

**The effect of high intensity resisted cycling with and
without explosive resistance training on performance in
competitive cyclists**

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Attestation of Authorship

I hereby declare that this submission is my own work and that, to the best of my knowledge and belief, it contains no material previously published or written by another person (except where explicitly defined in the acknowledgements), nor material which to a substantial extent has been submitted for the award of any other degree or diploma of a university or other institution of higher learning.

Joe McQuillan

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List of Publications, Conferences and Reports from this Thesis

Conference Proceedings

One published conference abstract has resulted from the work presented in this thesis.

McQuillan, J.A., Hopkins, W.G., Kilding, A.E., & Paton, C.D. (2006). The effect of high-intensity training on performance of competitive male cyclists. Sports Medicine and Science New Zealand Conference. Wellington. Page 61.

Abstract

Training studies involving competitive runners and road cyclists have shown substantial gains in sprint and endurance performance when sessions of high-intensity interval training were added to their usual training in the competitive phase of a season. Further research has shown large performance benefits in sprint and endurance power (7 – 9%) when cyclists combined explosive single-leg jumps with cycling-specific high-intensity interval training during a competitive season. The aim of the present study was to assess the contribution of the jumps to the gains in performance in competitive cyclists in a randomized control trial.

The training protocol for the control group was based on previous experimental work in which the control group ($n=8$) completed cycle specific interval training followed by a series of explosive single-leg jumps. The experimental group ($n=7$) carried out the same cycle specific interval training but did not participate in the explosive single-leg jumps. While the current study did not use a true control group, the investigation was carried out in the knowledge that a combination of high intensity interval cycling and explosive single-leg jumps causes changes positive changes in performance. Participants took part in 10 x 30-min sessions consisting four sets of high intensity intermittent cycling (4 x 30-s maximum efforts at $50 - 60 \text{ min}^{-1}$ alternating with 30-s recovery). Between each set of 4 x 30 s sprints the control (ballistic) group carried out one set of explosive single-leg jumps (20 for each leg), while the experimental (continuous) group cycled for 20 s at $50 - 60 \text{ min}^{-1}$.

Before and after the training period all cyclists completed an incremental peak power test for assessment of VO_2max , lactate threshold, exercise economy and peak power, a 30 s Wingate sprint test and a 20 km time-trial. Relative to the control group the percent mean

changes ($\pm 90\%$ confidence limits) in the experimental group were: power at 4-mM lactate, -4.2 (± 6.3); VO_2max , -3.1 (± 3.7); mean time-trial power, -0.7 (± 4.7); peak incremental power, -1.7; (± 5.0); power at 80% max heart rate, -2.8; (± 5.6); Wingate peak power, -4.2; (± 7.8). We conclude that high-intensity training may improve performance but the combination of high-intensity training and explosive resistance training in the competitive phase is likely to produce greater gains in trained cyclists than high intensity cycling alone.

Thesis Rationale

Of great interest to coaches and sport scientists is the effectiveness of training programs and the combination of endurance and resistance training on athletic performance. Following an extensive period of aerobic development, endurance athletes will use interval training to increase both sprint performance and ability to recover from high-intensity activity in preparation for key events. Other methods of training such as explosive resistance training have been shown to enhance endurance performance. Recent studies on cyclists have shown large enhancements in sprint performance and aerobic power using a combination of explosive resistance training and interval training. The current study aims to investigate the contribution of explosive resistance training to overall performance.

This study will further the current body of knowledge that is available to researchers and coaches and inform both groups as to the usefulness of explosive resistance training to enhancing overall performance.

Organisation of Thesis

The first chapter is the combination of two literature reviews. My intention with the first section in the initial chapter was to give readers an up to date view on testing assessments currently used by cyclists. The use of testing methodologies such as VO_2max , lactate threshold and the Wingate test are evaluated against current literature. The incorporation of new technologies has given an accurate indicator of power output and intensity during cycling events and has promoted the use of mobile power ergometers in training and competition. The second section updates the reader on current training techniques used by coaches and athletes towards achieving performance goals. I explain the mechanisms behind periods of training and present a summary of the benefits of combining explosive resistance training with high-intensity training. In the concluding remarks, I suggest future directions for researchers wishing to investigate the role of resistance training in endurance performance.

