would have changed $\dot{V}O_2$ and/or lactate kinetics in their study. Analyses of long *Tour de France* time-trials (68 − 83 min) revealed that about 50 % − 65 % was spent at exercise intensities above $RCP$ when the time-trial was performed in the first ten days of the race (Lucia et al., 2004a). In the third time-trial, which was held on the penultimate stage (i.e. day 20), the contribution of the high intensity zone was reduced to 10 % despite the fact that one rider from the study finished in $2^{nd}$ place. Cumulative muscle fatigue and hormonal decreases of testosterone and cortisol levels after three weeks of strenuous exercise are mainly responsible for the low percentage of high intensity exercise (Chicharro et al., 2001; Lucia et al., 2001a, 2004a).

Recently it has been suggested that regulation of exercise intensity is the result of a continuously modifying process regulated by the central nervous system in response to informations from peripheral anatomical and physiological systems (Tucker et al., 2006). The ability of athletes to "manage" and fine tune their efforts in a small physiological zone might also be the result of training adaptations and gained experiences. The fact that MLSS assessment last 30 min and the findings that endurance athletes are able to perform up to one hour at 90 % of $\dot{V}O_2max$ might suggest that TT20 would result in higher relative intensities as found in the present study (i.e. 79 % $Pmax$ and 86 % $\dot{V}O_2max$). However, based on the results it cannot be excluded that the subjects from this study, who were experienced racing cyclists, would be able to maintain the same intensity over prolonged durations. In fact unpublished observations from three participants revealed almost identical power outputs during competition time-trials lasting 27 min, 34 min and 42 min. These observations could be interpreted with an extra motivation during competition and/or the existence of a "functional" or "performance threshold" which leads to exhaustion within $20 - 60$ min.

## 8.5 Conclusion

In conclusion the main findings of the present study were that power output during both the 4-min and the 20-min field tests showed strong test-retest correlations. A bias close to zero and a random error of $\sim 5$ % reflects the accuracy to detect small performance changes. Therefore it can be stated that average power output obtained from the field tests is reliable in elite cyclists. In addition the strong correlation to performance markers from incremental exercise tests shows the validity to assess the performance capacity of elite cyclists with the described field tests. The agreement between TT20, *RCP* and *LTP 2* is a remarkable finding of this study since these measures of "anaerobic threshold" can be used interchangeably. From a practical point of view it has been shown that the simple application with only minor recommendations for route choice are important for users of power meters to use this field test on a routinely basis. Future studies should address the transferability of these results to other populations like female or adolescent cyclists. Applying the same methodology during uphill cycling may provide an insight to individual time-trial strength. The additional measurement of physiological variables like oxygen uptake or blood lactate concentration may enhance the results. However, it was the intention of the study to conceive a reliable and valid field test as an "easy to use" tool. Furthermore, the description of exercise intensities based on the field test and investigations of exercise intensities recorded with power meters during training and competition are a field of application for future studies

# 9 Longitudinal Monitoring of Power Output and Heart Rate Profiles in Elite Cyclists

## 9.1 Introduction

Two of the most important physiological determinants of endurance performance are an athlete's maximum oxygen uptake ($\dot{V}O_2max$) and the fractional use of $\dot{V}O_2max$ during competition (Bassett & Howley, 2000). Consequently, the objectives of endurance training are to improve both maximal and sub-maximal physiological components. The total training load is determined by several training variables of which volume, intensity and frequency are the most important (Busso et al., 2002; Esteve-Lanao et al., 2005; Mujika et al., 1996). Although there is general agreement that performance at elite or world-class level requires several years of high volume endurance training, it is still unclear what the most effective mixture of the essential training variables is. While a number of studies have investigated the adaptations to a certain training intervention over 2 to 6 weeks in active subjects (Burgomaster et al., 2008; Glaister et al., 2007) and competitive athletes (Lindsay et al., 1996; Westgarth-Taylor et al., 1997), limited information exists about the longitudinal training strategies and the relationship with performance (Esteve-Lanao et al., 2005). A rigorously controlled study over a racing season with international successful athletes is almost impossible. However, the description of performance and training data of such athletes provide useful informations for coaches and researchers. Recently training related changes in gross efficiency over the season in competitive cyclists have been reported (Hopker et al., 2009a).

Heart rate is commonly used to monitor exercise intensity in endurance sports. The relationship between heart rate and work rate during incremental laboratory exercise is used to define exercise intensity zones and several studies have used heart rate to estimate exercise intensity in the field (Fernandez-Garcia et al., 2000; Impellizzeri et al., 2002; Lucia et al., 1999a; Padilla et al., 2001). However, the applied stimulus to induce physiological adaptations during cycling is power output.

To date only a few studies have described the exercise intensity profiles of road cycling (Ebert et al., 2005; Vogt et al., 2006, 2007b) and off-road cycling (Gregory et al., 2007; Hurst & Atkins, 2006; Stapelfeldt et al., 2004) using mobile power meters. Recently the results of Vogt et al. (2006) have shown different distributions of exercise intensity when heart rate and power output were measured simultaneously. Since monitoring of a single event provides only a "snapshot" of the accumulated training stress this study was conducted to investigate the exercise behaviour during a complete racing season. To date there are no published studies that have investigated power output and heart rate characteristics during training and racing on a longitudinal basis (i.e. one season) in a group of competitive racing cyclists.

Table 9: Performance characteristics of the riders

| Performance Classification | Discipline | Category | Results, Victories |
|---|---|---|---|
| 1 | MTB (female) | World Class | Winner of WC races and General Classification, OG < 10, ECH and WCH medalist, UCI ranking < 5 |
| 2 | MTB | World Class | Winner of UCI Cat.1 MTB races, OG < 10, WC < 10, WCH < 10, ECH medalist, UCI ranking < 10 |
| 3 | Road, Track | International Competitive | NCH Track medalist TT and Individual Pursuit, WC member Individual and Team Pursuit |
| 4 | Road, Track | International Competitive | NCH Track medalist Points Race and Madison, WC member Points Race and Madison |
| 5 | Road, Track | U23 | NCH Juniors Track medalist Individual Pursuit and TT |
| 6-11 | Road | Elite | Successful in national events |

WC = World Cup; OG = Olympic Games; WCH = World Championships; ECH = European Championships; NCH = National Championships; TT = Time-trial; UCI = International Cycling Federation

The aims of the present study were: a) to compare power output and heart rate distributions for different training goals (e.g. basic endurance, anaerobic power, strength intervals); b) to assess exercise intensity and c) to relate training variables to performance measures in a group of elite cyclists across a whole season.

## 9.2 Materials and Methods

### 9.2.1 Participants

Ten male (mean ± *SD*; age: 29.1 ± 6.7 years; stature: 181.3 ± 4.6 cm; body mass: 72.7 ± 6.3 kg) and one female (age: 23.1 year; stature: 165 cm; body mass: 45.5 kg) competitive cyclist volunteered to participate in this study. All riders had a training history of at least six years and competed successfully in national and international races (Table 9). All riders received a medical examination prior to participation and gave written informed consent to participate in the study. The study was conducted in accordance with the ethical principles of the Declaration of Helsinki (Harris & Atkinson, 2009) and was approved by the institutional ethics committee.

### 9.2.2 Periodization

The season for the athletes started in the first week of December and lasted until the end of October of the following year. Most of the athletes followed a biphasic periodization model that was divided into two macrocycles. The first macrocycle was composed of a preparatory phase ($10 - 12$ weeks), a pre-competition phase ($6-8$ weeks) and a competition phase ($6-8$ weeks). During the second macrocycle the preparatory, pre-competition and competition phases lasted $6-8$ weeks, $4-6$ weeks and $4-6$ weeks, respectively. This periodization model aimed to achieve a high performance level from April to June and from August to October.

### 9.2.3 Quantification of Exercise Intensity

Monitoring of power output and heart rate were the key variables in this study. Therefore, all participants used a SRM professional power meter (Schoberer Rad Messtechnik – SRM, Juelich, Germany) at least on one of their bikes throughout the season. The SRM is capable of storing power output, heart rate, cadence and speed simultaneously. All files were screened to identify outliers within the data which were defined as a) a sudden change in heart rate of 10 % to the pre value b) an implausible peak in power output and c) the lack of data irrespective of the error source (i.e. technical problems or a not worn heart rate belt). In case of a) and b) the erroneous values were manually corrected when they occur for less than 30 consecutive seconds and did not exceed 5 % of the training time. Otherwise and in case of c) the files were excluded from further analyses. From a total number of 1895 sampled data sets 1802 (96 %) met the inclusion criteria and were further analysed with the software "Trainingspeaks WKO+" (Peaksware LLC, Colorado, USA). Data were sampled at 1 $Hz$ for the majority of the sessions ($n$ = 1743). However, during some track sessions ($n$ = 28) and short-interval sessions ($n$ = 31) the sampling rate was $2-5$ $Hz$. Since most athletes used more than one bike for their specific trainings and races (e.g. Road – Track – or Mountain-bike), not all of the cycling sessions could be monitored. However, the captured training sessions corresponds to 60 % of the total training time and 69 % of the cycling training time. All participants had trained for at least two years with mobile power meters, were familiar with the calibration procedure of the power meter and carried out a zero offset calibration prior to each training session according to the manufacturer's instruction. To analyse total training that includes other activities like running, cross-country skiing, and strength training, the participants were provided with a PC spreadsheet to record their daily training activities. The main goals of each training session, as well as the content, time and distance (if applicable) were recorded (see Appendix 13.4 on page 168 for an example of a diary).

### 9.2.4 Exercise Intensity Zones

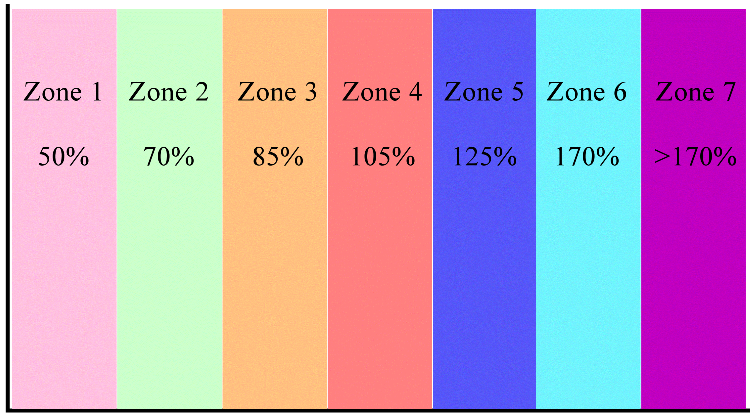
Many studies that have monitored heart rate as a measure of exercise intensity in running (Esteve-Lanao et al., 2005; Seiler & Kjerland, 2006) or cycling (Lucia et al., 1999a) established a three intensity-zone model based on the results of graded exercise tests ($GXT$). These include a "low intensity" zone (i.e. below the ventilatory threshold ($VT$) or lactate threshold ($LT$)), a "moderate intensity" zone (i.e.

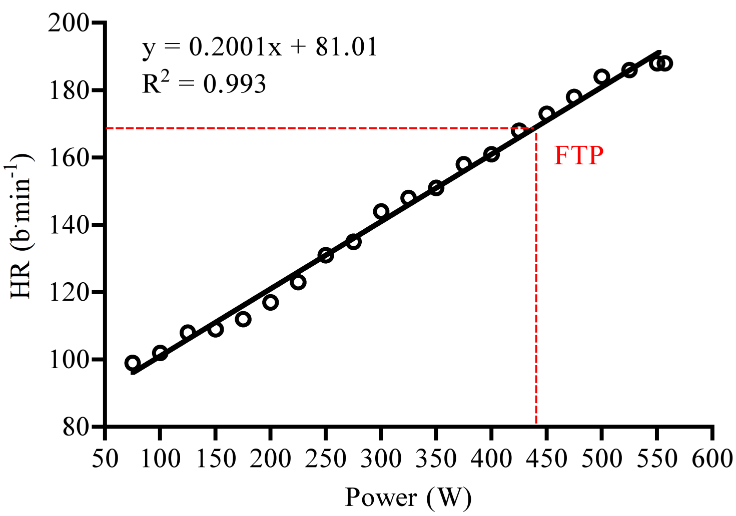
between $VT/LT$ and the respiratory compensation point ($RCP$) or onset of blood lactate accumulation ($OBLA$)) and a "high intensity" zone (i.e. above $RCP/OBLA$). This model has been used to describe the physiological demands during both training and racing in elite athletes (Esteve-Lanao et al., 2005; Lucia et al., 1999a, 2003; Padilla et al., 2001; Seiler & Kjerland, 2006). Nevertheless, in the present study this three intensity-zone heart rate model has been modified and a power model with seven intensity zones (Zone 1 – Zone 7) is introduced to cover the whole spectrum of power output. This has been done for two reasons: firstly, the range of the low intensity-zone is too wide. Considering a $VT/LT$ of approximately $200 - 400$ $W$ in elite cyclists (Impellizzeri et al., 2005a; Lucia et al., 2004a) the three intensity-zone model suggests the same zone for 50 $W$ as for 400 $W$. Therefore, Zone 1 was used to distinguish between very low activities usually applied for active recovery and Zone 2, which is encountered to improve basic endurance. Secondly, heart rate cannot accurately reflect high power outputs above maximal power ($Pmax$) obtained during an incremental graded exercise test. To quantify these supra-maximal efforts two intensity bands above $Pmax$ were used.

In the first study of this thesis (chapter 8 on page 75) power outputs measured during a 20-min field test (TT20) and at respiratory compensation point ($RCP$) were found to be similar. Both were used as performance measures in the present study and are denominated as "Functional Threshold Power" ($FTP$) throughout this study. The proposed exercise intensity zones were related to $FTP$: Zone 1 $< 50$ % (of $FTP$), Zone 2: $50 - 70$ %, Zone 3: $71 - 85$ %, Zone 4: $86 - 105$ %, Zone 5: $106 - 125$ %, Zone 6: $126 - 170$ %, Zone 7 $> 170$ %. The relationship between power output and heart rate during $GXT$ was used to calculate heart rate zones for comparisons of the exercise intensity distribution based on power output or heart rate measurement (Lucia et al., 2000d). In Figure 22 an example of the calculated exercise intensity zones is presented.

#### 9.2.5 Mean Power, Normalized Power, Intensity Factor

As recently indicated by Jobson et al. (2009), the stochastic nature of power output when cycling outdoors presents a challenge to the evaluation of training sessions. The calculation of mean power output ($Pmean$) is a simple approach to evaluate exercise intensity. However, it does not provide a detailed insight into the characteristics of training. For example, a mean power output of 200 $W$ for 30 min might be accomplished by a) 200 $W$ constant power b) 2 min intervals of 300/100 $W$ or c) 10 min at 400 $W$ and 20 min at 100 $W$. Consequently, mean power output does not reflect the physiological strain during different training sessions. Coggan (2003) has challenged this limitation and proposed the use of "Normalized Power" ($NP$). In this approach power data were smoothed over a 30 s average because many physiological responses (e.g. $\dot{V}O_2$, heart rate) to exercise intensity are in the order of 30 s. The values obtained were raised to the $4^{th}$ power (derived from a regression of




| | Power | HR |
|---|---|---|
| Zone 1 | 223 | 126 |
| Zone 2 | 312 | 145 |
| Zone 3 | 378 | 159 |
| Zone 4 | 467 | 175 |
| Zone 5 | 556 | 188 |
| Zone 6 | 757 | |
| Zone 7 | >757 | |

Figure 22: Exercise intensity zones calculated from Functional Threshold Power

blood lactate concentration and exercise intensity; rounded from 3.9 to 4.0):

$$Blood\, lactate\, (\%\, lactate\, at\, LT) = Power\, (\%\, of\, Power\, at\, LT)^{3.9} \quad (11)$$

$n = 76$; $R^2 = 0.806$

Finally, the $4^{th}$ root of the average of these values was taken to obtain normalized power (Coggan, 2003). The only study that has evaluated this method to date reported very strong correlations ($R^2 = 0.978$; $p < 0.001$) between *NP* obtained from highly variable criterium-races and individual time-trial mean power over 1 h (Skiba, 2007). This approach might be superior to mean power output in describing the physiological strain of variable power tasks. As a measure of relative exercise intensity an intensity factor (*IF*) was calculated as the ratio of mean power output to Functional Threshold Power for each training session (e.g. $200/400 = 0.5$).

### 9.2.6 Workout Categories

As each training session has particular goals, the participants were asked to record these in their diaries. The total numbers of training sessions as well as the training volume were recorded. On the basis of interviews with 5 cycling coaches and 15 experienced cyclists, 9 main workout goals were identified and described as follows: *"recovery", "basic aerobic endurance", "aerobic capacity", "anaerobic threshold", "maximum oxygen uptake", "strength", "maximum power", "competition"* and *"non-cycling activities"*. The distribution of exercise intensity for both power output and heart rate zones was assessed for each workout category (except for non-cycling activities). In addition, mean power, Normalized Power and the intensity factors were calculated for each workout category. The training was mainly applied in a "continuous mode" during recovery, basic aerobic endurance, and aerobic capacity sessions. In contrast, the higher intensities corresponding to anaerobic threshold, maximum oxygen uptake, strength and maximum power sessions were performed in an "interval mode". To account for the intermittent exercise profiles in these workouts the intensity factor was calculated as average for the total workout (as described above) as well as for each interval.

### 9.2.7 Laboratory Incremental Graded Exercise Tests

At the start of the season an incremental graded exercise test ($GXT$) was performed as described in chapter 7.1 on page 72. For the female participant the initial work rate was 30 $W$ and the increase was 15 $W \cdot min^{-1}$. As sub-maximal performance measures ventilatory threshold ($VT$) and respiratory compensation point ($RCP$) were determined (chapter 7.1 on page 72).

### 9.2.8 Performance Tests

In study one (chapter 8 on page 75) the validity and reliability of a 20-min field test (TT20) on self selected flat courses has been examined. It was found that power output obtained during TT20 was highly reproducible (− 0.6 ± 4.4 %; Intraclass correlation coefficient = 0.98) and strongly correlated with $RCP$ (− 0.3 ± 14.3 %; $r = 0.8$) in elite cyclists. In the present study the 20-min time-trial was used as a performance measure to adopt the bands of the intensity zones and to properly calculate the intensity factors. The performance tests were scheduled every 10 − 12 weeks. All participants performed three tests during the season to assess exercise-induced adaptations.

### 9.2.9 Data Analyses

Descriptive data are reported as mean ± standard deviation ($SD$) and 95 % confidence limits (95 % $CL$). The assumption of normality was verified using Kolmogorov-Smirnov's test and Liliefors probability. Repeated measures ANOVA were used to compare the performance tests (power output at $RCP$ and TT20) and the interactions of workout categories with mean power, normalized power and intensity factor. To identify the interactions of power output and heart rate zone distributions with workout categories, data were analysed by a two factor ANOVA. Bonferroni's post-hoc test was applied to identify differences revealed by the ANOVA. The relationship between training variables and performance measures obtained during $GXT$ and TT20 was verified using Pearson's product moment correlation coefficient. To correlate the training variables with the rider's classification according to international and national rankings (Table 9) Spearman's rank correlation was calculated. For all statistical analysis the level of significance was set at $p < 0.05$.

## 9.3 Results

### 9.3.1 Performance Measures

The physiological measures from the laboratory incremental exercise test are presented in Table 10. The $VT$ occurred at 49 ± 4 % (95 % $CL$: 46 − 51), 57 ± 4 % (95 % $CL$: 54 − 60) and 72 ± 5 % (95 % $CL$: 69 − 76) of $Pmax$, $\dot{V}O_2max$ and $HRmax$, respectively. At $RCP$ the fractional use of $Pmax$, $\dot{V}O_2max$ and $HRmax$ was 77 ± 3 % (95 % $CL$: 75 − 79), 83 ± 4 % (95 % $CL$: 81 − 86) and 90 ± 3 % (95 % $CL$: 88 − 92), respectively. Functional Threshold Power significantly increased from 4.7 ± 0.5 $W \cdot kg^{-1}$ (4.4 − 5.1) to 4.8 ± 0.5 $W \cdot kg^{-1}$ (4.4 − 5.1), 5.0 ± 0.4 $W \cdot kg^{-1}$ (4.7 − 5.3) and 5.1 ± 0.5 $W \cdot kg^{-1}$ (4.8 − 5.4) during the season ($F_{3,\,30} = 8.6$; $p < 0.001$). The increase was strongly correlated with the training time for the strength category ($r = 0.83$; $p < 0.05$). Figure 23 shows the changes of Functional Threshold Power ($FTP$) during the season and the correlation with the training time to improve strength.

Table 10: Maximal and sub-maximal characteristics obtained during $GXT$ (mean ± $SD$)

| Measure | $VT$ Male | Female | $RCP$ Male | Female | Maximum Male | Female |
|---|---|---|---|---|---|---|
| Power ($W$) | 213 ± 25 | 152 | 343 ± 47 | 215 | 445 ± 52 | 275 |
| 95 % $CL$ | 195 − 231 | | 310 − 377 | | 408 − 483 | |
| Power ($W \cdot kg^{-1}$) | 3.0 ± 0.3 | 3.2 | 4.8 ± 0.5 | 4.6 | 6.2 ± 0.6 | 6.0 |
| 95 % $CL$ | 2.7 − 3.2 | | 4.4 − 5.1 | | 5.7 − 6.6 | |
| $\dot{V}O_2$ | 37.7 ± 5.0 | 43.5 | 55.4 ± 7.6 | 58.7 | 66.5 ± 7.1 | 71.5 |
| ($mL \cdot min^{-1} \cdot kg^{-1}$) 95 % $CL$ | 34.1 − 41.3 | | 50.0 − 60.1 | | 61.4 − 71.5 | |
| $HR$ ($b \cdot min^{-1}$) | 135 ± 7.6 | 154 | 170 ± 7.6 | 174 | 190 ± 8.7 | 189 |
| 95 % $CL$ | 130 − 141 | | 164 − 175 | | 184 − 196 | |

$\dot{V}O_2$ = oxygen uptake; $HR$ = heart rate; $VT$ = ventilatory threshold; $RCP$ = respiratory compensation point; $CL$ = confidence limit

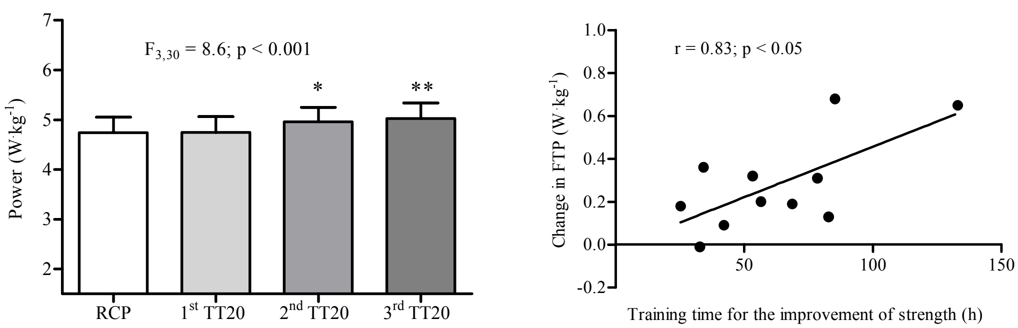



Figure 23: Changes in Functional Threshold Power during the season (left panel) and the relationship with training time to improve strength (right panel). Error bars represents 95 % $CL$. Significantly different from $RCP$ and the $1^{st}$ TT20 at: * $p < 0.05$; ** $p < 0.01$

### 9.3.2 Quantification of Total Training

Analyses of the diaries showed that the participants trained for 689 ± 191 h (95 % $CL$: 529 − 848) and covered 17031 ± 4268 km (95 % $CL$: 13462 − 20599) in 268 ± 60 training sessions (95 % $CL$: 218 − 317). Total training time ($r = -0.96$; $p < 0.001$) and numbers of training sessions ($r = -0.83$; $p < 0.01$) but not distance were strongly correlated with the riders classification. In addition, training time was strongly correlated with power outputs ($W \cdot kg^{-1}$) at $VT$ ($r = 0.85$; $p < 0.01$) and the $3^{rd}$ TT20 ($r = 0.84$; $p < 0.01$) as well as with $\dot{V}O_2max$ ($mL \cdot min^{-1} \cdot kg^{-1}$) ($r = 0.82$; $p < 0.01$).

The athletes dedicated 46 ± 22 h (95 % $CL$: 28 − 64), 294 ± 85 h (95 % $CL$: 222 − 364), 83 ± 39 h (95 % $CL$: 50 − 116), 58 ± 43 h (95 % $CL$: 23 − 94), 31 ± 7 h (95 % $CL$: 25 − 36), 65 ± 36 h (95 % $CL$: 32 − 98), 10 ± 6 h (95 % $CL$: 3 − 16), 56 ± 27 h (95 % $CL$: 33 −

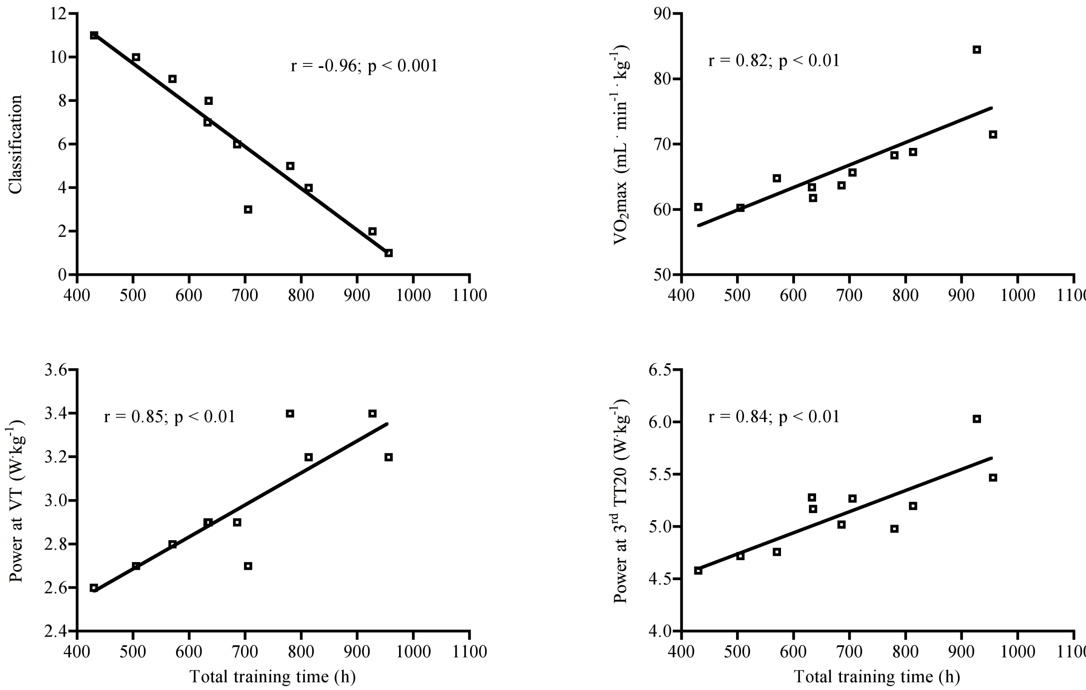



Figure 24: Correlations of total training time with the riders classification and performance measures

78) and 59 ± 58 h (95 % $CL$: 11 − 108) of their total training time to workouts which focused on recovery, basic aerobic endurance, aerobic capacity, anaerobic threshold, maximum oxygen uptake, strength, maximum power, competition and non-cycling activities, respectively. Strong correlations were observed between classification and recovery ($r = -0.79$; $p = 0.02$), basic aerobic endurance ($r = -0.82$; $p < 0.01$), strength ($r = -0.86$; $p < 0.01$) and non-cycling activities ($r = -0.8$; $p = 0.02$). In addition strong correlations were found between basic aerobic endurance and power output ($W \cdot kg^{-1}$) at $VT$ ($r = 0.81$; $p = 0.02$) and with $\dot{V}O_2max$ ($mL \cdot min^{-1} \cdot kg^{-1}$) ($r = 0.85$; $p < 0.01$) (Figure 24). No significant correlations were observed when workout categories are expressed as percentages of total training time.

For each workout category, with the exception of non-cycling activities, the coefficient of variation ($CV$) of power output was calculated. The $CVs$ were 39 ± 8 % (95 % $CL$: 32 − 45) for recovery, 39 ± 12 % (95 % $CL$: 30 − 47) for basic aerobic endurance, 42 ± 11 % (95 % $CL$: 34 − 50) for aerobic capacity, 47 ± 12 % (95 % $CL$: 38 − 56) for anaerobic threshold, 52 ± 10 % (95 % $CL$: 45 − 60) for maximum oxygen uptake, 42 ± 7 % (95 % $CL$: 37 − 48) for strength, 56 ± 16 % (95 % $CL$: 36 − 77) for maximum power and 68 ± 6 % (95 % $CL$: 63 − 73) for competition. ANOVA revealed a significant effect of the workout category on $CV$ ($F_{7,58} = 7.93$; $p < 0.001$). During competition the $CV$ was significantly higher compared to the other categories ($p < 0.001$), whereas no differences were observed among other categories. With the exception of the $CV$ for competition, strong correlations were observed between the $CVs$ and $\dot{V}O_2max$ ($mL \cdot min^{-1} \cdot kg^{-1}$) ($r = -0.71$ to $-0.8$; $p < 0.05$), power output during the $3^{rd}$ TT20 ($r = -0.73$ to $-0.84$; $p < 0.01$) as well as with total training time ($r = -0.82$ to $-0.96$; $p < 0.01$) and training time in the basic aerobic endurance category ($r = -0.77$ to $-0.94$; $p < 0.01$) (Figure 25).

### 9.3.3 Exercise Intensity Zones

The distribution of power output from all sampled data during the season was 110 ± 63 h (95 % *CL*: 62 – 159), 155 ± 74 h (95 % *CL*: 98 – 211), 53 ± 27 h (95 % *CL*: 32 – 74), 26 ± 23 h (95 % *CL*: 8 – 43), 9 ± 5 h (95 % *CL*: 5 – 13), 4 ± 2 h (95 % *CL*: 3 – 6) and 1.5 ± 0.8 h (95 % *CL*: 0.7 – 2) for Zone 1 to Zone 7, respectively. Strong correlations were observed between time in Zone 2 and power outputs ($W \cdot kg^{-1}$) during the $2^{nd}$ and $3^{rd}$ TT20 ($r = 0.86$; $p < 0.01$) as well as with $CVs$ obtained from basic aerobic endurance and aerobic capacity ($r = 0.81$; $p < 0.05$). A significant main effect of workout categories on power output distribution was found ($F_{7,391} = 29.8$; $p < 0.001$). Figure 26 shows the intensity zones and the percentage of appearance for every workout category. No significant interactions of power output and heart rate on exercise intensity distribution for the total season were found ($F_{4,40} = 1.8$; $p = 0.15$) (Figure 27). However, when power output and heart rate distributions were compared for every workout category, significant effects were observed for anaerobic threshold, maximum oxygen uptake, strength, maximum power and competition (Figure 27).

### 9.3.4 Mean Power, Normalized Power, Intensity Factor

Mean power output ($Pmean$) for all sampled data was 2.8 ± 0.3 $W \cdot kg^{-1}$ (95 % *CL*: 2.5 – 3.1). During recovery, basic aerobic endurance, aerobic capacity, anaerobic threshold, maximum oxygen uptake, strength, maximum power and competition the $Pmeans$ were 2.3 ± 0.4 $W \cdot kg^{-1}$ (95 % *CL*: 2.0 – 2.6), 2.7 ± 0.4 $W \cdot kg^{-1}$ (95 % *CL*: 2.4 – 2.9), 2.9 ± 0.4 $W \cdot kg^{-1}$ (95 % *CL*: 2.6 – 3.1), 3.0 ± 0.4 $W \cdot kg^{-1}$ (95 % *CL*: 2.7 – 3.3), 2.8 ± 0.3 $W \cdot kg^{-1}$ (95 % *CL*: 2.6 – 3.1), 2.7 ± 0.4 $W \cdot kg^{-1}$ (95 % *CL*: 2.4 – 3.1), 2.9 ± 0.5 $W \cdot kg^{-1}$ (95 % *CL*: 2.2 – 3.6) and 3.5 ± 0.4 $W \cdot kg^{-1}$ (95 % *CL*: 3.1 – 3.8), respectively.

Normalized power ($NP$) was 3.2 ± 0.3 $W \cdot kg^{-1}$ (95 % *CL*: 2.9 – 3.4) for all sampled data and 2.6 ± 0.4 $W \cdot kg^{-1}$ (95 % *CL*: 2.3 – 3.0) for recovery, 2.9 ± 0.3 $W \cdot kg^{-1}$ (95 % *CL*: 2.7 – 3.2) for basic aerobic endurance, 3.3 ± 0.3 $W \cdot kg^{-1}$ (95 % *CL*: 3.1 – 3.5) for aerobic capacity, 3.6 ± 0.5 $W \cdot kg^{-1}$ (95 % *CL*: 3.3 – 4.0) for anaerobic threshold, 3.4 ± 0.3 $W \cdot kg^{-1}$ (95 % *CL*: 3.2 – 3.7) for maximum oxygen uptake, 3.2 ± 0.5 $W \cdot kg^{-1}$ (95 % *CL*: 2.9 – 3.6) for strength, 3.6 ± 0.6 $W \cdot kg^{-1}$ (95 % *CL*: 2.7 – 4.6) for maximum power and 4.3 ± 0.5 $W \cdot kg^{-1}$ (95 % *CL*: 3.8 – 4.7) for competition.

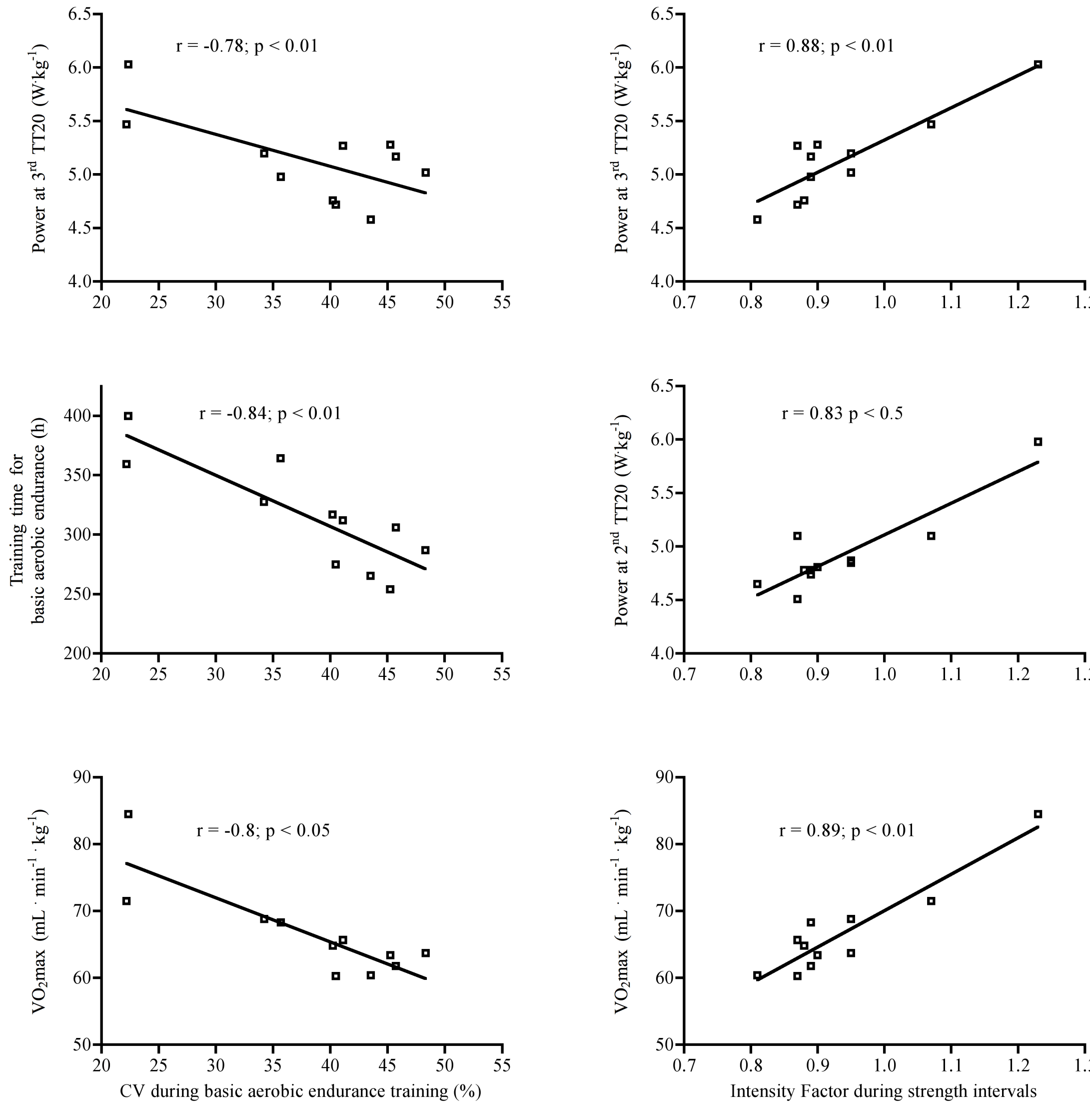



Figure 25: Correlations of the coefficient of variation during basic endurance workouts (left panel) and the intensity factor during strength workouts (right panel) with training time and performance measures

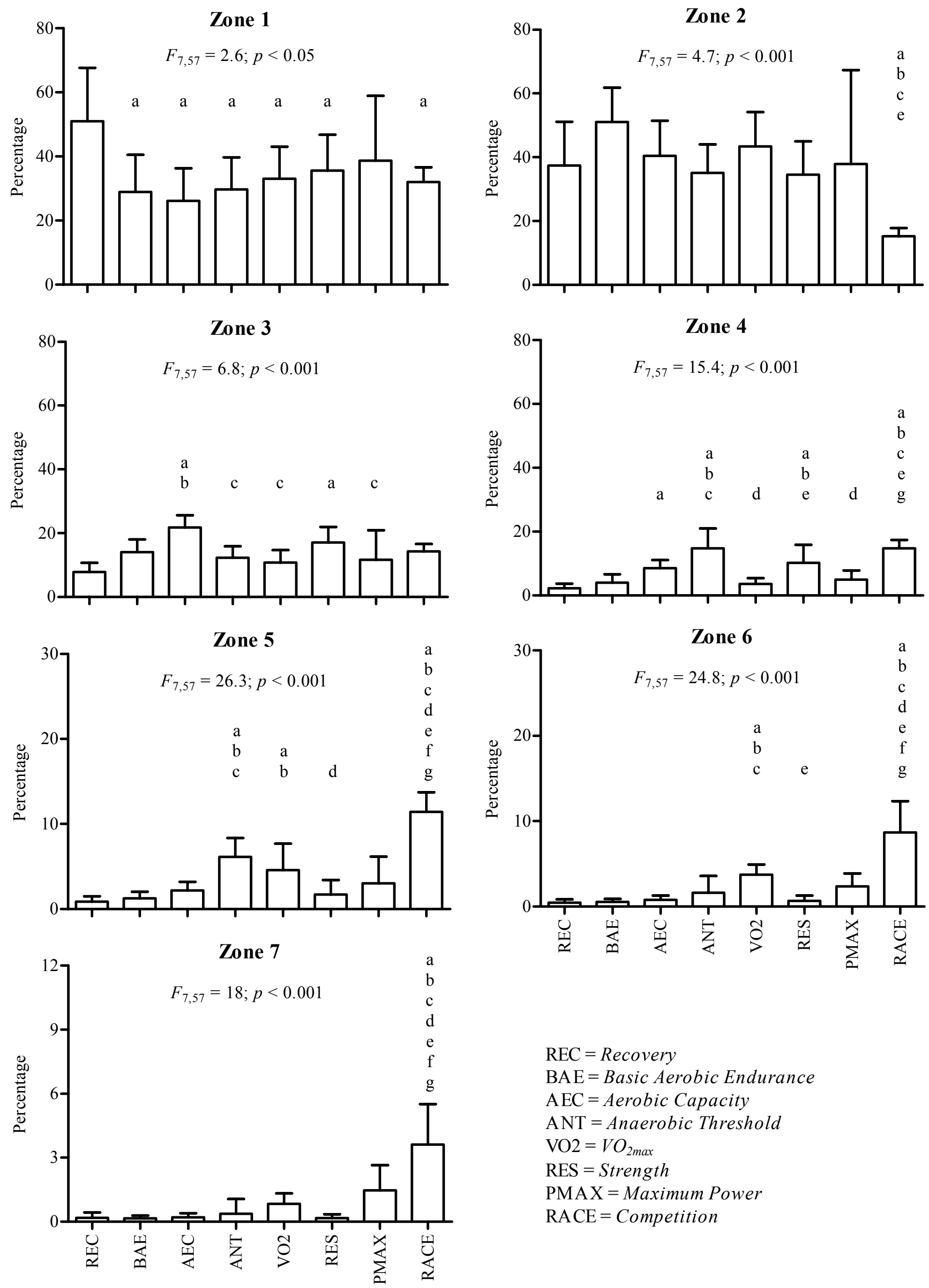



Figure 26: Percentage of intensity zones for every workout category. Error bars represents 95 % *CL*. Significantly different from: a = REC; b = BAE; c = AEC; d = ANT; e = VO2; f = RES; g = PMAX

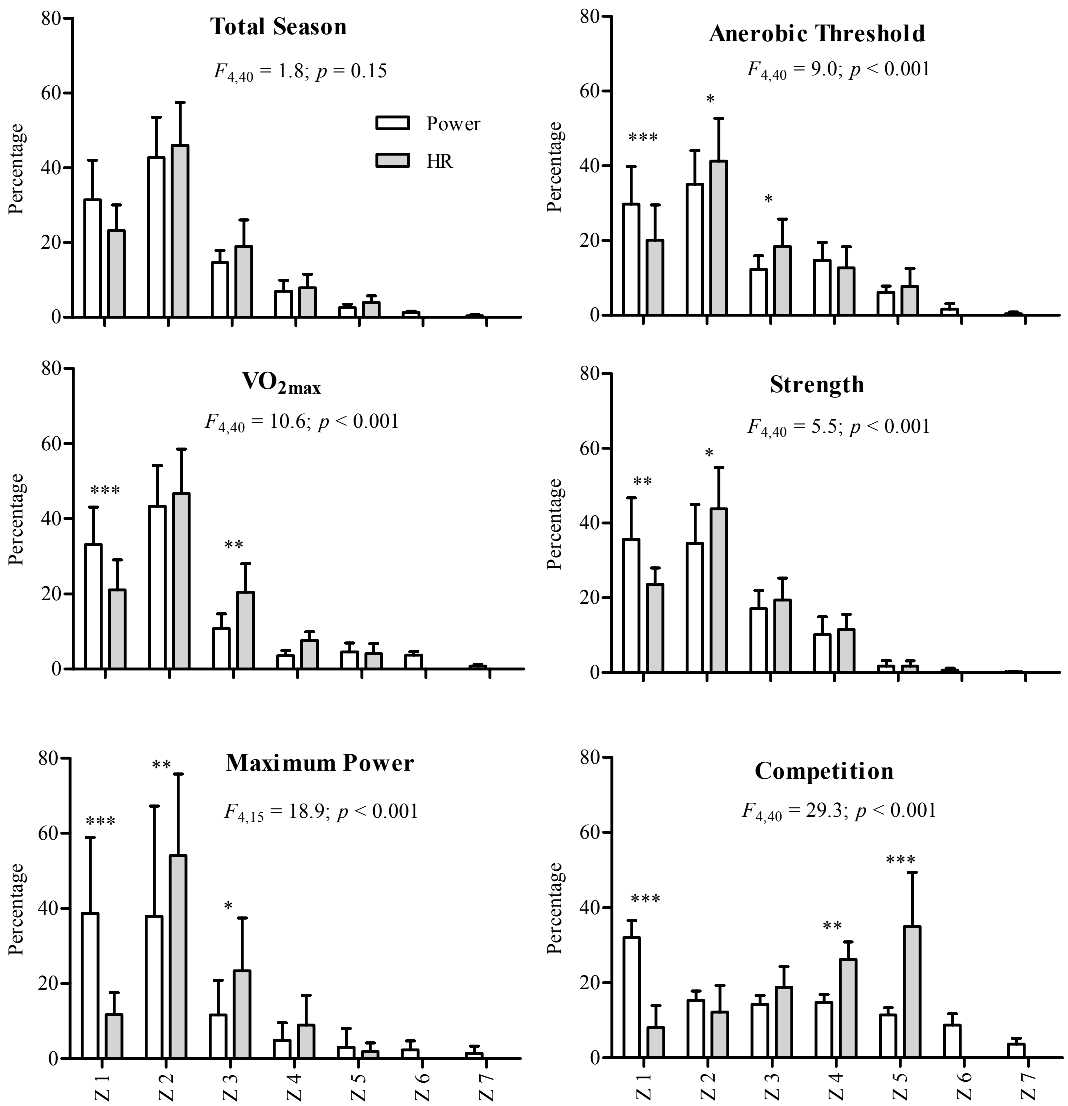



Figure 27: Exercise intensity distributions of power output (white bars) and heart rate (grey bars) for total season and selected workout categories. Error bars represents 95 % *CL*. Note that Zone 6 and Zone 7 contains only power data. Significantly different at: * $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$

A significant main effect of the workout category on *Pmean* ($F_{7,57} = 5.6$; p $< 0.001$) and normalized power ($F_{7,57} = 11.8$; p $< 0.001$) was observed (Figure 28).