I have presented chapter two as a manuscript suitable for application to a journal. In this section I summarise relevant findings from the literature review, present the research project and a summary of findings. I focus the discussion on the changes in the study and compare these results with that of previous researchers in the area. Finally, I provide recommendations for researchers who wish to investigate mechanisms behind high-intensity training and explosive resistance training.

I have presented chapter three as a report that enables coaches, athletes and sport scientists to read a summary of key literature findings, significant findings of the study and how these findings may be used in a practical setting.

CHAPTER ONE – PART A

The Physiological Demands of Cycling - A Review

Abstract

Cycling events range from short duration, “supra-maximal” intensity sprint events of 200 m up to 3-wk tours of 4000 km. Energy system contribution in these races is largely determined by competition duration: track events of 200 m last ~10 s and have ~95% contribution from the anaerobic system, whereas longer distance road-based events and multi-week tours place greater demands on the aerobic energy system. Some stages and sprint “primes” in the longer events tax both the aerobic and anaerobic systems. Sport scientists assess performance of the energy systems with laboratory-based incremental tests, time trials, and all-out sprints. Measures derived from these assessments include maximum oxygen uptake, anaerobic threshold, exercise economy, anaerobic capacity, mean power and peak power. The relative importance and trainability of these measures are topics of ongoing research. With the advent of mobile ergometers, coaches and sport scientists can derive power profiles of cyclists in training and competitions; the usefulness of such devices is also being evaluated.

Introduction

Cycling events range from short duration, “supra-maximal” intensity sprint events of 200 m up to 3-wk tours of 4,000 km (Atkinson, Davison, Jeukendrup, & Passfield, 2003; Jeukendrup, Craig, & Hawley, 2000; Lucia, Hoyos, & Chicharro, 2001a). The duration of the competition largely determines the energy system that is most utilised (Jeukendrup et al., 2000). Track events of 200 m lasting ~10 s having a 95% contribution from the anaerobic system (Jeukendrup et al., 2000) whereas longer distance road-based events and multi-week tours place great demands on the aerobic energy system (Lucia et al., 2001a). Despite the lack of aerobic dependency in shorter track events, track based athletes report well developed aerobic measures (Schumacher & Mueller, 2002) when compared with road based athletes (Padilla, Mujika, Cuesta, & Goiriena, 1999).

A common measure for evaluation of aerobic capacity in cyclists is $VO_2\text{max}$ (Lucia, Hoyos, Perez, Santalla, & Chicharro, 2002; Mujika & Padilla, 2001). $VO_2\text{max}$ is widely reported in literature and a variety of opinions exist as to the sensitivity of $VO_2\text{max}$ in detecting alteration of training status or performance in cyclists (Hoogeveen, 2000). Tests that are reported to be more sensitive as predictors of performance than $VO_2\text{max}$ are various measures of anaerobic threshold (Bishop, Jenkins, & MacKinnon, 1998). Elite level professional male road cyclists typically have higher percentages than those of lesser trained cyclists and possess the ability to ride at this threshold for a longer time (Lucia et al., 2001a; Padilla et al., 1999). This performance enhancement in elite cyclists is due to the combination of large volumes of training and regular competition at high intensities year in and year out (Padilla, Mujika, Orbananos, & Angulo, 2000). The product of years of training and competing is an increase in exercise economy (Coyle, 2005). Anaerobic capacity is considered important in cycle performance especially in the evaluation of peak

power (Craig & Norton, 2001). Measures most commonly used in evaluation of anaerobic capacity are the Wingate anaerobic test (Inbar, Bar-Or, & Skinner, 1996) and the maximal accumulated oxygen deficit test (Medbo et al., 1988).