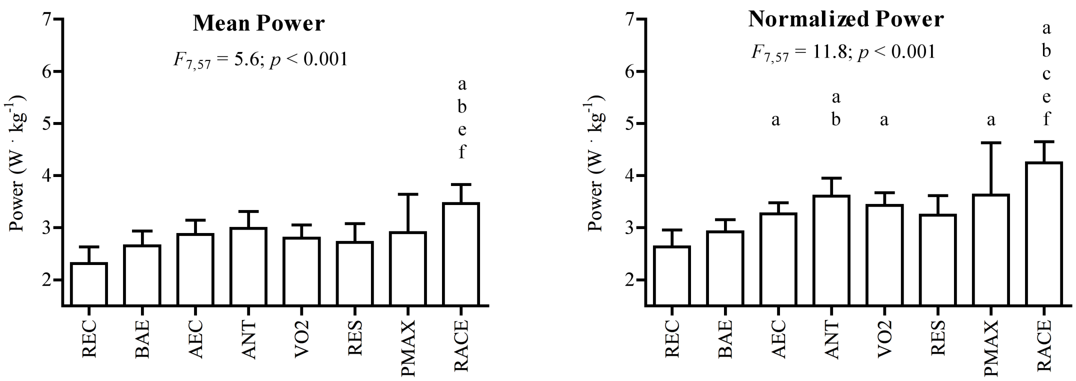



Figure 28: Mean power and Normalized power for each workout category. Error bars represent 95 % *CL*. Significantly different from: a = REC; b = BAE; c = AEC; e = VO2; f = RES.

In addition ANOVA showed a significant main effect on power output when calculated as *Pmean* or *NP* ($F_{1,30} = 60.3$; p $< 0.001$). Post hoc analysis revealed significant differences between *Pmean* and *NP* during anaerobic threshold, maximum oxygen uptake and competition (p $< 0.01$).

With the exception of recovery, *Pmeans* were strongly correlated with $\dot{V}O_2max$ ($mL \cdot min^{-1} \cdot kg^{-1}$) ($r = 0.67$ to 0.9; $p < 0.01$) and power output ($W \cdot kg^{-1}$) during the $3^{rd}$ TT20 ($r = 0.81$ to 0.98; $p < 0.001$). Also strong correlations were observed between normalized power and $\dot{V}O_2max$ ($mL \cdot min^{-1} \cdot kg^{-1}$) ($r = 0.72$ to 0.93; $p < 0.01$), maximum power output ($W \cdot kg^{-1}$) obtained during the graded exercise test ($r = 0.81$ to 0.95; $p < 0.001$) and power outputs ($W \cdot kg^{-1}$) at the respiratory compensation point ($r = 0.73$ to 0.99; $p < 0.01$) and the $3^{rd}$ TT20 ($r = 0.72$ to 0.9; $p < 0.01$). In addition a strong correlation was found between normalized power during competition and the riders classification ($r =$ -0.73; $p < 0.05$).

The average intensity factor (*IF*) calculated as the ratio of mean power output to Functional Threshold Power (*FTP*) for all sampled data was 0.55 ± 0.04 (95 % *CL*: 0.52 − 0.58). During recovery, basic aerobic endurance, aerobic capacity, anaerobic threshold, maximum oxygen uptake, strength, maximum power and competition the intensity factors were 0.46 ± 0.06 (95 % *CL*: 0.41 − 0.51), 0.53 ± 0.04 (95 % *CL*: 0.50 − 0.56), 0.57 ± 0.03 (95 % *CL*: 0.55 − 0.6), 0.6 ± 0.05 (95 % *CL*: 0.56 − 0.64), 0.56 ± 0.03 (95 % *CL*: 0.54 − 0.58), 0.54 ± 0.04 (95 % *CL*: 0.5 − 0.57), 0.55 ± 0.03 (95 % *CL*: 0.5 − 0.6) and 0.69 ± 0.06 (95 % *CL*: 0.64 − 0.75), respectively. A significant main effect of the workout category on *IF* was found ($F_{7,57} = 17.2$; $p < 0.001$). The intensity factors were significantly higher during competition and lower during recovery in comparison to all other categories

($p < 0.001$). No significant correlations between the intensity factors and performance measures were observed.

The average intensity factors for intervals ($IF_{INT}$) performed at anaerobic threshold, maximum oxygen uptake, strength, and maximum power workouts were 0.99 ± 0.05 (95 % *CL*: 0.95 − 1.04), 1.44 ± 0.13 (95 % *CL*: 1.33 − 1.55), 0.95 ± 0.15 (95 % *CL*: 0.82 − 1.1) and 1.98 ± 0.38 (95 % *CL*: 1.37 − 2.58), respectively. ANOVA showed a significant main effect on $IF_{INT}$ ($F_{3,23} = 38.2$; $p < 0.001$). Post hoc analysis revealed significant differences between each category ($p < 0.001$) with the exception of anaerobic threshold versus strength.

Strong correlations were found between $IF_{INT}$ during maximum power workouts and power outputs ($W \cdot kg^{-1}$) at the respiratory compensation point ($r = 0.98$; $p < 0.01$), the $1^{st}$ TT20 ($r = 0.95$; $p < 0.01$) and maximum power output ($W \cdot kg^{-1}$) obtained from the graded exercise test ($r = 0.99$; $p < 0.001$). In addition, $IF_{INT}$ during strength workouts was strongly correlated with $\dot{V}O_2max$ ($mL \cdot min^{-1} \cdot kg^{-1}$) ($r = 0.89$; $p < 0.01$) and power outputs ($W \cdot kg^{-1}$) during the $2^{nd}$ TT20 ($r = 0.83$; $p < 0.05$) and the $3^{rd}$ TT20 ($r = 0.88$; $p < 0.01$) (Figure 25).

## 9.4 Discussion

The main findings of this study were that workout categories had an influence on exercise intensity distributions, mean power, normalized power and intensity factors. In addition, differences between heart rate and power output distributions were found. Finally, relationships of training time, *CVs*, mean power and normalized power output values and intensity factors during intervals with performance measures and the performance classification of the participants were observed.

This was not an experimental study, where the athletes or their coaches were influenced to train in one particular way. It was an observational study and the results provide an insight into the training strategies of elite cyclists. The participants were world-class cyclists, international successful cyclists and national racing cyclists. To the best of the author's knowledge no other study has been published where continuous longitudinal data from a power meter and a diary were analysed over a whole season in high-level elite cyclists.

The findings that total training time was related to classification and performance measures was in agreement with the results of Esteve-Lanao et al. (2005). The mean training time per week was $\sim 16\ h \cdot wk^{-1}$ for the national competitive athletes and $\sim 25\ h \cdot wk^{-1}$ for the two world class athletes included in the present study and indicates the importance of a high training volume in endurance athletes (Jobson et al., 2009). Previous studies on runners (Esteve-Lanao et al., 2005) and cross-country skiers (Seiler & Kjerland, 2006) evaluated heart rate distributions based on the three intensity-zone model described above. In contrast to the polarized training model described by Seiler & Kjerland

(2006), who suggested a “75 % – 5 % – 20 %” distribution of exercise intensity across the “low – moderate – hard” zones, Esteve-Lanao et al. (2005) reported a distribution of “71 % – 21 % – 8 %”. In accordance with previous studies of heart rate distributions in professional road cyclists (Lucia et al., 2003; Padilla et al., 2001), power output distributions of 73 % for the low-intensity Zones 1 (30 %) and 2 (43 %), 22 % for the moderate-intensity Zones 3 (15 %) and 4 (7 %) and 5 % for the high-intensity Zones 5 (3 %), 6 (1.5 %) and 7 (0.5 %) were observed . These results emphasises that endurance athletes generally spent most of their training to improve basic endurance. The three intensity-zone model based on heart rate has two main limitations. Firstly, very high intensities above maximum power obtained during a laboratory incremental graded exercise test cannot accurately be quantified. Secondly, the phenomenon of cardiac drift (i.e. the slow rise in heart rate at constant work rates during prolonged exercise) influences the indirect estimation of exercise intensity (Achten & Jeukendrup, 2003). Vogt et al. (2006) quantified different distributions of intensity zones when power output and heart rate were measured during six stages of a cycling race. The results show that differences between power output and heart rate distributions occur during high intensity workouts where the training stimulus is mainly applied in a discontinuous or interval mode. In accordance to Vogt et al. (2006) we observed a shift from low to high intensity zones and consequently an overestimation of exercise intensity when heart rate was analysed. Instantaneous changes in power output and the delayed response from heart rate might influence the intensity distributions. However, no differences between power output and heart rate were found when the total season or low intensity workouts were analysed.

When total training time was subdivided into workout categories relationships of recovery, basic aerobic endurance, strength and non-cycling activities with performance were observed. Workouts applied for the “improvement of strength” were performed mainly as intervals of 2 – 20 min at low cadences (i.e. 40 – 60 $rev \cdot min^{-1}$). The rationale of this method is to increase the applied torque on the crank and consequently the muscular force as a result of the reduced cadence (Paton et al., 2009). In addition, a relationship between the intensity factor for the intervals ($IF_{INT}$) during strength workouts and performance was found. These results suggest that successful riders not only trained more but also more intensively to improve their strength. The strong correlation with seasonal changes in functional threshold power emphasise the importance of these workouts. In addition, the time spent for non-cycling activities was related to performance. This category was not analysed in detail but included activities like running, cross-country skiing and a main part of weight training. It has been shown that weight training can improve performance of trained cyclists (Bastiaans et al., 2001; Yamamoto et al., 2010). It should be noted that no relationships between workout categories and performance were observed when expressed as percentages of total time. This indicates that training time in, but not the distribution of these categories had an influence on performance measures.

One of the main concerns on monitoring power output is the stochastic nature of power during cycling in the field. In fact power output can change from 0 to 1000 $W$ in a few seconds as opposed to the cardiovascular response to that effort. As a measure of this inherent variability the coefficient of variation ($CV$) for every workout category was calculated. The observed $CV$ for the competition category ($68 \pm 6$ %) was significantly higher than the remaining categories (approximately $40 - 50$ %) and emphasises the high variability of cycling races (Stapelfeldt et al., 2004; Vogt et al., 2007a). This difference could be explained by the fact that cycling races are most likely mass start events whereas the majority of training sessions are encountered by the riders alone. The $CVs$ for the training categories were negatively correlated with performance measures ($\dot{V}O_2max$; Functional Threshold Power) as well as with training time. These results indicate that athletes with a higher performance level had less variation of power output during their workouts. While the two world-class cyclists participated in this study exhibit a $CV$ of $20 - 25$ % during basic aerobic endurance workouts the national competitive athletes have shown a $CV$ of $45 - 50$ %. However, it is unclear whether this is the result of a more rigid pacing (i.e. *"keep the power on the desired level"*) or the ability to reduce power fluctuations on a subconscious level. Both could be prerequisites for world-class performance. It could be argued that the experience with power-based training might influence the variability of power output. However, all participants in the present study were proficient users of mobile power meters for several years and therefore the findings are not biased by the experience of the riders. Further studies are needed to confirm this observation and explain the underlying mechanisms.

Mean power output ($Pmean$) across all categories was $2.8 \pm 0.3$ $W \cdot kg^{-1}$ and, with the exception of competition ($3.5 \pm 0.4$ $W \cdot kg^{-1}$), was not significantly different from each other. This finding shows that mean power output is not sensitive to reflect the physiological strain across workouts with different goals (Jobson et al., 2009). In comparison to $Pmean$, normalized power ($NP$) was significantly higher during anaerobic threshold, maximum oxygen uptake and competition workouts. More importantly $NP$ distinguished at least partly, the low intensity from the high intensity workout categories (Figure 28). As a measure of relative exercise intensity the calculated intensity factor (i.e. $Pmean/FTP$) was $0.55 \pm 0.04$ across all categories and was significantly higher during competition ($0.69 \pm 0.06$) and lower during recovery ($0.46 \pm 0.06$) compared to the other categories. The intensities of the intervals performed during anaerobic threshold, maximum oxygen uptake, strength and maximum power workouts, expressed as $IF_{INT}$, ranged from approximately $0.8 - 3.0$. These results suggest that the high intensity efforts encountered during the intervals must be compensated for during the rest period between the intervals and the remaining time of the training session. While mean power outputs were correlated with $\dot{V}O_2max$ and $FTP$, no significant relationships between intensity factors and performance measures were observed. This indicates that elite cyclists adopt a relative exercise intensity independent to their performance. However, $IF_{INT}$ during strength and maximum power intervals were strongly correlated with performance. As discussed for the category strength on page 100, the relative intensity during these intervals was higher for the better athletes. It should be noted that only the four best participants used the category maximum power as a training method. This category was described as the "improvement of maximum power" and consisted of maximum power efforts over $15 - 60$ s. These high intensity efforts were between 8.0 and 16.0 $W \cdot kg^{-1}$ and might be important to initiate or counteract decisive attacks during races (Ebert et al., 2005). To include this kind of exercise could be advantageous for successful competitions.

This study is not without limitations. In a longitudinal study over a complete racing season it is almost impossible to collect data from every training or race. Athletes at elite level have usually more than one bike for their rides and not all of these are equipped with power meters. The majority of the data were sampled during road cycling, which represents the main part of the total training time for all cycling disciplines. However, one mountain-biker and two track cyclists used a second power-meter during their specific workouts. It is currently unclear whether the relationship between power output and heart rate, the distributions into intensity zones and the variability of power output are influenced while riding on different bikes and/or in different terrains. Therefore, larger cohorts are needed to investigate these effects and to identify possible differences of training strategies in the sub-disciplines of cycling.

## 9.5 Conclusion

The results of this longitudinal study provide a comprehensive insight into the training strategies of elite cyclists. It has been shown that both power output and heart rate are valid to describe exercise intensity distribution of a whole season or low intensity workouts. For high intensity intermittent workouts or races the application of heart rate is limited since it didn't accurately reflect the instantaneous changes of power output. The distributions into exercise intensity zones are influenced by the training goal. Cyclists spent the main part of their training time to improve basic endurance. Total training time is increased in the better athletes, whereas the percentages across workout categories are not influenced by performance level. The relative exercise intensity across all cycling training sessions was $\sim 55$ % of Functional Threshold Power and not related to performance level. However, the results show that more successful cyclists performed their intervals during "maximum power" and "strength" sessions with higher relative exercise intensities. In addition, a lower variability of power output in these athletes was observed.

# 10 The Effects of Low and High Cadence Interval Training in the Field on Power Output in Flat and Uphill Cycling Time-Trials

## 10.1 Introduction

The term “interval training” can be characterised as performing repeated bouts of exercise interspersed with recovery periods within a training session. This definition implies that several variables can be modified to describe such training sessions. The modification of number, duration and intensity of the exercise bout, as well as for the recovery phase, affect the impact of the training. The numerous variations of interval training modalities have been reviewed by Billat (2001).

During cycling the crank inertial load depends on the moment of inertia of the flywheel or the rear wheel. It has been shown that at the same power output and cadence, crank inertial load is higher during level ground than during uphill cycling because crank inertia increases as a quadratic function of the gear ratio (Fregly et al., 2000). In addition an increase in crank inertia is accompanied by an increase in peak crank torque and therefore it was suggested that cyclists prefer higher cadences during level cycling to reduce peak crank torque (Hansen et al., 2002). This finding was supported by Lucia et al. (2001c) who reported a significantly lower mean cadence during high mountain passes (71.0 $\pm$ 1.4 $rev \cdot min^{-1}$) than during flat mass start stages (89.3 $\pm$ 1.0 $rev \cdot min^{-1}$) and time-trials (92.4 $\pm$ 1.3 $rev \cdot min^{-1}$) in professional cyclists. During cycling training the pedalling speed or cadence can be manipulated to alter the muscle force applied to the cranks. To change the gear ratio is a unique opportunity for cyclists to influence the force-velocity relationship of the muscular contraction. Depending on the range of the gearshift, a variety of forces and velocities are applicable at constant power output. For example to produce a power output of 300 $W$ with cadences of 60 $rev \cdot min^{-1}$ and 100 $rev \cdot min^{-1}$ requires forces of 281 $N$ and 169 $N$, respectively. With a standard crank length of 172.5 mm the crank torques are 48 $N \cdot m^{-1}$ and 29 $N \cdot m^{-1}$ for 60 $rev \cdot min^{-1}$ and 100 $rev \cdot min^{-1}$, respectively. Therefore, a training stimulus with the same power output but different cadences might result in specific adaptations.

The scientific literature offers a variety of studies investigating performance changes (Burgomaster et al., 2006; Stepto et al., 1999; Westgarth-Taylor et al., 1997), metabolic adaptations (Aughey et al., 2007; Burgomaster et al., 2008, 2005) and skeletal muscle adaptations (Gibala et al., 2006) in response to interval training. The vast majority of interval training studies are conducted on ergometers to control external variables and exercise intensity. However, the differences between laboratory and outdoor cycling have been discussed recently (Jobson et al., 2008a,b) suggesting that the position on the bike, rolling resistance, road gradient, lateral bike movement and flywheel inertia induce different physiological demands during laboratory and outdoor cycling. With the use of mobile power meters exercise intensity can be monitored in the field and therefore can be studied during actual cycling conditions, which improves the ecological validity of the measurements.

Therefore, the purpose of this study was to investigate the effect of a period of interval training applied over 4 weeks during uphill and level cycling at the same relative exercise intensity but different cadences, on power output during a 20-min uphill and flat time-trial. Also, a question raised during study one (chapter 8 on page 75) with regard to whether or not a difference in power output exists between uphill and flat time-trial cycling has been addressed.

## 10.2 Materials and Methods

### 10.2.1 Participants

Eighteen trained cyclists (Table 11) were randomly assigned to one of three groups. Group 1 performed uphill interval training with a cadence of 60 $rev \cdot min^{-1}$ ($\text{Int}_{60}$), group 2 performed level ground interval training with a cadence of 100 $rev \cdot min^{-1}$ ($\text{Int}_{100}$) and group 3 performed no interval training (Con). One participant of the control group became injured and therefore his data from the pre-tests were excluded from further analyses.

Table 11: Characteristics of the riders

| | Group | | |
|---|---|---|---|
| | $\text{Int}_{60}$ ($n$ = 6) | $\text{Int}_{100}$ ($n$ = 6) | Con ($n$ = 5) |
| Age (y) | 30 ± 6.8 | 31 ± 6.9 | 33 ± 7.1 |
| Stature (cm) | 179 ± 3.2 | 177 ± 4.8 | 182 ± 7.0 |
| Body mass (kg) | 70.9 ± 6.4 | 71.5 ± 5.0 | 75.4 ± 4.2 |

Values are means ± $SD$. No significant differences between groups.

The participants had a training history of at least five years and trained for 11.8 ± 2.7 $h \cdot wk^{-1}$ in the last 12 weeks prior to the study. All participants completed a medical examination prior to the study, were informed of the experimental procedures and provided written informed consent to participate. The study was conducted in accordance with the ethical principles of the Declaration of Helsinki (Harris & Atkinson, 2009) and was approved by the institutional ethics committee. During study one (chapter 8 on page 75) the test-retest reliability of power output during 20-min time-trials was investigated. An intraclass correlation coefficient of 0.98 (95 % $CL$: 0.95 to 0.99) and a bias ± random error of − 1.8 ± 14 $W$ or 0.6 ± 4.4 % was found. The smallest worthwhile effect for the present study has been set to 15 $W$. At an estimated power output of 280 $W$ for the subjects in this study, a change of 15 $W$ (5 %) would result in a difference of ± 24 s (2 %) during a 13-km time-trial.

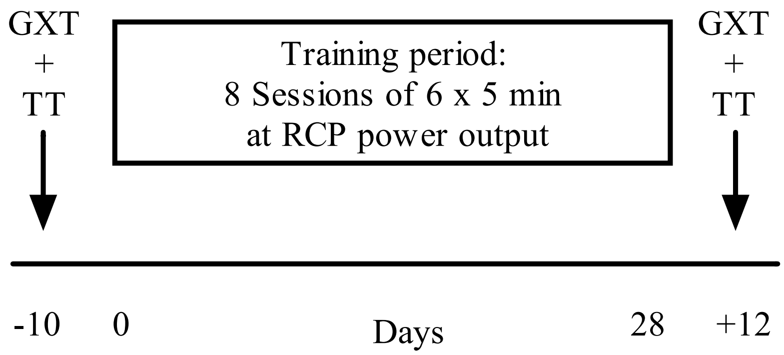



Figure 29: Schematic overview of the general study design. $GXT$ = incremental graded exercise test; TT = time-trial;

Based on these assumptions, it was calculated that it was necessary to have six participants in each group to have a 90 % chance of detecting a mean difference of 15 $W$ at an alpha level of 0.05.

#### 10.2.2 Study Design

During the 10 days preceding the start of the intervention, participants performed an incremental graded exercise test in the laboratory ($GXT$) and two 20-min maximal power time-trials on a level ($TT_{flat}$) and uphill ($TT_{up}$) road. For four weeks both training groups performed two interval training sessions per week, whereas no interval training was conducted for the control group. Between the $7^{th}$ and $12^{th}$ day after the last training session, the $GXT$ and the time-trials were repeated (Figure 29). All participants were provided with a PC spreadsheet to record the time and the rating of perceived exertion for each training (session RPE score $6-20$) (Borg, 1970; Foster et al., 2001) to calculate an integrated training impulse (TRIMP = session RPE x training time) (Banister & Calvert, 1980; Foster et al., 2001).

#### 10.2.3 Laboratory Incremental Graded Exercise Tests

The incremental graded exercise test ($GXT$) was performed as described in chapter 7.1 on page 72. As sub-maximal performance measures ventilatory threshold ($VT$) and respiratory compensation point ($RCP$) were determined (chapter 7.1 on page 72). To determine the maximal blood lactate concentration ($BL_{max}$) blood samples were obtained from the hyperemic ear lobe 1 min post-exercise.

### 10.2.4 Time-Trials

Two 20-min maximal power time-trials were performed on a level ($TT_{flat}$) and uphill ($TT_{up}$) road. The route profiles for the time-trials are shown in Figure 30. The uphill course had a length of 7 km, the altitude at the top was 1000 m and the average gradient was 8.5 %. Since that specific course has been used for cycling competitions before and the best ascending time achieved by a world-class cyclist was 19 min, it was assumed that none of the participants in this study would complete the course faster than the required 20 min. The time-trials were separated by at least 1 h. The order of the first time-trial (i.e. uphill or flat) was randomised during the pre-tests and reversed at the post-tests. A 30-min standardised warm up procedure preceded the time-trials. After 15 min at $40 - 60$ % of $RCP$ power output, three 1-min efforts at $RCP$ power output separated by 2 min and followed by another 6 min at $40 - 60$ % $RCP$, where performed. After the first time-trial, the athletes cycled for 15 min at a self-selected low intensity before they rested for $30 - 40$ min. A warm up of 15 min at $40 - 60$ % of $RCP$ power output preceded the second time-trial.

Power output, heart rate, cadence and speed were recorded at 1 Hz throughout the time-trials using SRM professional power cranks (Schoberer Rad-Messtechnik, Juelich, Germany). Before each trial, the zero offset frequency was adjusted by the investigator according to the manufacturer's instructions. The only information the cyclists received during the time-trials was elapsed time. One minute after completion of each time-trial, a blood sample was obtained from the ear lobe for the determination of blood lactate concentration.

### 10.2.5 Interval Training

The participants in the training groups substituted two training sessions per week, which usually contained $2 - 4$ h steady rides, with interval training. For 4 weeks, both training groups performed 6 x 5 min intervals at an intensity corresponding to $RCP$ power, interspersed with 5 min at $30 - 50$ % of $RCP$ power. It has been shown that 4 to 8 repetitions of aerobic intervals between 4 to 5 min at 80 to 85 % $Pmax$ performed over 3 to 6 weeks is an appropriate stimulus to improve $\dot{V}O_2max$, $Pmax$ and time-trial performance in trained cyclists (Lindsay et al., 1996; Stepto et al., 1999; Westgarth-Taylor et al., 1997). The rest period of 5 min was selected to allow the riders to return to the start.

The same warm up procedure as described for the time-trials was used before the training sessions. According to the group, $Int_{60}$ performed intervals on a climb with an average gradient of 7 % (Figure 31) and with a cadence of 60 $rev \cdot min^{-1}$, whereas participants in the $Int_{100}$ group accomplished their training on a flat road with a cadence of 100 $rev \cdot min^{-1}$. All training sessions were recorded with SRM power cranks as described above. During the $1^{st}$, $4^{th}$ and $8^{th}$ training, blood samples were taken after each bout for the determination of blood lactate concentration. The control group continued

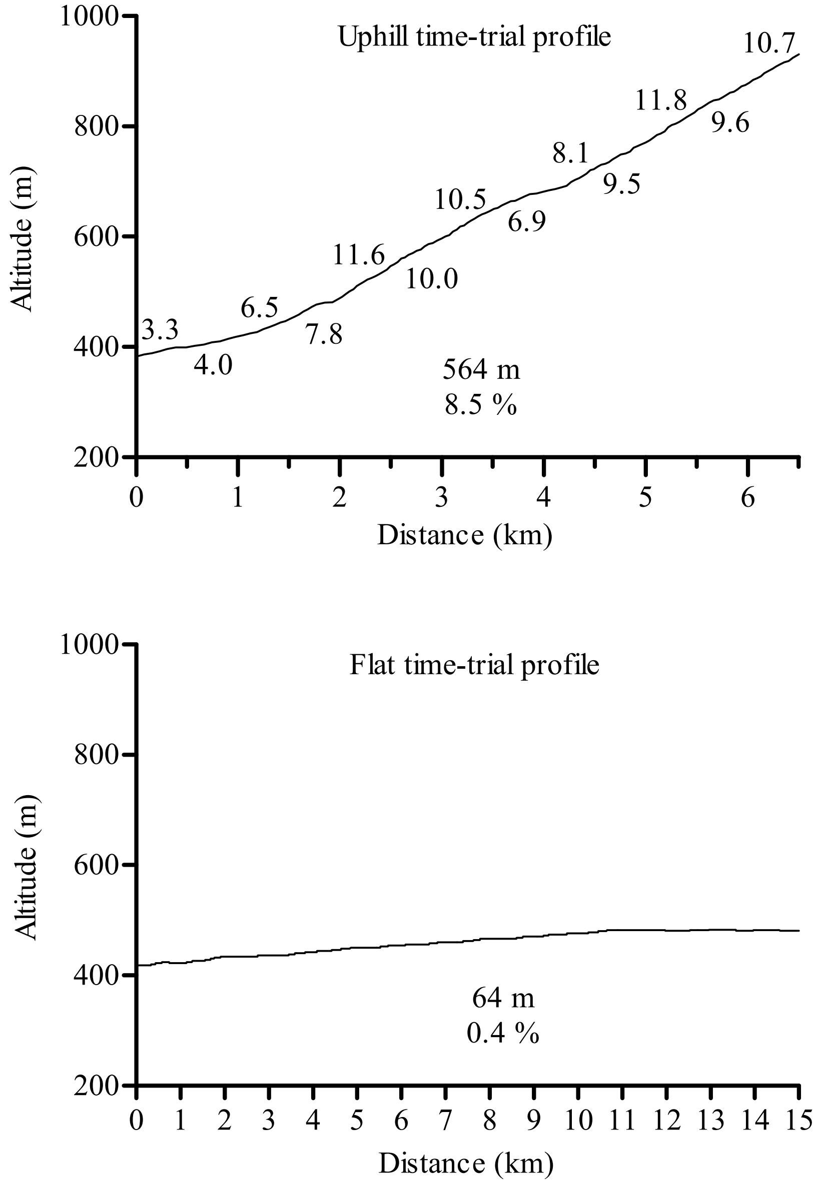



Figure 30: Route profiles for the uphill (upper panel) and flat time-trial (lower panel). Numbers for the average gradient of every 500 m section are shown on the upper panel.

with their steady training but no interval training was permitted throughout the 4 weeks.

### 10.2.6 Data Analyses

Descriptive data are shown as mean ± standard deviation (*SD*) and 95 % confidence limits (*CL*). After the assumption of normality was verified using Kolmogorov-Smirnov's test and Liliefors probability, a three-factor mixed ANOVA was used to analyse power output, cadence, torque, heart rate and blood lactate concentration during the time-trials [Group ($Int_{60}$ vs. $Int_{100}$ vs. Con) x Time (pre vs. post) x Route ($TT_{up}$ vs. $TT_{flat}$)] and to analyse heart rates and blood lactate concentrations measured during the training [Group ($Int_{60}$ vs. $Int_{100}$) x Training ($1^{st}$ vs. $4^{th}$ vs. $8^{th}$) x Interval (1 to 6)]. Results from the incremental graded exercise test before and after the intervention, as well as the weekly training time before and during the intervention, were compared with a two-factor mixed ANOVA [Group ($Int_{60}$ vs. $Int_{100}$ vs. Con) x Time (pre vs. post)]. Differences between the groups for TRIMP and RPE scores were assessed with a one-way ANOVA. Significant interactions and main effects were identified with a Tukey's HSD post hoc test. Effect sizes are reported as partial Eta-squared ($\eta_P^2$) and considered as small (0.01), moderate (0.1) and large (0.25) effects (Cohen, 1988). Relationships between variables were examined with Pearson's product moment correlations. For all statistical analyses the level of significance was set at $p < 0.05$.

## 10.3 Results

### 10.3.1 Training Records

There was no significant difference in training time between the three groups ($F_{2,14} = 2.1; p = 0.15$; $\eta_P^2 = 0.23$; Con: 10.4 ± 2.7 $h \cdot wk^{-1}$; 95 % *CL*: 7.1 to 13.8; $Int_{100}$: 13.3 ± 2.0 $h \cdot wk^{-1}$; 95 % *CL*: 11.2 to 15.4; $Int_{60}$: 12.8 ± 2.8 $h \cdot wk^{-1}$; 95 % *CL*: 9.8 to 15.7). There was a small (0.5 ± 0.4 $h \cdot wk^{-1}$; 95 % *CL*: 0.15 to 0.86) but significant ($F_{1,14} = 9.1$; $p < 0.01$; $\eta_P^2 = 0.39$) increase in training time during the intervention in comparison to the 12 weeks before the study. The mean session RPE scores were significantly higher ($F_{2,14} = 10.1$; $p < 0.01$; $\eta_P^2 = 0.59$) for $Int_{100}$ (13.7 ± 0.6; 95 % *CL*: 13.0 to 14.3) and $Int_{60}$ (13.7 ± 0.7; 95 % *CL*: 13.1 to 14.4) than for Con (11.9 ± 1.0; 95 % *CL*: 10.7 to 13.1). In addition the TRIMP scores were significantly higher ($F_{2,14} = 6.9$; $p < 0.01$; $\eta_P^2 = 0.5$) for $Int_{100}$ (42812 ± 6409; 95 % *CL*: 36086 to 49537) and $Int_{60}$ (40666 ± 7370; 95 % *CL*: 32932 to 48399) compared to Con (28119 ± 7126; 95 % *CL*: 19271 to 36968).

### 10.3.2 Laboratory Incremental Graded Exercise Test

The results of the incremental exercise tests are presented in Table 12. A significant main effect of time was observed for $Pmax$ ($F_{1,14} = 14.5$; $p < 0.01$; $\eta_P^2 = 0.51$), power output ($F_{1,14} = 4.8$; $p <$

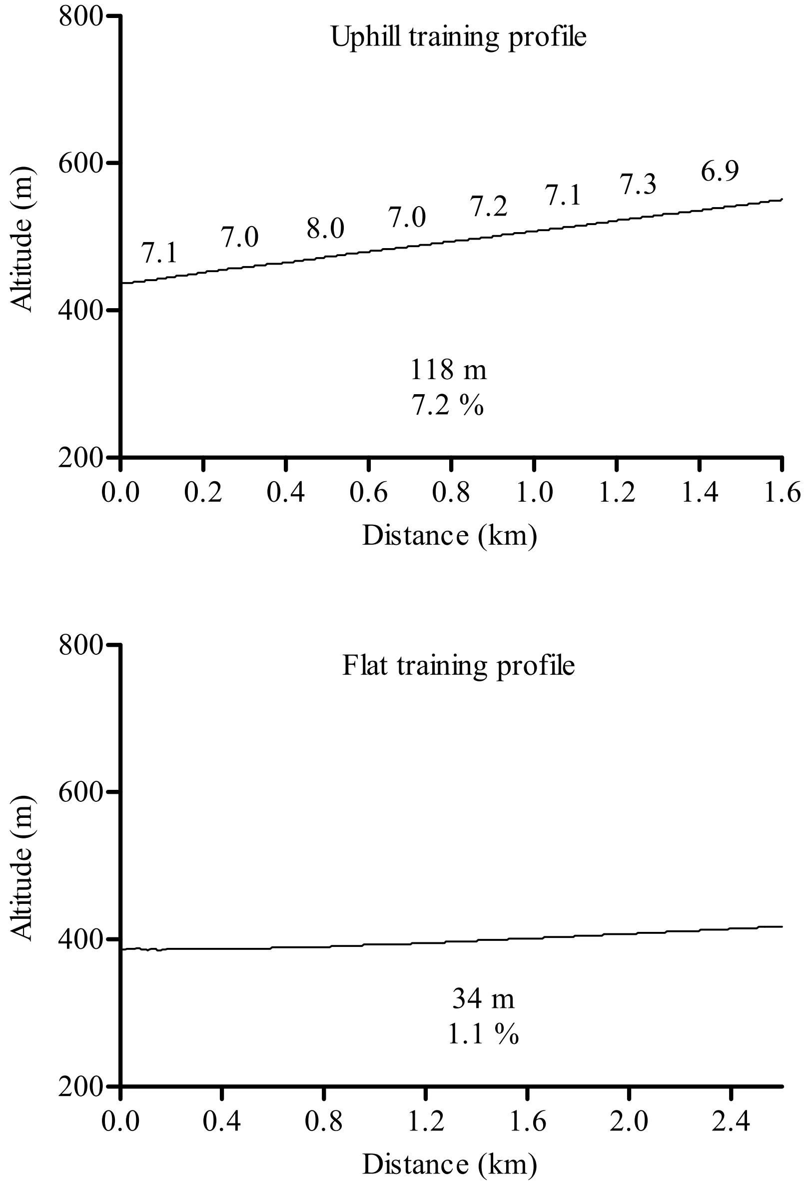



Figure 31: Route profiles for the uphill (upper panel) and flat training (lower panel). Numbers for the average gradient of every 200 m section are shown on the upper panel.

0.05; $\eta_P^2 = 0.26$) and oxygen uptake ($F_{1,14} = 5.3$; $p < 0.05$; $\eta_P^2 = 0.27$) at $RCP$ and for oxygen uptake at $VT$ ($F_{1,14} = 14.1$; $p < 0.01$; $\eta_P^2 = 0.5$). After the training $Pmax$, power output and oxygen uptake at $RCP$ and oxygen uptake at $VT$ increased by 2.8 ± 3.0 % (95 % $CL$: 1.2 to 4.4), 3.6 ± 6.3 % (95 % $CL$: 0.3 to 6.8), 4.7 ± 8.2 % (95 % $CL$: 0.5 to 8.9) and 4.9 ± 5.6 % (95 % $CL$: 2.2 to 7.8), respectively. No significant interactions of group x time ($p = 0.48$ to 0.77; $\eta_P^2 = 0.1$ to 0.04) were observed.

Table 12: Results from the $GXT$ before and after the training intervention (mean ± $SD$)

| | Group | | |
|---|---|---|---|
| Measure | $Int_{60}$ | $Int_{100}$ | Con |
| Pre $Pmax$ ($W$) | 392 ± 21 | 391 ± 57 | 394 ± 31 |
| 95 % $CL$ | 370 − 414 | 331 − 451 | 355 − 433 |
| Post $Pmax$ ($W$) * | 400 ± 16 | 402 ± 61 | 408 ± 34 |
| 95 % $CL$ | 383 − 418 | 338 − 466 | 365 − 450 |
| Pre $\dot{V}O_2max$ ($mL \cdot min^{-1} \cdot kg^{-1}$) | 61.1 ± 5.0 | 58.8 ± 6.0 | 55.4 ± 4.3 |
| 95 % $CL$ | 55.9 − 66.4 | 52.5 − 65.1 | 50.1 − 60.7 |
| Post $\dot{V}O_2max$ ($mL \cdot min^{-1} \cdot kg^{-1}$) | 60.8 ± 3.3 | 60.1 ± 7.7 | 57.2 ± 5.2 |
| 95 % $CL$ | 57.3 − 64.3 | 52.0 − 68.1 | 50.7 − 63.7 |
| Pre $RCP$ ($W$) | 297 ± 11 | 304 ± 55 | 298 ± 36 |
| 95 % $CL$ | 286 − 308 | 246 − 361 | 253 − 342 |
| Post $RCP$ ($W$) * | 311 ± 21 | 316 ± 59 | 301 ± 37 |
| 95 % $CL$ | 289 − 333 | 255 − 378 | 256 − 347 |
| Pre $RCP$ ($mL \cdot min^{-1} \cdot kg^{-1}$) | 50.4 ± 4.8 | 48.6 ± 6.3 | 45.2 ± 5.2 |
| 95 % $CL$ | 45.3 − 55.4 | 41.9 − 55.2 | 38.7 − 51.7 |
| Post $RCP$ ($mL \cdot min^{-1} \cdot kg^{-1}$) * | 51.5 ± 5.0 | 51.6 ± 6.6 | 47.2 ± 3.7 |
| 95 % $CL$ | 46.3 − 56.8 | 44.7 − 58.5 | 42.6− 51.8 |
| Pre $VT$ ($W$) | 190 ± 21 | 199 ± 38 | 187 ± 21 |
| 95 % $CL$ | 168 − 212 | 160 − 239 | 160 − 213 |
| Post $VT$ ($W$) | 198 ± 11 | 200 ± 36 | 187 ± 26 |
| 95 % $CL$ | 186 − 209 | 162 − 238 | 155 − 219 |
| Pre $VT$ ($mL \cdot min^{-1} \cdot kg^{-1}$) | 35.7 ± 3.1 | 35.3 ± 5.2 | 30.7 ± 3.8 |
| 95 % $CL$ | 32.5 − 38.9 | 29.9 − 40.8 | 26.1− 35.4 |
| Post $VT$ ($mL \cdot min^{-1} \cdot kg^{-1}$) * | 37.4 ± 3.6 | 36.4 ± 4.5 | 32.9 ± 3.8 |
| 95 % $CL$ | 33.6 − 41.2 | 31.7 − 41.0 | 28.1− 37.6 |

$P$ = power output; $\dot{V}O_2$ = oxygen uptake; $VT$ = ventilatory threshold; $RCP$ = respiratory compensation point; $CL$ = confidence limit; * $p < 0.05$; main effect of time (post > pre)

### 10.3.3 Time-Trials

A significant main effect of the route was found on power output ($F_{1,14} = 25.3$; $p < 0.001$; $\eta_P^2 = 0.64$), cadence ($F_{1,14} = 651.5$; $p < 0.001$; $\eta_P^2 = 0.98$), torque ($F_{1,14} = 296.8$; $p < 0.001$; $\eta_P^2 = 0.96$), heart rate ($F_{1,14} = 57.1$; $p < 0.001$; $\eta_P^2 = 0.8$) and blood lactate concentration ($F_{1,14} = 17.5$; $p < 0.001$; $\eta_P^2 = 0.56$). Power output was significantly higher during uphill time-trials, which was accompanied by significantly higher heart rates and blood lactate concentrations (Table 13). ANOVA revealed a significant main effect of time on heart rate ($F_{1,14} = 8.5$; $p < 0.05$; $\eta_P^2 = 0.38$) (post < pre). No significant main effects of group ($p = 0.39$ to 0.88; $\eta_P^2 = 0.13$ to 0.02) were observed.

Table 13: Power output and physiological measures during the time-trials before and after the training intervention (mean ± $SD$)

| | Group | | | | | |
|---|---|---|---|---|---|---|
| | Int$_{60}$ | | Int$_{100}$ | | Con | |
| Measure | TT$_{up}$ | TT$_{flat}$ | TT$_{up}$ | TT$_{flat}$ | TT$_{up}$ | TT$_{flat}$ |
| Pre $P$ | | | | | | |
| $(W)$ * | 307 ± 14 | 295 ± 15 | 314 ± 47 | 299 ± 48 | 302 ± 29 | 292 ± 18 |
| 95 % $CL$ | 292 − 322 | 280 − 310 | 265 − 363 | 248 − 349 | 266 − 339 | 269 − 315 |
| Post $P$ | | | | | | |
| $(W)$ * | 321 ± 20 | 300 ± 25 | 310 ± 49 | 306 ± 49 | 314 ± 26 | 283 ± 30 |
| 95 % $CL$ | 299 − 342 | 274 − 326 | 259 − 361 | 255 − 357 | 281 − 347 | 245 − 320 |
| Pre $HR$ | | | | | | |
| $(b \cdot min^{-1})$ * | 180 ± 8 | 178 ± 13 | 177 ± 7 | 174 ± 7 | 177 ± 10 | 174 ± 10 |
| 95 % $CL$ | 171 − 189 | 164 − 191 | 169 − 185 | 166 − 181 | 164 − 189 | 161 − 186 |
| Post $HR$ | | | | | | |
| $(b \cdot min^{-1})$ * | 179 ± 8 | 174 ± 8 | 176 ± 7 | 173 ± 8 | 173 ± 8 | 168 ± 9 |
| 95 % $CL$ | 171 − 187 | 165 − 182 | 168 − 183 | 164 − 181 | 163 − 183 | 157 − 178 |
| Pre $BL$ | | | | | | |
| $(mmol \cdot L^{-1})$ * | 10.0 ± 2.7 | 9.7 ± 2.5 | 9.2 ± 2.3 | 8.1 ± 2.3 | 9.1 ± 2.7 | 8.4 ± 0.9 |
| 95 % $CL$ | 6.3 − 13.6 | 7.1 − 12.2 | 6.8 − 11.6 | 5.6 − 10.5 | 5.8 − 12.5 | 7.3 − 9.5 |
| Post $BL$ | | | | | | |
| $(mmol \cdot L^{-1})$ * | 11.2 ± 2.6 | 9.5 ± 2.8 | 8.9 ± 2.1 | 7.9 ± 2.0 | 10.3 ± 1.6 | 7.6 ± 1.4 |
| 95 % $CL$ | 8.4 − 13.9 | 6.6 − 12.4 | 6.7 − 11.1 | 5.8 − 10.0 | 8.4 − 12.3 | 5.8 − 9.4 |

$P$ = power output; $HR$ = heart rate; $BL$ = blood lactate concentration; $CL$ = confidence limit; * $p < 0.001$; main effect of route (uphill > flat)

Significant time x route x group interactions on power output were observed ($F_{2,14} = 6.2$; $p < 0.05$; $\eta_P^2 = 0.47$) (Figure 32). These indicate that both interval training groups increased power output after the training during the flat time-trial (Int$_{100}$: 2.6 ± 6.0 %; − 3.7 to 8.9 and Int$_{60}$: 1.5 ± 4.5 %; − 3.2 to 6.2) in contrast to the control group (− 3.5 ± 5.4 %; − 10.1 to 3.2). Power output during the uphill time-trial was increased after the training for Int$_{60}$ (4.4 ± 5.3 %; − 1.2 to 9.9) and Con (4.0 ± 4.6 %; − 1.7 to 9.8) but not for Int$_{100}$ (− 1.3 ± 3.6 %; − 5.1 to 2.4). All three groups showed higher power outputs before the intervention during the uphill time-trial (Con: 3.4 ± 6.6 %; − 4.8 to 11.6, Int$_{100}$: 5.4 ± 5.8 %; − 0.7 to 11.5 and Int$_{60}$: 4.4 ± 6.7 %; − 2.7 to 11.4). Post training power output was still higher during the uphill time-trial. The difference to the flat time-trial increased for Int$_{60}$ (7.2 ± 4.9 %; 2.0 to 12.3) due to a higher increase of power output during the uphill time-trial in comparison to the flat time-trial. Also the control group increased the difference between the uphill and the flat time-trial (11.4 ± 4.6 %; 5.7 to 17.1). However, this was the result of both an increase and decrease in power output during the uphill and flat time-trial, respectively. Finally, the Int$_{100}$ group reduced the difference (1.3 ± 2.0 %; − 0.8 to 3.4). This was attributed to an increase and decrease in power output during the flat and uphill time-trial conditions, respectively. In Figure 33 and Figure 34 the individual responses of the intervention on power output are presented.

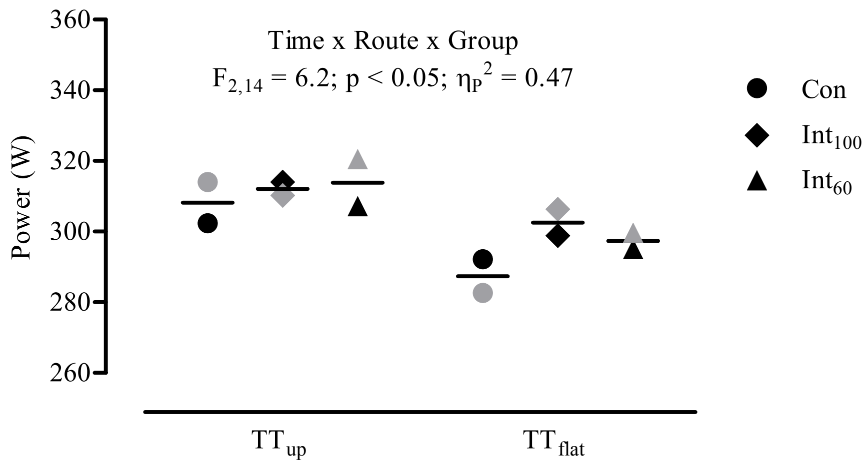



Figure 32: Interactions between the factors time x route x group on power output during uphill and flat time-trials. Black figures indicates pre training, grey figures post training.

Power outputs during the pre- and post-training uphill time-trials were strongly correlated with $Pmax$ ($r$ = 0.92 and 0.91; $p < 0.001$), $RCP$ ($r$ = 0.9 and 0.85; $p < 0.001$) and time-trial cadence ($r$ = 0.71 and 0.72; $p < 0.01$). Also, the velocities during the pre- and post-training uphill time-trials were strongly correlated with $Pmax$ ($r$ = 0.71 and 0.74; $p < 0.001$), $\dot{V}O_2max$ ($r$ = 0.8 and 0.88; $p < 0.001$), $RCP$ ($r$ = 0.85 and 0.72; $p < 0.001$ and 0.01), uphill time-trial power output ($r$ = 0.71 and 0.74; $p < 0.01$) and time-trial cadence ($r$ = 0.78 and 0.79; $p < 0.001$). For the pre- and post-training flat time-trials strong correlations between power outputs and $Pmax$ ($r$ = 0.86 and 0.88; $p < 0.001$) and $RCP$ ($r$ = 0.84 and 0.88; $p < 0.001$) were observed, whereas a moderate correlation with cadences were found ($r$ = 0.69 and 0.45; $p < 0.01$ and $p = 0.07$). In addition, the correlations between velocities and performance measures were non-significant or moderate for the pre training time-trials ($r = 0.36$; $p = 0.14$ for $Pmax$; $r = 0.38$; $p = 0.14$ for $\dot{V}O_2max$; $r = 0.53$; $p < 0.05$ for $RCP$; $r = 0.52$; $p < 0.05$ for flat time-trial power output and $r = 0.43$; $p = 0.08$ for cadence). However, post training these correlations were stronger for $Pmax$ ($r = 0.76$; $p < 0.001$), $\dot{V}O_2max$ ($r = 0.76$; $p < 0.001$), $RCP$ ($r = 0.82$; $p < 0.001$), flat time-trial power output ($r = 0.79$; $p = 0.001$) and cadence ($r = 0.57$; $p = 0.05$).

### 10.3.4 Interval Training

As the assumption of sphericity was violated for the factor interval (Mauchly's test: $\chi^2$ (14) = 71.4; $p < 0.001$), the degrees of freedom were adjusted (Greenhouse-Geisser: $\epsilon = 0.26$). A significant main effect of interval was observed for heart rate ($F_{1.3,\,13.1} = 16.3$; $p < 0.001$; $\eta_P^2 = 0.62$). Heart rate significantly increased during the intervals (Figure 35). No significant main effect of interval was found

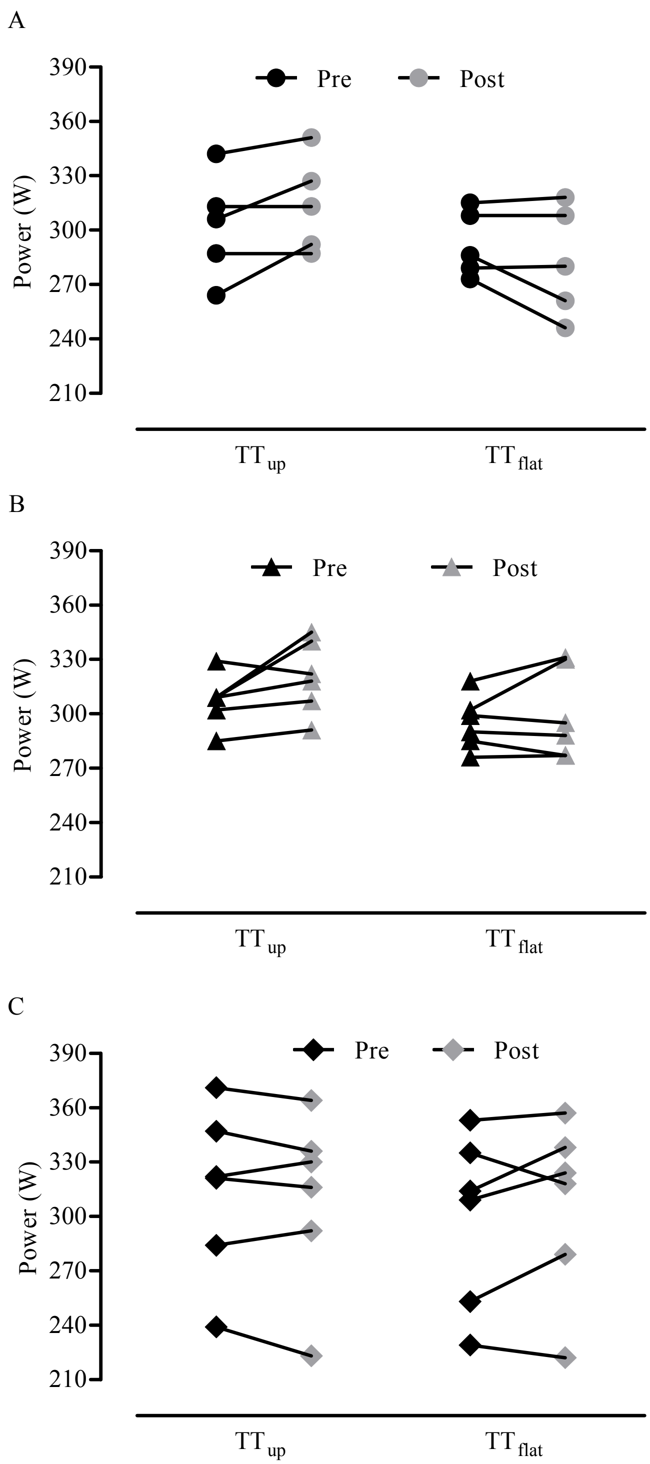



Figure 33: Individual responses on power output during uphill and flat time-trials. A = Control; B = $Int_{60}$; C = $Int_{100}$. Significant main effect of route (uphill > flat, $p < 0.001$; $\eta_P^2 = 0.64$). Significant interactions of time x route x group ($p < 0.05$; $\eta_P^2 = 0.47$).

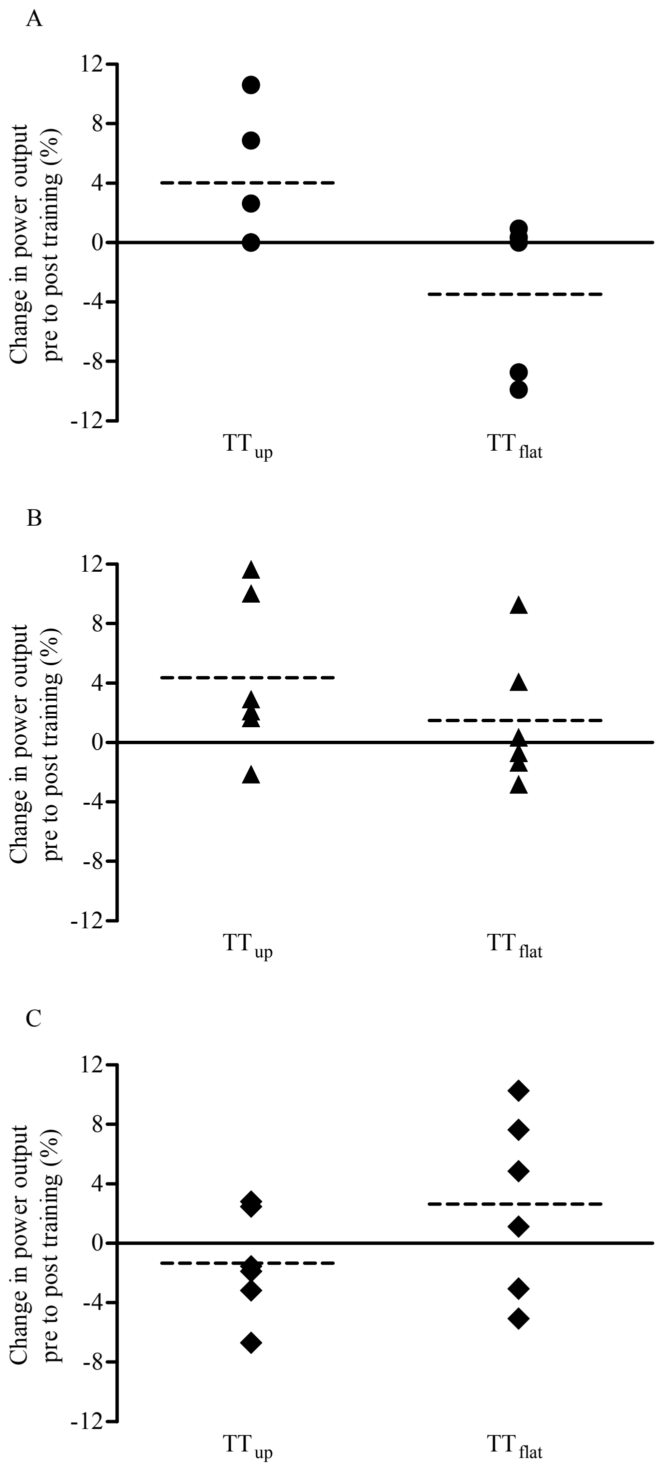



Figure 34: Individual pre to post training changes. Dotted lines represent mean values. A = Control; B = $Int_{60}$; C = $Int_{100}$.

for the blood lactate concentration (($F_{1.3,\,12.7} = 1.1$; $p = 0.36$; $\eta_P^2 = 0.09$) (Figure 35). In addition, no significant main effects of group ($p = 0.68$ to 0.95; $\eta_P^2 = 0.04$ to 0.01), training ($p = 0.23$ to 0.83; $\eta_P^2 = 0.13$ to 0.04) and interactions of group x training x interval ($p = 0.39$ to 0.99; $\eta_P^2 = 0.1$ to 0.01) were observed. The coefficients of variation ($CV$) of power output and cadence between the training sessions ($n = 8$) were 1.1 ± 0.3 % and 1.6 ± 0.3 % for $Int_{60}$ and 1.5 ± 0.3 % and 1.2 ± 0.2 % for $Int_{100}$. Between the intervals ($n = 48$) the $CVs$ of power output and cadence were 1.5 ± 0.6 % and 2.4 ± 1.1 % vs. 2.4 ± 1.0 % and 1.5 ± 0.5 % for $Int_{60}$ and $Int_{100}$, respectively.

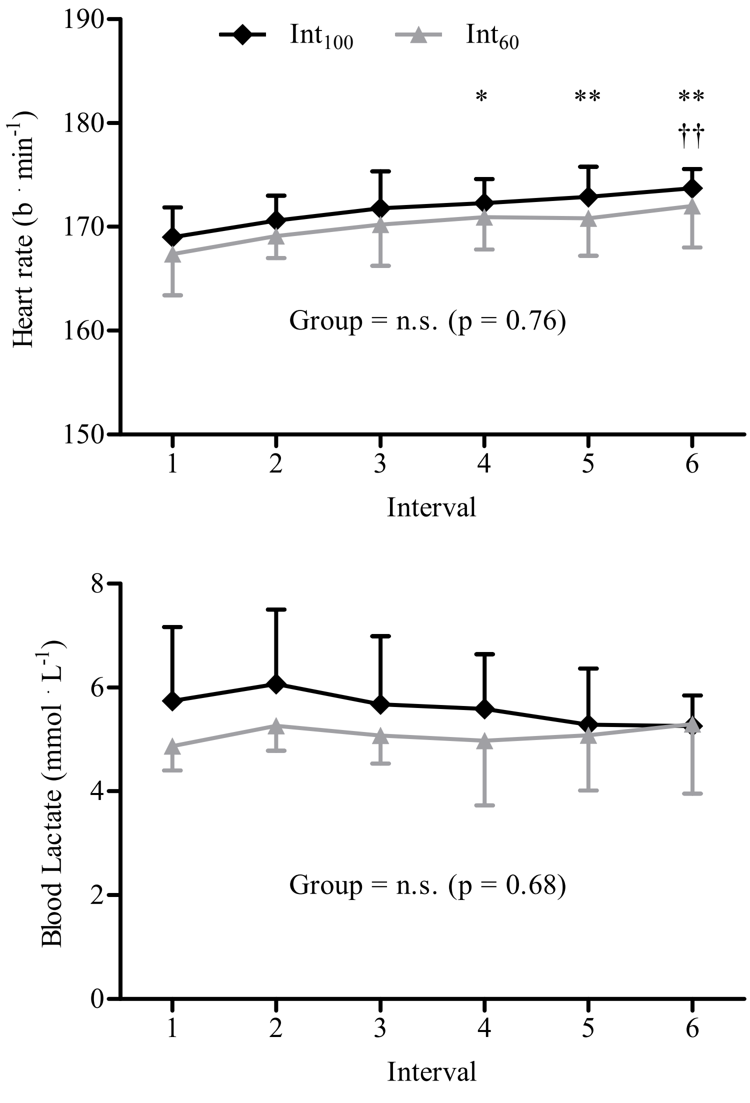



Figure 35: Heart rate (upper panel) and blood lactate (lower panel) profiles during the interval trainings. Error bars represents 95 % $CL$. * significantly different from interval 1 at $p < 0.05$ and ** at $p < 0.01$; †† significantly different from interval 2 at $p < 0.01$; n.s. = not significant.

## 10.4 Discussion

To the best of the author's knowledge, this was the first study that investigated the effects of aerobic interval training at different terrains and cadences in the field, on performance during incremental graded exercise tests and time-trials. The new findings indicate that substituting two continuous endurance training sessions per week over four weeks with interval training on a level-ground or uphill course, has no additional benefit on performance measures obtained from a $GXT$ in well-trained cyclists. However, the magnitude of changes in power output during uphill and flat time-trials significantly differed between the training groups. This suggests that specific field-tests should be favored to reveal adaptations to a specific training strategy. In addition, it was shown that power output during a 20-min uphill time-trial was higher compared to a flat time-trial.

In the present study, no significant differences in the performance improvements assessed during a laboratory incremental graded exercise test between the two interval training groups and the control group were observed. Although the total training time was not significantly different between the groups, the TRIMP and the session RPE scores were significantly higher for the interval groups. This finding indicates the importance of training volume as a main stimulus for endurance athletes as discussed in chapter 9.4 on page 99 (Jobson et al., 2009) and that an increase of exercise intensity does not necessarily enhance performance gains.

While several studies have reported the physiological and performance adaptations in response to various interval training modes, the effects of cadence during such intervals remained to be shown. The author is aware of only one study that compared the effects of low cadence ($60-70\ rev \cdot min^{-1}$) and high cadence ($110-120\ rev \cdot min^{-1}$) during 30 s sprint interval training on performance (Paton et al., 2009). In the latter study, the performance gains (i.e. $Pmax$, $\dot{V}O_2max$ and power output at 4 $mmol \cdot L^{-1}$ blood lactate) were higher for the low cadence group ($6-11$ %) in comparison to the high cadence group ($2-3$ %), which was attributed to a higher testosterone concentration in response to higher pedal forces in the low cadence group (Paton et al., 2009).

In contrast to the results of the $GXT$ in the present study, a significant interaction of time x route x group was observed for time-trial power output. According to Bertucci et al. (2005a), who concluded that "*... it appears necessary to train in specific conditions (uphill road cycling and level ground, low and high cadences) in order to develop these specific muscular adaptations ...*" (*p 1008*), the two interval training groups in the present study showed higher performance improvements on the terrain where the interval training sessions were performed ($\text{Int}_{100}$: 2.6 ± 6.0 % and -1.3 ± 3.6 % for flat and uphill time-trial power output, respectively; $\text{Int}_{60}$: 4.4 ± 5.3 % and 1.5 ± 4.5 % for uphill and flat time-trial power output, respectively). The magnitude of the improvements and the fact that the $\text{Int}_{60}$ group increased power output during both, uphill and flat time-trials supported the results of Paton et al. (2009), that low-cadence interval training is potentially superior to high-cadence intervals. This was emphasised by the findings of the longitudinal study of this thesis (chapter 9.4 on page 100) where the training time spent to improve strength (i.e. intervals of $2 - 20$ min at $40 - 60\ rev \cdot min^{-1}$) was strongly correlated with the classification of the riders ($r = -0.86$; $p < 0.01$) and the intensity of these intervals was related to 20-min time-trial power output ($r = 0.88$; $p < 0.01$) and $\dot{V}O_2max$ ($r = 0.89$; $p < 0.01$). Although the underlying mechanisms are not entirely clear, possible explanations are: 1) at any given power output, low cadences require higher forces which 2) increases neuromuscular fatigue, as indicated by an increase of root mean-square EMG in the vastus lateralis and glutaeus maximus muscles at high power outputs (i.e. $> 300\ W$) (Lucia et al., 2004b). To generate and sustain higher forces suggests 3) an additional recruitment of type II fibres which have been shown to be more efficient at higher contraction velocities than type I fibres (Sargeant, 1994) and 4) increases in testosterone (Paton et al., 2009) and human growth hormone (Lafortuna et al., 2003) concentrations.

It might be argued that low-cadence training does not comply with observations from recent studies (Lucia et al., 2004b; Vercruyssen & Brisswalter, 2010) that have shown freely chosen cadences between $90 - 100\ rev \cdot min^{-1}$ in trained cyclists at high power outputs. However, a low cadence strategy during some high-intensity intervals and the associated benefits, is not contrary to a higher freely chosen cadence. Moreover, this observation underpins a basic training principle that taxing a physiological system during exercise is necessary to improve performance. It should be noted that the control group also increased power output during the uphill time-trial by $4.0 \pm 4.6$ %, but not during the flat time-trial ($-3.5 \pm 5.4$ %). Even after revisiting the diaries, no explanation for this adaptation in the control group is evident. Further studies are required to evaluate this finding.

This study also showed for the first time, that trained cyclists are able to produce significantly higher power outputs during uphill than flat time-trials of the same duration. This was observed in both the pre- and post-training conditions ($4.4 \pm 6.0$ % and $6.4 \pm 5.6$ %, respectively). The higher power outputs were accompanied by higher cardiovascular and metabolic responses and indicates a higher physiological strain during uphill time-trials (Padilla et al., 2000b). These results extend the findings of study one of this thesis (chapter 8 on page 75) where flat time-trial power output was strongly correlated with $GXT$ measures ($p < 0.001$) and not significantly different from the power output at $RCP$ ($p = 0.97$). The strong correlations between uphill and flat time-trial power outputs and $GXT$ measures observed in the present study are in agreement with previous studies (Balmer et al., 2000a). The velocities during the uphill time-trials were strongly related to $GXT$ measures and uphill time-trial power outputs, whereas the relationships between flat time-trial velocities and performance measures are much more variable (Jobson et al., 2009). This indicates that velocity, especially on flat terrain, is largely influenced by external conditions (e.g. aerodynamics, rolling resistance) and therefore should be used with caution as performance measure especially in repeated measure study designs.

Finally, the low $CVs$ observed for power output and cadence between 8 training sessions and 48 intervals indicate that the 12 participants completed the required task accurately. This observation shows that trained cyclists are able to control both variables within a narrow range despite the fact that nine of the athletes had no prior experience with mobile power meters. The cardiovascular and metabolic response was slightly but not significantly higher for the $\text{Int}_{100}$ compared to the $\text{Int}_{60}$ training groups. This finding is supported by Vercruyssen et al. (2005) who reported significantly lower heart rates and blood lactate concentrations at lower cadences in triathletes, but in contrast to Lucia et al. (2004b) who reported the opposite in professional cyclists. It was concluded that the higher efficiency at a high cadence is one of the main adaptations of professional cyclists (Lucia et al., 2004b).

The present study is not without limitations. By design, the study aimed to replicate an outdoor cycling interval training situation which is usually completed on a certain route in an out-and-back direction. Consequently, the rest periods between the intervals were longer than in comparable studies with a laboratory set-up (Stepto et al., 2001; Weston et al., 1997). The current study had a limited number of SRM devices and therefore it was not possible to complete the entire study at exactly the same time of the year for all athletes. Data sampling was conducted from May to August in three stages. Although two riders of each group were allocated to the three stages the possibility that a small seasonal performance change may have affected the results cannot be eliminated (chapter 9.3.1 on page 91).

## 10.5 Conclusion

This study has shown that interval training on level-ground or uphill roads, at high or low cadences, leads to similar significant performance gains during a laboratory graded exercise test as those which may be observed after a continuous aerobic endurance training intervention. However, the performance improvements during uphill and flat 20-min time-trials have shown specific adaptations in response to the interval training sessions and indicate the ecological validity of the time-trials. The magnitude of these improvements suggests that the application of higher pedalling forces via low cadences provides a potentially higher training stimulus with a cross-over effect to flat time-trials. High-cadence intervals on level ground are more likely to enhance flat time-trial power output with no cross-over to uphill time-trials. When evaluating power output data or prescribing training zones, it is important to note that trained cyclists are able to produce higher power outputs during uphill compared to flat time-trial conditions.

# Part IV

# Summary

## 11 General Discussion

In the present thesis training and performance-related data of elite athletes who successfully competed in national or international events have been presented to establish a framework for the use of mobile power meters. One of the purposes was to evaluate an "easy-to-use" field test for the assessment of endurance performance. It was found that the field test presented here was reliable and valid to predict results from a laboratory exercise test. A comprehensive amount of training data measured across a whole competitive season, have improved the knowledge of training strategies of elite athletes. The key findings were that performance improvements across the season were related to low-cadence strength workouts and that better athletes trained at higher intensities at these workouts. In addition, better athletes had lower variation in power output during their training sessions. The influence of different cadences during interval training revealed that low-cadence intervals are potentially beneficial to improve performance.

The following sections will summarise and put together the results from the experimental chapters.

### 11.1 Maximum Power Field Tests

**Reliability of the Field Tests** The 4-min (TT4) and 20-min (TT20) maximum power field tests presented in this thesis were characterised by high test-retest reliability ($-\ 0.2 \pm 5.5$ % and $0.6 \pm 4.4$ % for TT4 and TT20, respectively). In addition, the predictive validity, expressed as standard error of estimates, between power output during the field tests and laboratory tests was found to be 17 to 21 $W$. Amann et al. (2004) recently investigated the reliability of ventilatory thresholds and the correlations with a 40 km laboratory time-trial. The authors reported a high test-retest reliability (intraclass correlation coefficient of $0.87 - 0.98$) and predictive validity of 15 to 24 $W$ between ventilatory thresholds and the 40-km time-trial.

The incremental field tests described in section 4.3 on page 61 (Padilla et al., 1996; Gonzalez-Haro et al., 2007) requires constant velocity over a given time or distance and consequently standardised test conditions. The field test evaluated in the present study require very limited standardisation of conditions and therefore can be used by athletes alone (see riders instructions in Appendix 12.3 on page 146). This is an important practical consideration since most athletes spent the biggest part of their training alone and therefore a valid and reliable field test can be useful to monitor performance progresses. In contrast to an incremental test, the field test used was a performance test which has probably a higher functional validity (Burnley et al., 2006; Vanhatalo et al., 2007a).

Although a high reliability is a prerequisite for any test a high agreement with results from laboratory incremental tests would enhance the strength of the tests.

**Relation Between Laboratory and Field Tests** The times of 4 min and 20 min have been chosen as a result of previous studies (Bentley et al., 2001b; Billat et al., 1996). These studies have demonstrated that power output at $\dot{V}O_2max$ and at 90 % of $\dot{V}O_2max$ can be sustained for approximately 4 min and 20 min, respectively (Bentley et al., 2001b; Billat et al., 1996).

It was hypothesised that power output during the 4-min time-trial would agree with *Pmax* obtained from the incremental laboratory test. However, a significant difference was found (− 7.4 ± 14 %; $p < 0.001$). As discussed, the protocol of the incremental test can influence *Pmax* (Davis et al., 1982) and consequently the relationship with the 4-min time-trial. Several studies have shown the relationship between time-trial performance and laboratory variables. While in some of the studies time to complete a given distance have been used as the performance marker (Anton et al., 2007; Bentley et al., 1998; Lucia et al., 2004a; Smith et al., 1999), others have related time-trial power to laboratory variables (Amann et al., 2006; Balmer et al., 2000a; Bentley et al., 2001b; Tan & Aziz, 2005). It has been shown that performance in flat time-trials is correlated with *Pmax* (Anton et al., 2007; Balmer et al., 2000a; Bentley et al., 2001b; Tan & Aziz, 2005) as well as with $\dot{V}O_2max$ (Bentley et al., 1998). In addition sub-maximal thresholds were found to be strongly related to flat time-trial performance in the studies of Amann et al. (2006) and Lucia et al. (2004a). In other endurance sports like running (Grant et al., 1997) or rowing (Ingham et al., 2002) similar relationships were observed. Since mass is the major contributor to gravitational resistance (di Prampero, 2000; Mognoni & di Prampero, 2003) it has been shown that maximal and sub-maximal values scaled to body mass are related to uphill cycling performance (Anton et al., 2007; Davison et al., 2000; Heil, 1998; Nevill et al., 2006; Tan & Aziz, 2005). The results of the present study are in agreement with the existing literature. Correlation coefficients between power output during the 4-min time-trial and power output at maximal and sub-maximal performance markers ranged from 0.791 to 0.878. Therefore aerobic performance markers can explain 63 % − 77 % of the variation of power output during a 4-min time-trial. It was estimated that the contribution of anaerobic energy pathways during maximal exhaustive exercise over 240 s is 21 % (Gastin, 2001). Capelli et al. (1998) reported a contribution of anaerobic energy from 40 % − 4 % of maximal metabolic power with increasing exhaustive times from 81 s − 890 s in track cycling.

The duration of the 4-min time-trial used in this study comes close to international performance times in the individual pursuit race over 4 km (4:15 − 4:30). To accelerate from a standing start

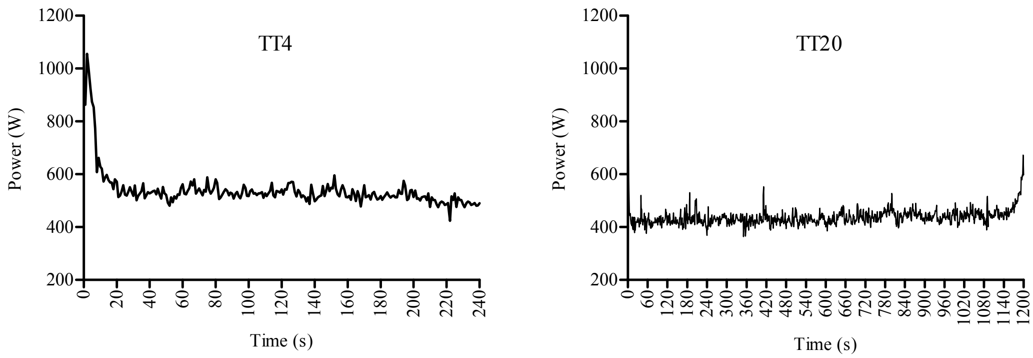



Figure 36: Profile of power output for TT4 (left panel) and TT20 (right panel)

position to a speed of 54.07 $km \cdot h^{-1}$ it takes about 13 s and a necessary work of 11.8 $kJ$ (Broker et al., 1999) which corresponds to an initial power output of 908 $W$. Within 30 s − 40 s power decreases to the maximum sustainable power which should be ideally, kept constant throughout the race. Broker et al. (1999) estimated an average power output of 435 $W$ for a steady speed of 53.1 $km \cdot h^{-1}$ and a pursuit time of 4:31 min. The profile of the 4-min time-trial (Figure 36) is very similar to the 4-km pursuit race. However, the initial phase during the 4-min time-trial is not so pronounced since it was started from a slow speed instead of a standing position. A steady state power was reached within 90 s − 120 s and in the final 30 s a slightly increase was found.

As previously reported by Billat et al. (1996) it was observed that the world-class athletes included in this thesis were able to work at approximately 100 % of *Pmax* during the 4-min time-trials, whereas the elite cyclists produced ∼ 91 % of *Pmax*. Future studies with larger cohorts of world-class, elite and well-trained cyclists should investigate the relationship between maximum power time-trials and *Pmax* obtained from incremental exercise tests with different protocols.

In contrast to the 4-min time-trial, no significant differences were observed between the 20-min field test and *RCP* (− 0.4 ± 49 $W$; $p = 0.97$) and *LTP 2* (0.5 ± 44 $W$; $p = 0.98$). Therefore, the 20-min time-trial has been used as a performance measure throughout this thesis. In addition to the observed reliability and validity, it was shown that the 20-min time-trial was sensitive to track small performance changes across a season in competitive cyclists and in contrast to a laboratory test, revealed specific performance changes as a result of a flat and uphill training intervention. Moreover, trained cyclists are able to produce significantly higher power outputs during uphill compared to flat time-trials of the same duration. As a consequence to the latter finding, higher heart rates and blood lactate concentrations during uphill time-trials were observed.

**Power Output during 20-min Uphill and Flat Time-Trials** Although the results of this study have shown that cyclists can ride harder while climbing, it is not entirely clear why this is the case. The body position on the bike and the corresponding joint angles affect the force production of the muscles (Dorel et al., 2009; Duc et al., 2008; Hug et al., 2008). A comparison between uphill (9.25 %) and level ground cycling on a treadmill showed a tendency for crank torque to be higher during climbing at a crank angle of 45° when riding at the same power output and cadence (Bertucci et al., 2005a). The same authors reported different crank torque profiles when ergometer and outdoor cycling conditions were compared (Bertucci et al., 2007). Recently the study of Duc et al. (2008) have shown that EMG activity was largely influenced by a change from seated to standing posture but not when inclination was increased (4 % − 7 % − 10 % inclination).

Padilla et al. (2000b) investigated different types of time-trials (i.e. prologue, short, long, uphill and team time-trial) in a group of professional cyclists. In the long time-trial (3975 s) and the uphill time-trial (4495 s) the authors reported 347 $W$ and 342 $W$, respectively. When riders where separated into an "all out group" (i.e. riding at full strength) and a "strategy group" power output in the all out group was 359 $W$ and 376 $W$ for long time-trial and uphill time-trial, respectively. The difference does not reach statistical significance, but the fact that power output was higher despite a longer effort ($\sim$ 500 s) in the uphill time-trial, suggests that higher power outputs can be produced during uphill cycling. However, a major concern arises from the fact that in the study of Padilla et al. (2000b), power output was not measured but only estimated from the linear relationship between heart rate and power output during an incremental laboratory test. In the present study no differences were found for mean $HR$ (173.8 $b \cdot min^{-1}$ vs. 173.6 $b \cdot min^{-1}$) and end test $HR$ (180.1 $b \cdot min^{-1}$ vs. 180.3 $b \cdot min^{-1}$) between the 4-min and the 20-min time-trial, respectively. Using the approach from Padilla et al. (2000b), almost identical power outputs would be estimated. In fact power output was significantly higher during the 4-min (412.2 $W$) compared to the 20-min time-trial (347.1 $W$).

Several studies reported an increase in the physiological demand (i.e. oxygen uptake, heart rate) when riding in an aerodynamic versus an upright position (Faria et al., 1978; Jobson et al., 2008a). Although the 20-min field test aimed to evaluate power output and not velocity, where an aerodynamic position enhance the results, cyclists usually adopt a tucked-in position with the hands on the drops during the flat time-trials. In contrast, the uphill time-trials were performed in an upright position with the hands on the brake hoods or on the flat part of the handlebar. Recently Jobson et al. (2008a) reported 15 $W$ ($\sim$ 6 %) higher power outputs ($p < 0.05$) during simulated 40 km laboratory time-trials riding in an upright position compared to an aerodynamic position.

Another explanation for the higher power outputs observed during the uphill time-trials might be that the crank inertial load increase as a quadratic function of the gear ratio (Fregly et al., 2000). It was reported that an increased cadence is a strategy to overcome the higher peak crank torques associated to flat cycling as a result of the high gear ratios required to travel at high velocities (Hansen et al., 2002). In addition, the observation that the freely chosen cadence is usually higher than the energetically optimal cadence indicates, that cyclists try to reduce muscular forces rather than the metabolic cost (Hansen, 2009; Vercruyssen & Brisswalter, 2010). The required neuromuscular forces in response to the high crank inertia during flat cycling might be a limitation to use larger gear ratios at lower cadences which possibly could result in higher power outputs. In support of this speculation Watson & Swensen (2006) reported 2.5 % faster times to complete a 5-mile simulated time-trial ($p < 0.05$) during a low-cadence ($83 \pm 6\ rev \cdot min^{-1}$) in comparison to a preferred-cadence ($92 \pm 2\ rev \cdot min^{-1}$) and a high-cadence ($101 \pm 6\ rev \cdot min^{-1}$) strategy. However, low cadences during flat cycling could also increase lateral bicycle oscillations which potentially impair aerodynamics and eventually the travelling velocity.

In summary, the differences between uphill and flat time-trial power outputs should be considered when power-data are analysed or exercise intensities are prescribed for training.

It should be noted that the field test presented in this thesis evaluated the endurance performance of cyclists. Nevertheless, unpublished data have shown that a 10 s and a 60 s maximal power field test to assess neuromuscular power and anaerobic capacity, could complete the physiological assessment of aerobic and anaerobic power characteristics in cyclists.

In Figures 37 and 38 an example of the aerobic and anaerobic power characteristics of a successful elite cyclist is shown. The 10 s neuromuscular power test allows the calculation of the linear force − velocity, or as shown in Figure 38 the torque − cadence relationship which is attributed to the contractile properties of the muscle fibres (Dorel et al., 2010; Sargeant, 1994; Sargeant et al., 1981). The relationships between power/torque and cadence and the derived measures of neuromuscular properties (see Figure 13 on page 52) are important when evaluating sprint-cycling abilities (Dorel et al., 2005; Gardner et al., 2007; Martin et al., 2007).

The ability to produce high power outputs over 30 − 60 s is crucial in decisive race situations across many cycling disciplines (Ebert et al., 2005; Faria et al., 2005b; Impellizzeri & Marcora, 2007). Surprisingly, in the longitudinal study of this thesis it was observed that only the four best participants used interval training sessions with the aim to improve maximum power despite the fact that all participating cyclists were experienced elite athletes. It was concluded that high-intensity efforts between 20 − 60 s should be included into the training regime of elite cyclists. The energy production via anaerobic pathways could be assessed with the 60 s maximal power field test as shown in Figures 37 and 38. Finally, the power vs. time relationship of the four maximum power field tests (Figure 37) allows the application of the critical power concept (Monod & Scherrer, 1965; Vautier et al., 1995) which is reportedly a strong indicator of endurance performance (Jones et al., 2010; Vanhatalo et al., 2007a).