Competitive Cycling Events

Competitive cycle competitions include distances from 200 m for a track-based “sprint” event to major road based tours of three weeks or up to 4000 km (Atkinson et al., 2003; Jeukendrup et al., 2000; Lucia et al., 2001a). Other track based sprint events include races such as the 500 m and 1000 m time-trials for women and men respectively (Jeukendrup et al., 2000). Longer distance track-based races range from women’s 3,000 m and men’s 4000 m team and individual pursuits through to the prestigious 1-h record. Road events consist of circuit-based criteriums, single day events (classics) of up to 300-km, extreme endurance races such as Race Across the Alps and Paris-Brest-Paris of 500 to 600 km in distance and multi-day tours of up to three weeks (Atkinson et al., 2003; Jeukendrup et al., 2000; Lucia et al., 2001a; Neumayr, Pfister, Mitterbauer, Maurer, & Hoertnagl, 2004). The wide spectrum of distances in cycle racing is mirrored by the range of intensities required, from "supra-maximal" intensity (that is, intensity eliciting more than maximum oxygen consumption, VO_{2max}) to those of a low to moderate intensity (I. E. Faria, 1984). For the benefit of the reader the term ‘cycling’ will relate to all forms of road, track and mountain biking unless stated in the following text.

Track-based performance events of ~5 min duration are heavily dependent on high volume endurance training (Schumacher & Mueller, 2002) and success in these types of events are often associated with high VO_{2max} (Passfield & Doust, 2000). Similarly, high values of VO_{2max} (~70 $ml \cdot kg^{-1} \cdot min^{-1}$ to 85 $ml \cdot kg^{-1} \cdot min^{-1}$) have been found in elite level professional

male road cyclists (Padilla et al., 1999). Within a full season of training and competing, elite cyclists are able to improve VO_2max by 13% (Hoogeveen, 2000). The average VO_2max of a sample of women's World Cup female cyclists was recently measured as $\sim 65 \text{ ml}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$ (Ebert et al., 2005). Table 1 shows a range of athletic abilities according to cycling event, gender and specialist discipline. Lowest values of VO_2max relative to body weight are seen in female road cyclists; the highest values are seen in uphill specialist cyclists. Male track cyclists show the highest values of absolute peak power, but uphill specialists display the highest power output relative to body mass. Similarly, the effects of body mass on relative VO_2max can clearly be seen in the data of Padilla (1999) where the lightest cyclists (uphill specialists) show the highest relative VO_2max . A limitation in the comparison of measures presented in Table 1 is that each group of athletes was tested on different cycle ergometers (Paton & Hopkins, 2001) and protocols used to assess physiological variables differ between studies (E. W. Faria, Parker, & Faria, 2005b).

Table 1. Descriptive physiological and anthropometric variables of elite road and track cyclists and mountain bikers.

Author	Subjects	Peak Power (W)	Peak Power (W.kg ⁻¹)	VO ₂ max (ml.kg ⁻¹ .min ⁻¹)	Body Mass (kg)	Height (cm)
Padilla et al (1999)	Male Flat Terrain	461 ± 39	6.0 ± 0.3	74.4 ± 3.0	76.2 ± 3.2	186 ± 4
	Male Time	457 ± 46	6.4 ± 0.1	79.2 ± 1.9	71.2 ± 6.0	181 ± 6
	Male All	432 ± 27	6.4 ± 0.2	78.9 ± 1.9	68.0 ± 2.8	180 ± 2
	Male Uphill	404 ± 34	6.5 ± 0.3	80.9 ± 3.9	62.4 ± 4.4	175 ± 7
Lee et al (2002)	Male MTB	413 ± 36	6.3 ± 0.5	78.3 ± 4.4	65.3 ± 6.5	178 ± 7
	Male Road	431 ± 12	5.8 ± 0.3	73.0 ± 3.4	74.7 ± 3.8	184 ± 3
Schumacher et al (2002)	Male Track Cyclists	501 ± 42	6.4 ± 0.3	67.6 ± 2.7	77.9 ± 4.1	186 ± 3
Ebert et al (2005)	Female Road	310 ± 25	-	63.6 ± 2.4	57.9 ± 3.6	169 ± 6

Data are mean ± standard deviation.

Measurement of Energy Expenditure

Factors influencing energy cost of movement for a cyclist include physiological status, anthropometric dimensions, environmental conditions and mechanical considerations (Jeukendrup et al., 2000). Previously, measurement of energy expenditure has depended on modelling or other indirect methods (Schumacher & Mueller, 2002). However, recent developments in technology have allowed for a more direct measurement of work from the cyclist's own bike in training and/or competition (Basset, Kyle, Passfield, Broker, & Burke, 1999; Ebert et al., 2005; Gardner et al., 2004; Vogt et al., 2006); the most popular devices being the SRM power crank (Schoberer Rad Messtechnik, Welldorf, Germany) and Power Tap (Cycle-Ops, Madison Wisconsin). Both of these devices have previously been validated for use (Bertucci, Duc, Villerius, Pernin, & Grappe, 2005; Gardner et al., 2004).