Name: **Example**

Weight: **63,0** kg

Date: **17.03.09**

Time: **11:00** hh:mm

Temp.: **12** °C

**Test 1:** **10 sec. all out**

| | Measured | | Calculated | |
|---|---|---|---|---|
| Gear / Ratio: | 53/17 | 3,12 | | |
| P max: | 1060 | Watt | P opt: | 1004 |
| | 16,83 | Watt/kg | | 15,94 |
| P mean 5sec: | 933 | Watt | | |
| | 14,81 | Watt/kg | | |
| P mean 10sec: | 910 | Watt | | |
| | 14,44 | Watt/kg | | |
| Cad. P max: | 103 | rpm | Cad opt: | 96 |
| Cad max: | 119 | rpm | Cad max: | 193 |
| T max: | 153 | Nm | T max: | 199 |
| Work: | 9,10 | kJ | | |
| | 54,60 | kJ/min | | |
| FI 5/10 | 2,5 | % | | |
| FR 5/10 | 2,3 | W/s | | |

**Test 2:** **60 sec. all out**

| | P mean | | Cad mean | | | |
|---|---|---|---|---|---|---|
| Time (sec) | Watt | Watt/kg | rpm | | | |
| 1-5 | 728 | 11,56 | 57 | FI 30 | 40,4 | % |
| 6-10 | 915 | 14,52 | 89 | FI 60 | 63,7 | % |
| 11-15 | 824 | 13,08 | 102 | FI 30/60 | 38,9 | % |
| 16-20 | 680 | 10,79 | 105 | FR 30 | 12,3 | W/s |
| 21-25 | 617 | 9,79 | 101 | FR 60 | 9,7 | W/s |
| 26-30 | 545 | 8,65 | 96 | | | |
| 31-35 | 522 | 8,28 | 95 | | | |
| 36-40 | 501 | 7,96 | 94 | | | |
| 41-45 | 456 | 7,24 | 92 | | | |
| 46-50 | 436 | 6,92 | 91 | | | |
| 51-55 | 386 | 6,12 | 87 | | | |
| 56-60 | 332 | 5,27 | 85 | | | |
| 1-30 sec | 718 | 11,40 | 92 | Work: | 21,54 | kJ |
| 31-60 sec | 439 | 6,97 | 91 | | 13,16 | kJ |
| 1-60 sec | 578 | 9,18 | 91 | | 34,70 | kJ |

**Test 3:** **4 min**

| | P mean | | HR | Cad mean |
|---|---|---|---|---|
| Time (sec) | Watt | Watt/kg | bpm | rpm |
| 1-30 | 464 | 7,37 | 167 | 78 |
| 31-60 | 397 | 6,30 | 180 | 86 |
| 61-90 | 377 | 5,98 | 182 | 88 |
| 91-120 | 346 | 5,49 | 184 | 88 |
| 121-150 | 332 | 5,28 | 184 | 87 |
| 151-180 | 359 | 5,69 | 184 | 78 |
| 181-210 | 379 | 6,02 | 186 | 73 |
| 211-240 | 382 | 6,06 | 187 | 71 |
| 1-240 | 379 | 6,02 | 182 | 81 |
| Work: | 91 | kJ | | |
| | 23 | kJ/min | | |
| FI 30/240 | 17,9 | % | | |
| FR 30/240 | 0,35 | W/s | | |

**Test 4:** **20 min**

| | P mean | | HR | Cad mean |
|---|---|---|---|---|
| Time (sec) | Watt | Watt/kg | bpm | rpm |
| 1-240 | 342 | 5,44 | 173 | 85 |
| 241-480 | 319 | 5,07 | 180 | 81 |
| 481-720 | 314 | 4,99 | 180 | 74 |
| 721-960 | 319 | 5,07 | 183 | 80 |
| 961-1200 | 316 | 5,01 | 185 | 87 |
| 1-1200 | 322 | 5,11 | 180 | 81 |
| Work: | 387 | kJ | | |
| | 19 | kJ/min | | |
| FI 240/1200 | 7,8 | % | | |
| FR 240/1200 | 0,02 | W/s | | |

**Summary:**

| | P mean | | 00.01.00 | Diff. |
|---|---|---|---|---|
| Time (sec) | Watt | Watt/kg | Watt | % |
| 10 | 910 | 14,44 | #DIV/0! | #DIV/0! |
| 60 | 578 | 9,18 | #DIV/0! | #DIV/0! |
| 240 | 379 | 6,02 | #DIV/0! | #DIV/0! |
| 1200 | 322 | 5,11 | #DIV/0! | #DIV/0! |
| CP: | 313 | Watt | | |
| CP: | #DIV/0! | Watt | | |

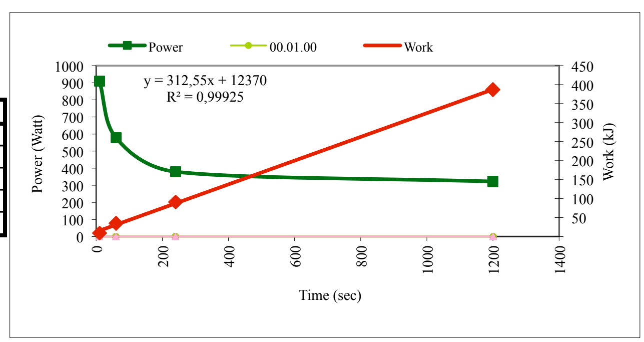





Figure 37: Assessment of aerobic and anaerobic power characteristics of a cyclist during maximum power field tests (unpublished data)

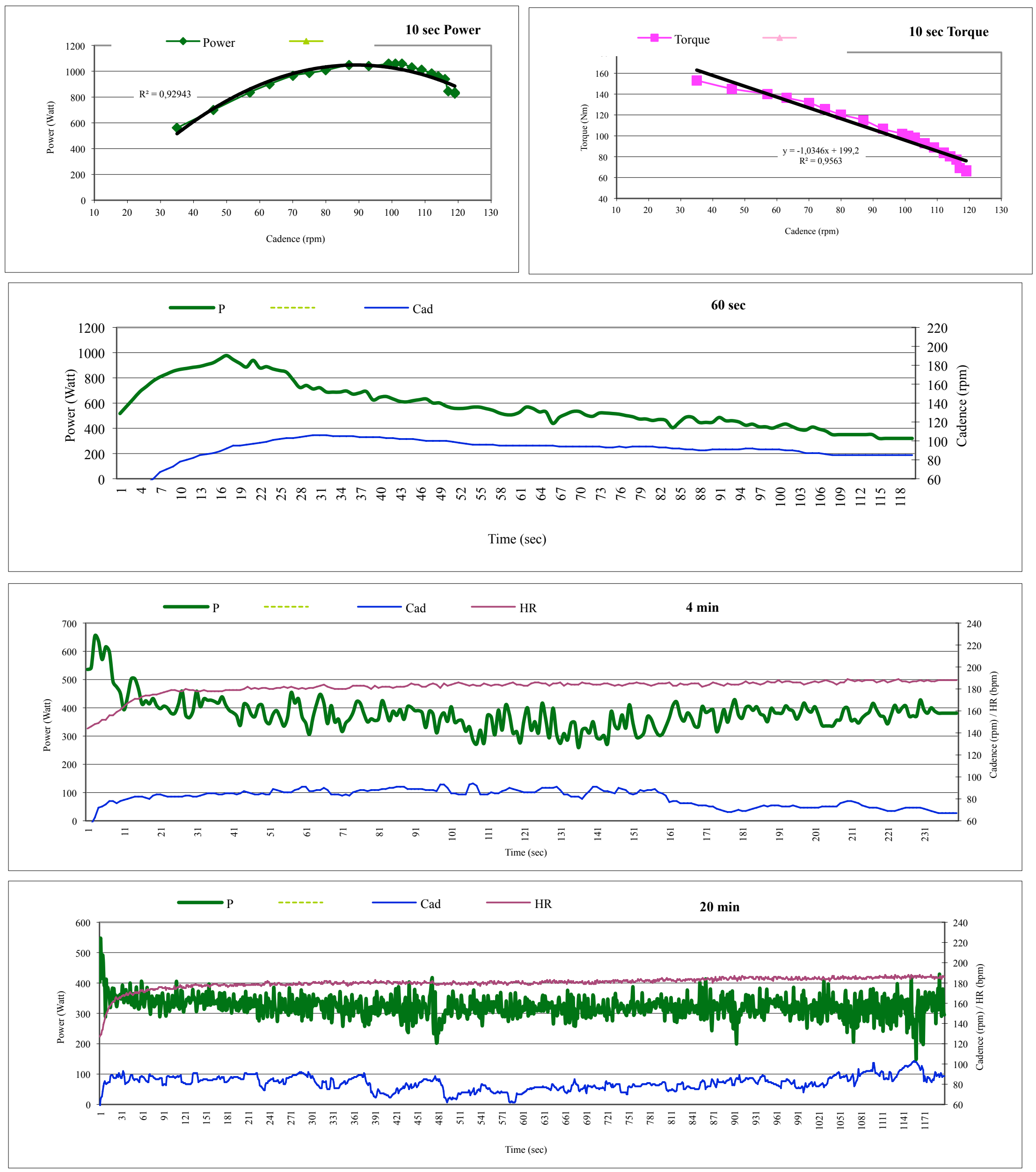





Figure 38: Graphics of the results from aerobic and anaerobic maximum power field tests (unpublished data)

## 11.2 Training Strategies in Cyclists

Longitudinal monitoring of training is of particular interest for trainers and researchers to investigate alterations in performance or competition. Moreover, training data from elite and world-class athletes provide a useful insight into the training strategies of a successful sub-population within a sport. However, data sampling across a whole competitive season in such athletes is hard to accomplish and consequently few data exist in the scientific literature. In the present thesis the approach was to measure power output and heart rate over a season for analyses of exercise intensity and duration in relation to performance and classification of the cyclists. To back up for lost or erroneous data or for the fact that cyclists usually used more than one bike and not all of those are equipped with power meters, a self reported standardised diary was used (see Appendix 13.4 on page 168 for an example of the diary).

**Workout Categories and Intensity Factors** One aim of this longitudinal study was to investigate whether or not a difference in the average exercise intensity exists between workouts with specific goals. For this purpose the athletes were asked to record the goal of each cycling training in the diary (as described in section 9.2.6 on page 90) in addition to the measurement of power output and heart rate. It was found that $Pmean$ and the intensity factor ($IF$) allows to distinguish competition from training but not between workouts (except $IF$ during recovery workouts). The high-intensity workouts corresponding to anaerobic threshold, maximum oxygen uptake, strength and maximum power, are usually performed as interval training. For example, in a training with the goal to improve maximum power (see Appendix 13.9 on page 172) with 3 sets of 10 × 20 s at 720 $W$ the total time in the high-intensity zone is 10 min and accounts for only 6 % of the total training time of 170 min in this training session. The accumulated time spent at high-intensities seems to be too short to influence $Pmean$ or $IF$.

It was hypothesised that the exercise intensities would be significantly correlated to the performance level of our participants. However, no significant correlations between the intensity factors and performance measures were observed. This finding indicate that the world-class cyclists involved in that study trained at the same relative exercise intensities than the national racing cyclists. In contrast, world-class cyclists completed significantly higher training volumes. These results support previous studies (Lucia et al., 1999a, 2000d; Padilla et al., 2001) as discussed in section 5 on page 63. However, the intensity factors during intervals performed at *"strength" and "maximal power"* workouts were strongly correlated with performance. In addition, the time spent at the workout category *"strength"* was related to performance, indicating that better cyclists spent more time to train at and perform harder during this intervals.

The ability to influence the force-velocity relationship of the muscular contraction is a unique opportunity for cyclists. A reduction in cadence at any given power output requires higher forces to keep that power output on the desired level. Therefore, a low-cadence − high-force training strategy during cycling is by some authors termed as "strength training" (Lindner, 2003). Strength can be defined as the ability to produce force (Stone et al., 2003). From a physical point of view force is one of the factors influencing power output and therefore a strength oriented training modality might improve cycling performance. However, from a methodological and physiological point of view strength oriented training during cycling should not be confused with strength or weight training during resistance exercise in the gym.

During weight training the recruitment of muscle fibres is required to produce the force to perform the resistance exercise. The skeletal muscle is composed of different muscle fibre types (see page 34), that are recruited hierarchically depending on the intensity of the required force production (Henneman et al., 1965). According to this size principle, low-activation motor units (type I) are recruited first when lower forces are required, whereas the high-activation (type II) fibres are recruited with increasing demand. Slow twitch muscle fibres are related to endurance exercise due to their aerobic capacity (Goldspink, 2003; Gollnick et al., 1972; Spiering et al., 2008) and consequently during weight training the exercise intensity must be high enough to recruit and stimulate type II muscle fibres. A threshold level of at least 30 − 50 % of the maximal voluntary contraction has been reported as the lowest intensity required that induces strength gains (Fleck & Kraemer, 2004; Schnabel et al., 1997).

However, during cycling training such high forces are unlikely to occur. For example in Figure 39 the torque − cadence relationship obtained from a 10 s maximum power field test is depicted. The y-intercept of the linear regression line indicates a maximum torque ($Tzero$) of 277 $N \cdot m^{-1}$ and the horizontal dashed line at 83 $N \cdot m^{-1}$ represents 30 % of $Tzero$ as the threshold level. The four data points (A-D) are calculated from the power outputs and cadences measured during different training sessions as $Torque = Power/(Cadence \times \Pi/30)$. The mean torque during a basic endurance training (data point D) with an average of 260 $W$ and 90 $rev \cdot m^{-1}$ is 28 $N \cdot m^{-1}$ or 10 % of $Tzero$. The examples A-C are representative for some typical low-cadence − high-torque training sessions during cycling. It can be seen that the torques produced during such training sessions are approximately 2.5 − 3 fold higher in comparison to the basic endurance session and therefore indicates the efficacy of these interventions. However, the 30 % threshold level is just slightly touched during a high intensity 570 $W$ interval training session at 65 $rev \cdot m^{-1}$ (data point C).

The association between the percentage of maximal voluntary contraction and the number of repetitions to fatigue shown in Figure 40 raises a methodological issue on "strength training" during cycling. The repetition maximum (RM) for a given percentage of maximal voluntary contraction or maximal

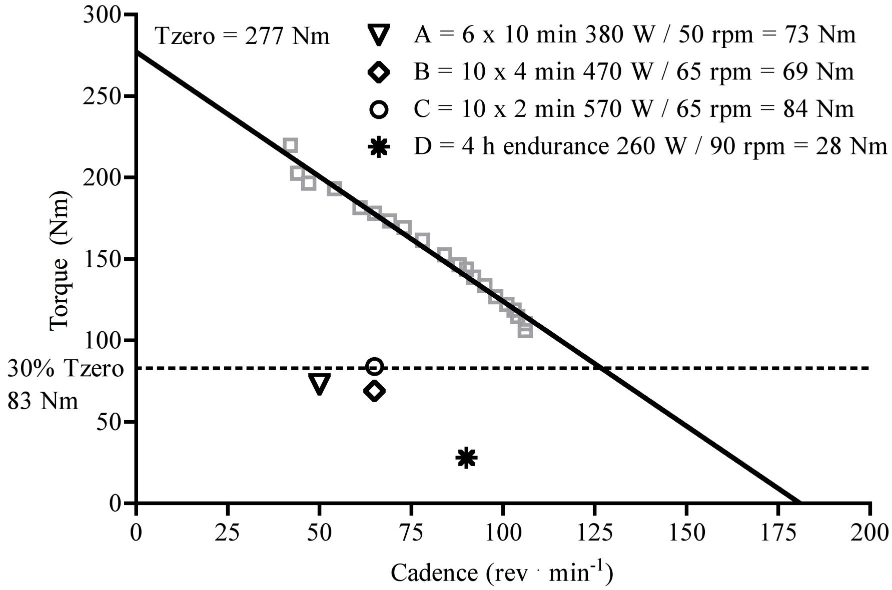



Figure 39: Torque vs. cadence relationship obtained from a 10 s maximum power field test and the torques produced during cycling training sessions. See text for further explanations

strength might differ between muscle groups as well as between trained and untrained people (Hoeger et al., 1990; Zatsiorsky, 1995). However, it has been shown that weights corresponding to the $1-8$ RM are appropriate to induce maximal dynamic strength gains, the $8-12$ RM is most effective for an increase in muscular hypertrophy and weights corresponding to the $12-25$ RM appears to be most effective to improve local muscular endurance (Campos et al., 2002; Fleck & Kraemer, 2004; Tan, 1999; Zatsiorsky, 1995). Strength gains above the 25 RM are described as small and are related to enhanced motor performance or learning effects (Fleck & Kraemer, 2004).

Comparing the examples of the strength oriented cycling training sessions shown in Figure 39, it becomes obvious that the number of repetitions or revolutions of 500, 260 and 130 for A, B and C respectively, exceeds the number of repetitions associated with strength gains by far. Considering both, the forces as well as the repetitions during so called "strength" cycling training, such sessions should be more appropriately termed as *"high resistance endurance"* training.

Nevertheless, despite this ambiguous terminology it was shown that a low-cadence − high-torque training strategy was related to the classification of the participants and to performance improvements across the season. Recently Hopker et al. (2009a) have shown, that an improvement in gross efficiency across a season was strongly correlated to the training time spent around the onset of blood lactate accumulation ($OBLA$). Although no details of pedalling cadences have been reported, the exercise intensity at the $OBLA$ is approximately the same as the intensity factor during strength intervals in the present study ($0.95 \pm 0.15$). It is possible that the performance improvements observed in

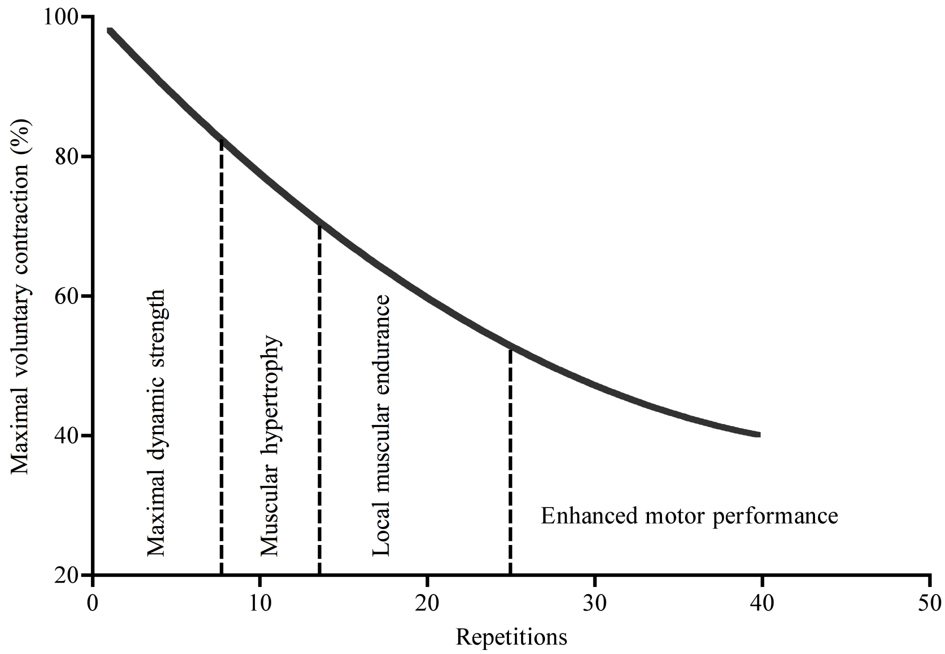



Figure 40: Inverse relationship between the maximal strength and the number of repetitions to fatigue (adapted from Fleck & Kraemer, 2004; Zatsiorsky, 1995)

the present study are associated with an improvement in efficiency. It has been shown that both weight training (Paton & Hopkins, 2005; Yamamoto et al., 2010) and a low-cadence cycling training (Paton et al., 2009) can improve cycling performance, which might lead to an improvement in leg strength. As a consequence, the recruitment of inefficient type II muscle fibres might be delayed and thus increases efficiency (Hausswirth et al., 2009; Paton & Hopkins, 2005). These observations suggest that in addition to the training volume also the amount of high-intensity training is important.

The efficacy of an increase in resistance via low-cadence cycling was supported by the results of the third study. The group that performed uphill intervals at a low cadence improved power outputs during both, uphill and flat time-trials in contrast to the control group and the group with a high-cadence strategy during level-ground cycling that improved only flat time-trial performance. Specific adaptations occur within four weeks in already trained cyclists and it was shown that a specific field test is necessary to reveal these adaptations since no differences between the groups were observed during an incremental laboratory test.

**Distribution of Power Output and Heart Rate Exercise Intensity Zones** Another aim of this thesis was to compare the distributions of power output and heart rate into exercise intensity zones. Several studies have used the accumulated time within a zone to determine the physiological demand during competitions (Esteve-Lanao et al., 2005; Lucia et al., 1999a; Padilla et al., 2001;

Rodríguez-Marroyo et al., 2003). However, most studies monitor heart rate despite the numerous factors that can affect it (Achten & Jeukendrup, 2003). Although some studies have analysed power output distributions (Ebert et al., 2005; Stapelfeldt et al., 2004; Vogt et al., 2007b) it was just recently that the traditional method of heart rate monitoring was compared with power output measurement (Bernard et al., 2009; Vogt et al., 2006). Both studies reported that the use of heart rate underestimated the time spent in lower intensity zones and overestimated the time spent in higher intensity zones. Vogt et al. (2006) concluded that the differences between heart rate and direct power output measurement indicate that describing exercise intensity with heart rate does not precisely reflect pacing strategies and thus, monitoring of power output could be more suitable to quantify the exercise intensity of a race. It should be noted however, that in the study of Bernard et al. (2009) only one triathlon race and in the study of Vogt et al. (2006) six days of a stage race were monitored. A longitudinal comparison of power output and heart rate monitoring during training seems to be important to clarify whether or not both methods can be used interchangeably to quantify the physiological demand.

The results of the present study have shown that differences between power output and heart rate distributions occur during workouts associated with higher exercise intensities (i.e. *"anaerobic threshold"*, *"maximum oxygen uptake"*, *"strength"*, *"maximum power"* and *"competition"*). As observed by Vogt et al. (2006), heart rate distributions elicit a shift from low- to high-intensity zones. However, no differences in exercise intensity distributions were found for low-intensity workouts (i.e. *"recovery"*, *"basic aerobic endurance"* and *"aerobic capacity"*) as well as for the total season. As discussed in section 9.4 on page 99 the intermittent exercise mode during high-intensity workouts and the delayed response from heart rate in contrast to the immediate changes in power output seems to be responsible for the differences. In addition, the pronounced cardiac drift at high exercise intensities leads to a rise in heart rate and fortify the shift toward higher intensity zones.

It should be noted that the model used to quantify exercise intensity could influence the distributions. To account for the instantaneous changes in power output, a seven-zone power model has been used in this study in contrast to previous studies where a three- or four-zone heart rate model was used (Esteve-Lanao et al., 2005; Lucia et al., 1999a; Seiler & Kjerland, 2006; Stapelfeldt et al., 2004). The reasons for this approach have been explained in section 9.2.4 on page 87. Nevertheless, regardless of the model used, any of these requires to set specific borders to delineate the zones. For example, in the present study exercise intensity zones were related to functional threshold power (Zone 1 $< 50$ % (of $FTP$), Zone 2: $50 - 70$ %, Zone 3: $71 - 85$ %, Zone 4: $86 - 105$ %, Zone 5: $106 - 125$ %, Zone 6: $126 - 170$ %, Zone 7 $> 170$ %), whereas others used $VT/LT$ and $RCP/OBLA$ as boundaries between zones. If a boundary has been set for instance at 200 $W$, values of 199 or 201 $W$ falls into different zones despite the presumably negligible differences on the physiological response. Given the delayed response of heart rate to changes in power output it seems that heart rate zones are much more floating and therefore the three- or four-zone model is sufficient to determine the demand of exercise. However, as power output is the main stimulus for exercise-induced adaptations and changes in power output occur instantaneously, more intensity zones better reflect the whole spectrum of power output. When the seven power zones are merged into a low-intensity (Zone 1 and 2), moderate-intensity (Zone 3 and 4) and high-intensity zone (Zone 5, 6 and 7), a distribution of $73 - 22 - 5$ % was found. This distribution is very similar to previous studies in cycling (Hopker et al., 2009a; Lucia et al., 2003; Padilla et al., 2001) and running (Esteve-Lanao et al., 2005) where the three-zone heart rate model has been used. Thus, the power model employed reflects the physiological responses to exercise as described on page 60.

In the interval-training study of the present thesis it was shown that trained cyclists are able to control power output in a very narrow range of ± 2.5 %. At a target power output of 300 $W$ this refers to a lower and upper limit of 293 and 308 $W$, respectively. It is very unlikely to control such a small difference of 15 $W$ with a heart rate monitor. A slope of approximately 0.25 $b \cdot min^{-1} \cdot W^{-1}$ in the relationship between heart rate and power output (Grazzi et al., 1999) refers to a difference of 3.8 $b \cdot min^{-1}$ or a range of ± 2 $b \cdot min^{-1}$ for a difference in power output of 15 $W$. Given the delayed and slow response of heart rate the accuracy to fine-tune exercise intensity via heart rate is obviously limited.

**Variability in Power Output** One observation in the longitudinal study was that world-class cyclists had less variability in power output. As discussed, it is currently unknown whether or not this is the result of a conscious pacing. As shown in the paragraph above, trained cyclists have the ability to very accurately control power output and therefore it is possible that this is used as a training strategy. It was also observed that the variability in races is significantly higher than during training, which could be explained by the mass-start character of most races. In fact a strategy during races is to draft behind others at low power outputs in an attempt to save energy for decisive race situations where higher power outputs are required, thereby increasing the variability in power output and probably enhance performance. In contrast, a lower variability during training might improve the quality of the workout.

Recently it has been proposed, that exercise intensity is regulated on a subconscious level controlled by a "central governor" in the brain, which continuously regulate physiological functions with the aim to avoid "physiological catastrophe" (Noakes et al., 2004). Knowledge of an end point and prior experience are important variables for the central governor to set a certain pacing strategy at the start of an effort. Athletes are almost always aware of both factors during cycling and therefore, high fluctuations of power output might be explained by a neuromuscular and/or biochemical feedback system (St Clair Gibson et al., 2006; Tucker et al., 2006). For example, analyses of power fluctuations from data of the present thesis revealed that during a road race every $6 - 10$ s and during training every $60 - 90$ s a change in power output occurs. A change was defined as the difference of a data point by ± 25 % to the previous data point (Weber et al., 2005). Therefore, $1440 - 2400$ or $160 - 240$ changes have been observed in a 4 h road race or training, respectively. It should be noted that the sampling rate could have an influence on the variability of the data and the high resolution of 1 $Hz$ for most samples in the present study could have emphasised the power fluctuations. However, it remains to be shown whether or not a) a lower variation of power output is a characteristic of world-class cyclists and b) the application of such a training strategy will result in better performance adaptations.

## 11.3 Appraisal of Hypotheses

1. *Power output during a 4-min and 20-min time-trial will be reproducible*: high test-retest reliabilities for both time-trials were found. Therefore this hypothesis is accepted.

2. *Power output during a 4-min and 20-min time-trial will correspond to Pmax and LTP 2 / RCP obtained during a laboratory incremental exercise test*: significant differences between the 4-min time-trial and *Pmax*, but no differences between the 20-min time-trial and *LTP 2 / RCP* were found. Therefore, this hypothesis is rejected for the 4-min time-trial, but accepted for the 20-min time-trial.

3. *There will be no significant difference in power output during 20-min uphill and flat time-trials*: significant differences between 20-min uphill and flat time-trials were found. Therefore, this hypothesis is rejected.

4. *Power output during a 20-min time-trial is sensitive to track exercise induced performance changes*: significant improvements in 20-min time-trial power output were found across a cycling season. Therefore, this hypothesis is accepted.

5. *There will be a significant difference between the distributions of power output and heart rate exercise intensity zones*: significant differences between power output and heart rate distributions were observed for high-intensity, intermittent workouts, but not for low-intensity continuous workouts or the total season. Therefore, this hypothesis is accepted for the former but rejected for the latter workouts.

6. *There will be a significant difference in average exercise intensity in training sessions with different goals*: average exercise intensity was significantly higher during competitions but no significant differences between training sessions were observed . Therefore, this hypothesis is rejected.

7. *There will be a significant positive correlation between performance level and relative exercise intensities during training*: no significant correlation between the performance level and relative exercise intensities were observed. Therefore, this hypothesis is rejected.

8. *Uphill and flat interval training will specifically increase power output during 20-min uphill and flat time-trials*: an interval-training intervention on uphill and flat roads led to specific improvements during 20-min uphill and flat time-trials. Therefore, this hypothesis is accepted.

9. *Performance improvements during a laboratory incremental exercise test will be greater for the uphill-training group*: no significant differences in performance improvements between the

interval-training groups and the continuous-training group were found. Therefore, this hypothesis is rejected.

## 11.4 Conclusions and Directions for Future Research

The results of this thesis have provided evidence for the usefulness of mobile power meters. The applied 20-min field test was reliable and valid to predict performance measures from laboratory tests. It has been shown that the field test was sensitive to detect small performance changes across a season in world-class cyclists and finally it revealed performance adaptations to a specific training intervention.

The longitudinal data shown in this thesis are unique in a homogeneous cohort of world-class and elite cyclists and have a practical relevance for trainers and researchers. The results have shown that better cyclists spent more time to improve their strength and trained at higher exercise intensities during these workouts. In addition, better performance by cyclists was characterised by lower variability in power output, greater training volume and the production of higher exercise intensities during interval training. Direct measurement of power output more precisely reflects cycling performance. Differences between power output and heart rate distributions occur during high-intensity workouts where the training stimulus was mainly applied in a discontinuous or interval mode. However, the indirect estimation of exercise intensity through heart rate was accurate when a total season or low-intensity workouts were analysed. The findings from study three suggest that higher forces during low-cadence interval training are potentially beneficial to improve cycling performance. These latter findings emphasise the observations from the longitudinal study.

Further studies are required to:

- Investigate the applicability of the 20-min time-trial to other populations (e.g. adolescents, females)
- Investigate the relationship between maximum power time-trials and *Pmax* obtained from incremental exercise tests with different protocols
- Compare the distribution of exercise intensity zones during training and racing in different cycling sub-groups (e.g. mountain-bike, road cycling)
- Investigate effects on performance of a low-variability power strategy during training
- Investigate effects on performance of different interval-training modalities at different cadences and terrains

# Part V

# Appendices

## 12 Appendix 1

### 12.1 Publication Resulted from Study One

160 Training & Testing

# Evaluation of a Field Test to Assess Performance in Elite Cyclists

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**Key words**
- cycling
- power output
- athletic performance
- exercise physiology
- exercise test

**Abstract**

The study aimed to assess the reproducibility of power output during a 4 min (TT4) and a 20 min (TT20) time-trial and the relationship with performance markers obtained during a laboratory graded exercise test (GXT). Ventilatory and lactate thresholds during a GXT were measured in competitive male cyclists ($n = 15$; $\dot{V}O_{2max}$ $67 \pm 5$ ml $\cdot$ min$^{-1}$ $\cdot$ kg$^{-1}$; $P_{max}$ $440 \pm 38$W). Two 4 min and 20 min time-trials were performed on flat roads. Power output was measured using a mobile power-meter (SRM). Strong intraclass-correlations for TT4 ($r = 0.98$; 95% CL: 0.92–0.99) and TT20 ($r = 0.98$; 95% CL: 0.95–0.99) were observed. TT4 showed a bias ± random error of – 0.8 ± 23W or – 0.2 ± 5.5%. During TT20 the bias ± random error was – 1.8 ± 14W or 0.6 ± 4.4%. Both time-trials were strongly correlated with performance measures from the GXT ($p < 0.001$). Significant differences were observed between power output during TT4 and GXT measures ($p < 0.001$). No significant differences were found between TT20 and power output at the second lactate-turn-point (LTP2) ($p = 0.98$) and respiratory compensation point (RCP) ($p = 0.97$). In conclusion, TT4 and TT20 mean power outputs are reliable predictors of aerobic endurance. TT20 was in agreement with power output at RCP and LTP2.

## Introduction

Endurance is one of the main physical abilities required for many sports. Therefore the measurement of aerobic fitness is an essential requirement to determine training intensities and to evaluate changes in performance. This especially applies to endurance athletes such as road cyclists. Several studies have investigated the relationship between physiological variables obtained during laboratory tests and cycling performance [2, 7, 10, 35]. Correlations have been found between flat time-trial performance and maximal power output reached during incremental exercise [5, 7, 10] as well as with maximum oxygen uptake ($\dot{V}O_{2max}$) [10]. Sub-maximal thresholds are also highly correlated with flat time-trial performance [2, 35]. Studies that compare laboratory measurements with outdoor measurements often use time to complete a certain distance or average speed as performance measures [27, 35]. However, external conditions like wind, road surface and gradient, as well as body mass and size have a large influence on these performance variables [30, 31]. Power output is independent of external influences like wind or gradient and therefore it is more appropriate to use power output as a valid parameter in field test conditions.

To evaluate the performance of elite athletes the specificity of field tests is an important consideration. The validation of an incremental field test performed in a velodrome and based on power output has recently been reported [22]. Few studies have analysed the advantages of mobile power meters to investigate the physiological demands of road race cycling [19, 29, 46, 47] and mountain bike racing [43], or to study the biomechanical aspects of pedalling [11]. While exercise tests in the laboratory might be time consuming, expensive and sometimes invasive, the application of power meters for performance assessment under specific field conditions should be considered. A field test can be easily integrated into the training routine of athletes. However, beside the practical application a field test should provide valid and reliable results and detect accurately small performance changes.

Since maximal and sub-maximal power output during incremental exercise tests is correlated with time-trial performance, a field test for the assessment of these measures of aerobic endur-

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ance would provide a valuable tool for athlete development. Times to exhaustion at the velocity and power output at $\dot{V}O_{2max}$ have been found to be 321 ± 84 s and 222 ± 91 s in running and cycling, respectively [12, 14], compared to a time to exhaustion of 17 min being reported at 90 % of the velocity at $\dot{V}O_{2max}$ [13]. Previous studies have shown that the respiratory compensation point (RCP) as a measure of anaerobic threshold, occurred at ~90 % of $\dot{V}O_{2max}$ in professional cyclists [35] and that the average power output during a 20 min time-trial approximated 90 % of maximal power output [10]. Based on these findings it was hypothesised that power output during a 4 min and a 20 min maximal power time-trial would be equal to maximal and threshold powers, respectively. Therefore, the aim of the study was to investigate the test-retest reliability of power output during a 4 min and a 20 min time-trial. Validity was assessed by comparison with maximal and sub-maximal performance measures obtained during a laboratory incremental exercise test.

## Materials and Methods

### Participants

Fifteen competitive male cyclists (mean ± SD; age: 25.6 ± 5.2 years; stature: 180.6 ± 4.5 cm; body mass: 70.6 ± 4.4 kg) participated in this study. The riders followed a regular training regimen and participated in races throughout the season. Characteristics of the riders are presented in **Table 1**. All athletes underwent a medical examination prior to participation and were informed of the experimental procedures. The study was conducted in accordance with the ethical principles of the Declaration of Helsinki [24] and was approved by the institutional ethics committee. All participants provided written informed consent to participate in the study.

### Study design

The participants completed one laboratory incremental graded exercise test and two maximal power field tests in randomised order within 20 days. The riders were asked to refrain from strenuous exercise and from alcohol and caffeine ingestion in the 24 h preceding each test. To ensure sufficiently high glycogen stores and euhydration, athletes were instructed to follow a carbohydrate rich diet that elicited ~ 70 % of the total caloric intake during the last 24 h before the tests and to drink at least 4 litres. All tests were separated by at least 48 h. Experimental trials were scheduled at least 72 h after competition.

### Laboratory incremental graded exercise test

After a medical examination a graded exercise test (GXT) was performed on an electromagnetically braked ergometer (Lode Excalibur, Groningen, The Netherlands) between 9–11 h in the morning. The calibration report for power outputs between 25–1 000 W revealed a coefficient of variation (CV) < 1 % which is in accordance with the suggestions of Hopkins et al. [25]. The ergometer was equipped with a racing saddle and drop handlebars and with the riders own pedals. After a 5 min warm up at 50 W the work rate was increased by 25 W every minute until exhaustion. If the last work rate was not completed, maximal power was calculated according to Kuipers et al. [32];

$$P_{max} = P_L + (t/60 \times 25)$$

where $P_L$ is the last completed work rate (W) and t is the time for the incomplete work rate (s).

Oxygen uptake was measured continuously throughout the test via breath-by-breath open circuit spirometry (Master Screen CPX, VIASYS Healthcare, Hoechberg, Germany). Before each test, flow and volume were calibrated with the integrated system according to the manufacturer's guidelines. Achievement of maximal oxygen uptake ($\dot{V}O_{2max}$) was assumed when at least two of the following criteria were observed: a plateau (i.e. increase of less than 2.1 $ml \cdot min^{-1} \cdot kg^{-1}$ over two or more consecutive 1 min $\dot{V}O_2$ samples) in $\dot{V}O_2$ despite an increase in work rate [26, 44], a respiratory exchange ratio above 1.10 [18], a heart rate within ± 10 $b \cdot min^{-1}$ of age predicted maximum (220–0.7 × age) [21]. Ventilatory threshold (VT) was determined using the criteria of an increase of the ventilatory equivalent of $O_2$ ($\dot{V}E/\dot{V}O_2$) without a concomitant increase of the ventilatory equivalent of $CO_2$ ($\dot{V}E/\dot{V}CO_2$), the first loss of linearity in pulmonary ventilation ($\dot{V}E$) and the first loss of linearity of carbon dioxide ventilation ($\dot{V}CO_2$) [9]. Respiratory compensation point (RCP) was determined using the criteria of an increase in both $\dot{V}E/\dot{V}O_2$ and $\dot{V}E/\dot{V}CO_2$, the second loss of linearity in $\dot{V}E$, the second loss of linearity in $\dot{V}CO_2$ [48]. The current protocol and the methods of VT and RCP detection have been used in several studies with professional cyclists [17, 34, 35] and have been shown to be valid and reliable [3, 49]. The methods used for the detection of sub-maximal thresholds in our laboratory revealed intraclass correlation coefficients (ICC) of $r = 0.94–0.99$ for intra-rater reliability and $r = 0.91–0.97$ for inter-rater reliability (unpublished data). Blood samples were taken every minute [4, 40] from the hyperaemic earlobe for the measurement of blood lactate concentrations using an enzymatic amperometric procedure (Biosen S – line, EKF Diagnostic, Barleben, Germany). The analyser was calibrated with a standard solution of 12.0 $mmol \cdot L^{-1}$ and accuracy was verified by using control solutions with known concentrations. Lactate turn points were determined as the intensity corresponding to the first (LTP 1) and second (LTP 2) nonlinear increase in the lactate vs. power

**Table 1** Performance characteristics of the riders.

| No | Discipline | Category | Results, Victories |
|---|---|---|---|
| 1 | Road | World class | Track: WC winner, OG 5th place, WCH runner up |
| 2 | MTB | World class | Winner of UCI Cat.2 MTB races, UCI ranking < 150 |
| 3 | MTB | World class | Winner of UCI Cat.1 MTB races, OG 6th place, WC Top 10, WCH 6th place, ECH runner up, UCI ranking < 10 |
| 4 | Road | U23 | NCH Track: runner up Madison Elite |
| 5 | Road | U23 | NCH juniors Track: runner up Pursuit and TT |
| 6 | Road | U23 | NCH juniors road, 3rd place TT Elite |
| 7 | Road | U23 | NCH Track: runner up TT Elite |
| 8–15 | Road | Elite | Successful in national events |

WC = World Cup; OG = Olympic Games; WCH = World Championships; ECH = European Championships; NCH = National Championships; TT = Time trial; UCI = International Cycling Federation

output plot [16,42]. Determinations of gas exchange as well as lactate thresholds were conducted by two observers using a custom written application (◦ **Fig. 1**) (Microsoft Excel 2003, Microsoft Corporation, Redmond, USA). In case of disagreement, a third investigator was consulted.
Heart rate was monitored continuously throughout the test with a 12 lead electrocardiograph (Cardiovit AT 104 PC, Schiller, Baar, Switzerland).

### Field tests

On separate occasions two field tests were performed between 10–14 h. Each field test consisted of a 4 min (TT4) and a 20 min (TT20) maximal power time-trial, separated by a 30 min easy recovery phase. Athletes were advised to choose almost flat or slightly undulating roads with the right of way and without traffic lights. We expected that at least 2.5 km and 11 km would be covered during the 4 min and 20 min time-trial, respectively. To keep the average gradient below 0.5 % a difference in altitude < 10 m for the 4 min time-trial and < 50 m for the 20 min time-trial was allowed. In total ten different courses were used and evaluated by the first investigator before the time-trials.
Data were collected on separate occasions for every cyclist between April and June and therefore environmental conditions were not standardised [7]. All time-trials were supervised and the participants were asked to produce the highest possible power output during the tests. The riders' bicycles were equipped with a mobile SRM professional power meter (Schoberer Rad Messtechnik – SRM, Juelich, Germany) for the measurement of mechanical power output and heart rate. To assure accurate measures a static calibration procedure was applied before the study [50]. Before each test the zero offset frequency of the power meter was adjusted by the supervisor according to the manufacturer's instructions. This device has been shown to provide valid measures in laboratory and field conditions [8,41] and to provide comparable power values to the Lode Excalibur ergometer [39]. It has been shown that the accuracy of SRM power meters over a range of 50–1 000 W was 2.3 ± 4.9 % [20]. Elapsed time was the only information participants received during the self-paced time-trials. Data were sampled at 1 Hz throughout the tests.

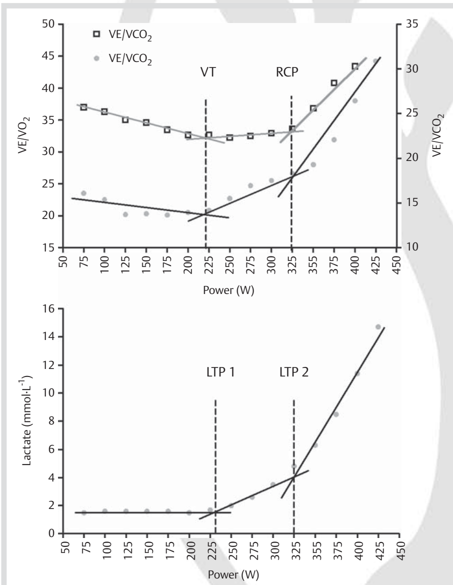


**Fig. 1** Determination of the ventilatory threshold and respiratory compensation point (upper panel) and the first and second lactate turn point (lower panel).

### Data analyses

All descriptive results are reported as mean ± standard deviation (SD). The assumption of normality was verified using Kolmogorov-Smirnov's test and Liliefors probability. Statistical differences between laboratory and field test measures were assessed using repeated measures ANOVA. Tukey's post-hoc test was applied to identify differences revealed by the ANOVA. The relationship between field tests and laboratory variables was verified using Pearson's product moment correlation coefficient. Bland Altman Plot's and 95 % limits of agreement were applied to assess the agreement between field tests and laboratory measures [6,15]. Mean values from the field tests (i. e. trial 1 and trial 2) were used for all calculations.
For the assessment of test-retest reliability, systematic bias and random error were calculated by the methods of Bland and Altman [15]. Repeated measures ANOVA was used to assess whether a difference occurred between the field tests and to calculate the intraclass correlation coefficient (ICC) [45]. No heteroscedasticity was present in the data using the examinations described previously [6]. 95% confidence limits (CL) are provided for all reliability measures. Statistical significance was accepted at $p < 0.05$.

## Results

▼

The maximal and sub-maximal physiological measures from the laboratory test are presented in ◦ **Table 2**. Mean power output and heart rate during TT4 and TT20 were 412 ± 53 W vs. 347 ± 42 W and 174 ± 13 b · min$^{-1}$ vs. 174 ± 10 b · min$^{-1}$, respectively. In the

**Table 2** Maximal and sub-maximal characteristics obtained during GXT (mean ± SD).

| Measure | LTP 1 | LTP 2 | VT | RCP | $P_{max}$ |
|---|---|---|---|---|---|
| Power (W) | 263 ± 37 | 344 ± 38 | 243 ± 27 | 344 ± 37 | 440 ± 38 |
| Power (W · kg$^{-1}$) | 3.7 ± 0.4 | 4.9 ± 0.5 | 3.5 ± 0.3 | 4.9 ± 0.5 | 6.2 ± 0.5 |
| $\dot{V}O_2$ (ml · min$^{-1}$ · kg$^{-1}$) | 47 ± 4.6 | 57 ± 4.6 | 43 ± 4.2 | 58 ± 4.7 | 67 ± 5.0 |
| HR (b · min$^{-1}$) | 146 ± 14 | 166 ± 13 | 141 ± 13 | 166 ± 12 | 186 ± 12 |
| Lactate (mmol · L$^{-1}$) | 1.5 ± 0.3 | 3.6 ± 0.4 | | | 11.9 ± 1.8 |

$\dot{V}O_2$ = oxygen uptake; HR = heart rate; LTP = lactate turn point; VT = ventilatory threshold; RCP = respiratory compensation point

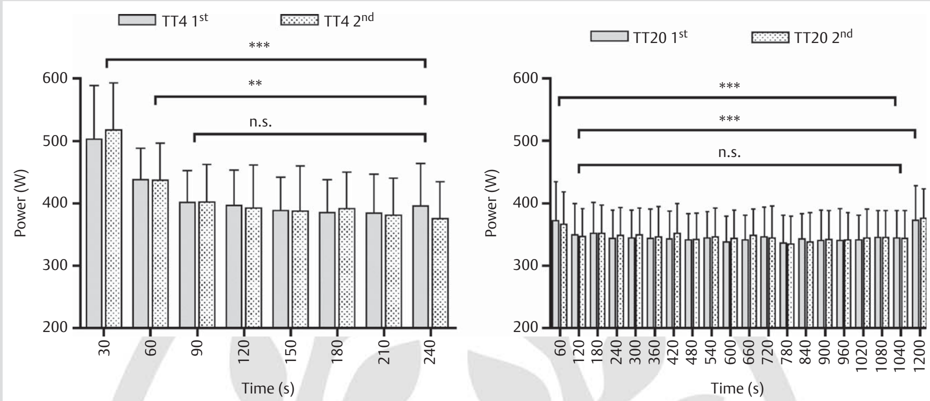


**Fig. 2** Mean power outputs for 30 s intervals (TT4; left panel) and 60 s intervals (TT20; right panel). ANOVA was calculated as mean of the repeated trials in every time interval. ** Significant at p<0.01; *** Significant at p<0.001; n. s. = Not significant.

**Table 3** Comparative statistics of power output at maximal and sub-maximal measures between GXT and field-tests.

| | LTP1 | LTP2 | VT | RCP | $P_{max}$ |
|---|---|---|---|---|---|
| TT4 | | | | | |
| Pearson's (*r*) | 0.90*** | 0.87*** | 0.77** | 0.78** | 0.84*** |
| 95 % CL | 0.65–0.96 | 0.60–0.95 | 0.38–0.92 | 0.45–0.93 | 0.54–0.95 |
| ANOVA | *** | *** | *** | *** | *** |
| SEE (W) | 16.9 | 18.6 | 16.7 | 20.8 | 20.0 |
| TT20 | | | | | |
| Pearson's (*r*) | 0.86*** | 0.84*** | 0.75** | 0.80*** | 0.82*** |
| 95 % CL | 0.62–0.96 | 0.56–0.95 | 0.35–0.91 | 0.46–0.93 | 0.51–0.94 |
| ANOVA | *** | 0.98 n. s. | *** | 0.97 n. s. | *** |
| SEE (W) | 17.8 | 19.6 | 17.3 | 20.6 | 20.9 |

** Significant at p<0.01; *** Significant at p<0.001; n. s. = not significant; CL = Confidence limit; SEE = Standard error of estimate

last minute of the field tests, heart rate reached 180 ± 13 $b \cdot min^{-1}$ and 180 ± 9 $b \cdot min^{-1}$ during TT4 and TT20, respectively. In **Fig. 2** mean power outputs over 30 s and 60 s intervals are presented for TT4 and TT20, respectively.

Strong correlations were observed between the 4 min and 20 min time-trials for both power output (r = 0.93, p < 0.001) and heart rate (r = 0.94, p < 0.001). Power output was significantly higher during TT4 (p < 0.001), whereas no significant differences were found for mean heart rate (p = 0.58) and maximal heart rate (p = 0.76).

Power output during the 4 min and the 20 min time-trial was significantly correlated with power output at maximal and sub-maximal measures from the graded exercise test (**Table 3**). Repeated measures ANOVA revealed significant differences between TT4 and GXT measures (**Table 3**). No significant differences were observed between TT20 and power output at LTP 2 and RCP, whereas power outputs at LTP 1, VT and $P_{max}$ were significantly different from TT20 (**Table 3**).

Bland Altman plots of TT4 and $P_{max}$ showed a bias ± random error of – 30 ± 58 W or – 7.4 ± 14 % (**Fig. 3**). The bias ± random error of TT20 and LTP 2 was 0.5 ± 44 W or 0.02 ± 13 % (**Fig. 4**). For TT20 and RCP the bias ± random error was – 0.4 ± 49 W or – 0.3 ± 14.3 % (**Fig. 4**). Heart rate during the field tests was significantly different from heart rate at LTP 1, LTP 2, VT, RCP and from maximal heart rate measured during GXT (p < 0.001).

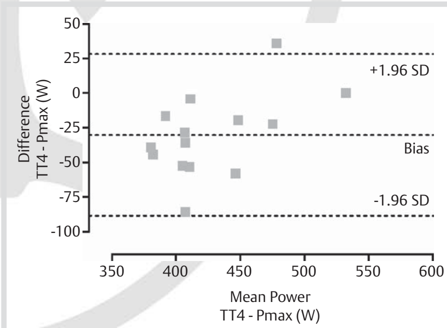


**Fig. 3** Bland Altman plot of the absolute difference between TT4 and $P_{max}$ vs. the mean power of TT4 and $P_{max}$.

Strong test-retest correlations during the 4 min and 20 min time-trials were observed for both power output and heart rate.

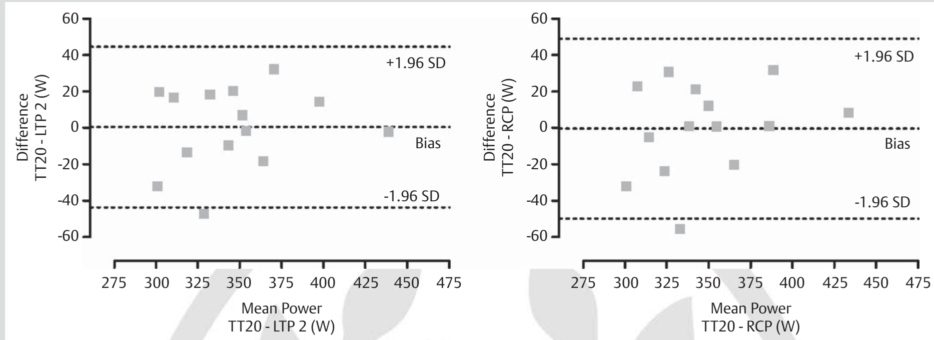


**Fig. 4** Bland Altman plot of the absolute difference between TT20 and LTP2 (left panel) and between TT20 and RCP (right panel) vs. their respective mean power outputs.

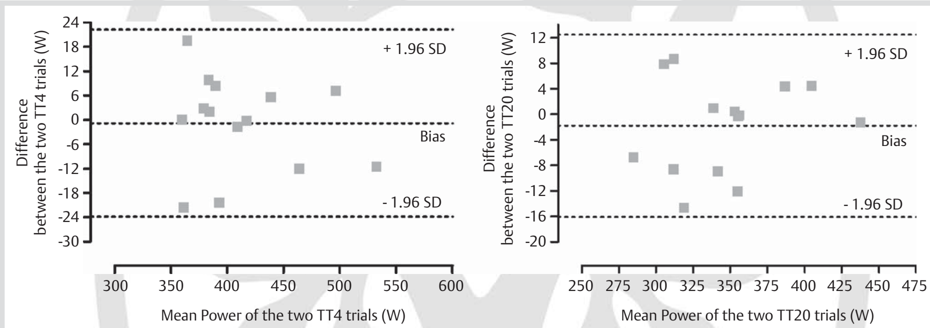


**Fig. 5** Bland Altman plot of the absolute difference between the two 4 min time-trials (left panel) and the two 20 min time trials (right panel) vs. their respective mean power outputs.

For power output during TT4 and TT20 ICC was 0.98 (95 % CL 0.92–0.99) and 0.98 (95 % CL 0.95–0.99), respectively. ICC was 0.94 (95 % CL 0.8–0.98) for heart rate during both, TT4 and TT20.

Bland Altman plot's of power output during the two 4 min time-trials showed a bias ± random error of – 0.8 ± 23 W or – 0.2 ± 5.5 % (▶ **Fig. 5**). The bias ± random error of power output during the two 20 min time-trials was – 1.8 ± 14 W or 0.6 ± 4.4 % (▶ **Fig. 5**).

## Discussion

The main findings of this study were that the applied field tests had very high test-retest reproducibility and that power output during the 20 min time-trial correlated with power output at the second lactate turn point (LTP 2) and the respiratory compensation point (RCP). It should be noted that the field test was designed to be used on self-selected flat courses as an easy to use tool for cyclists and coaches. Nevertheless the high reliability of mean power output during the field test was in agreement with the CV of 1.3–4.3 % for mean power output during a 40 km outdoor time-trial [41]. An improvement of reliability following a familiarisation trial has been shown by Laursen et al. [33] They reported a CV of 2.0 ± 1.8 %, 2.3 ± 1.8 % and 1.2 ± 1.3 % for trials 1 vs. 2, 1 vs. 3 and 2 vs. 3, respectively. In the present study all participants were experienced time-trial cyclists. This may explain the small amount of bias between repeated trials. The lengths of the field tests in this study were shorter than the 40 km (~55 min) reported in the studies of Smith et al. [41] and Laursen et al. [33]. Since the training load in cycling is between 20–30 h per week there is limited compliance of athletes to perform a 50–60 min time-trial for testing purposes. The field tests performed in the present study could be easily integrated into the training routine of athletes and therefore can be recommended for regular use.

The repeatability of the 4 min and 20 min field tests has been shown by a high intraclass correlation coefficient, a small bias and an acceptable random error. It is well known that the heterogeneity of a sample will yield high correlation coefficients [6]. However, in the homogenous group of elite cyclists used for this study high correlations were observed. Recently Gonzalez-Haro et al. [22] reported a bias ± random error of – 8.1 ± 52.6 W for maximal power output during an incremental field test on the velodrome. The authors considered their field protocol with a random error of 12.9 % as repeatable. In comparison the small error of ~5 % found in the present study illustrates the sensitivity of the TT4 and TT20 field trials to detect changes in power output from – 23 to + 22 W and from – 16 to + 12 W, respectively. Using the formula of Mognoni et al. [36] for example, a change from 340 W of ± 15 W would result in a difference of ~20 s or ~1.6 % in a 15 km flat time-trial. Despite the different and freely chosen courses used in this study it was shown that power output is highly reproducible in flat time-trials in elite athletes.

However, it is currently unknown whether or not differences in power output occur between flat and uphill time-trials of the same duration. Padilla et al. [38], investigated different types of time-trials in professional cyclists. In the long time-trial (3975 s) and the uphill time-trial (4495 s) the authors reported mean power outputs of 359 W and 376 W, respectively for those athletes that were riding at full strength. The difference did not reach statistical significance, but the fact that power output was higher despite a longer effort (~500 s) in the uphill time-trial, may suggest that higher power outputs can be produced during uphill cycling. However, a major concern arises from the fact that power output was not measured but estimated from the linear relationship between heart rate and power output during incremental laboratory tests [38]. In the present study no significant differences were found for mean HR (174 $b \cdot min^{-1}$ vs. 174 $b \cdot min^{-1}$) and end test HR (180 $b \cdot min^{-1}$ vs. 180 $b \cdot min^{-1}$) in the 4 min and 20 min time-trial, respectively. Using the approach from Padilla et al. [38] almost identical power outputs would be estimated. In fact power output was significantly higher during TT4 than during TT20. Further studies are required to assess the relationship of power output achieved during uphill and flat cycling.

The relationship of time-trial performance with maximal and sub-maximal laboratory variables has been reported in several studies [2, 5, 7, 10, 35]. In other endurance sports like running [23] or rowing [28] similar relationships were observed. The results of the present study are in agreement with the existing literature. Power output during the 4 min and 20 min time-trials was correlated with power output at maximal and sub-maximal performance markers obtained during a laboratory graded exercise test. We hypothesised an agreement between TT4 and $P_{max}$. However, a significant difference was observed. There was a bias of – 30 W and the 95 % limits of agreement were located between – 88 and + 28 W. The protocol of the incremental test can affect the assessment of maximal power [17]. $P_{max}$ values of 6.0–6.5 $W \cdot kg^{-1}$ are reported during tests with 4 min increments in professional cyclists [37], whereas 6.5–7.5 $W \cdot kg^{-1}$ have been found when increments of 1 min were applied [34]. Therefore the increment of 25 $W \cdot min^{-1}$ used in the present study to assess $P_{max}$ could be an explanation of the systematic bias of – 7.4 %. It has been shown that high-level elite athletes are able to tolerate exercise intensities of 95–105 % of $P_{max}$ over 4–15 min [12, 14]. In fact the two most successful athletes (i.e. world class) who participated in the present study performed the 4 min time-trial at 99 % and 108 % of $P_{max}$, whereas a fractional use of 91 % of $P_{max}$ was observed for the remaining athletes. This ability could be a prerequisite for world-class endurance athletes.

In contrast to TT4, no significant differences were observed between TT20, LTP 2 and RCP. The bias was close to zero and the random error was found to be approximately 13 %. Therefore, the hypothesis that power output during a 20 min time-trial would agree with these measures of "anaerobic threshold" was accepted.

Recently Amann et al. [3] investigated the reliability of ventilatory thresholds and the correlations with a 40 km laboratory time-trial. The authors reported high test-retest reliabilities (ICC 0.87–0.98) and predictive validities, expressed as standard error of the estimate (SEE), of 15 to 24 W between power output at ventilatory thresholds and the 40 km time-trial. In the present study SEE of 17 to 21 W between the field tests and GXT power outputs were found.

Finally, similar heart rates during the field tests and significant heart rate differences between laboratory and field tests were observed. The decoupling of heart rate and power output which has been reported previously [1] leads to differences when exercise intensity is described based on power or heart rate [46]. Therefore, estimations of power output based on heart rate measurements during outdoor cycling should be used with caution.

## Conclusion

In conclusion, the main findings of the present study were that power output during a 4 min and a 20 min time-trial on self-selected flat courses is a reliable performance measure in competitive elite cyclists. The sensitivity to detect performance changes is reflected by a small bias and random error. Power output measured during TT20 was in agreement with power output at the respiratory compensation point and the second lactate turn point and has acceptable accuracy to determine these markers of "anaerobic threshold". Power output during TT4 and TT20 has the predictive validity to estimate performance markers obtained during incremental exercise tests. From a practical point of view, the described field test can be easily integrated into the training routine of athletes. Further studies should address the difference between flat and uphill time-trials and the transferability of the presented results to other populations.

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## 12.2 Conference Communication European College of Sports Sciences, Oslo 2009

Evaluation of a field test to assess aerobic endurance and performance in elite cyclists

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**Introduction**

The assessment of endurance performance is usually conducted during laboratory ergometer tests. In field tests, time to complete a given distance is often the chosen performance measure. Since external conditions can largely influence these measures, the aim was to evaluate the reliability of power output in a field test and validate performance measures obtained from a traditional laboratory ergometer test.

**Methods**

Fifteen competitive male cyclists (age: 25.6 ± 5.2 y; height: 180.6 ± 4.5 cm; weight: 70.6 ± 4.4 kg; $\dot{V}O_2max$: 67.1 ± 5.0 $ml \cdot min^{-1} \cdot kg^{-1}$) completed an incremental graded exercise test (GXT) to determine ventilatory threshold, respiratory compensation point (VT, RCP) and lactate turn points (LTP1, LTP2) and two maximal aerobic power 4-min (MAP 4) and 20-min (MAP 20) time-trials, during which power output was measured with mobile power cranks (SRM).

**Results**

Power (W) was 263 ± 37, 344 ± 38, 243 ± 27, 344 ± 37 and 440 ± 38 W, for LTP1, LTP2, VT, RCP and Pmax, respectively. Average power during the 4-min time-trial (412 ± 53 W) was significantly higher ($p < 0.001$) than during the 20-min time-trial (347 ± 42 W) and was correlated with ($r = 0.791$ to 0.878, $p < 0.001$) but significantly different from ($p < 0.001$) performance markers obtained during GXT. No significant differences were observed between the 20-min time-trial, LTP2 ($p = 0.946$) and RCP ($p = 0.853$). Strong test-retest correlations for MAP 4 (ICC = 0.976, $p < 0.001$) and MAP 20 (ICC = 0.985, $p < 0.001$) were observed.

**Discussion**

The test-retest reproducibility was in agreement with the results of a 40-km outdoor time-trial reported by Smith et al. (2001). The reliability of a 3-min laboratory all out test has been published by Burnley et al. (2006) where typical error was found to be ± 7 W or 3 %, which is similar to the results of the 4-min time-trial (± 8 W or 2.2 %). Measures of aerobic performance explained 65 % - 77 % of the variance in MAP 4 and MAP 20. The 4-min time-trial was on average 93 % of Pmax from GXT, reflecting the ability of high-level athletes to tolerate intensities of 95 % - 105 % over 4-15 min. Average power during 20-min time-trial was 79 % of Pmax, which is in accordance with exercise intensities during time-trials in professional cyclists (Lucia, et al., 2001). In conclusion the 4-min and 20-min time-trials are reliable measures of aerobic endurance. The 20-min time-trial is valid to predict RCP and LTP2.

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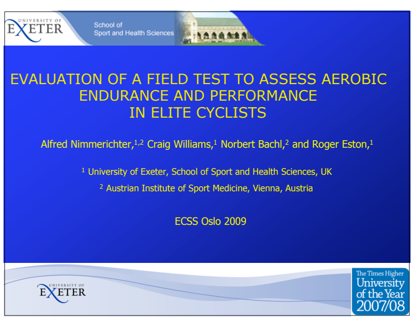
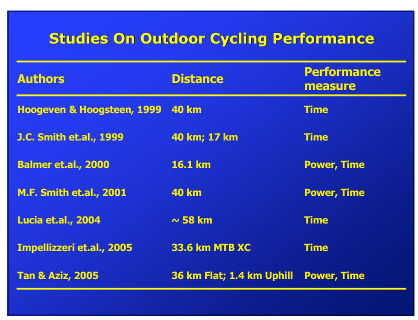
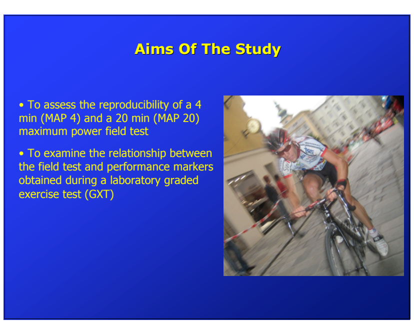
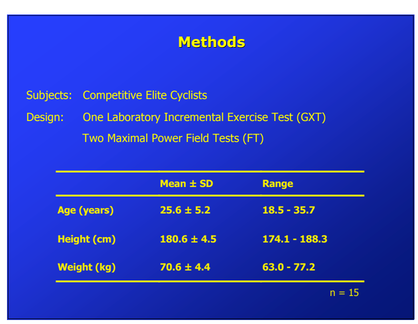


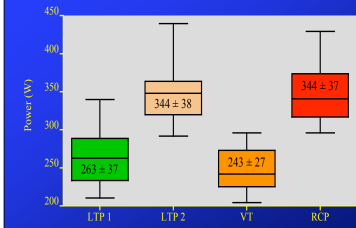



## Maximal Physiological Characteristics Obtained During The GXT

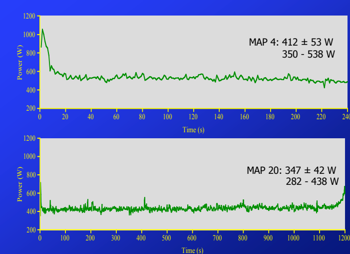
| Measure | Mean ± SD | Range |
|---|---|---|
| $P_{max}$ (W) | 439.5 ± 37.9 | 400 - 532 |
| $P_{max}$ ($W \cdot kg^{-1}$) | 6.2 ± 0.5 | 5.7 - 7.3 |
| $VO_{2max}$ ($ml \cdot min^{-1} \cdot kg^{-1}$) | 67.1 ± 5.0 | 60.1 - 79.5 |
| $HR_{max}$ ($b \cdot min^{-1}$) | 186.1 ± 12.3 | 159 - 201 |
| Blood $Lactate_{max}$ ($mmol \cdot L^{-1}$) | 11.9 ± 1.8 | 8.7 - 16.1 |

n = 15

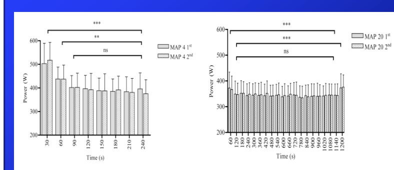
## Sub-Maximal Measures Determined From GXT




## Power Output During MAP 4 And MAP 20

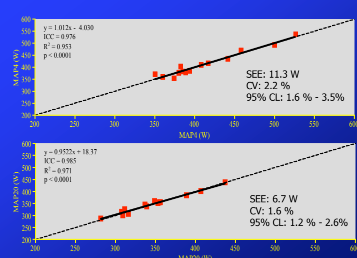



## Characteristics Of Power Output During MAP 4 And MAP 20

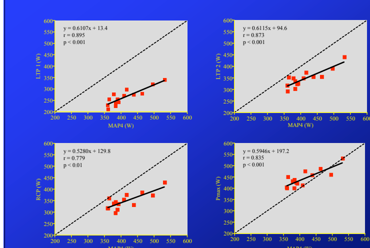


** p < 0.01; *** p < 0.001

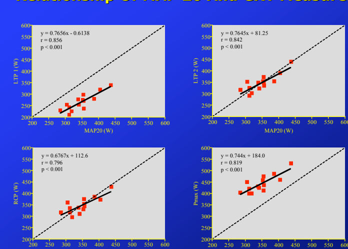
## Test-Retest Reliability Of MAP 4 And MAP 20




## Relationship Of MAP 4 And GXT Measures



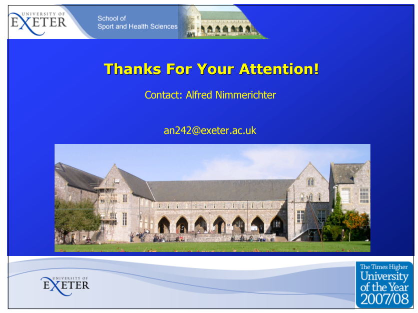
## Relationship Of MAP 20 And GXT Measures



## Mean Differences And Comparative Statistics Of Power Output During MAP 20, LTP 2 And RCP

| | LTP 2 95% CL | RCP 95% CL |
|---|---|---|
| CiM (W) | -0.5 | -0.4 |
| Lower CL | -13.5 | -14.2 |
| Upper CL | 12.5 | 14.9 |
| CiM (%) | -0.0 | -0.3 |
| Lower CL | -3.9 | -4.0 |
| Upper CL | 4.0 | 4.8 |
| Paired t-Test (p) | 0.946 | 0.853 |

CiM = Change in the mean; CL = Confidence limit;


## 12.3 Field Test Instructions

**Instructions for the administration of the Maximum Power Test**

- Perform the test in a sufficiently rested state
- Try to perform the test always at the same Time of Day (e.g. morning, afternoon, evening)
- Properly warm up, with a few intensified efforts (i.e. as you would warm up for a time-trial)
- IMPORTANT: Set the storage interval of your device to 1 second and make sure you have done the zero-offset calibration

**Test 1: 4 minutes Maximum Aaerobic Power**

- Choose a quiet road, almost flat or slightly rising (< 1%), depending on your level you need 2 – 4 km
- Choose the gear ratio in a way, that you can maintain the highest possible power output for 4 minutes
- Shifting gears is permitted
- Start the test from a slow Velocity (i.e. 20 – 25 km/h), set a marker on your device
- Perform a MAXIMUM effort for 4 minutes, keep up the power output at the highest possible level
- Set a marker immediately after cessation
- REST: easy pedalling for 25 – 30 minutes

**Test 2: 20 minutes Aaerobic Capacity**

- Choose a quiet course or roads with the right of way, flat or slightly undulating, avoid longer downhill sections
- Choose the gear ratio in a way, that you can maintain the highest possible power output for 20 minutes, small interruptions, due to bends or roundabouts, are screened during data analyses
- Shifting gears is permitted
- Start the test from a slow Velocity (i.e. 20 – 25 km/h), set a marker on your device
- Perform a MAXIMUM effort for 20 minutes, keep up the power output at the highest possible level
- Set a marker immediately after cessation
- RECOVERY: easy pedalling for 20 – 30 minutes

## 12.4 Example of the Results from the 4-min and 20-min Maximal Power Time-Trial

| | | | | | |
|---|---|---|---|---|---|
| Name: | MTB World Class | Date: | 09.04.2008 | Temp.: | 13 °C |
| Weight: | 73,0 kg | Time: | 11:00 hh:mm | | |

**Test 1:** 4 min MAP

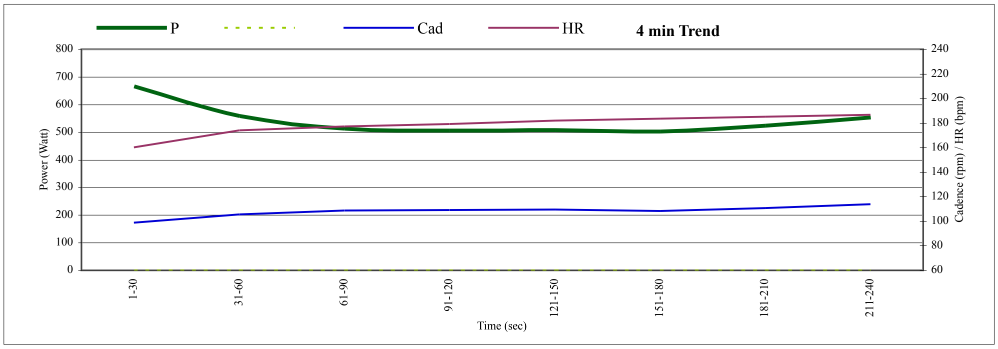
| | P mean | | HR | Cad mean |
|---|---|---|---|---|
| Time (sec) | Watt | Watt/kg | bpm | rpm |
| 1-30 | 667 | 9,14 | 160 | 99 |
| 31-60 | 559 | 7,66 | 174 | 106 |
| 61-90 | 513 | 7,03 | 177 | 109 |
| 91-120 | 507 | 6,95 | 179 | 109 |
| 121-150 | 509 | 6,97 | 182 | 109 |
| 151-180 | 503 | 6,90 | 183 | 108 |
| 181-210 | 524 | 7,17 | 185 | 111 |
| 211-240 | 555 | 7,60 | 187 | 114 |
| 1-240 | 542 | 7,42 | 178 | 108 |
| Work: | 130 | kJ | | |
| | 33 | kJ/min | | |
| FI 30/240 | 16,8 | % | | |
| FR 30/240 | 0,47 | W/s | | |

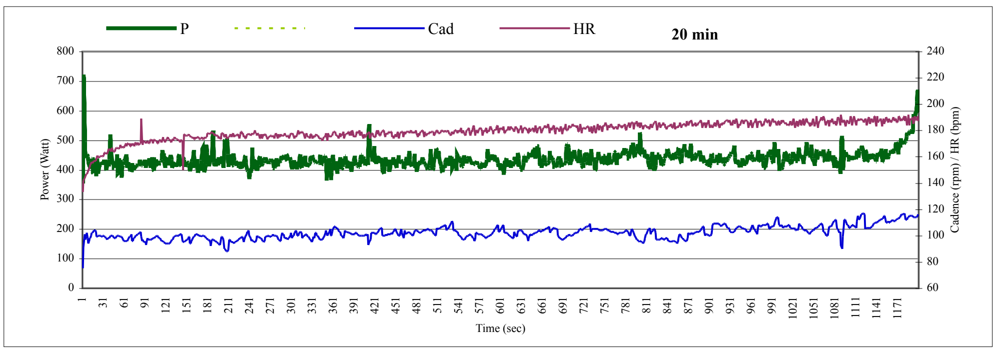
**Test 2:** 20 min MAP

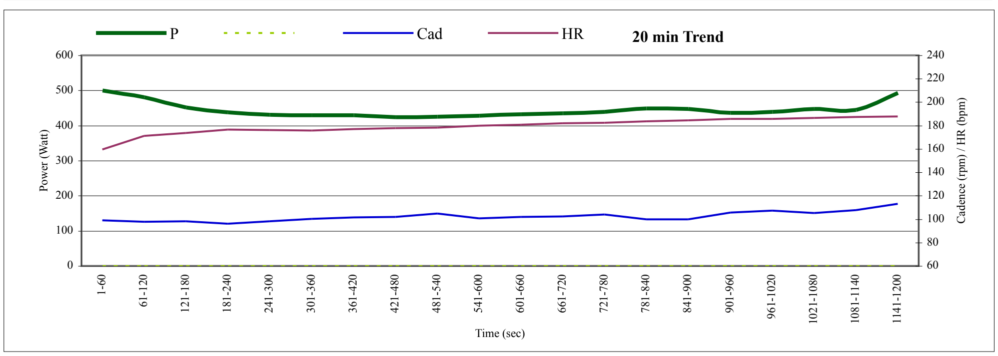
| | P mean | | HR | Cad mean |
|---|---|---|---|---|
| Time (sec) | Watt | Watt/kg | bpm | rpm |
| 1-60 | 501 | 6,86 | 159 | 99 |
| 61-120 | 481 | 6,59 | 171 | 98 |
| 121-180 | 452 | 6,19 | 174 | 98 |
| 181-240 | 438 | 6,00 | 176 | 96 |
| 241-300 | 431 | 5,90 | 176 | 98 |
| 301-360 | 430 | 5,89 | 176 | 100 |
| 361-420 | 429 | 5,88 | 177 | 101 |
| 421-480 | 425 | 5,82 | 178 | 102 |
| 481-540 | 426 | 5,84 | 178 | 105 |
| 541-600 | 428 | 5,87 | 180 | 101 |
| 601-660 | 432 | 5,92 | 181 | 102 |
| 661-720 | 435 | 5,96 | 182 | 102 |
| 721-780 | 440 | 6,03 | 182 | 104 |
| 781-840 | 449 | 6,15 | 184 | 100 |
| 841-900 | 447 | 6,13 | 184 | 100 |
| 901-960 | 436 | 5,98 | 186 | 106 |
| 961-1020 | 439 | 6,01 | 186 | 107 |
| 1021-1080 | 448 | 6,13 | 186 | 105 |
| 1081-1140 | 446 | 6,10 | 187 | 108 |
| 1141-1200 | 494 | 6,77 | 188 | 113 |
| 1-1200 | 445 | 6,10 | 180 | 102 |
| Work: | 534 | kJ | | |
| | 27 | kJ/min | | |

| | P mean | | HR | Cad mean |
|---|---|---|---|---|
| Time (sec) | Watt | Watt/kg | bpm | rpm |
| 1-240 | 468 | 6,41 | 170 | 98 |
| 241-480 | 429 | 5,88 | 177 | 100 |
| 481-720 | 430 | 5,90 | 180 | 102 |
| 721-960 | 443 | 6,07 | 184 | 102 |
| 961-1200 | 457 | 6,26 | 187 | 108 |
| 1-1200 | 445 | 6,10 | 180 | 102 |
| Work: | 534 | kJ | | |
| | 27 | kJ/min | | |
| FI 240/1200 | 2,4 | % | | |
| FR 240/1200 | 0,01 | W/s | | |


P
Cad
HR
4 min
Power (Watt)
0
200
400
600
800
1000
1200
Cadence (rpm) / HR (bpm)
60
80
100
120
140
160
180
200
220
240
1 11 21 31 41 51 61 71 81 91 101 111 121 131 141 151 161 171 181 191 201 211 221 231
Time (sec)


P
Cad
HR
4 min Trend
Power (Watt)
0
100
200
300
400
500
600
700
800
Cadence (rpm) / HR (bpm)
60
80
100
120
140
160
180
200
220
240
1-30 31-60 61-90 91-120 121-150 151-180 181-210 211-240
Time (sec)


P
Cad
HR
20 min
Power (Watt)
0
100
200
300
400
500
600
700
800
Cadence (rpm) / HR (bpm)
60
80
100
120
140
160
180
200
220
240
1 31 61 91 121 151 181 211 241 271 301 331 361 391 421 451 481 511 541 571 601 631 661 691 721 751 781 811 841 871 901 931 961 991 1021 1051 1081 1111 1141 1171
Time (sec)


P
Cad
HR
20 min Trend
Power (Watt)
0
100
200
300
400
500
600
Cadence (rpm) / HR (bpm)
60
80
100
120
140
160
180
200
220
240
1-60 61-120 121-180 181-240 241-300 301-360 361-420 421-480 481-540 541-600 601-660 661-720 721-780 781-840 841-900 901-960 961-1020 1021-1080 1081-1140 1141-1200
Time (sec)

## 12.5 Example of the Results from a Laboratory Graded Exercise Test

| | | | | |
|---|---|---|---|---|
| **Name:** | **MTB World Class** | | **Date:** | 13.08.2008 |
| **Date of birth:** | 11.10.1980 | | **Location:** | OEISM |
| **Age:** | 27,8 | years | **Device:** | Lode |
| **Height:** | 184,0 | cm | **Sport:** | MTB |
| **Weight:** | 73,2 | kg | **Team:** | |
| | | | **Test:** | GXT |

| | | |
|---|---|---|
| **Initial stage:** | 75 | Watt |
| **Increment:** | 25 | Watt |
| **Step length:** | 60 | sec |
| **Cessation:** | 557 | Watt |

**Comment:**
2 weeks before the Olympic MTB XC race

**Measured values**

| Time mm:ss | Power Watt | Lactate mmol/l | HR b/min |
|---|---|---|---|
| **Prestart:** | | 1,0 | 45 |
| 01:00 | 75,0 | 1,2 | 99 |
| 02:00 | 100,0 | 1,3 | 102 |
| 03:00 | 125,0 | 1,3 | 108 |
| 04:00 | 150,0 | 1,4 | 109 |
| 05:00 | 175,0 | 1,3 | 112 |
| 06:00 | 200,0 | 1,4 | 117 |
| 07:00 | 225,0 | 1,3 | 123 |
| 08:00 | 250,0 | 1,3 | 131 |
| 09:00 | 275,0 | 1,4 | 135 |
| 10:00 | 300,0 | 1,3 | 144 |
| 11:00 | 325,0 | 1,5 | 148 |
| 12:00 | 350,0 | 1,6 | 151 |
| 13:00 | 375,0 | 1,9 | 158 |
| 14:00 | 400,0 | 2,3 | 161 |
| 15:00 | 425,0 | 2,8 | 168 |
| 16:00 | 450,0 | 3,5 | 173 |
| 17:00 | 475,0 | 4,5 | 178 |
| 18:00 | 500,0 | 5,7 | 184 |
| 19:00 | 525,0 | 7,5 | 186 |
| 20:00 | 550,0 | 9,8 | 188 |
| 20:16 | 557,0 | 10,6 | 188 |

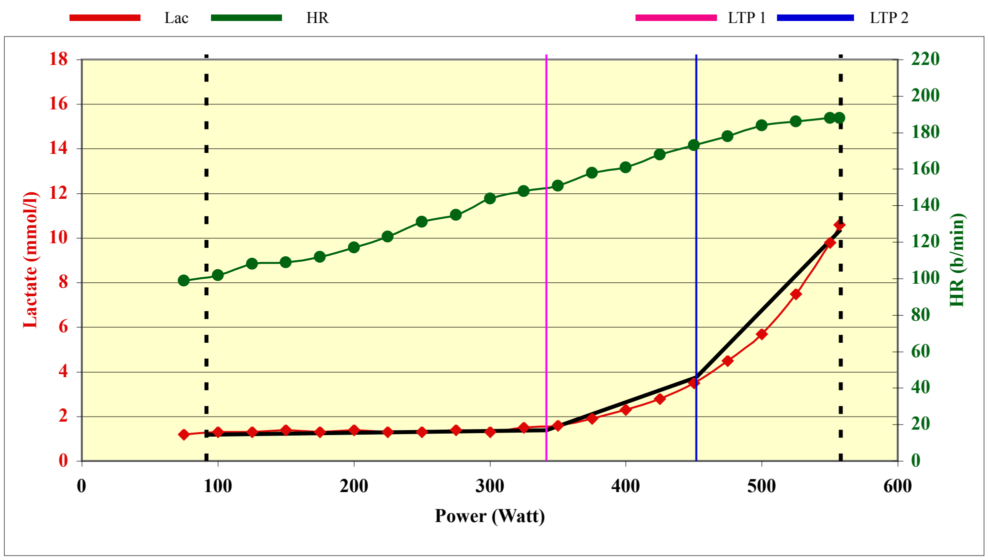
**Calculated values**

| Lactate mmol/l | Power Watt | Power Watt/kg | HR b/min | VO2 ml/min/kg |
|---|---|---|---|---|
| 1,5 | 356,0 | 4,86 | 153 | 61,37 |
| 2,0 | 390,0 | 5,33 | 159 | 65,83 |
| 2,5 | 413,0 | 5,64 | 164 | 68,79 |
| 3,0 | 431,0 | 5,89 | 167 | 71,09 |
| 3,5 | 445,0 | 6,08 | 170 | 72,86 |
| 4,0 | 458,0 | 6,26 | 173 | 74,49 |
| 4,5 | 469,0 | 6,41 | 175 | 75,86 |
| 5,0 | 480,0 | 6,56 | 177 | 77,22 |
| 5,5 | 489,0 | 6,68 | 179 | 78,33 |
| 6,0 | 498,0 | 6,80 | 180 | 79,43 |
| 7,0 | 514,0 | 7,02 | 184 | 81,38 |
| 8,0 | 529,0 | 7,23 | 187 | 83,18 |
| 9,0 | 542,0 | 7,40 | 189 | 84,73 |
| 10,0 | 554,0 | 7,57 | 191 | 86,16 |

| End Test Values | | |
|---|---|---|
| **Time** | **20:16** | mm:ss |
| **Power** | **557** | Watt |
| | **7,61** | Watt/kg |
| **HR** | **188** | bpm |
| **VO2 max** | **6147** | ml/min |
| | **83,98** | ml/min/kg |
| **Lactate** | **10,6** | mmol/l |
| **Workrate** | **33,42** | kJ/min |

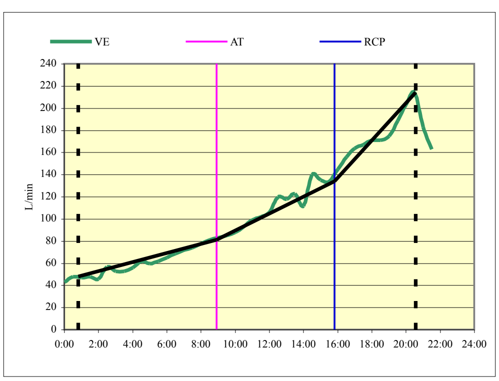
| | **LTP 1** | **LTP 2** | |
|---|---|---|---|
| Power | **341,7** | **452,1** | Watt |
| | **4,67** | **6,18** | Watt/kg |
| % Pmax | **61,3** | **81,2** | % |
| HR | **150** | **172** | b/min |
| % HRmax | **79,6** | **91,2** | % |
| Lactate | **1,4** | **3,7** | mmol/l |
| VO2 | **4353** | **5399** | ml/min |
| | **59,46** | **73,75** | ml/min/kg |
| % VO2max | **70,8** | **87,8** | % |
| Energy expenditure | **89,9** | **111,7** | kJ/min |
| Workrate | **20,5** | **27,1** | kJ/min |

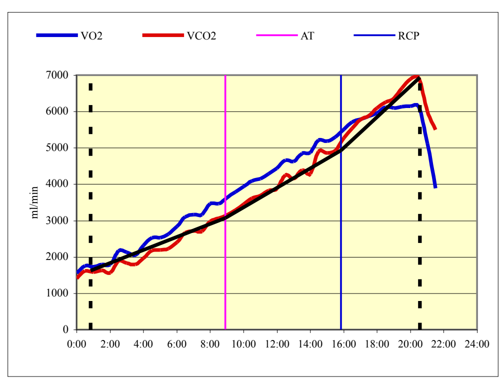
| | **Trainingzones** | **%** | **Watt** | **HR** |
|---|---|---|---|---|
| 1 | Recovery | 40 | **- 223** | **- 126** |
| 2 | Basic endurance | 55 | **- 306** | **- 143** |
| 3 | Aerobic capacity | 70 | **- 390** | **- 159** |
| 4 | Anaerobic threshold | 80 | **- 446** | **- 170** |
| 5 | VO2 max | 100 | **- 557** | **- 192** |

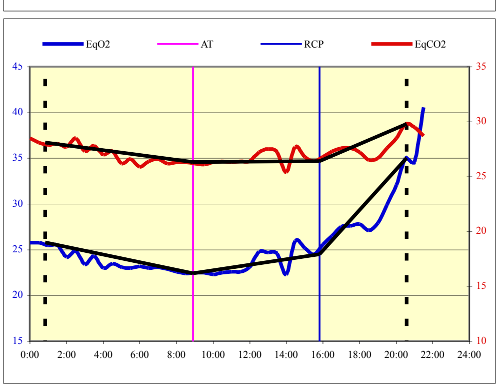


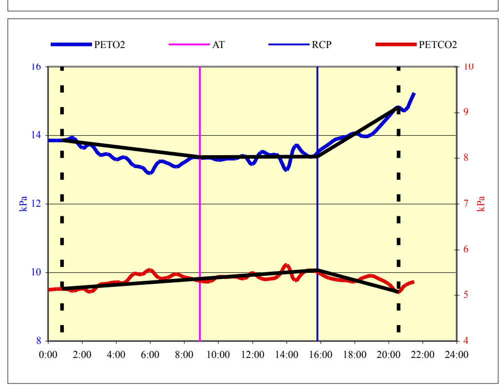

| | AT | RCP | |
|---|---|---|---|
| Power | 272,9 | 445,8 | Watt |
| | 3,73 | 6,09 | Watt/kg |
| % Pmax | 49,0 | 80,0 | % |
| HR | 136 | 170 | b/min |
| %HRmax | 72,3 | 90,6 | % |
| VO2 | 3466 | 5299 | ml/min |
| | 47,35 | 72,39 | ml/min/kg |
| %VO2max | 56,4 | 86,2 | % |
| Energy expenditure | 71,4 | 109,6 | kJ/min |
| Workrate | 16,38 | 26,75 | kJ/min |
| Gross efficiency | 22,93 | 24,41 | % |
| Economy | 4,72 | 5,05 | kJ/l/min |
| Delta efficiency | 28,30 | | |

| End Test Values | | |
|---|---|---|
| **Time** | 20:16 | mm:ss |
| **Power** | 557 | Watt |
| | 7,61 | Watt/kg |
| **HR** | 188 | bpm |
| **VO2 max** | 6147 | ml/min |
| | 83,98 | ml/min/kg |
| **Workrate** | 33,42 | kJ/min |