Contribution of Energy Systems

Several studies have reported power outputs during different competitive events (Table 2). Such data is useful for the sport scientist and coach as it provides information relating to success in a range of events (Gardner et al., 2004). Shorter duration events require average power outputs that are closer to, and in some cases higher than, the cyclist's peak incremental power output (Vogt et al., 2006). It is clear that as the duration of an endurance event increases, greater demands are placed on aerobic processes for supply of energy (Gastin, 2001; Jeukendrup et al., 2000; Spencer & Gastin, 2001). The predominant energy requirement for both the multi-day tour and 13-km time-trial are provided by aerobic mechanisms, however in shorter events such as the 4000-m teams and individual pursuit lasting ~4 min, anaerobic processes contribute ~25% to the total energy requirement (Jeukendrup et al., 2000). Similar energy contributions were reported by Spencer and Gastin (2001) for running, where events of ~4 min utilise 84% of the aerobic system. Gastin (2001) also reported that in a maximal running event lasting ~50 s, 43% of the energy requirement is supplied by the aerobic system while at ~113 s the same system contributes 66% to energy expenditure. With this in mind, training should be specific enough in nature to the demands of the sport to allow a sufficient training response to take place (I. E. Faria, 1984).

Table 2. Power output measures in moderate to elite male and female cyclists for road and track competitions using mobile ergometers, and peak power obtained during laboratory-based incremental tests.

Author	Subjects	Competition	Distance and/or Time	Mean Power in Competition		Peak Incremental Power (W)
				Absolute (W)	Relative (W·kg ⁻¹)	
(Vogt et al., 2006)	6 elite male professional road cyclists	International Multi-day Tour	758 km	220 ± 22	3.1 ± 0.2	390 ± 28
(Vogt et al., 2006)	6 elite male professional road cyclists	Uphill time-trial	13 km	392 ± 60	5.5 ± 0.4	390 ± 28

(Ebert et al., 2005)	15 elite female professional road cyclists	19 World Cup racing events	173 ± 87 min (flat stages)	192 ± 21	3.3 ± 0.3	310 ± 25
(Ebert et al., 2005)	15 elite female professional road cyclists	8 World Cup racing events	187 ± 19 min (hilly stages)	169 ± 17	3.0 ± 0.4	310 ± 25
(Broker, Kyle, & Burke, 1999)	4 elite male individual pursuit cyclists	Individual pursuit	4000 m; 4.4 min	422 ± 16	5.3 ± 0.2	-
(Schumacher & Mueller, 2002)	7 elite male individual pursuit cyclists	Personal best individual pursuit	4000 m; 4.3 min	502 ± 42 ^a	6.4 ± 0.2	-
(Tan & Aziz, 2005)	8 male moderately trained cyclists	Flat time-trial	36 km; 56 min	231 ± 26	-	343 ± 27
(Tan & Aziz, 2005)	8 male moderately trained cyclists	Hilly time-trial	1.4 km; 3.6 min	335 ± 38	-	343 ± 27

Data are mean ± standard deviation.

^abased on power prediction equation (Broker et al., 1999)

Track Cycling

Due to the relative ease of power measurement and standardisation of race distance, track cycling is well suited to measurement and prediction of energy system requirements and utilisation (Schumacher & Mueller, 2002). The wide range of distances reflects the various energy requirements that are used in track racing (Craig & Norton, 2001). Distances as short as 200 m require energy contributions of ~95% from anaerobic sources in elite male and female competitors (Jeukendrup et al., 2000). Events lasting ~60 s, such as the kilo, require an equal contribution from aerobic and anaerobic energy systems, while an event of 4 min requires a 75% contribution from the aerobic system. The longest track-based events, such as the hr record, 50-km points race or Madison require >95% contribution from aerobic sources (Jeukendrup et al., 2000). Despite the high dependence on the aerobic

system, elite cyclists in track-based events such as the Madison display peak powers of 1150 W, with average power output in the event being 290 W (Jeukendrup et al., 2000) .