**Name: MTB World Class** **Date:** 13.08.2008

| Time [hh:mm:ss] | Phase | V'E [L/min] | V'O2 [ml/min] | VO2/kg [ml/min/kg] | V'CO2 [ml/min] | RER | EqO2 | EqCO2 | PETCO2 [kPa] | PETO2 [kPa] | EE [kJ/min] | EE [kcal/min] |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 0:00:00 | | 43 | 1560 | 21,10 | 1411 | 0,90 | 25,80 | 28,50 | 5,12 | 13,85 | 32,33 | 7,72 |
| 0:00:30 | | 48 | 1765 | 23,90 | 1619 | 0,92 | 25,80 | 28,10 | 5,14 | 13,86 | 36,69 | 8,76 |
| 0:01:00 | 75,00 | 47 | 1737 | 23,50 | 1590 | 0,92 | 25,50 | 27,90 | 5,14 | 13,87 | 36,09 | 8,62 |
| 0:01:30 | | 48 | 1791 | 24,20 | 1635 | 0,91 | 25,50 | 28,00 | 5,10 | 13,92 | 37,19 | 8,88 |
| 0:02:00 | 100,00 | 46 | 1798 | 24,30 | 1571 | 0,87 | 24,20 | 27,70 | 5,15 | 13,64 | 36,99 | 8,83 |
| 0:02:30 | | 57 | 2165 | 29,30 | 1894 | 0,88 | 24,90 | 28,50 | 5,08 | 13,74 | 44,55 | 10,64 |
| 0:03:00 | 125,00 | 53 | 2136 | 28,90 | 1828 | 0,86 | 23,40 | 27,30 | 5,23 | 13,44 | 43,75 | 10,45 |
| 0:03:30 | | 53 | 2053 | 27,70 | 1791 | 0,87 | 24,30 | 27,80 | 5,26 | 13,46 | 42,22 | 10,08 |
| 0:04:00 | 150,00 | 56 | 2319 | 31,30 | 1975 | 0,85 | 23,00 | 27,00 | 5,29 | 13,30 | 47,45 | 11,33 |
| 0:04:30 | | 62 | 2533 | 34,20 | 2188 | 0,86 | 23,50 | 27,30 | 5,28 | 13,37 | 51,98 | 12,41 |
| 0:05:00 | 175,00 | 60 | 2529 | 34,20 | 2194 | 0,87 | 23,10 | 26,20 | 5,47 | 13,13 | 51,94 | 12,41 |
| 0:05:30 | | 62 | 2635 | 35,60 | 2235 | 0,85 | 23,00 | 26,60 | 5,46 | 13,07 | 53,87 | 12,87 |
| 0:06:00 | 200,00 | 65 | 2850 | 38,50 | 2410 | 0,85 | 23,20 | 25,90 | 5,56 | 12,90 | 58,22 | 13,91 |
| 0:06:30 | | 69 | 3110 | 42,00 | 2665 | 0,86 | 23,00 | 26,40 | 5,38 | 13,23 | 63,71 | 15,22 |
| 0:07:00 | 225,00 | 72 | 3175 | 42,90 | 2720 | 0,86 | 23,10 | 26,60 | 5,39 | 13,19 | 65,04 | 15,53 |
| 0:07:30 | | 74 | 3170 | 42,80 | 2709 | 0,85 | 22,90 | 26,20 | 5,47 | 13,08 | 64,90 | 15,50 |
| 0:08:00 | 250,00 | 78 | 3469 | 46,90 | 2980 | 0,86 | 22,60 | 26,30 | 5,40 | 13,22 | 71,10 | 16,98 |
| 0:08:30 | | 81 | 3466 | 46,80 | 3067 | 0,88 | 22,40 | 26,30 | 5,36 | 13,37 | 71,49 | 17,08 |
| 0:09:00 | 275,00 | 83 | 3637 | 49,10 | 3158 | 0,87 | 22,50 | 26,20 | 5,31 | 13,34 | 74,71 | 17,85 |
| 0:09:30 | | 85 | 3799 | 51,30 | 3300 | 0,87 | 22,50 | 26,10 | 5,31 | 13,35 | 78,05 | 18,64 |
| 0:10:00 | 300,00 | 88 | 3940 | 53,20 | 3458 | 0,88 | 22,30 | 26,30 | 5,41 | 13,28 | 81,12 | 19,38 |
| 0:10:30 | | 93 | 4094 | 55,30 | 3619 | 0,88 | 22,50 | 26,40 | 5,40 | 13,33 | 84,42 | 20,16 |
| 0:11:00 | 325,00 | 99 | 4151 | 56,10 | 3688 | 0,89 | 22,60 | 26,30 | 5,41 | 13,33 | 85,69 | 20,47 |
| 0:11:30 | | 102 | 4289 | 58,00 | 3829 | 0,89 | 22,60 | 26,40 | 5,37 | 13,41 | 88,63 | 21,17 |
| 0:12:00 | 350,00 | 106 | 4439 | 60,00 | 3880 | 0,87 | 23,10 | 26,40 | 5,49 | 13,16 | 91,32 | 21,81 |
| 0:12:30 | | 120 | 4671 | 63,10 | 4259 | 0,91 | 24,80 | 27,20 | 5,37 | 13,51 | 96,97 | 23,16 |
| 0:13:00 | 375,00 | 118 | 4632 | 62,60 | 4157 | 0,90 | 24,70 | 27,50 | 5,36 | 13,43 | 95,83 | 22,89 |
| 0:13:30 | | 123 | 4857 | 65,60 | 4390 | 0,90 | 24,60 | 27,20 | 5,42 | 13,41 | 100,64 | 24,04 |
| 0:14:00 | 400,00 | 112 | 4875 | 65,90 | 4293 | 0,88 | 22,30 | 25,40 | 5,67 | 13,00 | 100,45 | 23,99 |
| 0:14:30 | | 140 | 5218 | 70,50 | 4899 | 0,94 | 26,00 | 27,70 | 5,33 | 13,69 | 109,04 | 26,04 |
| 0:15:00 | 425,00 | 135 | 5194 | 70,20 | 4871 | 0,94 | 25,20 | 26,80 | 5,51 | 13,48 | 108,51 | 25,92 |
| 0:15:30 | | 134 | 5299 | 71,60 | 4926 | 0,93 | 24,50 | 26,40 | 5,55 | 13,38 | 110,48 | 26,39 |
| 0:16:00 | 450,00 | 145 | 5516 | 74,50 | 5272 | 0,96 | 25,60 | 26,80 | 5,47 | 13,59 | 115,73 | 27,64 |
| 0:16:30 | | 156 | 5718 | 77,30 | 5544 | 0,97 | 26,50 | 27,30 | 5,38 | 13,75 | 120,36 | 28,75 |
| 0:17:00 | 475,00 | 164 | 5786 | 78,20 | 5775 | 1,00 | 27,50 | 27,60 | 5,34 | 13,91 | 122,62 | 29,29 |
| 0:17:30 | | 167 | 5877 | 79,40 | 5891 | 1,00 | 27,60 | 27,60 | 5,33 | 13,96 | 124,67 | 29,78 |
| 0:18:00 | 500,00 | 171 | 5964 | 80,60 | 6104 | 1,02 | 27,80 | 27,20 | 5,30 | 14,06 | 127,15 | 30,37 |
| 0:18:30 | | 171 | 6126 | 82,80 | 6269 | 1,02 | 27,10 | 26,50 | 5,39 | 13,98 | 130,60 | 31,19 |
| 0:19:00 | 525,00 | 175 | 6100 | 82,40 | 6368 | 1,04 | 27,90 | 26,70 | 5,43 | 14,03 | 130,67 | 31,21 |
| 0:19:30 | | 189 | 6136 | 83,10 | 6648 | 1,08 | 29,90 | 27,60 | 5,35 | 14,28 | 132,66 | 31,68 |
| 0:20:00 | 550,00 | 203 | 6147 | 82,90 | 6900 | 1,12 | 32,10 | 28,50 | 5,25 | 14,56 | 134,10 | 32,03 |
| 0:20:30 | 557,00 | 214 | 6140 | 79,90 | 6932 | 1,17 | 35,00 | 29,80 | 5,07 | 14,82 | 134,14 | 32,04 |
| 0:21:00 | | 183 | 5133 | 69,40 | 6017 | 1,17 | 34,60 | 29,50 | 5,23 | 14,74 | 113,25 | 27,05 |
| 0:21:30 | | 163 | 3895 | 52,60 | 5500 | 1,41 | 40,60 | 28,70 | 5,30 | 15,25 | 90,61 | 21,64 |

# 13 Appendix 2

## 13.1 Publication Resulted from Study Two

*Journal of Sports Sciences*, May 2011; 29(8): 831–839

Routledge
Taylor & Francis Group

### Longitudinal monitoring of power output and heart rate profiles in elite cyclists

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*(Accepted 7 February 2011)*



**Abstract**
Power output and heart rate were monitored for 11 months in one female ($\dot{V}O_{2max}$: 71.5 mL · kg$^{-1}$ · min$^{-1}$) and ten male ($\dot{V}O_{2max}$: 66.5 ± 7.1 mL · kg$^{-1}$ · min$^{-1}$) cyclists using SRM power-meters to quantify power output and heart rate distributions in an attempt to assess exercise intensity and to relate training variables to performance. In total, 1802 data sets were divided into workout categories according to training goals, and power output and heart rate intensity zones were calculated. The ratio of mean power output to respiratory compensation point power output was calculated as an intensity factor for each training session and for each interval during the training sessions. Variability of power output was calculated as a coefficient of variation. There was no difference in the distribution of power output and heart rate for the total season ($P = 0.15$). Significant differences were observed during high-intensity workouts ($P < 0.001$). Performance improvements across the season were related to low-cadence strength workouts ($P < 0.05$). The intensity factor for intervals was related to performance ($P < 0.01$). The variability in power output was inversely associated with performance ($P < 0.01$). Better performance by cyclists was characterized by lower variability in power output and higher exercise intensities during intervals.

**Keywords:** *Oxygen consumption, anaerobic threshold, athletic performance, cycling, mobile power meter*

#### Introduction

Two of the most important physiological determinants of endurance performance are an athlete's maximum oxygen uptake ($\dot{V}O_{2max}$) and the fractional use of $\dot{V}O_{2max}$ during competition (Bassett & Howley, 2000). Consequently, the objective of endurance training is to improve both maximal and sub-maximal physiological components. The total training load is determined by several variables, of which volume, intensity, and frequency are the most important (Busso, Benoit, Bonnefoy, Feasson, & Lacour, 2002; Esteve-Lanao, San Juan, Earnest, Foster, & Lucia, 2005; Mujika et al., 1996). Although there is general agreement that performance at elite or world-class level requires several years of high-volume endurance training, it is unclear what the most effective mixture of the essential training variables is. While a number of studies have investigated the adaptations to a certain training intervention over 2–6 weeks in active individuals (Burgomaster et al., 2008; Glaister, Stone, Stewart, Hughes, & Moir, 2007) and competitive athletes (Lindsay et al., 1996; Westgarth-Taylor et al., 1997), limited information exists about longitudinal training strategies and the relationship with performance (Esteve-Lanao et al., 2005). A rigorously controlled study over a racing season with international successful athletes is impossible. However, the description of performance and training data of such athletes provide useful information for coaches and researchers. Training-related changes in gross efficiency over a season in competitive cyclists have recently been reported (Hopker, Coleman, & Passfield, 2009).

The relationship between heart rate and work rate during incremental laboratory exercise is used to define exercise intensity zones and several studies have used heart rate to estimate exercise intensity in the field (Impellizzeri, Sassi, Rodriguez-Alonso,

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Mognoni, & Marcora, 2002; Lucia, Hoyos, Carvajal, & Chicharro, 1999; Padilla et al., 2001). However, power output has been described as the most direct measure of intensity during cycling despite its higher variation compared with heart rate (Vogt et al., 2006). Vogt et al. (2006) observed different distributions of exercise intensity when heart rate and power output were measured simultaneously.

To the best of our knowledge, no study has investigated power output and heart rate characteristics during training and racing on a longitudinal basis (i.e. one season) in a group of competitive racing cyclists. Therefore, the aims of the present study were: (a) to compare exercise intensity distributions of power output and heart rate; (b) to assess relative exercise intensity and variability of power output; and (c) to relate training variables to performance measures in a group of elite cyclists across one complete season.



## Methods

### *Participants*

One female (age 23.1 years, stature 1.65 m, body mass 45.5 kg) and ten male (age 29.1 ± 6.7 years, stature 1.81 ± 0.05 m, body mass 72.7 ± 6.3 kg; mean ± *s*) competitive cyclists volunteered to participate in this study. All riders had a training history of at least 6 years and competed successfully in national and international races (Table I). Before the study began, the athletes provided written informed consent to participate in the study, which was conducted in accordance with the ethical principles of the Declaration of Helsinki and was approved by the institutional ethics committee.

### *Periodization*

The season for the athletes started in the first week of December and lasted until end October of the following year. Most of the athletes followed a biphasic periodization model, which was divided into two macro-cycles. The first macro-cycle was composed of a preparatory phase (10–12 weeks), a pre-competition phase (6–8 weeks), and a competition phase (6–8 weeks). During the second macro-cycle, the preparatory, pre-competition, and competition phases lasted 6–8 weeks, 4–6 weeks, and 4–6 weeks, respectively. This periodization model aimed to achieve a high level of performance from April to June and from August to October.

### *Quantification of exercise intensity*

All participants used an SRM professional power-meter (Schoberer Rad Messtechnik–SRM, Juelich, Germany) on at least one of their bikes throughout the season. The SRM is capable of storing power output, heart rate, cadence, and speed simultaneously. All files were screened to identify outliers within the data, which were defined as (a) a sudden change in heart rate of 10% compared with the pre value, (b) an implausible peak in power output, and (c) the lack of data irrespective of the error source (i.e. technical problems or an unworn heart rate belt). In the case of (a) and (b), the erroneous values were manually corrected when they occurred for less than 30 consecutive seconds and did not exceed 5% of the training time. Otherwise and in the case of (c), the files were excluded from further analyses. From a total number of 1895 sampled data sets, 1802 (96%) met the inclusion criteria and were analysed further using the software "Trainingspeaks WKO+" (Peaksware LLC, Colorado, USA). Data were sampled at 1 Hz for the majority of the sessions ($n = 1743$). However, during some track sessions ($n = 28$) and short-interval sessions ($n = 31$), the sampling rate was 2–5 Hz. The captured training sessions correspond to 60% of the total training time and 69% of the cycling training time. All participants had trained for at least 2 years with mobile power-meters, were

Table I. Performance characteristics of the riders.

| Performance classification | Discipline | Category | Results, victories |
|---|---|---|---|
| 1 | MTB (female) | World-class | Winner of WC races and General Classification, OG <10, ECH and WCH medalist, UCI ranking <5 |
| 2 | MTB | World-class | Winner of UCI Category 1 MTB races, OG <10, WC <10, WCH <10, ECH medalist, UCI ranking <10 |
| 3 | Road, Track | International Competitive | NCH Track medalist TT and Individual Pursuit, WC member Individual and Team Pursuit |
| 4 | Road, Track | International Competitive | NCH Track medalist Points Race and Madison, WC member Points Race and Madison |
| 5 | Road, Track | U-23 | NCH Juniors Track medalist Individual Pursuit and TT |
| 6–11 | Road | Elite | Successful in national events |

*Note*: WC = World Cup; OG = Olympic Games; WCH = World Championships; ECH = European Championships; NCH = National Championships; TT = Time trial; UCI = International Cycling Federation.

familiar with the calibration procedure, and carried out a zero offset calibration before each training session according to the manufacturer's instructions. To ensure accurate measures, a static calibration procedure was applied on all devices prior to the study (Wooles, Robinson, & Keen, 2005).

In a previous study, power outputs measured during a 20-min field test and at respiratory compensation point were found to be similar (Nimmerichter, Williams, Bachl, & Eston, 2010). Both were used as performance measures in the present study and are denoted as ''functional threshold power'' (FTP) throughout this paper. The exercise intensity zones were related to FTP: Zone 1 < 50% FTP, Zone 2 = 50–70% FTP, Zone 3 = 71–85% FTP, Zone 4 = 86–105% FTP, Zone 5 = 106–125% FTP, Zone 6 = 126–170% FTP, and Zone 7 > 170% FTP. The relationship between power output and heart rate during a graded exercise test was used to calculate heart rate zones for comparisons of the exercise intensity distribution based on power output or heart rate (Lucia, Hoyos, Perez, & Chicharro, 2000). As a measure of relative exercise intensity, an intensity factor was calculated as the ratio of mean power output to functional threshold power for each training session (e.g. 200/400 = 0.5) as well as for each interval during high-intensity workouts. The variability of power output was calculated as a coefficient of variation.

To analyse total training, the participants were provided with a PC spreadsheet to record the goal of each training session as well as the content, time, and distance (if applicable) in the diaries. Nine workout goals were identified and described as follows: ''recovery'', ''basic aerobic endurance'', ''aerobic capacity'', ''anaerobic threshold'', ''maximal oxygen uptake'', ''strength'', ''maximal power'', ''competition'', and ''non-cycling activities''. The distribution of exercise intensity for both power output and heart rate zones was assessed for each workout category, except for non-cycling activities.

### *Laboratory incremental graded exercise test*

At the start of the season, all participants performed a graded exercise test to exhaustion on an electromagnetically braked ergometer (Lode Excalibur, Groningen, Netherlands). After a 5-min warm-up at 50 W and 30 W, the work rate was increased by 25 W $\cdot$ min$^{-1}$ and 15 W $\cdot$ min$^{-1}$ for the male and female participants, respectively. If the last work rate was not completed, maximal power was calculated according to the method of Kuipers and colleagues (Kuipers, Verstappen, Keizer, Geurten, & van Kranenburg, 1985):

$$P_{max} = P_L + (t/60 \times P_I)$$

where $P_L$ is the last completed work rate (W), $t$ is the time for the incomplete work rate (s), and $P_I$ is the incremental work rate (W). Gas exchange data were collected continuously throughout the test using breath-by-breath open-circuit spirometry (Master Screen CPX, VIASYS Healthcare, Hoechberg, Germany). Maximal oxygen uptake ($\dot{V}O_{2max}$) was recorded as the highest $\dot{V}O_2$ value obtained for any continuous 30-s period during the test. At least two of the following criteria were required for the attainment of $\dot{V}O_{2max}$: a plateau in $\dot{V}O_2$ despite an increase in work rate (Howley, Bassett, & Welch, 1995; Taylor, Buskirk, & Henschel, 1955), a respiratory exchange ratio above 1.10 (Duncan, Howley, & Johnson, 1997), and a heart rate within $\pm$ 10 beats $\cdot$ min$^{-1}$ of age-predicted maximum (220 – 0.7 $\times$ age) (Gellish et al., 2007). The ventilatory threshold was defined as an increase of the ventilatory equivalent of $O_2$ ($\dot{V}_E/\dot{V}O_2$) corresponding with a loss of linearity in pulmonary ventilation ($\dot{V}_E$) and without a concomitant increase of the ventilatory equivalent of $CO_2$ ($\dot{V}_E/\dot{V}CO_2$) (Beaver, Wasserman, & Whipp, 1986). The respiratory compensation point was considered to be where $\dot{V}_E/\dot{V}CO_2$ began to rise (Wasserman, Hansen, Sue, Casaburi, & Whipp, 1999). Two observers determined the ventilatory threshold and respiratory compensation point. In case of disagreement, a third investigator was consulted. Heart rate was monitored continuously throughout the test with a 12-lead electrocardiograph (Cardiovit AT 104 PC, Schiller, Baar, Switzerland).

### *Performance tests*

Recently, the validity and reliability of a 20-min field test on self-selected flat courses was reported (Nimmerichter et al., 2010). It was shown that power output obtained during the field test was highly reproducible (–0.6 $\pm$ 4.4%; intraclass correlation coefficient = 0.98) and strongly correlated with respiratory compensation point (–0.3 $\pm$ 14.3%; $r$ = 0.8) in elite cyclists. In the present study, we therefore used the field test as a performance measure to adopt the bands of the intensity zones and to properly calculate the intensity factors. All participants performed three tests during the season to assess exercise-induced adaptations.

### *Statistical analysis*

Descriptive data are reported as means $\pm$ standard deviations ($s$) and 95% confidence limits (95% CL). The assumption of normality was verified using Kolmogorov-Smirnov test and Liliefors probability.

Repeated-measures analysis of variance (ANOVA) was used to compare the performance tests and the interactions of workout categories with the intensity factors and the coefficients of variation. To identify the interactions of power output and heart rate zone distributions with workout categories, we used a two-factor ANOVA. Bonferroni's *post-hoc* test was applied to identify differences revealed by the ANOVA. The relationship between training variables and performance measures was verified using Pearson's product–moment correlation coefficient. To correlate the training variables with the rider's classification according to international and national rankings (Table I), Spearman's rank correlation was calculated. For all statistical analyses, statistical significance was set at $P < 0.05$.

## Results

### *Performance measures*

The physiological measures from the graded exercise test are presented in Table II. The ventilatory threshold occurred at 49 ± 4% (95% CL 46–51), 57 ± 4% (54–60), and 72 ± 5% (69–76) of maximal power, $\dot{V}O_{2max}$, and maximal heart rate, respectively. At the respiratory compensation point, the fractional use of maximal power, $\dot{V}O_{2max}$, and maximal heart rate was 77 ± 3% (95% CL 75–79), 83 ± 4% (81–86), and 90 ± 3% (88–92), respectively. Functional threshold power increased significantly from 4.7 ± 0.5 $W \cdot kg^{-1}$ (95% CL 4.4–5.1) to 4.8 ± 0.5 $W \cdot kg^{-1}$ (4.4–5.1), 5.0 ± 0.4 $W \cdot kg^{-1}$ (4.7–5.3), and 5.1 ± 0.5 $W \cdot kg^{-1}$ (4.8–5.4) during the season ($F_{3,30} = 8.6$; $P < 0.001$) (Figure 1). The increase was strongly correlated with the training time for the strength category ($r = 0.83$, $P < 0.05$) (Figure 1).

### *Quantification of total training*

Total training time (689 ± 191 h, 95% CL 529–848; $r = -0.96$, $P < 0.001$) and numbers of training sessions (268 ± 60, 95% CL 218–317; $r = -0.83$, $P < 0.01$) were strongly correlated with the rider's classification. Training time was strongly correlated with functional threshold power ($W \cdot kg^{-1}$) ($r = 0.84$, $P < 0.01$) and $\dot{V}O_{2max}$ ($mL \cdot kg^{-1} \cdot min^{-1}$) ($r = 0.82$, $P < 0.01$). Strong correlations were observed between classification and recovery (46 ± 22 h, 95% CL 28–64; $r = -0.79$, $P < 0.05$), basic aerobic endurance (294 ± 85 h, 95% CL 222–364; $r = -0.82$, $P < 0.01$), strength (65 ± 36 h, 95% CL 32–98; $r = -0.86$, $P < 0.01$), and non-cycling activities (59 ± 58 h, 95% CL 11–108; $r = -0.8$, $P = 0.02$). In addition, strong correlations were found between basic aerobic endurance and functional threshold power ($W \cdot kg^{-1}$) ($r = 0.81$, $P < 0.05$) and $\dot{V}O_{2max}$ ($mL \cdot kg^{-1} \cdot min^{-1}$) ($r = 0.85$, $P < 0.01$).

### *Variability of power output*

There was a significant effect of workout category on the coefficients of variation ($F_{7,58} = 7.93$, $P < 0.001$). The coefficient of variation during competition (68 ± 6%, 95% CL 63–73) was significantly higher than for the other workout categories (45 ± 10%, 95% CL 32–49) ($P < 0.001$) (Figure 2). Strong correlations were observed between the coefficients of variation and functional threshold power ($W \cdot kg^{-1}$) ($r = -0.73$ to $-0.84$, $P < 0.01$) and $\dot{V}O_{2max}$ ($mL \cdot kg^{-1} \cdot min^{-1}$) ($r = -0.71$ to $-0.8$, $P < 0.05$).

### *Exercise intensity*

The distribution of power output from all sampled data during the season was 110 ± 63 h (95% CL 62–159), 155 ± 74 h (98–211), 53 ± 27 h (32–74), 26 ± 23 h (8–43), 9 ± 5 h (5–13), 4 ± 2 h (3–6), and 1.5 ± 0.8 h (0.7–2) for Zones 1 to 7, respectively. Strong correlations were observed between time in Zone 2 and functional threshold power ($W \cdot kg^{-1}$) ($r = 0.86$, $P < 0.01$). A significant main

Table II. Maximal and sub-maximal characteristics obtained during the incremental graded exercise test (mean ± *s*).

| Measure | Ventilatory threshold | | Respiratory compensation point | | Maximum | |
|---|---|---|---|---|---|---|
| | Males ($n = 10$) | Female ($n = 1$) | Males ($n = 10$) | Female ($n = 1$) | Males ($n = 10$) | Female ($n = 1$) |
| Power output (W) | 213 ± 25 | 152 | 343 ± 47 | 215 | 445 ± 52 | 275 |
| 95% CL | 195–231 | | 310–377 | | 408–483 | |
| Power output ($W \cdot kg^{-1}$) | 3.0 ± 0.3 | 3.2 | 4.8 ± 0.5 | 4.6 | 6.2 ± 0.6 | 6.0 |
| 95% CL | 2.7–3.2 | | 4.4–5.1 | | 5.7–6.6 | |
| $\dot{V}O_2$ ($mL \cdot kg^{-1} \cdot min^{-1}$) | 37.7 ± 5.0 | 43.5 | 55.4 ± 7.6 | 58.7 | 66.5 ± 7.1 | 71.5 |
| 95% CL | 34.1–41.3 | | 50.0–60.1 | | 61.4–71.5 | |
| Heart rate ($beats \cdot min^{-1}$) | 135 ± 7.6 | 154 | 170 ± 7.6 | 174 | 190 ± 8.7 | 189 |
| 95% CL | 130–141 | | 164–175 | | 184–196 | |

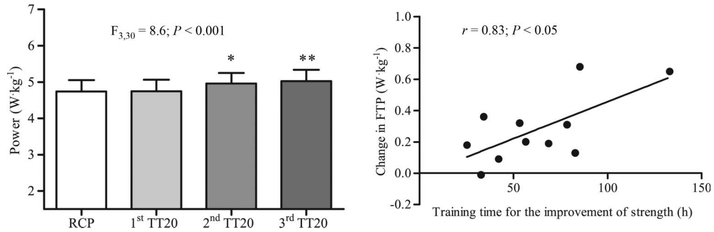


Figure 1. Changes in functional threshold power (FTP) during the season (left panel) and the relationship with training time to improve strength (right panel). Error bars represent 95% confidence limits. Significantly different from respiratory compensation point (RCP) and the first field test (TT20): *$P < 0.05$; **$P < 0.01$.



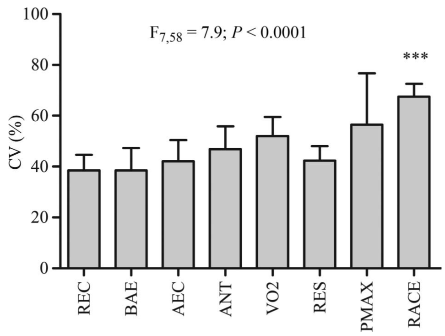


Figure 2. Coefficients of variation for each workout category. Error bars represent 95% confidence limits. REC = recovery, BAE = basic aerobic endurance, AEC = aerobic capacity, ANT = anaerobic threshold, VO2 = maximal oxygen uptake, RES = strength, PMAX = maximal power, and RACE = competition. Significantly different from all other categories: ***$P < 0.001$.

effect of workout categories on power output distribution was observed ($F_{7,391} = 29.8$, $P < 0.001$). Figure 3 shows the intensity zones and the percentage of appearance for each workout category. No significant interactions of power output and heart rate on exercise intensity distribution were observed for the season as a whole ($F_{4,40} = 1.8$, $P = 0.15$) (Figure 4). However, when distributions were compared by workout category, significant effects were observed for anaerobic threshold, maximal oxygen uptake, strength, maximal power, and competition (Figure 4).

The mean intensity factor for all sampled data was $0.55 \pm 0.04$ (95% CL 0.52–0.58). A significant main effect of workout category on the intensity factor was found ($F_{7,57} = 17.2$, $P < 0.001$). Intensity factors were significantly higher during competition ($0.69 \pm 0.06$, 95% CL 0.64–0.75) and lower during recovery ($0.46 \pm 0.06$, 95% CL 0.41–0.51) compared with all other categories ($P < 0.001$). No significant correlations between the intensity factors and performance measures were observed.

The mean intensity factors for intervals performed at the anaerobic threshold, maximal oxygen uptake, strength, and maximal power workouts were $0.99 \pm 0.05$ (95% CL 0.95–1.04), $1.44 \pm 0.13$ (1.33–1.55), $0.95 \pm 0.15$ (0.82–1.1), and $1.98 \pm 0.38$ (1.37–2.58), respectively ($F_{3,23} = 38.2$, $P < 0.001$). *Post-hoc* analysis revealed significant differences between categories ($P < 0.001$) with the exception of anaerobic threshold versus strength. Strong correlations were found between the intensity factor during maximal power workouts and functional threshold power ($W \cdot kg^{-1}$) ($r = 0.95$, $P < 0.01$) and maximal power ($W \cdot kg^{-1}$) obtained from the graded exercise test ($r = 0.99$, $P < 0.001$). In addition, the intensity factor during strength workouts was strongly correlated with functional threshold power ($W \cdot kg^{-1}$) ($r = 0.88$, $P < 0.01$) and $\dot{V}O_{2max}$ ($mL \cdot kg^{-1} \cdot min^{-1}$) ($r = 0.89$, $P < 0.01$).

## Discussion

The main findings of the present study were that workout categories had an influence on exercise intensity distributions and intensity factors. In addition, we found differences between heart rate and power output distributions. Finally, there were relationships of training time, coefficients of variation, and intensity factors during intervals with performance measures and the classification of our participants.

This was not an experimental study, where we influenced our athletes or their coaches to train in any particular way. It was an observational study and our results provide an insight into the training strategies of elite cyclists. Our participants were world-class cyclists, internationally successful cyclists, and national racing cyclists. To the best of our knowledge, no other study has analysed continuous longitudinal data from a power-meter and a diary over a whole season in elite cyclists.

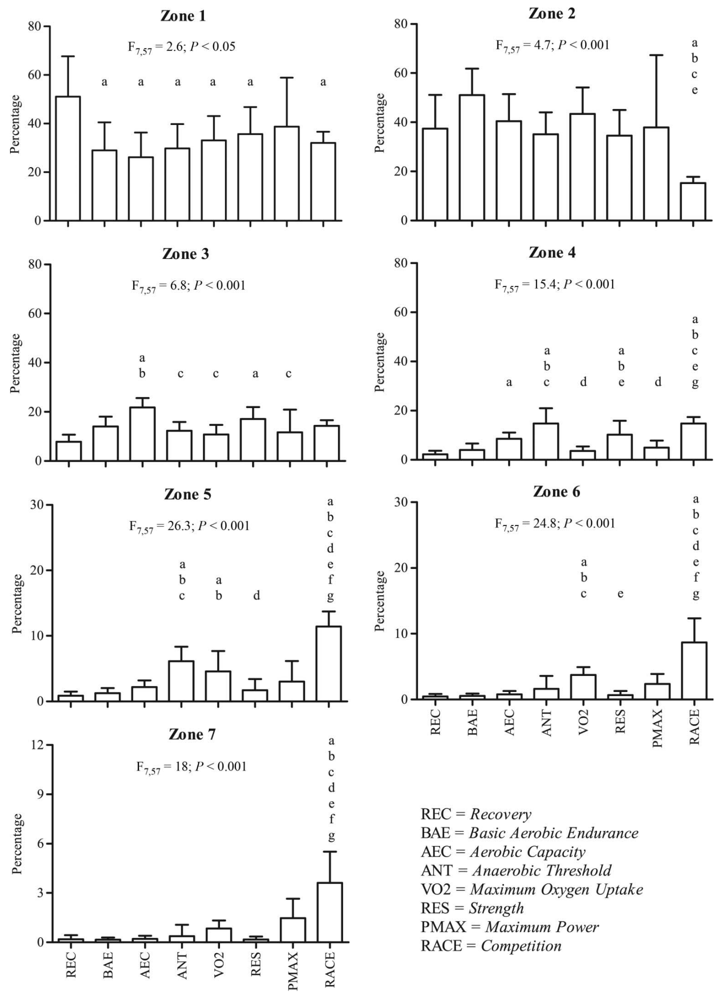


Figure 3. Percentage of intensity zones for each workout category. Error bars represent 95% confidence limits. Significantly different from: a = REC; b = BAE; c = AEC; d = ANT; e = VO2; f = RES; g = PMAX.

The finding that total training time was related to classification and performance measures is in line with the results of Esteve-Lanao et al. (2005). The mean training time was $\sim 16 \text{ h} \cdot \text{week}^{-1}$ for the national competitive athletes and $\sim 25 \text{ h} \cdot \text{week}^{-1}$ for the two world-class athletes in the present study, indicating the importance of a high training volume in endurance athletes (Jobson, Passfield, Atkinson, Barton, & Scarf, 2009).

Many studies that have monitored heart rate as a measure of exercise intensity in running (Esteve-Lanao et al., 2005; Seiler & Kjerland, 2006) or cycling (Lucia et al., 1999) used a model with three intensity zones: a ''low-intensity'' zone (i.e. below ventilatory threshold (VT) or lactate threshold (LT)), a ''moderate-intensity'' zone (i.e. between VT/LT and respiratory compensation point (RCP) or onset of blood lactate accumulation (OBLA)), and

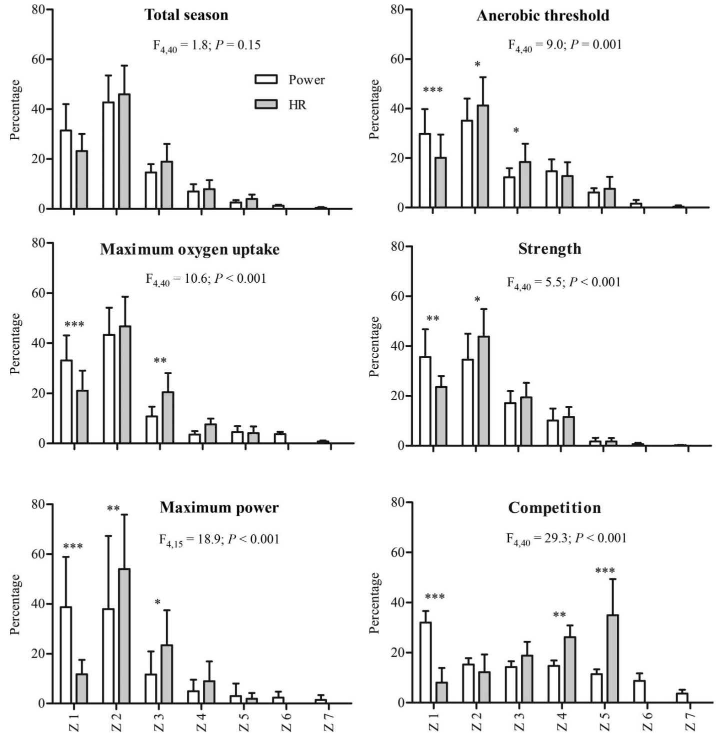


Figure 4. Exercise intensity distributions of power output (white bars) and heart rate (grey bars) for total season and selected workout categories. Error bars represent 95% confidence limits. Z1–Z7 = Zones 1–7. Significantly different: $^*P < 0.05$; $^{**}P < 0.01$; $^{***}P < 0.001$.



a ''high-intensity'' zone (i.e. above RCP/OBLA). This model has been used to describe the physiological demands during both training and racing in elite athletes (Esteve-Lanao et al., 2005; Lucia et al., 1999; Padilla et al., 2001; Seiler & Kjerland, 2006). In the present study, however, we introduced a power model with seven intensity zones to cover the whole spectrum of power output. The three intensity-zone model based on heart rate has two main limitations. First, very high intensities above maximum power obtained during a graded exercise test cannot accurately be quantified. Second, the phenomenon of cardiac drift (i.e. the slow rise in heart rate at constant work rates during prolonged exercise) influences the indirect estimation of exercise intensity (Achten & Jeukendrup, 2003). Vogt et al. (2006) quantified different distributions of intensity zones when power output and heart rate were measured during six stages of a cycling race. Our results show that differences between power output and heart rate distributions occur during high-intensity workouts where the training stimulus is mainly applied in a discontinuous or interval mode. In accordance with Vogt et al. (2006), we observed a shift from low- to high-intensity zones when heart rate was analysed. Instantaneous changes in power output and the delayed response from heart rate might influence the intensity distributions. However, no differences between power output and heart rate were found when the total season or low-intensity workouts were analysed. In contrast to the polarized training model described by Seiler and Kjerland (2006), who suggested a ''75%–5%–20%'' distribution of exercise intensity across the ''low–moderate–hard'' zones, Esteve-Lanao et al. (2005) reported a distribution of ''71%–21%–8%''. In accordance with previous studies of heart rate distributions in professional road cyclists (Hopker et al., 2009; Padilla et al., 2001), we observed power output distributions of 73% for the low-intensity Zones 1 (30%) and 2 (43%), 22% for the moderate-intensity Zones 3 (15%) and 4 (7%), and 5% for the high-intensity Zones 5 (3%), 6 (1.5%), and 7 (0.5%). These results emphasize that endurance athletes generally spend most of their training improving basic endurance.

When total training time was subdivided into workout categories, relationships of recovery, basic aerobic endurance, strength, and non-cycling activities with performance were observed. Workouts to improve strength were performed mainly as intervals of 2–20 min at low cadences (i.e. 40–60 $\text{rev} \cdot \text{min}^{-1}$). The rationale of this method is to increase the applied torque on the crank and consequently the muscular force as a result of the reduced cadence (Paton, Hopkins, & Cook, 2009). In addition, we observed a relationship between the intensity factor for the intervals during strength workouts and performance. These results suggest that successful riders not only trained more but also more intensively to improve their strength. The strong correlation with seasonal changes in functional threshold power emphasizes the importance of these workouts. In addition, the time spent for non-cycling activities, which included a main part of weight training, was related to performance. It has been shown that weight training can improve performance of trained cyclists (Bastiaans, van Diemen, Veneberg, & Jeukendrup, 2001; Yamamoto et al., 2010). It should be noted that no relationships between workout categories and performance were observed when expressed as percentages of total time. This indicates that training time in, but not the distribution of, these categories had an influence on performance measures.

One of the main concerns when monitoring power output is the stochastic nature of power during cycling in the field. Indeed, power output can change from 0 to 1000 W in a few seconds as opposed to the cardiovascular response to that effort. The observed coefficient of variation during competition was significantly higher than those for the remaining categories and emphasizes the high variability of cycling races (Stapelfeldt, Schwirtz, Schumacher, & Hillebrecht, 2004; Vogt et al., 2007). This might be due to the fact that cycling races are usually mass start events where cyclists are drafting in an attempt to save energy for decisive race situations. In contrast, most training sessions are undertaken by a single rider alone to fulfil a particular training goal. The coefficients of variation for the training categories were inversely associated with performance measures ($\dot{V}O_{2max}$, functional threshold power) as well as with training time. These results indicate that athletes with a higher standard of performance had less variation of power output during their workouts. While the two world-class cyclists who participated in this study exhibited a coefficient of variation of 20–25% during basic aerobic endurance workouts, the national competitive athletes has a coefficient of variation of 45–50%. It is unclear, however, whether this is the result of a more rigid pacing (i.e. "keep the power on the desired level") or the ability to reduce power fluctuations subconsciously. Both could be prerequisites for world-class performance. It could be argued that the experience with power-based training might have influenced the variability of power output. However, we do not think this is the case, since the participants in the present study were proficient users of mobile power-meters for several years. Further studies are needed to confirm this observation and explain the underlying mechanisms.

The calculated intensity factors were not related to performance measures. This indicates that elite cyclists adopt relative exercise intensities independent of their performance. However, the intensity factors during strength and maximal power intervals were strongly correlated with performance and ranged from approximately 0.8 to 3.0. As discussed for the category strength, the relative intensity during these intervals was higher for the better athletes. The intervals for the improvement of maximal power lasted 15–60 s. These high-intensity efforts were between 8.0 and 16.0 $\text{W} \cdot \text{kg}^{-1}$ and might be important to initiate or counteract decisive attacks during races (Ebert et al., 2005). To include this kind of exercise could be advantageous for successful competitions.

This study is not without limitations. In a longitudinal study over 11 months, it is almost impossible to collect data from every training session or race. Elite athletes have usually more than one bike for their rides and not all of these are equipped with power-meters. Most of the data were sampled during road cycling, which represents the main cycling discipline. It is currently unclear whether the relationships between power output and heart rate, the distributions into intensity zones, and the variability of power output are influenced while riding on different bikes and/or in different terrains. Larger cohorts are needed to investigate these effects and to identify possible differences of training strategies in the sub-disciplines of cycling.

**Conclusion**

The results of this longitudinal study provide a comprehensive insight into the training strategies of elite cyclists. It has been shown that both power output and heart rate are valid measures to assess the exercise intensity distribution of a whole season or low-intensity workouts. For high-intensity intermittent workouts or races, the application of heart rate is limited, since it does not accurately reflect the instantaneous changes of power output. The distributions into exercise intensity zones were influenced by the training goal. Cyclists spent the greater part of their training improving basic endurance. Total training time was increased in the better athletes, whereas the percentages across workout categories were not influenced by level of performance. The relative exercise intensity across all cycling training sessions was ~55% of functional threshold power and not related to level of performance. However, better performance by cyclists was characterized by lower variability in power output and higher exercise intensities during intervals.

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## 13.2 Conference Communication World Congress on Cycling Science, Edinburgh 2010

Using power output to monitor exercise intensity: a longitudinal study in elite cyclists

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[2]Austrian Institute of Sports Medicine, Vienna, Austria

Introduction

Power output (PO) has been described as the most direct measure of intensity during cycling despite its higher variation compared to heart rate (Vogt *et al*. 2006: *Med Sci Sports Exerc*, 38, 147-151). Therefore, the aim of this study was to investigate the relationship between relative exercise intensity and variability of PO with performance measures across a whole training season.

Methods

Ten male (age: 29.1, $s$ = 6.7y; $\dot{V}O_2max$: 66.5, $s$ = 7.1 $ml\cdot min^{-1}\cdot kg^{-1}$) and one female (age: 23.1y; $\dot{V}O_2max$: 71.5 $ml\cdot min^{-1}\cdot kg^{-1}$) international competitive cyclists measured PO for 11 months with an SRM power-meter. A total of 1802 data sets were sampled and an intensity factor (IF) was calculated as the ratio of mean PO to PO at the respiratory compensation point (RCP) for every training session and for each interval ($IF_{INT}$) performed during high-intensity workouts. The variability of PO was calculated as the coefficient of variation (CV). A laboratory incremental graded exercise test at the start of the season and 20-min time-trial PO during the season were used as performance measures (Nimmerichter *et al*. 2010: *Int J Sports Med*, 31, 160-166). The interactions of training sessions with intensity factors and PO CV were assessed by repeated measures ANOVA. Relationships with performance measures were verified by Pearson's product moment correlation.

Results

The exercise IF for all sampled data was 0.55, *s* = 0.04. IF was significantly higher during races (0.69, *s* = 0.06) and lower during recovery workouts (0.46, *s* = 0.06) in comparison to all other training sessions ($p<0.001$). $IF_{INT}$ for intervals performed to improve anaerobic threshold, $\dot{V}O_2max$, strength and anaerobic power were 0.99, *s* = 0.05, 1.44, *s* = 0.13, 0.95, *s* = 0.15 and 1.98, *s* = 0.38, respectively. No significant correlations between IF and performance measures were observed. In contrast, $IF_{INT}$ were significantly correlated to maximal power, PO at RCP and during the 20-min time-trials and $\dot{V}O_2max$ ($r = 0.89$ to 0.98; $p<0.01$).

Mean CV across workouts was 48, *s* = 12%. During races the CV (68, *s* = 6%) was significantly higher than other workouts ($p<0.001$). The variability of PO across workouts was inversely associated with laboratory and field-test performance measures (PO during the 20-min time-trials and $\dot{V}O_2max$, $r = -0.71$ to -0.84; $p<0.01$).

Discussion

These results suggest that elite cyclists adopt a relative exercise intensity independent of their performance. IF appears not to be sensitive enough to distinguish low-intensity from high-intensity workouts. Better cyclists perform their intervals at higher relative exercise intensities. In addition, a lower coefficient of variation of power output was observed for these athletes. However, it is unclear whether this is the result of a more rigid pacing (i.e.*"keep the power on the desired level"*) or the subconscious ability to reduce power fluctuations. In conclusion, high-intensity efforts and a low PO CV were associated with laboratory and field-test performance.

## POWER OUTPUT TO MONITOR EXERCISE INTENSITY: A LONGITUDINAL STUDY IN ELITE CYCLISTS

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[2] Austrian Institute of Sports Medicine, Vienna, Austria

1st World Congress on Cycling Science

Edinburgh 2010

## Introduction

- Volume, Intensity, Frequency
- Heart rate to estimate exercise intensity in the field

*(Impellizzeri et al. 2002: Med Sci Sports Exerc, 34, 1808-13; Lucia et al. 1999: Int J Sports Med, 20, 167-72; Padilla et al. 2001: Med Sci Sports Exerc, 33, 796-802)*

- Power output is the most direct measure of exercise intensity

*(Vogt et al. 2006: Med Sci Sports Exerc, 38, 147-51)*

## Aims Of The Study

- To assess relative exercise intensity
- To assess variability of power output

and the relationships with performance measures across a whole season in competitive cyclists

## Methods

- Power output was recorded with SRM mobile power meters for 11 month
- Data were divided into workout categories according to the goal of each training session


## Methods

- Power output was recorded with SRM mobile power meters for 11 month
- Data were divided into workout categories according to the goal of each training session
- Relative exercise intensity:

Intensity Factor (IF) = $P_{mean}$/Functional Threshold Power (FTP)

$IF_{INT}$ = $P_{mean}$Interval/FTP

## Performance Measures

- **One laboratory incremental exercise test (Dec)**

  $VO_{2max}$; $P_{max}$; Ventilatory Threshold (VT); Respiratory Compensation Point (RCP)

- **Three 20-min maximal power time-trials (Mar, Jun, Aug)**

  $P_{mean}$ 20-min and RCP = Functional Threshold Power (FTP)

*Nimmerichter et al. 2010: Int J Sports Med, 31, 160-66*

## Methods

- Power output was recorded with SRM mobile power meters for 11 month
- Data were divided into workout categories according to the goal of each training session
- Relative exercise intensity:

Intensity Factor (IF) = $P_{mean}$/Functional Threshold Power (FTP)

$IF_{INT}$ = $P_{mean}$Interval/FTP

- Variability of power output:

  Coefficient of Variation (CV)

## Participants

| Performance Level | |
|---|---|
| **World Class (n = 2)** | Winner of WC races and General Classification; Top 10 UCI ranking; Top 10 Olympic Games; ECH and WCH medalists |
| **International (n = 3)** | WC members Track; Time-Trial, Pursuit, Points Race, Madison |
| **National (n = 6)** | Successful in national events |

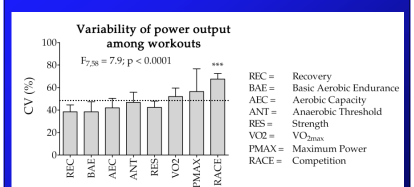
| | Male (n = 10) | Female (n = 1) |
|---|---|---|
| **Age (years)** | 29.1 ± 6.7 | 23.1 |
| **Stature (cm)** | 181.3 ± 4.6 | 165 |
| **Body mass (kg)** | 72.7 ± 6.3 | 45.5 |

## Performance Measures Obtained From The Graded Exercise Test And The Time-Trials

| Measure | Male (n = 10) | Female (n = 1) |
|---|---|---|
| $P_{max}$ (W · kg$^{-1}$) | 6.2 ± 0.6 | 6.0 |
| $VO_{2max}$ (mL · min$^{-1}$ · kg$^{-1}$) | 66.5 ± 7.1 | 71.5 |
| **Respiratory Compensation Point** | | |
| Power (W · kg$^{-1}$) | 4.8 ± 0.5 | 4.6 |
| **20-min Time-Trial Power (W · kg$^{-1}$)** | | |
| March | 4.7 ± 0.5 | 4.8 |
| June | 4.9 ± 0.5 | 5.1 |
| August | 5.0 ± 0.4 | 5.5 |

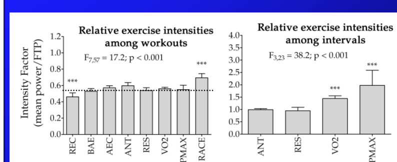
Mean ± SD

## Coefficients Of Variation For Every Workout Category




Error bars represents 95% CL
Significantly different from all other categories at: *** $p < 0.001$

## Relative Exercise Intensities For Every Workout Category And For Intervals During High Intensity Workouts

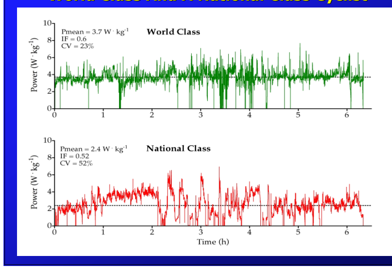



Error bars represents 95% CL
Significantly different from all other categories at: *** $p < 0.001$

## Significant Correlations Of Exercise Intensities During Intervals and Coefficients Of Variation With Performance Measures

| | $VO_{2max}$ (mL · min⁻¹ · kg⁻¹) | $P_{max}$ (W · kg⁻¹) | FTP (W · kg⁻¹) |
|---|---|---|---|
| $IF_{INT}$ Maximum Power | | $r = 0.99$<br>$p < 0.001$ | |
| $IF_{INT}$ Strength | $r = 0.89$<br>$p < 0.01$ | | $r = 0.88$<br>$p < 0.01$ |
| CV's | $r$ = -0.71 to -0.8<br>$p < 0.05$ | | $r$ = -0.73 to -0.84<br>$p < 0.01$ |

## Basic Aerobic Endurance Workouts From A World Class And A National Class Cyclist




## Summary

- Relative exercise intensities were not related to performance measures
- Better performance by cyclists was characterized by lower variability in power output and the production of higher exercise intensities during intervals

University of EXETER School of Sport and Health Sciences

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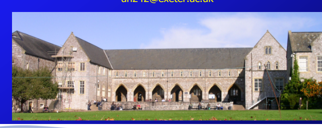
## Thank You For Your Attention!

Contact: Alfred Nimmerichter

an242@exeter.ac.uk



University of EXETER

## 13.3 Conference Communication European College of Sports Sciences, Antalya 2010

DISTRIBUTIONS OF POWER OUTPUT AND HEART RATE: A LONGITUDINAL STUDY IN ELITE CYCLISTS

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[1]University of Exeter, School of Sport and Health Sciences, Exeter, United Kingdom;

[2]Austrian Institute of Sports Medicine, Vienna, Austria

**Introduction**

In cycling, power output (PO) and heart rate (HR) can be used to describe exercise intensity. Vogt et al. (2006) quantified different distributions of intensity zones when PO and HR were measured during six stages of a cycling race. However the link to training is unclear. Therefore, the aim of this study was to compare PO and HR distributions across a whole season for a group of elite cyclists.

**Methods**

Ten male (age: 29.1 ± 6.7 y; height: 181.3 ± 4.6 cm; weight: 72.7 ± 6.3 kg; $\dot{V}O_2max$: 66.5 ± 7.1 $ml \cdot min^{-1} \cdot kg^{-1}$) and one female (age: 23.1 y; height: 165 cm; weight: 45.5 kg; $\dot{V}O_2max$: 71.5 $ml \cdot min^{-1} \cdot kg^{-1}$) competitive cyclists participated in this study. During the season a SRM mobile power meter measured PO and HR. A total of 1802 data sets were sampled and divided into workout categories based on the goal of each training session: Recovery (REC), Basic endurance (BAE), Aerobic capacity (AEC), Anaerobic threshold (ANT), Maximum oxygen uptake (VO2), Strength (RES), Maximum power (PMAX) and Race (RACE). Based on PO at respiratory compensation point (RCP) obtained during an incremental exercise test, seven intensity zones were used: Z1 < 50% (of RCP), Z2: 50-70%, Z3: 71-85%, Z4: 86-105%, Z5: 106-125%, Z6: 126-170%, Z7 > 170%. PO and HR distributions into Z1-Z7 were calculated for all sampled data and workout categories.

**Results**

No significant interactions of PO and HR on exercise intensity distribution for the total season were found ($F_{4,40}$ = 1.8; $p$ = 0.15). When distributions were compared for every workout category, significant effects were observed for ANT, VO2, RES, PMAX and RACE ($F_{4,40}$ = 5.5-29.3; $p < 0.001$). During ANT, VO2, RES and PMAX less time was spent in Z1 and more time in Z2 and Z3 when HR distributions were compared with PO. During RACE, the incidence of HR was higher for Z4 and Z5 and lower for Z1.

## Discussion

As the cardiac drift influences the indirect estimation of exercise intensity through HR (Achten & Jeukendrup, 2003), direct measurement of PO more precisely reflects cycling performance. Our results show that differences between PO and HR distributions occur during high intensity workouts where the training stimulus is mainly applied in a discontinuous or interval mode. Instantaneous changes in PO and the delayed response from HR might influence the intensity distributions. In conclusion, HR accurately reflects exercise intensity when a total season or low intensity workouts are analysed but is limited when applied to high intensity workouts and races.

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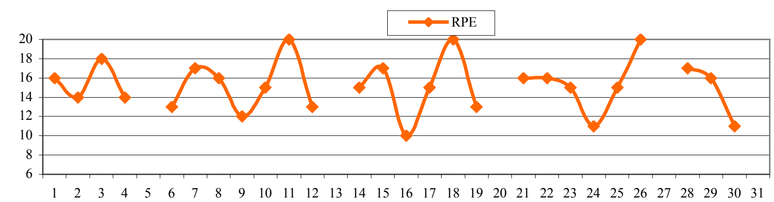
Vogt, S., Heinrich, L., Schumacher, Y. O., Blum, A., Roecker, K., Dickhuth, H. H., et al. (2006). Power output during stage racing in professional road cycling. *Med Sci Sports Exerc, 38*(1), 147-151.

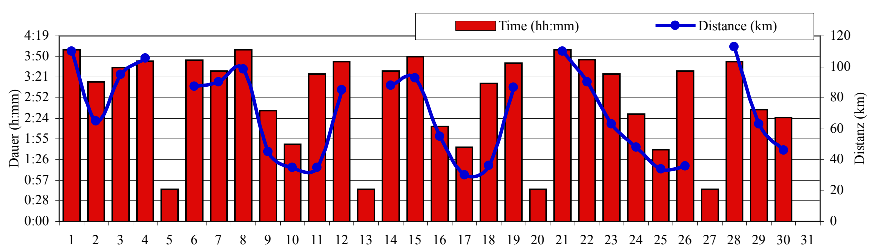
## 13.4 Example of the Diary

April 2009

Name: Winner of the general classification in the female MTB XC World Cup

| | Workout category | Comment | Time (hh:mm) | Distance (km) | RPE (6-20) | TRIMP |
|---|---|---|---|---|---|---|
| 1 | AEC | Kraftkammer Maxkraft, Bike Fahrtspiel bis A3 | 4:00 | 110,0 | 16 | 3840 |
| 2 | BAE | Lauf ABC, Bike, Dehnen | 3:15 | 65,0 | 14 | 2730 |
| 3 | VO2 1-5 | Stabis, Rennrad Intervalle, 9x20´´Max.A56x1´250W.A4 4x2´220W | 3:35 | 94,9 | 18 | 3870 |
| 4 | BAE | Rennrad | 3:44 | 105,6 | 14 | 3136 |
| 5 | | Reise Südafrika, Dehnen | 0:45 | | | |
| 6 | BAE | ruhige GA | 3:45 | 87,3 | 13 | 2925 |
| 7 | ANT 1-5 | Straßenrad 4x5´A4 200W 80-90rpm | 3:30 | 90,2 | 17 | 3570 |
| 8 | P max <1 | Stabis, Rennrad Intervalle, 9x20´´Max.A56x1´250W.A4 4x2´220W | 4:00 | 98,5 | 16 | 3840 |
| 9 | Rec | Stabis, Bike; Dehnen | 2:35 | 45,0 | 12 | 1860 |
| 10 | BAE | Streckenbesichtigung, WKVP | 1:48 | 35,0 | 15 | 1620 |
| 11 | Race | WC Südafrika Sieg!!! | 3:26 | 35,0 | 20 | 4120 |
| 12 | BAE | Stabis, Bike/Straße | 3:43 | 85,0 | 13 | 2899 |
| 13 | | Heimreise, Dehnen | 0:45 | | | |
| 14 | BAE | Kraftkammer-Maxkraft, Rolle mit 8x3´115rpm | 3:30 | 88,0 | 15 | 3150 |
| 15 | P max <1 | Stabis, Rennrad Intervalle, 7x20´´Max, A5 5x1´260W, A4 3x2´220W | 3:50 | 92,7 | 17 | 3910 |
| 16 | Rec | Stabis, Bike, Dehnen | 2:13 | 55,0 | 10 | 1330 |
| 17 | BAE | Streckenbesichtigung, WKVP | 1:44 | 30,0 | 15 | 1560 |
| 18 | Race | Rennen, Münsingen, 1. Platz | 3:13 | 36,2 | 20 | 3860 |
| 19 | BAE | Stabis, Rennrad | 3:41 | 86,6 | 13 | 2873 |
| 20 | | Dehnen | 0:45 | | | |
| 21 | BAE | ruhige GA | 4:00 | 110,0 | 16 | 3840 |
| 22 | VO2 <1 | Rennrad, 3x (8x20´´ Maxantritte) Stabis | 3:46 | 90,4 | 16 | 3616 |
| 23 | BAE | Bike, Streckenbesichtigung, Offenburg | 3:26 | 63,0 | 15 | 3090 |
| 24 | Rec | Bike, Dehnen, Stabis | 2:30 | 48,0 | 11 | 1650 |
| 25 | BAE | WKVP | 1:40 | 34,0 | 15 | 1500 |
| 26 | Race | WC Offenburg 5 Platz. | 3:30 | 35,7 | 20 | 4200 |
| 27 | | Reise, Dehnen | 0:45 | | | |
| 28 | VO2 <1 | Stabis, Bike, 3x (8x20´´ Maxantritte) | 3:43 | 113,0 | 17 | 3791 |
| 29 | AEC | Bike, Streckenbesichtigung mit A4, Houffalize | 2:36 | 63,0 | 16 | 2496 |
| 30 | Rec | Stabis, Bike, Dehnen | 2:25 | 46,0 | 11 | 1595 |
| 31 | | | | | | |
| | | **Summe** | **86:08** | **1843,1** | | **76871** |

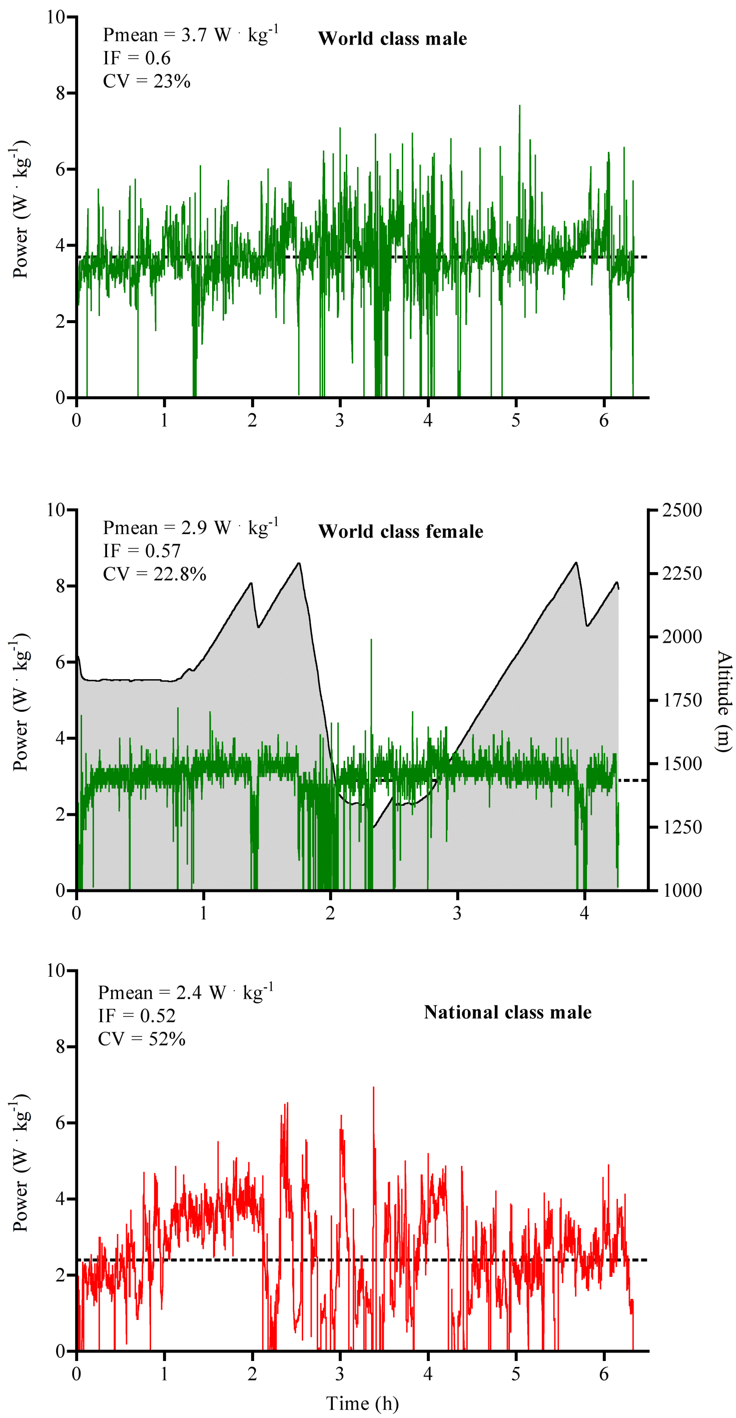



| RPE | |
|---|---|
| No exertion at all | 6 |
| Extremely light | 7 |
| | 8 |
| Very light | 9 |
| | 10 |
| Light | 11 |
| | 12 |
| Somewhat hard | 13 |
| | 14 |
| Hard | 15 |
| | 16 |
| Very Hard | 17 |
| | 18 |
| Extremely hard | 19 |
| Maximal exertion | 20 |

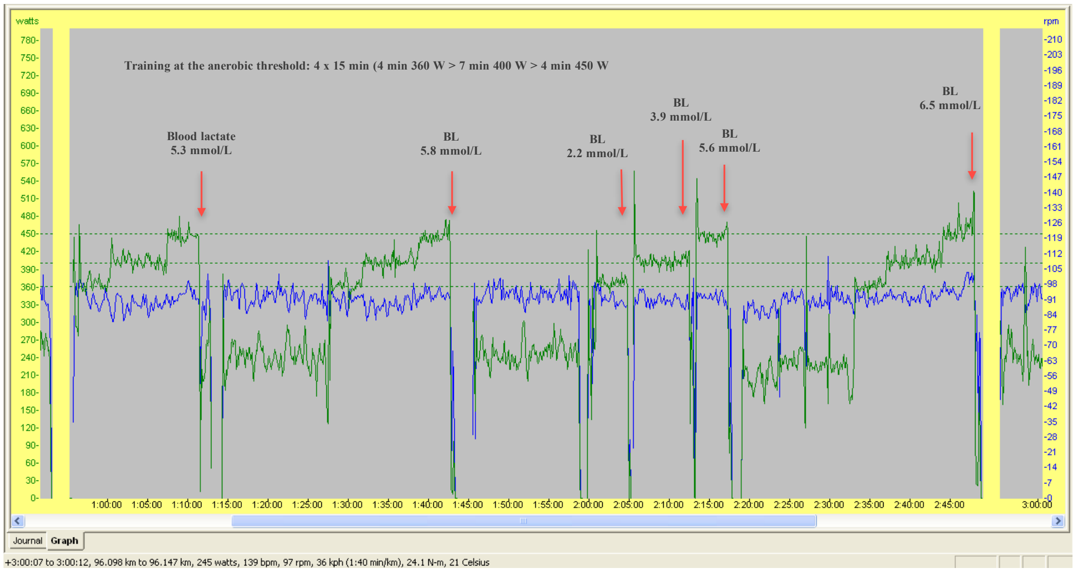
| Workout category | |
|---|---|
| Warm up | Warm up |
| Recovery | Rec |
| Basic Endurance | BAE |
| Aerobic Capacity | AEC |
| Anaerobic Threshold Intervals 1-5min | ANT 1-5 |
| Anaerobic Threshold Intervals 5-10min | ANT 5-10 |
| Anaerobic Threshold Intervals >10min | ANT >10 |
| VO2 max Intervals <1min | VO2 <1 |
| VO2 max Intervals 1-5min | VO2 1-5 |
| Strength Intervals <1min | F <1 |
| Strength Intervals 1-5min | F 1-5 |
| Strength Intervals >5min | F >5 |
| P max Intervals <1min | P max <1 |
| Competition | Race |

## 13.5 Example of the CVs during Basic Aerobic Endurance Training Sessions in World Class and National Class Cyclists



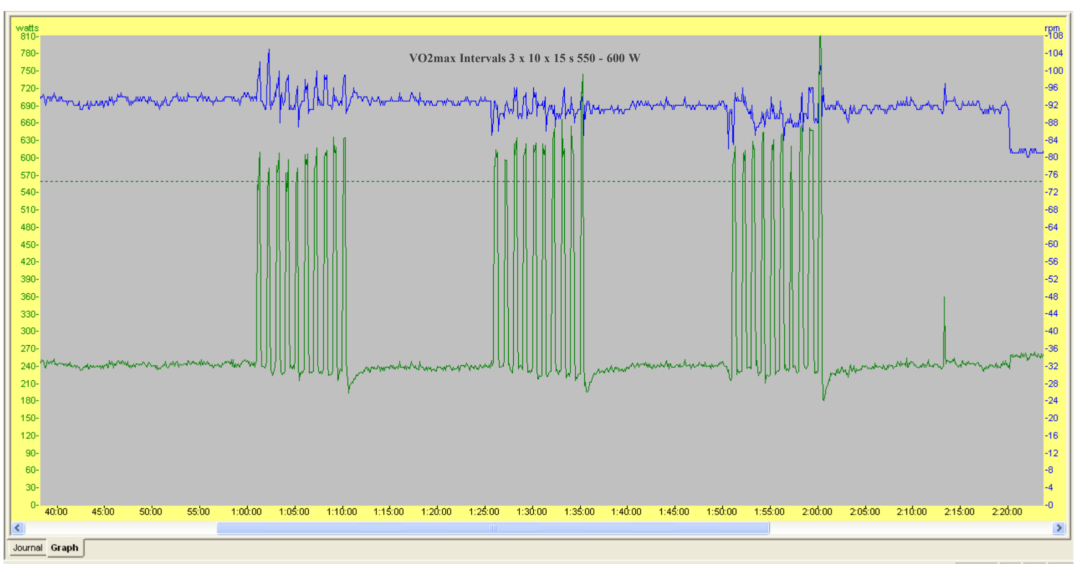

Note the CV of the female cyclist despite 1950 m of vertical climbing

## 13.6 Example of a Training Session at the Anaerobic Threshold



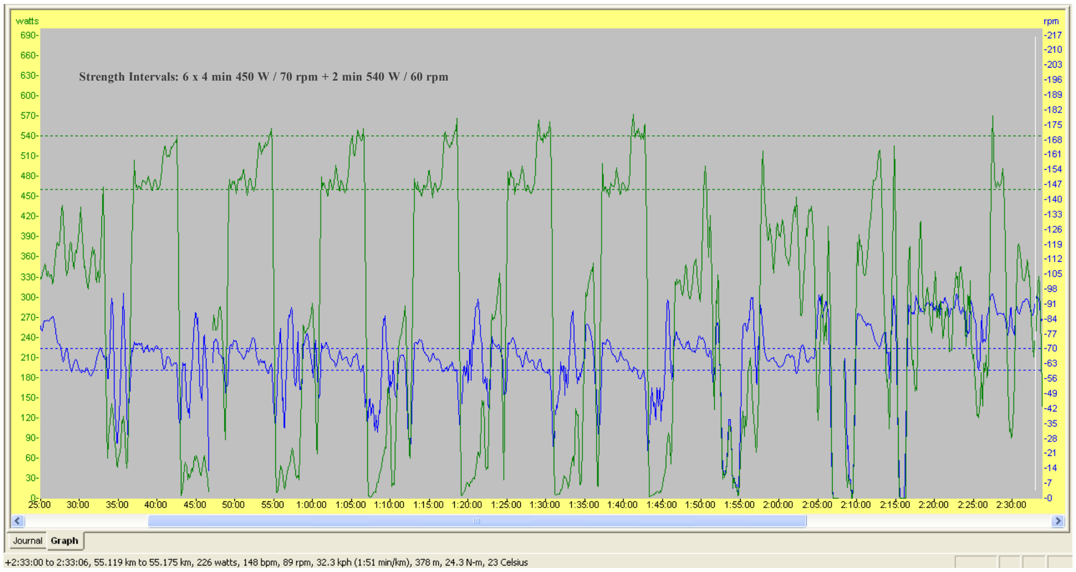

Interval training at the anaerobic threshold (Zone 4) with measurement of blood lactate concentration during road cycling (4 × 15 min: 4 min 360 $W$ → 7 min 400 $W$ → 4 min 450 $W$)

## 13.7 Example of an Interval Training Session to Improve Maximum Oxygen Uptake

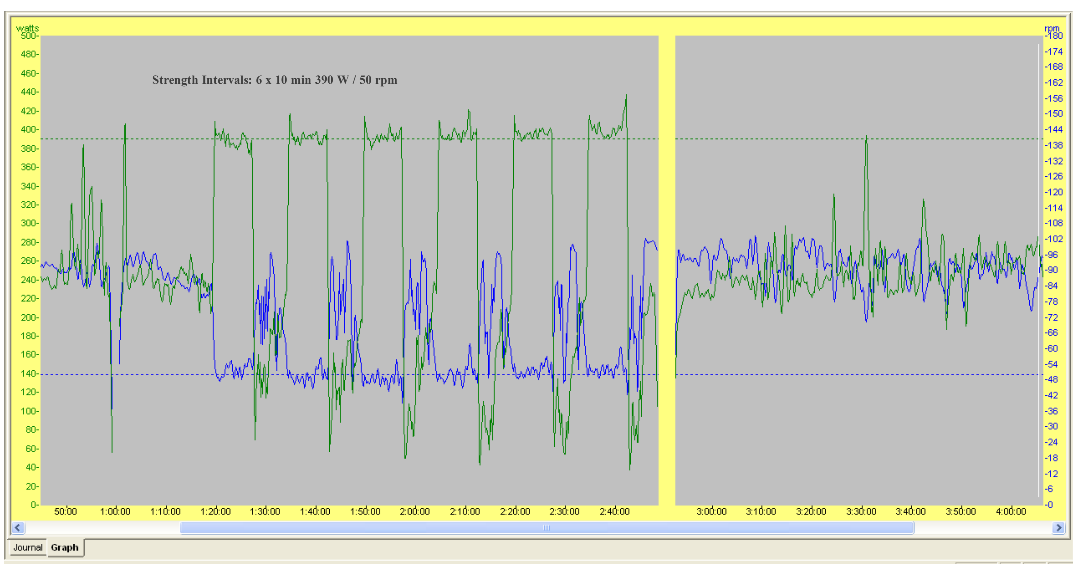



Maximum oxygen uptake interval training session (Zone 5) during road cycling (3 sets of 10 × 15 s $550 - 600\ W$)

## 13.8 Examples of Low-cadence/High-force Interval Training Sessions of a World Class MTB Cyclist

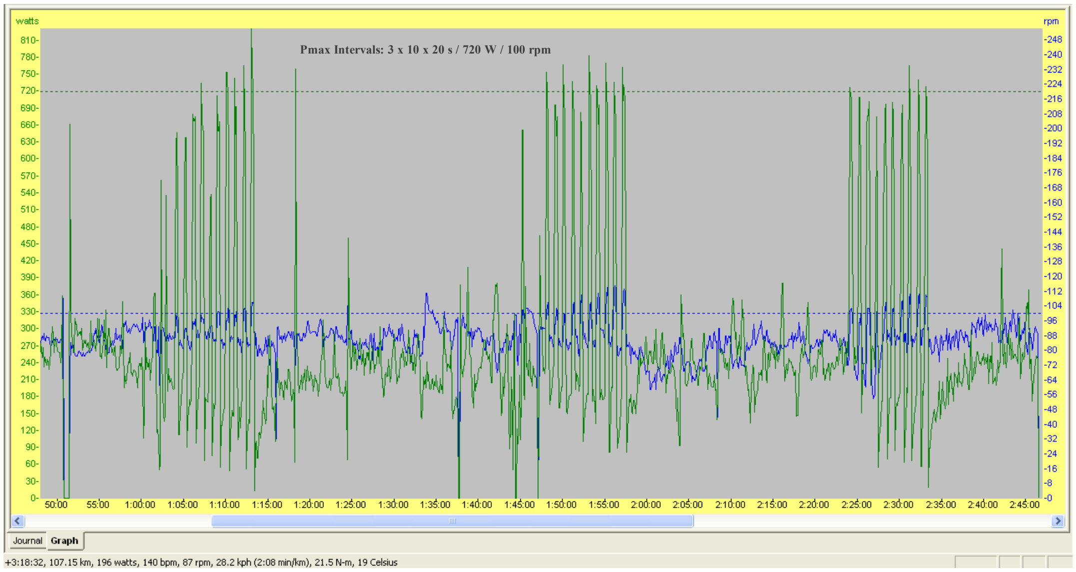



High intensity strength intervals at the respiratory compensation point ($\sim 450\ W$; Zone 4) and $Pmax$ ($\sim 560\ W$; Zone 5) during a MTB off-road training session




Strength interval training session during road cycling in Zone 3 ($6 \times 10$ min $360\ W$ with $50\ rev \cdot min^{-1}$)

## 13.9 Example of a Maximum Power Interval Training Session

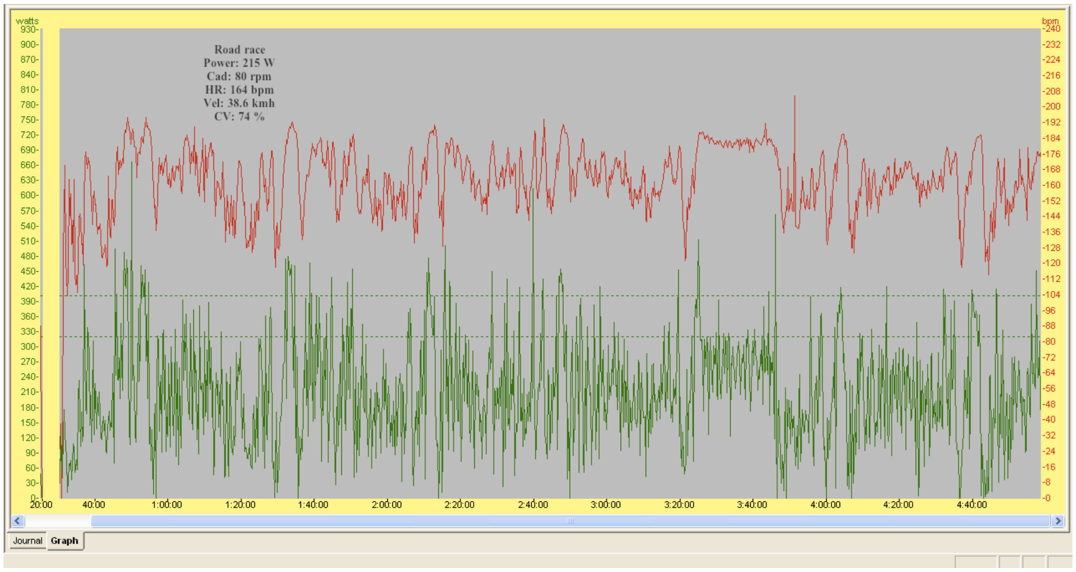



Maximum power interval training session (Zone 6) during road cycling (3 sets of 10 × 20 s 720 $W$)

## 13.10 Example of a mountain-bike Cross Country Race

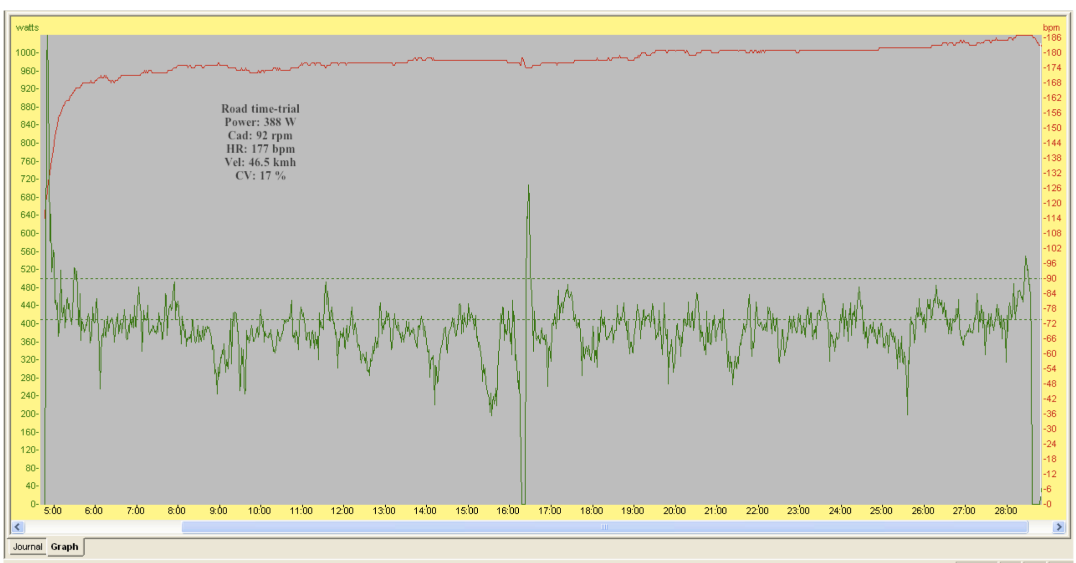

Mountain-bike cross country race: Horizontal dashed lines represent power output at $RCP$ and $Pmax$

## 13.11 Example of a Road Race



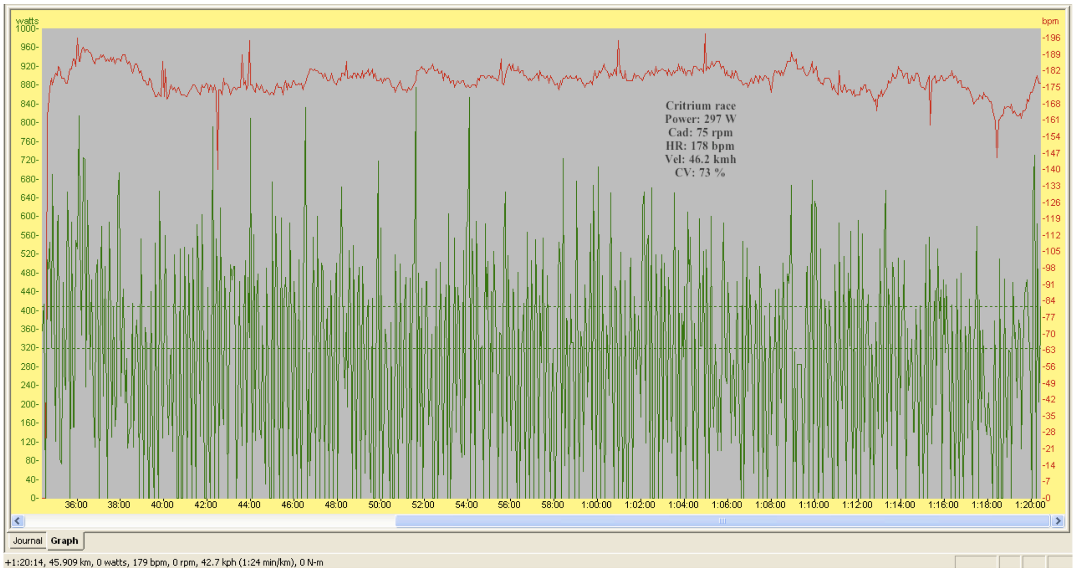

Road race: Horizontal dashed lines represent power output at *RCP* and *Pmax*

## 13.12 Example of a Road Time-Trial




Time-trial race: Horizontal dashed lines represent power output at *RCP* and *Pmax*

## 13.13 Example of a Short-Circuit Criterium Race




Criterium race: Note the highly intermittent power profile in contrast to a stable heart rate. Horizontal dashed lines represent power output at *RCP* and *Pmax*


10-min close up of the criterium race shown above: Note the occurrence of 36 efforts between $8 - 15$ sec above *Pmax* within 10 min. Horizontal dashed lines represent power output at *RCP*, *Pmax* and 170 % of *FTP*

# 14 Appendix 3

## 14.1 Publication Resulted from Study Three

Eur J Appl Physiol
DOI 10.1007/s00421-011-1957-5

ORIGINAL ARTICLE

### Effects of low and high cadence interval training on power output in flat and uphill cycling time-trials

**Alfred Nimmerichter · Roger Eston · Norbert Bachl · Craig Williams**

Received: 7 February 2011 / Accepted: 31 March 2011


**Abstract** This study tested the effects of low-cadence (60 rev min$^{-1}$) uphill (Int$_{60}$) or high-cadence (100 rev min$^{-1}$) level-ground (Int$_{100}$) interval training on power output (PO) during 20-min uphill (TT$_{up}$) and flat (TT$_{flat}$) time-trials. Eighteen male cyclists ($\dot{V}O_{2\,max}$: 58.6 ± 5.4 mL min$^{-1}$ kg$^{-1}$) were randomly assigned to Int$_{60}$, Int$_{100}$ or a control group (Con). The interval training comprised two training sessions per week over 4 weeks, which consisted of six bouts of 5 min at the PO corresponding to the respiratory compensation point (RCP). For the control group, no interval training was conducted. A two-factor ANOVA revealed significant increases on performance measures obtained from a laboratory-graded exercise test (GXT) ($P_{max}$: 2.8 ± 3.0%; $p < 0.01$; PO and $\dot{V}O_2$ at RCP: 3.6 ± 6.3% and 4.7 ± 8.2%, respectively; $p < 0.05$; and $\dot{V}O_2$ at ventilatory threshold: 4.9 ± 5.6%; $p < 0.01$), with no significant group effects. Significant interactions between group and uphill and flat time-trial, pre- versus post-training on PO were observed ($p < 0.05$). Int$_{60}$ increased PO during both TT$_{up}$ (4.4 ± 5.3%) and TT$_{flat}$ (1.5 ± 4.5%). The changes were −1.3 ± 3.6, 2.6 ± 6.0% for Int$_{100}$ and 4.0 ± 4.6%, −3.5 ± 5.4% for Con during TT$_{up}$ and TT$_{flat}$, respectively. PO was significantly higher during TT$_{up}$ than TT$_{flat}$ (4.4 ± 6.0; 6.3 ± 5.6%; pre and post-training, respectively; $p < 0.001$). These findings suggest that higher forces during the low-cadence intervals are potentially beneficial to improve performance. In contrast to the GXT, the time-trials are ecologically valid to detect specific performance adaptations.

**Keywords** Ecological validity · Training adaptation · Field test · Outdoor cycling · Cadence · SRM

Communicated by Jean-René Lacour.

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#### Introduction

The term 'interval training' can be characterized as performing repeated bouts of exercise interspersed with recovery periods within a training session. This definition implies that several variables can be modified to describe such training sessions. The modification of number, duration and intensity of the exercise bout, as well as for the recovery phase, affect the impact of the training. The numerous variations of interval-training modalities have been reviewed by Billat (2001).

During cycling, the crank inertial load depends on the moment of inertia of the flywheel or the rear wheel. It has been shown that at the same power output and cadence, crank inertial load is higher during level ground than during uphill cycling because crank inertia increases as a quadratic function of the gear ratio (Fregly et al. 2000). In addition, an increase in crank inertia is accompanied by an increase in peak crank torque and therefore it was suggested that cyclists prefer higher cadences during level-ground cycling to reduce peak crank torque (Hansen et al.

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2002). This finding was supported by Lucia et al. (2001) who reported a significantly lower mean cadence during high mountain passes (71.0 ± 1.4 rev min$^{-1}$) than during flat mass start stages (89.3 ± 1.0 rev min$^{-1}$) and time-trials (92.4 ± 1.3 rev min$^{-1}$) in professional cyclists.

During cycling training the pedaling speed or cadence can be manipulated to alter the muscle force applied to the cranks. To change the gear ratio is a unique opportunity for cyclists to influence the force–velocity relationship of the muscular contraction. Depending on the range of the gearshift, a variety of forces and velocities are applicable at constant power output. For example to produce a power output of 300 W with cadences of 60 and 100 rev min$^{-1}$ requires forces of 281 and 169 N, respectively. In a previous study (Paton et al. 2009) performance improvements in maximum power output ($P_{max}$), $\dot{V}O_{2\,max}$ and power output at 4 mmol L$^{-1}$ blood lactate were significantly higher for the low-cadence group (60–70 rev min$^{-1}$) in comparison to the high-cadence group (110–120 rev min$^{-1}$) (6–11 vs. 2–3%), which was attributed to a higher testosterone concentration in response to higher pedal forces in the low-cadence group. Therefore, a training stimulus with the same power output, but different cadences might result in specific adaptations.