Road Cycling

Despite being performed predominantly at submaximal intensities (Padilla et al., 1999), the demands of road cycling require athletes to possess high levels of both aerobic power (Hawley & Noakes, 1992; Mujika & Padilla, 2001) and peak power output (Mujika & Padilla, 2001). Mass start races typically display a greater range of power outputs and energy requirement fluctuations than time-trials (Jeukendrup et al., 2000; Mujika & Padilla, 2001). In a recent study on power output during a multistage tour, Vogt et al (2006) reported mean daily power outputs as well as pre-tour incremental peak power values (Vogt et al., 2006) as per table 2. Recorded intensity levels of elite cyclists during the Tour de France showed that athletes spent 70%, 23% and 7% in the low, medium and high intensity zones respectively based on pre-tour ventilatory measures (Lucia, Hoyos, Carvajal, & Chicharro, 1999). Despite the apparent ease with which data can be collected and reported, it should be noted that throughout a competitive cycling event major fluctuations in power and heart rate response will be caused by team tactics and race strategies (Padilla et al., 1999), hill descents, attacks, coasting within the bunch, sprint primes and stage finishes (Coggan, 2006). Therefore data should be treated in the environment of its capture and related within that context only.

Mountain Biking

While road and track cycling have received extensive physiological profiling (Lucia et al., 2001a; Mujika & Padilla, 2001), minimal data exists for mountain biking (Stapelheldt, Schwirtz, Schumacher, & Hillebrecht, 2004). Mountain biking is characterized by mass-

start, cross-country circuit racing (Impellizzeri, Sassi, Rodriguez-Alonso, Mognoni, & Marcora, 2002). At the highest level, competition duration is between 1.5 and 2.5 hrs and total hill ascent is ~1500 m (Stapelfeldt et al., 2004). Power outputs during ascents range from 250 to 500 W and are typically above the individual anaerobic threshold (Stapelfeldt et al., 2004). While the length of a race dictates reliance on an effective aerobic system, a substantial anaerobic requirement is necessary to be successful in mountain biking competitions (Baron, 2001).

Physiological Measures Important to Cycling Performance

According to Whipp et al (1981), four measurements make up the aerobic profile of an endurance athlete: VO_2 max, anaerobic threshold, work efficiency (oxygen cost of exercise), and VO_2 kinetics. Any attempt to discriminate between performers or to predict performance capability should consider these four measures of aerobic function (Atkinson et al., 2003; Jacobs, 1986; Jones & Carter, 2000; Jung, 2003; Whipp, Davis, Torres, & Wasserman, 1981).

Maximal Oxygen Uptake

VO_2 max is defined as the highest rate at which oxygen can be taken up and utilized by the body during severe exercise at sea level (Astrand & Rodahl, 1986). There is a large body of evidence citing VO_2 max as one of the defining measures of performance in endurance athletes (Bently, McNaughton, Thompson, Vleck, & Batterham, 2001; Jones & Carter, 2000; Lucia, Hoyos, Perez et al., 2002; Padilla, Mujika, Orbananos, Santisteban et al., 2000; Wilber, Zawadzki, Kearney, Shannon, & Disalvo, 1997). High values of VO_2 max have been reported extensively in the literature for endurance athletes, including runners (Hagan, Smith, & Gettman, 1981; McMiken & Daniels, 1976; Sjodin & Svedenhag, 1985),

track (Broker et al., 1999; Craig & Norton, 2001; Schumacher & Mueller, 2002) and road cyclists (Coyle, 2005; Lucia, Hoyos, & Santalla, 2002; Mujika & Padilla, 2001), triathletes (Hue, Le Gallais, Chollet, & Prefaut, 2000), and mountain bikers (Impellizzeri et al., 2002; Wilber et al., 1997) and it is one of the most cited physiological measures in exercise physiology research (Wenger & Bell, 1986).