The scientific literature offers a variety of studies investigating performance changes (Stepto et al. 1999; Burgomaster et al. 2006; Westgarth-Taylor et al. 1997), metabolic adaptations (Aughey et al. 2007; Burgomaster et al. 2005, 2008) and skeletal muscle adaptations (Gibala et al. 2006) in response to interval training. The vast majority of interval-training studies are conducted on ergometers to control external variables and exercise intensity. However, the differences between laboratory and outdoor cycling have been discussed recently (Jobson et al. 2008a, b) suggesting that the position on the bike, rolling resistance, road gradient, lateral bike movement and flywheel inertia induce different physiological demands during laboratory and outdoor cycling. With the use of mobile power meters, exercise intensity can be monitored in the field and therefore can be studied during actual cycling conditions, which improves the ecological validity of the measurements.

Therefore, the purpose of this study was to investigate the effect of a period of interval training applied over 4 weeks during uphill and level-ground cycling at the same relative exercise intensity, but different cadences, on power output during a 20-min uphill and flat time-trial. In addition, the effects on performance measures obtained during laboratory incremental exercise tests were investigated. Following the principle of specificity of training, it was expected that an interval training performed on uphill or flat roads would specifically increase the performance capacity during uphill and flat time-trials. According to the results of Paton et al. (2009) it was hypothesized that performance improvements during the incremental graded exercise tests would be greater for the uphill-training group. Finally, we addressed the question raised in a previous study (Nimmerichter et al. 2010), with regard to whether or not a difference in power output exists between uphill and flat time-trial cycling.

## Methods

### Participants

Eighteen trained cyclists (Table 1) were randomly assigned to one of three groups. Group 1 performed uphill interval training with a cadence of 60 rev min$^{-1}$ (Int$_{60}$), group 2 performed level-ground interval training with a cadence of 100 rev min$^{-1}$ (Int$_{100}$). Group 3 (Con) continued their steady training but no interval training was permitted throughout the 4 weeks. One participant of the control group became injured and therefore his data from the pre-tests were excluded from further analyzes. The participants had a training history of at least 5 years and trained for 11.8 ± 2.7 h week$^{-1}$ in the last 12 weeks prior to the study. All participants completed a medical examination prior to the study, were informed of the experimental procedures and provided written informed consent to participate. The study was conducted in accordance with the ethical principles of the Declaration of Helsinki (Harriss and Atkinson 2009) and was approved by the institutional ethics committee.

In a previous study (Nimmerichter et al. 2010), we investigated the test–retest reliability of power output during 20-min time-trials. We found an intraclass correlation coefficient of 0.98 (95% CL 0.95–0.99) and a bias ± random error of—1.8 ± 14 W or 0.6 ± 4.4%. The smallest worthwhile effect for the present study has been set to 15 W. At an estimated power output of 280 W for

**Table 1** Subjects' characteristics (mean ± SD)

| | Group | | |
|---|---|---|---|
| | Int$_{60}$ ($n$ = 6) | Int$_{100}$ ($n$ = 6) | Con ($n$ = 5) |
| Age (years) | 30 ± 6.8 | 31 ± 6.9 | 33 ± 5.1 |
| Stature (cm) | 179 ± 3.2 | 177 ± 4.8 | 182 ± 7.0 |
| Body mass (kg) | 70.9 ± 6.4 | 71.5 ± 5.0 | 75.4 ± 4.2 |
| $\dot{V}O_{2\,max}$ (mL min$^{-1}$ kg$^{-1}$) | 61.1 ± 5.0 | 58.8 ± 6.0 | 55.4 ± 4.3 |

No significant differences between groups the participants in this study, a change of 15 W (5%) would result in a difference of ±24 s (2%) during a 13-km time-trial. Based on these assumptions, it was calculated that it was necessary to have 6 participants in each group to have a 90% chance of detecting a mean difference of 15 W at an alpha level of 0.05.

## Study design

During the 10 days preceding the start of the intervention, participants performed an incremental graded exercise test in the laboratory (GXT) and two 20-min maximal power time-trials on a flat ($TT_{flat}$) and uphill ($TT_{up}$) road. Both training groups performed two interval-training sessions per week for 4 weeks, whereas no interval training was conducted for the control group. Between the 7th and the 12th day following the last training session, the GXT and the time-trials were repeated. All participants were provided with a PC spreadsheet to record the time and the rating of perceived exertion for each training (session RPE score 6–20) (Foster et al. 2001; Borg 1970) to calculate an integrated training impulse (TRIMP = session RPE × training time) (Foster et al. 2001; Banister and Calvert 1980).

## Laboratory test

The incremental graded exercise test was performed on an electromagnetically braked ergometer (Lode Excalibur, Groningen, The Netherlands) to assess maximal measures of oxygen uptake ($\dot{V}O_{2\,max}$), power output ($P_{max}$), heart rate ($HR_{max}$) and blood lactate concentration ($BL_{max}$). In addition, sub-maximal measures of ventilatory threshold (VT) and respiratory compensation point (RCP) were determined to set the individual exercise intensity for the interval training. After a 5 min warm up at 50 W the work rate was increased by 25 W $min^{-1}$ until exhaustion. If the last work rate was not completed, maximal power was calculated according to the method of Kuipers et al. (1985): $P_{max} = P_L + (t/60 \times P_I)$, where $P_L$ is the last completed work rate (*W*), *t* is the time for the incomplete work rate (s) and $P_I$ the incremental work rate (*W*). Gas exchange data were collected continuously throughout the test via breath-by-breath open circuit spirometry (Master Screen CPX, VIASYS Healthcare, Hoechberg, Germany). Before each test, flow and volume were calibrated with the integrated system according to the manufacturer. Maximal oxygen uptake ($\dot{V}O_{2\,max}$) was recorded as the highest $\dot{V}O_2$ value obtained for any continuous 30 s period during the test. At least two of the following criteria were required for the attainment of $\dot{V}O_{2\,max}$: a plateau in $\dot{V}O_2$ despite an increase in work rate (Taylor et al. 1955; Howley et al. 1995), a respiratory exchange ratio above 1.10 (Duncan et al. 1997), a heart rate within ±10 b $min^{-1}$ of age-predicted maximum (220 − 0.7 × age) (Gellish et al. 2007). Ventilatory threshold was determined using the criteria of an increase of the ventilatory equivalent of $O_2$ ($\dot{V}E/\dot{V}O_2$) without a concomitant increase of the ventilatory equivalent of $CO_2$ ($\dot{V}E/\dot{V}CO_2$), the first loss of linearity in pulmonary ventilation ($\dot{V}E$) and carbon dioxide ventilation ($\dot{V}CO_2$) (Beaver et al. 1986). RCP was determined using the criteria of an increase in both $\dot{V}E/\dot{V}O_2$ and $\dot{V}E/\dot{V}CO_2$ and the second loss of linearity in $\dot{V}E$ and in $\dot{V}CO_2$ (Wasserman et al. 1999). Two observers determined VT and RCP. In case of disagreement, a third investigator was consulted.

To determine $BL_{max}$ a 20 µl capillary blood sample was obtained from the hyperemic ear lobe 1 min post-exercise and diluted immediately in 1,000 µl glucose system solution. Blood lactate concentration (mmol $L^{-1}$) was measured using an automated lactate analyzer (Biosen S-line, EKF Diagnostic, Barleben, Germany). Heart rate was monitored continuously throughout the test with a 12-lead electrocardiograph (Cardiovit AT 104 PC, Schiller, Baar, Switzerland).

## Time-trials

Two 20-min maximal power time-trials were performed on a flat ($TT_{flat}$) and uphill ($TT_{up}$) road. The route profiles for the time-trials are shown in Fig. 1. The uphill course had a length of 7 km, the altitude at the top was 1,000 m and the average gradient was 8.5%. Since that specific course has been used for cycling competitions before and the ascending time achieved by a world-class cyclist was 19 min, it was assumed that none of the participants in this study would complete the course faster than the required 20 min. The time-trials were separated by at least 1 h. The order of the first time-trial (i.e. uphill or flat) was randomized and counter-balanced within the groups during the pre-tests and reversed at the post-tests. A 30-min standardized warm-up procedure preceded the time-trials. After 15 min at 40–60% of RCP power output, three 1-min efforts at RCP power output separated by 2 min and followed by another 6 min at 40–60% RCP, where performed. After the first time-trial, the athletes cycled for 15 min at a self-selected low intensity before they rested for 30–40 min. A warm up of 15 min at 40–60% of RCP power output preceded the second time-trial.

Power output, heart rate, cadence, and speed were recorded at 1 Hz throughout the time-trials using SRM professional power cranks (Schoberer Rad-Messtechnik, Jülich, Germany). A static calibration procedure was applied on all devices prior to the study according to the

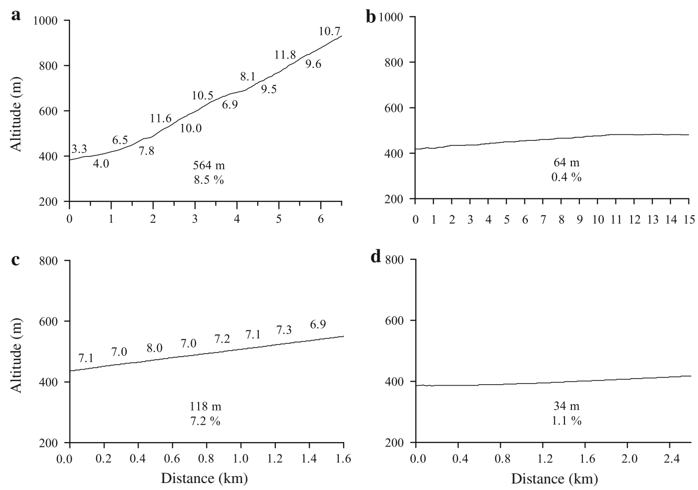


**Fig. 1** Profiles for the uphill (**a**) and flat (**b**) time-trial and uphill (**c**) and flat (**d**) training routes. Numbers for the average gradient of every 500 and 200 m section are shown for the uphill time-trial and training route, respectively

methods of Wooles et al. (2005). Before each trial, the zero offset frequency was adjusted by the investigator according to the manufacturer's instructions. The only information the cyclists received during the time-trials was elapsed time. One minute after completion of each time-trial, a blood sample was obtained from the ear lobe for the determination of blood lactate concentration.

### Interval training

The participants in the training groups substituted two training sessions per week, which usually contained 2–4 h steady rides, with interval training. For 4 weeks, both training groups performed 6 × 5 min intervals at an intensity corresponding to RCP power, interspersed with 5 min at 30–50% of RCP power. It has been shown that four to eight repetitions of aerobic intervals between 4 and 5 min at 80–85% $P_{max}$ performed over 3–6 weeks is an appropriate stimulus to improve $\dot{V}O_{2\,max}$, $P_{max}$ and time-trial performance in trained cyclists (Lindsay et al. 1996; Stepto et al. 1999; Westgarth-Taylor et al. 1997). The rest period of 5 min was selected to allow the riders to return to the start.

The same warm up procedure as described for the time-trials was used before the training sessions. According to the group, $Int_{60}$ performed intervals on an uphill road with an average gradient of 7% (Fig. 1) and with a cadence of 60 rev min$^{-1}$, whereas participants in the $Int_{100}$ group accomplished their training on a flat road with a cadence of 100 rev min$^{-1}$. All training sessions were recorded with SRM power cranks as described above. During the 1st, 4th, and 8th training sessions, blood samples were taken after each bout for the determination of blood lactate concentration.

### Statistical analyzes

Statistical analyzes were performed with the statistical software package PASW Statistics 18 for Mac OS X (SPSS Inc., Chicago, IL). Descriptive data are shown as mean ± standard deviation (SD) and 95% confidence limits (CL). After the assumption of normality was verified using Kolmogorov–Smirnov's test and Liliefors probability, a three-factor mixed ANOVA was used to analyze power output, cadence, heart rate and blood lactate concentration during the time-trials [Group ($Int_{60}$ vs. $Int_{100}$ vs. Con) × time (pre vs. post) × route ($TT_{up}$ vs. $TT_{flat}$)] and to analyze heart rates and blood lactate concentrations measured during the training [Group ($Int_{60}$ vs. $Int_{100}$) × training (1st vs. 4th vs. 8th) × interval (1–6)]. Results from the incremental graded exercise test before and after the intervention, as well as the weekly training time before and during the intervention, were compared with a two-factor mixed ANOVA [Group ($Int_{60}$ vs. $Int_{100}$ vs. Con) × time (pre vs. post)]. Differences between the groups for TRIMP and RPE scores were assessed with a one-way ANOVA. Significant interactions and main effects were identified with a Tukey's HSD post hoc test. Effect sizes are reported as partial Eta-squared ($\eta_P^2$) and considered as small (0.01), moderate (0.1) and large (0.25) effects (Cohen 1988). Relationships between variables were examined with Pearson's product moment correlations. For all statistical analyses, the level of significance was set at $p < 0.05$.

## Results

### Training records

There was no significant difference in training time between the three groups ($F_{2,14} = 2.1$; $p = 0.15$; $\eta_P^2 = 0.23$; Con: 10.4 ± 2.7 h week$^{-1}$; 7.1–13.8; $Int_{100}$: 13.3 ± 2.0 h week$^{-1}$; 11.2–15.4; $Int_{60}$: 12.8 ± 2.8 h week$^{-1}$; 9.8–15.7). There was a small (0.5 ± 0.4 h week$^{-1}$; 0.15–0.86) but significant ($F_{1,14} = 9.1$; $p < 0.01$; $\eta_P^2 = 0.39$) increase in training time during the intervention in comparison to the 12 weeks before the study with no significant group effects ($F_{2,14} = 1.4$; $p = 0.28$; $\eta_P^2 = 0.17$). The mean session RPE scores were significantly higher ($F_{2,14} = 10.1$; $p < 0.01$; $\eta_P^2 = 0.59$) for $Int_{100}$ (13.7 ± 0.6; 13.0–14.3) and $Int_{60}$ (13.7 ± 0.7; 13.1–14.4) than for Con (11.9 ± 1.0; 10.7–13.1). In addition the TRIMP scores were significantly higher ($F_{2,14} = 6.9$; $p < 0.01$; $\eta_P^2 = 0.5$) for $Int_{100}$ (42,812 ± 6,409; 36,086–49,537) and $Int_{60}$ (40,666 ± 7,370; 32,932–48,399) compared to Con (28,119 ± 7,126; 19,271–36,968).

### Incremental graded exercise test

The results of the incremental exercise tests are presented in Table 2. A significant main effect of time was observed for $P_{max}$ ($F_{1,14} = 14.5$; $p < 0.01$; $\eta_P^2 = 0.51$), power output ($F_{1,14} = 4.8$; $p < 0.05$; $\eta_P^2 = 0.26$) and oxygen uptake ($F_{1,14} = 5.3$; $p < 0.05$; $\eta_P^2 = 0.27$) at RCP and for oxygen uptake at VT ($F_{1,14} = 14.1$; $p < 0.01$; $\eta_P^2 = 0.5$). After the training $P_{max}$, power output and $\dot{V}O_2$ at RCP and $\dot{V}O_2$ at VT increased by 2.8 ± 3.0% (1.2–4.4), 3.6 ± 6.3% (0.3–6.8), 4.7 ± 8.2% (0.5–8.9) and 4.9 ± 5.6% (2.2–7.8), respectively. No significant interactions of group x time ($p = 0.48$–0.77; $\eta_P^2 = 0.1$–0.04) were observed.

### Time-trials

A significant main effect of the route was found on power output ($F_{1,14} = 25.3$; $p < 0.001$; $\eta_P^2 = 0.64$), cadence

**Table 2** Results from the GXT before and after the training intervention (mean ± SD)

| Measure | | Group | | |
|---|---|---|---|---|
| | | $Int_{60}$ | $Int_{100}$ | Con |
| $P_{max}$ (W)* | Pre | 392 ± 21 | 391 ± 57 | 394 ± 31 |
| 95% CL | | 370–414 | 331–451 | 355–433 |
| | Post | 400 ± 16 | 402 ± 61 | 408 ± 34 |
| | | 383–418 | 338–466 | 365–450 |
| $\dot{V}O_{2max}$ (mL min$^{-1}$ kg$^{-1}$) | Pre | 61.1 ± 5.0 | 58.8 ± 6.0 | 55.4 ± 4.3 |
| 95% CL | | 55.9–66.4 | 52.5–65.1 | 50.1–60.7 |
| | Post | 60.8 ± 3.3 | 60.1 ± 7.7 | 57.2 ± 5.2 |
| | | 57.3–64.3 | 52.0–68.1 | 50.7–63.7 |
| RCP (W)* | Pre | 297 ± 11 | 304 ± 55 | 298 ± 36 |
| 95% CL | | 286–308 | 246–361 | 253–342 |
| | Post | 311 ± 21 | 316 ± 59 | 301 ± 37 |
| | | 289–333 | 255–378 | 256–347 |
| RCP (mL min$^{-1}$ kg$^{-1}$)* | Pre | 50.4 ± 4.8 | 48.6 ± 6.3 | 45.2 ± 5.2 |
| 95% CL | | 45.3–55.4 | 41.9–55.2 | 38.7–51.7 |
| | Post | 51.5 ± 5.0 | 51.6 ± 6.6 | 47.2 ± 3.7 |
| | | 46.3–56.8 | 44.7–58.5 | 42.6–51.8 |
| VT (W) | Pre | 190 ± 21 | 199 ± 38 | 187 ± 21 |
| 95% CL | | 168–212 | 160–239 | 160–213 |
| | Post | 198 ± 11 | 200 ± 36 | 187 ± 26 |
| | | 186–209 | 162–238 | 155–219 |
| VT (mL min$^{-1}$ kg$^{-1}$)* | Pre | 35.7 ± 3.1 | 35.3 ± 5.2 | 30.7 ± 3.8 |
| 95% CL | | 32.5–38.9 | 29.9–40.8 | 26.1–35.4 |
| | Post | 37.4 ± 3.6 | 36.4 ± 4.5 | 32.9 ± 3.8 |
| | | 33.6–41.2 | 31.7–41.0 | 28.1–37.6 |

*P* power output, $\dot{V}O_2$ oxygen uptake, *RCP* respiratory compensation point, *VT* ventilatory threshold, *CL* confidence limit

* $p < 0.05$; main effect of time (post > pre)

($F_{1,14} = 651.5$; $p < 0.001$; $\eta^2_P = 0.98$), heart rate ($F_{1,14} = 57.1$; $p < 0.001$; $\eta^2_P = 0.8$) and blood lactate concentration ($F_{1,14} = 17.5$; $p < 0.001$; $\eta^2_P = 0.56$). Power output was significantly higher during uphill time-trials, which was accompanied by significantly higher heart rates and blood lactate concentrations (Table 3). ANOVA revealed a significant main effect of time on heart rate ($F_{1,14} = 8.5$; $p < 0.05$; $\eta^2_P = 0.38$) (post < pre). There were no significant main effects for group ($p = 0.39$–$0.88$; $\eta^2_P = 0.13$–$0.02$).

Significant time × route × group interactions on power output were observed ($F_{2,14} = 6.2$; $p < 0.05$; $\eta^2_P = 0.47$). These indicate that both interval-training groups increased power output after the training during $TT_{flat}$ ($Int_{100}$: 2.6 ± 6.0%; −3.7–8.9 and $Int_{60}$: 1.5 ± 4.5%; −3.2–6.2) in contrast to the control group (−3.5 ± 5.4%; −10.1–3.2). Power output during $TT_{up}$ was increased after the training for $Int_{60}$ (4.4 ± 5.3%; −1.2–9.9) and Con (4.0 ± 4.6%; −1.7–9.8), but not for $Int_{100}$ (−1.3 ± 3.6%; −5.1–2.4). All three groups showed higher power outputs before the intervention during $TT_{up}$ (Con: 3.4 ± 6.6%; −4.8–11.6, $Int_{100}$: 5.4 ± 5.8%; −0.7–11.5 and $Int_{60}$: 4.4 ± 6.7%; −2.7–11.4). Post training the difference to $TT_{flat}$ increased for $Int_{60}$ (7.2 ± 4.9%; 2.0–12.3). In addition, the control group increased the difference between the uphill and the flat time-trial (11.4 ± 4.6%; 5.7–17.1). However, this was the result of both an increase and decrease in power output during $TT_{up}$ and $TT_{flat}$, respectively. Finally, the $Int_{100}$ group reduced the difference between the uphill and the flat time-trial (1.3 ± 2.0%; −0.8–3.4). This was attributed to an increase and decrease in power output during the $TT_{flat}$ and $TT_{up}$ conditions, respectively. The changes in power output during the uphill and the flat time-trials are presented in Fig. 2.

Power outputs during the pre- and post-training uphill time-trials were strongly correlated with $P_{max}$ ($r = 0.92$ and $0.91$; $p < 0.001$) and RCP ($r = 0.9$ and $0.85$; $p < 0.001$). In addition, the velocities during the pre- and post-training uphill time-trials were strongly correlated with $P_{max}$ ($r = 0.71$ and $0.74$; $p < 0.001$), $\dot{V}O_{2\,max}$ ($r = 0.8$ and $0.88$; $p < 0.001$), RCP ($r = 0.85$ and $0.72$; $p < 0.001$ and $0.01$) and $TT_{up}$ power output ($r = 0.71$ and $0.74$; $p < 0.01$). For the pre- and post-training flat time-trials, strong correlations between power outputs and $P_{max}$ ($r = 0.86$ and $0.88$; $p < 0.001$) and RCP ($r = 0.84$ and $0.88$; $p < 0.001$) were observed. The correlations between velocities and performance measures were non-significant or moderate for the pre-training time-trials ($r = 0.36$; $p = 0.14$ for $P_{max}$; $r = 0.38$; $p = 0.14$ for $\dot{V}O_{2\,max}$; $r = 0.53$; $p < 0.05$ for RCP; and $r = 0.52$; $p < 0.05$ for $TT_{flat}$ power output). However, post training these correlations were stronger for $P_{max}$ ($r = 0.76$; $p < 0.001$), $\dot{V}O_{2\,max}$ ($r = 0.76$; $p < 0.001$), RCP ($r = 0.82$; $p < 0.001$) and $TT_{flat}$ power output ($r = 0.79$; $p = 0.001$).

### Interval training

As the assumption of sphericity was violated for the factor interval (Mauchly's test: $\chi^2$ (14) = 71.4; $p < 0.001$), the degrees of freedom were adjusted (Greenhouse-Geisser: $\varepsilon = 0.26$). A significant main effect of interval was

**Table 3** Power output and physiological measures during the time-trials before and after the training intervention (mean ± SD)

| Measure | | Group | | | | | |
|---|---|---|---|---|---|---|---|
| | | $Int_{60}$ | | $Int_{100}$ | | Con | |
| | | $TT_{up}$ | $TT_{flat}$ | $TT_{up}$ | $TT_{flat}$ | $TT_{up}$ | $TT_{flat}$ |
| *P* (W)* | Pre | 307 ± 14 | 295 ± 15 | 314 ± 47 | 299 ± 48 | 302 ± 29 | 292 ± 18 |
| 95% CL | | 292–322 | 280–310 | 265–363 | 248–349 | 266–339 | 269–315 |
| | Post | 321 ± 20 | 300 ± 25 | 310 ± 49 | 306 ± 49 | 314 ± 26 | 283 ± 30 |
| | | 299–342 | 274–326 | 259–361 | 255–357 | 281–347 | 245–320 |
| HR (b $min^{-1}$)* | Pre | 180 ± 8 | 178 ± 13 | 177 ± 7 | 174 ± 7 | 177 ± 10 | 174 ± 10 |
| 95% CL | | 171–189 | 164–191 | 169–185 | 166–181 | 164–189 | 161–186 |
| | Post | 179 ± 8 | 174 ± 8 | 176 ± 7 | 173 ± 8 | 173 ± 8 | 168 ± 9 |
| | | 171–187 | 165–182 | 168–183 | 164–181 | 163–183 | 157–178 |
| BL (mmol $L^{-1}$)* | Pre | 10.0 ± 2.7 | 9.7 ± 2.5 | 9.2 ± 2.3 | 8.1 ± 2.3 | 9.1 ± 2.7 | 8.4 ± 0.9 |
| 95% CL | | 6.3–13.6 | 7.1–12.2 | 6.8–11.6 | 5.6–10.5 | 5.8–12.5 | 7.3–9.5 |
| | Post | 11.2 ± 2.6 | 9.5 ± 2.8 | 8.9 ± 2.1 | 7.9 ± 2.0 | 10.3 ± 1.6 | 7.6 ± 1.4 |
| | | 8.4–13.9 | 6.6–12.4 | 6.7–11.1 | 5.8–10.0 | 8.4–12.3 | 5.8–9.4 |

*P* power output, *HR* heart rate, *BL* blood lactate concentration

* $p < 0.001$; main effect of route (uphill > flat)

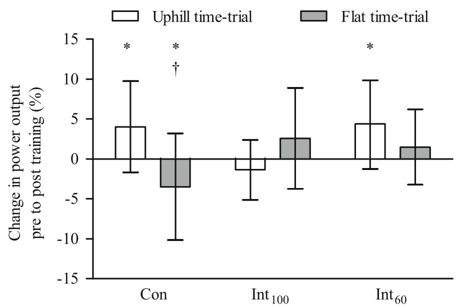


**Fig. 2** Pre- to post-training changes in power output during the uphill and flat time-trials. *Error bars* represents 95% CL. *Significantly different from $Int_{100}$ at $p < 0.05$; †significantly different from $Int_{60}$ at $p < 0.05$

observed for heart rate ($F_{1.3,13.1} = 16.3$; $p < 0.001$; $\eta^2_P = 0.62$). Heart rate significantly increased during the intervals (Fig. 3). No significant main effect of interval was found for the blood lactate concentration ($F_{1.3,12.7} = 1.1$; $p = 0.36$; $\eta^2_P = 0.09$) (Fig. 3). In addition, no significant main effects of group ($p = 0.68$–$0.95$; $\eta^2_P = 0.04$–$0.01$), training ($p = 0.23$–$0.83$; $\eta^2_P = 0.13$–$0.04$) and interactions of group x training x interval ($p = 0.39$–$0.99$; $\eta^2_P =$ 0.1–0.01) were observed. The coefficients of variation (CV) of power output and cadence between the training sessions ($n = 8$) were 1.1 ± 0.3 and 1.6 ± 0.3% for $Int_{60}$ and 1.5 ± 0.3 and 1.2 ± 0.2% for $Int_{100}$. Between the intervals ($n = 48$), the CVs of power output and cadence were 1.5 ± 0.6 and 2.4 ± 1.1% vs. 2.4 ± 1.0 and 1.5 ± 0.5% for $Int_{60}$ and $Int_{100}$, respectively.

## Discussion

To the best of our knowledge, this was the first study that investigated the effects of aerobic interval training at different terrains and cadences in the field, on performance during incremental graded exercise tests and time-trials. The new findings indicate that substituting two continuous endurance training sessions per week over 4 weeks with interval training on a level-ground or uphill course, has no additional benefit on performance measures obtained from a GXT in well-trained cyclists. However, the magnitude of changes in power output during uphill and flat time-trials significantly differed between the training groups. This suggests that specific field-tests should be favored to reveal adaptations to a specific training strategy. In addition, it was shown that power output during a 20-min uphill time-trial was higher compared to a flat time-trial.

In the present study, we observed no significant differences in the performance improvements assessed during a GXT between the two interval-training groups and the control group. Although the control group averaged approximately 2 h less training per week than both interval groups, the total training time as well as the increase during the intervention was not significantly different between the groups. The TRIMP and the session RPE scores were significantly higher for the interval groups. This finding indicates the importance of training volume as a main stimulus for endurance athletes (Jobson et al. 2009; Nimmerichter et al. 2011) and that an increase of exercise intensity does not necessarily enhance performance gains. This is in accordance with previous studies that have also shown similar performance gains after short-term sprint interval versus traditional endurance training in active, but untrained subjects (Burgomaster et al. 2008; Gibala et al. 2006).

While several studies have reported the physiological and performance adaptations in response to various interval-training modes, the effects of cadence during such intervals remained to be shown. We are aware of only one study that compared the effects of low cadence (60–70 rev min$^{-1}$) and high cadence (110–120 rev min$^{-1}$) during 30 s sprint interval training on performance (Paton et al. 2009). In the latter study, the performance gains (i.e. $P_{max}$, $\dot{V}O_{2max}$ and power output at 4 mmol L$^{-1}$ blood lactate) were higher for the low-cadence group (6–11%) in comparison to the high-cadence group (2–3%), which was attributed to a higher testosterone concentration in response

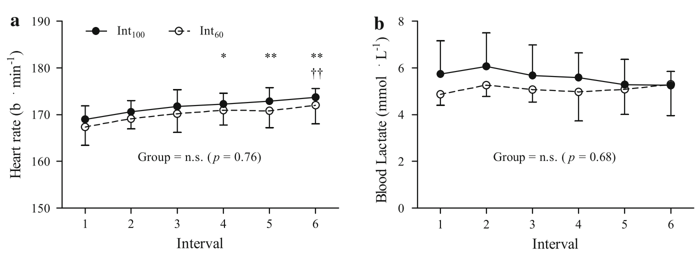


**Fig. 3** Heart rate (**a**) and blood lactate (**b**) profiles during the interval trainings. *Error bars* represents 95% CL. *Significantly different from interval 1 at $p < 0.05$ and **at $p < 0.01$; ††significantly different from interval 2 at $p < 0.01$; *n.s.* not significant

to higher pedal forces in the low-cadence group (Paton et al. 2009).

In contrast to the results of the GXT in the present study, a significant interaction of time × route × group was observed for time-trial power output. According to Bertucci et al. (2005, p 1008), who concluded that *"…it appears necessary to train in specific conditions (uphill road cycling and level ground, low and high cadences) in order to develop these specific muscular adaptations…"*, the two interval-training groups in our study showed higher performance improvements on the terrain where the interval-training sessions were performed ($Int_{100}$: 2.6 ± 6.0 and −1.3 ± 3.6% for $TT_{flat}$ and $TT_{up}$, respectively; $Int_{60}$: 4.4 ± 5.3 and 1.5 ± 4.5% for $TT_{up}$ and $TT_{flat}$, respectively). The magnitude of the improvements and the fact that the $Int_{60}$ group increased power output during both, uphill and flat time-trials supported the results of Paton et al. (2009), that low-cadence interval training is potentially superior to high-cadence intervals. This was emphasized by a longitudinal study of elite cyclists where the training time spent to improve strength (i.e. intervals of 2–20 min at 40–60 rev min$^{-1}$) was strongly correlated with the classification of the riders ($r = -0.86$; $p < 0.01$) and the improvement of 20-min time-trial power output during the season ($r = 0.83$; $p < 0.05$) (Nimmerichter et al. 2011). In addition, the intensity of these intervals was related to 20-min time-trial power output ($r = 0.88$; $p < 0.01$) and $\dot{V}O_{2\,max}$ ($r = 0.89$; $p < 0.01$) (Nimmerichter et al. 2011). Although the underlying mechanisms are not entirely clear, possible explanations are: (1) at any given power output, low cadences require higher forces which (2) increases neuromuscular fatigue, as indicated by an increase of root mean-square EMG in the vastus lateralis and gluteus maximus muscles at high power outputs (i.e. >300 W) (Lucia et al. 2004). To generate and sustain higher forces suggests (3) an additional recruitment of type II fibers which have been shown to be more efficient at higher contraction velocities than type I fibers (Sargeant 1994) and (4) increases in testosterone (Paton et al. 2009) and human growth hormone (Lafortuna et al. 2003) concentrations.

It might be argued that low-cadence training does not comply with observations from recent studies (Lucia et al. 2004; Vercruyssen and Brisswalter 2010) that have shown freely chosen cadences between 90 and 100 rev min$^{-1}$ in trained cyclists at high power outputs. However, we would like to emphasize that a low-cadence strategy during some high-intensity intervals and the associated benefits, is not contrary to a higher freely chosen cadence. Moreover, this observation underpins a basic training principle that taxing a physiological system during exercise is necessary to improve performance. It should be noted that the control group also increased power output during $TT_{up}$ by 4.0 ± 4.6%, but not during $TT_{flat}$ (−3.5 ± 5.4%). Even after revisiting the diaries, we have no explanation for this adaptation in the control group.

This study also showed for the first time, that trained cyclists are able to produce significantly higher power outputs during uphill than flat time-trials of the same duration. This was observed in both the pre- and post-training conditions (4.4 ± 6.0 and 6.4 ± 5.6%, respectively). The higher power outputs were accompanied by higher cardiovascular and metabolic responses and indicate a higher physiological strain during uphill time-trials (Padilla et al. 2000). These results extend a recent study (Nimmerichter et al. 2010) where flat time-trial power output was strongly correlated with GXT measures ($p < 0.001$) and not significantly different from the power output at RCP ($p = 0.97$). The strong correlations between uphill and flat time-trial power outputs and GXT measures observed in the present study are in agreement with previous studies (Balmer et al. 2000; Nimmerichter et al. 2010). The velocities during the uphill time-trials were strongly related to GXT measures and $TT_{up}$ power outputs, whereas the relationships between flat time-trial velocities and performance measures are much more variable (Jobson et al. 2009). This indicates that velocity, especially on flat terrain, is largely influenced by external conditions (e.g. aerodynamics, rolling resistance) and therefore should be used with caution as a performance measure especially in repeated measure study designs.

Finally, the low CVs observed for power output and cadence between 8 training sessions and 48 intervals indicate that the 12 participants completed the required task accurately. This observation shows that well-trained cyclists are able to control both variables within a narrow range despite the fact that nine of our athletes had no prior experience with mobile power meters. The cardiovascular and metabolic response was slightly but not significantly higher for the $Int_{100}$ compared to the $Int_{60}$ training group. This finding is supported by Vercruyssen et al. (2005) who reported significantly lower heart rates and blood lactate concentrations at lower cadences in triathletes, but in contrast to Lucia et al. (2004) who reported the opposite in professional cyclists. It was concluded, that the higher efficiency at a high cadence is one of the main adaptations of professional cyclists (Lucia et al. 2004).

The present study is not without limitations. By design, the study aimed to replicate an outdoor cycling interval-training situation, which is usually completed on a certain route in an out-and-back direction. Consequently, the rest periods between the intervals were longer than in comparable studies with a laboratory set-up (Stepto et al. 2001; Weston et al. 1997). The current study had a limited number of SRM devices and therefore it was not possible to complete the entire study at exactly the same time of the year for all athletes. Data sampling was conducted from May to August in three stages. Although two riders of each group were allocated to the three stages, we cannot eliminate the possibility that a small seasonal performance change may have affected the results (Nimmerichter et al. 2011).

In conclusion, this study has shown that interval training on level-ground or uphill roads, at high or low cadences, leads to similar significant performance gains during a GXT as those, which may be observed after a continuous aerobic endurance training intervention. However, the performance improvements during uphill and flat 20-min time-trials have shown specific adaptations in response to the interval-training sessions and indicate the ecological validity of the time-trials. The magnitude of these improvements suggests that the application of higher pedaling forces via low cadences provides a potentially higher training stimulus with a crossover effect to flat time-trials. High-cadence intervals on level ground are more likely to enhance flat time-trial power output with no crossover to uphill time-trials. When evaluating power output data or prescribing training zones, it is important to note that trained cyclists are able to produce higher power outputs during uphill compared to flat time-trial conditions.

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## 14.2 Example of the Results from the 20-min Maximum Power Uphill and Flat Time-Trials

**Name:** | **Date:** 19.08.2009 | **Temp.:** 24 °C

**Weight:** 64,0 kg | **Time:** 18:00 hh:mm

**Test 1:** 20 min Uphill **Lac:** 12,6

| | P mean | | HR | Cad mean |
|---|---|---|---|---|
| Time (sec) | Watt | Watt/kg | bpm | rpm |
| 1-60 | 362 | 5,65 | 163 | 78 |
| 61-120 | 357 | 5,57 | 178 | 78 |
| 121-180 | 365 | 5,71 | 180 | 69 |
| 181-240 | 363 | 5,67 | 182 | 70 |
| 241-300 | 360 | 5,62 | 181 | 66 |
| 301-360 | 328 | 5,12 | 182 | 73 |
| 361-420 | 348 | 5,44 | 182 | 74 |
| 421-480 | 354 | 5,53 | 184 | 69 |
| 481-540 | 342 | 5,35 | 185 | 73 |
| 541-600 | 324 | 5,07 | 186 | 77 |
| 601-660 | 328 | 5,12 | 185 | 82 |
| 661-720 | 355 | 5,55 | 186 | 72 |
| 721-780 | 337 | 5,27 | 188 | 75 |
| 781-840 | 327 | 5,10 | 188 | 72 |
| 841-900 | 341 | 5,33 | 187 | 64 |
| 901-960 | 327 | 5,10 | 188 | 67 |
| 961-1020 | 296 | 4,63 | 188 | 64 |
| 1021-1080 | 318 | 4,96 | 186 | 71 |
| 1081-1140 | 325 | 5,08 | 186 | 72 |
| 1141-1200 | 345 | 5,38 | 187 | 71 |
| 1-1200 | 340 | 5,31 | 184 | 72 |
| Work: | 408 | kJ | | |
| | 20 | kJ/min | | |

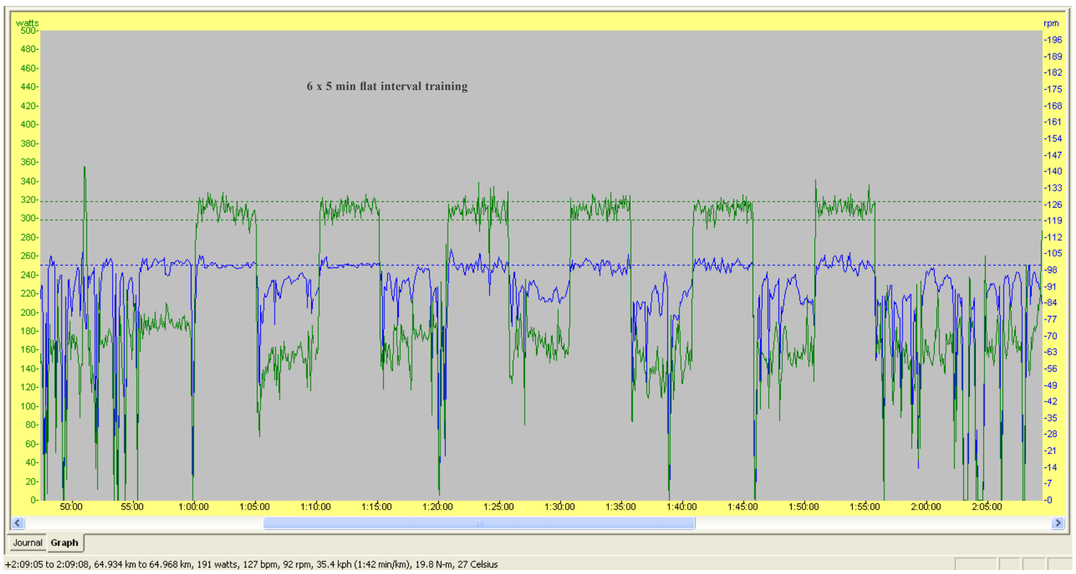
**Test 2:** 20 min Flat **Lac:** 9,9

| | P mean | | HR | Cad mean | |
|---|---|---|---|---|---|
| Time (sec) | Watt | Watt/kg | bpm | rpm | Diff |
| 1-60 | 343 | 5,36 | 156 | 83 | -5,25 |
| 61-120 | 330 | 5,16 | 171 | 87 | -7,40 |
| 121-180 | 331 | 5,18 | 174 | 90 | -9,34 |
| 181-240 | 337 | 5,27 | 176 | 89 | -7,06 |
| 241-300 | 331 | 5,17 | 178 | 91 | -8,02 |
| 301-360 | 326 | 5,10 | 179 | 91 | -0,53 |
| 361-420 | 324 | 5,06 | 179 | 88 | -6,99 |
| 421-480 | 333 | 5,20 | 180 | 90 | -6,07 |
| 481-540 | 329 | 5,15 | 180 | 90 | -3,78 |
| 541-600 | 330 | 5,16 | 180 | 89 | 1,74 |
| 601-660 | 331 | 5,17 | 181 | 89 | 1,05 |
| 661-720 | 324 | 5,06 | 182 | 90 | -8,68 |
| 721-780 | 322 | 5,02 | 182 | 90 | -4,62 |
| 781-840 | 330 | 5,15 | 182 | 89 | 0,95 |
| 841-900 | 327 | 5,11 | 183 | 91 | -4,08 |
| 901-960 | 326 | 5,10 | 184 | 91 | -0,11 |
| 961-1020 | 327 | 5,11 | 184 | 91 | 10,37 |
| 1021-1080 | 348 | 5,43 | 186 | 94 | 9,41 |
| 1081-1140 | 330 | 5,15 | 186 | 92 | 1,41 |
| 1141-1200 | 340 | 5,32 | 186 | 94 | -1,24 |
| 1-1200 | 331 | 5,17 | 179 | 90 | -2,67 |
| Work: | 397 | kJ | | | |
| | 20 | kJ/min | | | |

| | P mean | | HR | Cad mean |
|---|---|---|---|---|
| Time (sec) | Watt | Watt/kg | bpm | rpm |
| 1-240 | 362 | 5,65 | 176 | 74 |
| 241-480 | 347 | 5,43 | 183 | 71 |
| 481-720 | 337 | 5,27 | 186 | 76 |
| 721-960 | 333 | 5,20 | 188 | 70 |
| 961-1200 | 321 | 5,01 | 187 | 69 |
| 1-1200 | 340 | 5,31 | 184 | 72 |
| Work: | 408 | kJ | | |
| | 20 | kJ/min | | |
| FI 240/1200 | 11,3 | % | | |
| FR 240/1200 | 0,03 | W/s | | |

| | P mean | | HR | Cad mean | |
|---|---|---|---|---|---|
| Time (sec) | Watt | Watt/kg | bpm | rpm | |
| 1-240 | 335 | 5,24 | 169 | 87 | -7,27 |
| 241-480 | 328 | 5,13 | 179 | 90 | -5,50 |
| 481-720 | 329 | 5,14 | 181 | 90 | -2,57 |
| 721-960 | 326 | 5,10 | 183 | 90 | -2,01 |
| 961-1200 | 336 | 5,25 | 185 | 93 | 4,77 |
| 1-1200 | 331 | 5,17 | 179 | 90 | -2,67 |
| Work: | 397 | kJ | | | |
| | 20 | kJ/min | | | |
| FI 240/1200 | -0,3 | % | | | |
| FR 240/1200 | 0,00 | W/s | | | |

## 14.3 Example of an Uphill and Flat Interval Training Session


Uphill and flat interval training session: green horizontal dashed lines represent the power output at $RCP \pm 3$ %

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