Despite the overwhelming literature in favour of reporting VO_2max as a valid measure of physiological ability, there are suggestions that the theoretical concept of VO_2max is flawed (Noakes, 1997, 1998). Much debate surrounds the proposed mechanisms determining maximal oxygen uptake (Howley, Basset, & Welch, 1995; Noakes, 1997, 1998) and its relevance as a valid and sensitive enough performance indicator (Jeukendrup & Martin, 2001). Literature citing VO_2max at different phases during an elite cyclist's calendar year displayed a change of just 3.5%, despite the cyclists being tested during rest, pre-competition and competition periods (Lucia, Hoyos, Margarita, & Chicharro, 2000). Other studies monitoring elite cyclists' VO_2max suggest that changes in training volume have little effect on VO_2max , indicating that the subjects reached their limit with this measure (Barbeau, Serresse, & Boulay, 1993). Furthermore, training studies using high-intensity exercise show that, while peak power output increased post-intervention, there was no increase in VO_2max (Laursen, Blanchard, & Jenkins, 2002).

The sensitivity of VO_2max as a measure to track changes in fitness of athletes has been questioned (Jeukendrup & Martin, 2001; Jones, 1997; Shepard, 1984). Extensive monitoring of VO_2max of an elite middle distance runner was reported by Jones (1997). The case study highlighted that over the period of 5 yr relative VO_2max reduced by 9% but 3000 m performance time reduced by 8%. Similarly, despite an increase in performance,

VO₂max was found to be unchanged in runners (Acevedo & Goldfarb, 1989; Mikesell & Dudley, 1984) and cyclists (Lucia et al., 2000) following training interventions. Acevedo et al (1989) reported positive changes for 10-km performance times in competitive runners after an 8-wk period of high-intensity training. Subjects incorporated a weekly run consisting of high intensity intervals at 90–95% of VO₂max into their training program along with bi-weekly Fartlek running over 6 to 10 miles. After eight weeks of training no substantial change was observed in VO₂max, ventilatory threshold or body mass. Improvements were observed in plasma lactate variables at 85% VO₂max while 10-km run time decreased on average by 60 s (30 to 140 s) while time-to-exhaustion improved by 20%. In a comparative study by Miller et al (1987) the authors concluded that measures of anaerobic threshold expressed as ml·kg⁻¹·min⁻¹, L·min⁻¹ and as a percentage of VO₂max ($r = -0.94$, $r = -0.76$ and $r = -0.83$ respectively) were better predictors of 15-km time-trial performance than VO₂max expressed in both ml·kg⁻¹·min⁻¹ and L·min⁻¹ ($r = -0.68$ and $r = -0.68$ respectively). Lucia et al (2000) investigated the possibility that an initial maximal aerobic assessment pre-season was reliable enough for prescription of training throughout an entire competitive road-cycling season of ~8 months. The volume of training between the initial test in November and subsequent assessments in January (7430 ± 800 km) and April ($12,770 \pm 2042$ km) had positive increases in lactate parameters and ventilatory thresholds, but had no influence on VO₂max. The lack of VO₂max to track adaptations that enhance performance in competitive athletes over the course of the season and their careers suggests that its use as a performance monitoring for elite- and sub-athletes tool is questionable (Jones, 1997).

Authors suggesting that VO₂max is a valid measure of fitness have also stated that VO₂max is strongly related to the ability to recover from high intensity intermittent exercise (Tomlin

& Wenger, 2001), and that VO_2max is sensitive enough to accurately measure changes in moderately- and elite-trained cyclists after training at moderate- and high-intensity training loads (Hoogeveen, 2000; Tabata et al., 1996). Hoogeveen (2000) investigated the changes in elite level cyclists 6 weeks prior to the start of training and ~6 months later, at a point that was midway through a competition season. Cyclists showed a 2.2% increase in peak power but a 13% increase in VO_2max expressed in $\text{ml}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$ in the intervening 6-month period where training and racing took place. Although reduction in body mass can improve relative VO_2max (Fogelholm, 1994), there was only a 1.2% reduction in body mass in subjects over the course of the study (Hoogeveen, 2000). These findings suggest that VO_2max is sensitive to changes in training status.

Burke et al (1977) found a significant correlation between VO_2max and biochemical characteristics of muscle in elite cyclists against semi-competitive and untrained participants. A number of the subjects were national or world champions. No significant difference existed in the fibre-types of the groups, or between VO_2max and fibre type ($r = 0.29$) suggesting that despite the large volume of training that the elite cyclists undertook, VO_2max was a better predictor of performance than either histochemical or biochemical muscle analyses (Burke, Cerny, Costill, & Fink, 1977). A similar study involving a wider range of participants was undertaken by Bergh et al (1978). In this study 138 males and 41 females representing 25 different sports were measured for VO_2max . Similar measures were carried out on a second group of physically active ($n = 40$) and sedentary ($n = 50$) subjects. Muscle biopsies were taken from 53 male athletes across 9 sports and 38 trained non-athletes. A positive relationship existed between VO_2max and the relative number of slow twitch fibres ($r = 0.69$). Those athletes with the highest VO_2max also had the highest number of slow twitch fibres (75%).

Overall, conflicting evidence exists over the ability of VO₂max to predict performance and track changes in fitness over the course of a season (Hoogeveen, 2000; Lucia et al., 2000). Opposing views exist on the relationship between seasonal adjustments in peak power and VO₂max with some authors showing an increase in peak power but no change in VO₂max (Lucia et al., 2000) whereas, others have shown major changes in VO₂max with only minor changes in peak power (Hoogeveen, 2000). The use of VO₂max for tracking changes in moderately trained athletes, and as a talent identification tool, is justified however tracking performance measures in elite cyclists may not be warranted as the majority of studies presented showed no enhancement in VO₂max, while other performance parameters such as peak power had increased.

Anaerobic, Lactate and Ventilatory Thresholds

Wasserman (1984) describes the phenomenon of anaerobic threshold as the oxygen consumption above which aerobic energy production is supplemented by anaerobic energy production, which results in a marked increase in blood lactate. It is generally accepted that the lactate threshold occurs at between 84% and 90% of an elite cyclist's peak power output (Lucia et al., 2001a; Padilla et al., 1999). A substantial amount of time has been spent investigating and reporting on blood lactate thresholds (Beneke & von Duvillard, 1996; Billat, Sirvant, Py, Koralsztein, & Mercier, 2003; Crisafulli et al., 2005; Daniels & Scardina, 1984; Jones & Carter, 2000; Londeree, 1997; Xu & Rhodes, 1999), however there is still much debate into the significance of these biological responses and whether they are valid markers of fatigue and performance (Cairns, 2006; Gladden, 2004; Philp, MacDonald, & Watt, 2005). A myriad of terms have been used interchangeably to describe lactate accumulation kinetics during submaximal exercise including "lactate threshold" (Jacobs, 1986; Jenkins & Quigly, 1990; Maassen & Busse, 1989; Pyne,

Hamilton, & Swanwick, 2001), "onset of plasma lactate accumulation" (Acevedo & Goldfarb, 1989; Farrell, Wilmore, Coyle, Billing, & Costill, 1979) "aerobic threshold" (Aunola & Rusko, 1986; Skinner & McLellan, 1980), the "4 mmol/L" method (Bishop et al., 1998; W. G. Hopkins, Schabort, & Hawley, 2001; Jacobs, 1986) and the "D-max" method (Bishop et al., 1998; Withers, Gore, Gass, & Hahn, 2000).

It has been suggested that the ease at which lactate can now be measured, its capacity to evaluate exercise performance (in comparison to pre-event measures) at the conclusion of competition, and the general prediction of performance have assisted the assessment's popularity in physiological reporting and measurement (Jacobs, 1986). Bishop et al (1998) investigated the relationship between various plasma lactate parameters, peak power and one-hr cycling performance in competitive female cyclists. The authors found that all six of the plasma lactate parameters had a higher correlation to the one-hr performance test than VO_{2max} , with the D-max method of analysis method being the best predictor. Blood lactate parameters have shown to be responsive to tracking changes in bouts of endurance training (Pyne et al., 2001; Sjodin, Jacobs, & Svedenhag, 1982; Thompson, Garland, & Lothian, 2006). Sjodin et al (1982) investigated the effect of adding a 20-min treadmill-based single steady state training intensity run to the subject's normal program on VO_{2max} , enzymatic and lactate variables. The subjects, who were middle and long distance runners, maintained their weekly training schedule over the course of the 14-wk study which was undertaken in the non-competitive season. During the weekly treadmill based training sessions, the runners' blood lactate response was measured at 5 min and subsequent training speeds adjusted according to the reading. Following the training intervention, a significant change was found in steady state velocity, while changes in VO_{2max} were non-significant, suggesting that measurement of blood lactate at steady state

was more sensitive than VO_2max to changes following a period of training. There was no correlation between the changes in steady state velocity and enzyme activities (Sjodin et al., 1982). In a comprehensive meta-analytic review of reliability in performance tests (W. G. Hopkins et al., 2001) stated that lactate measures of anaerobic threshold are slightly better than that of ventilatory measures and that they are more reliable and sensitive to change than that of ventilatory measures. Authors suggested that 4 mmol/L is the most reliable (CV ~1.5%) measure of lactate threshold.

Ventilatory threshold has been identified as the point at which ventilation increases disproportionately to VO_2 (Dupont & Freedman, 1983). A disproportionate increase in carbon dioxide production has also been used to distinguish between two ventilatory thresholds (Wasserman, 1984). The ventilatory and lactate thresholds have been shown to be closely related (Lucia et al., 2000), because ventilation is stimulated by changes in the blood i.e. release of lactate by muscle during exercise of increasing intensity (Astrand & Rodahl, 1986). Ventilatory thresholds have been used to gauge the effect of periods of training (Lucia et al., 2000), to compare against other threshold measures (Solberg, Robstad, Skjonsberg, & Borchenius, 2005) and compare with other athletes of similar sports (Hue et al., 2000). Ventilatory threshold is a popular choice of medical practitioners (Wasserman, 1984) and exercise scientists (Solberg et al., 2005) because it is a non-invasive method of analysis which has also been identified as a factor in cycling performance (Lucia, 2004; Lucia, Sanchez, Carvajal, & Chicharro, 1999). These threshold measures are used to prescribe training intensities to professional cyclists (Lucia, Hoyos et al., 1999).

Accurate measurement of key physiological parameters allows coaches and sport scientists to track performance, evaluate training zones and monitor markers of over-training (Barbeau et al., 1993; W. G. Hopkins et al., 2001; Lucia et al., 2000). In order to measure the ability of ventilatory threshold and heart rate to track changes throughout the season, Lucia (2000) tested elite level cyclists at rest, pre-competition and in-competition phases. First and secondary ventilatory threshold workload (power output) increased as cyclists increased training volume, suggesting that ventilatory threshold measures are sensitive in tracking the change in performance of cyclists and can be used in training prescription as opposed to heart rate which showed minimal change during the testing sessions. Measures of first and secondary ventilatory thresholds have also been shown to display significant differences in highly trained cyclists and triathletes during a 40-km time trial when there was little change VO_2 max or peak power output (Laursen, Shing, Tennant, Prentice, & Jenkins, 2003). The difference in first and secondary ventilatory threshold was recognised as contributing to the cyclist group completing the 40-km time trial in a shorter time than the triathlete group. In a recent study it was found that ventilatory threshold was the closest related lab variable to time-trial performance of >50 km in elite cyclists; however the sample size ($n = 4$) was too small for conclusive findings (Lucia, 2004).

The maximal lactate steady state is defined as the highest blood lactate concentration and work load that can be maintained over time without continual lactate accumulation (Beneke & von Duvillard, 1996; Billat et al., 2003). In terms of training and performance prediction, the maximal lactate steady state has been suggested as being a useful physiological parameter (E. W. Faria et al., 2005b) and is a commonly investigated measure in sport science literature (Harnish, Swenson, & Pate, 2001; Jenkins & Quigly, 1990; LaFontaine, Londeree, & Spath, 1981; Laplaud, Guinot, Favre-Juvin, & Flore, 2006; MacIntosh, Esau,

& Svedal, 2002; Swenson, Harnish, Beitman, & Keller, 1999). Traditional identification of maximal lactate steady state requires the athlete to complete a series (3 to 6) of 10-30 min exercise bouts (Harnish et al., 2001; MacIntosh et al., 2002; Swenson et al., 1999) which requires a large time commitment (Harnish et al., 2001). Consequently, researchers have investigated alternative methods of estimating the maximal lactate steady state using single-visit protocols (Harnish et al., 2001; Laplaud et al., 2006; Swenson et al., 1999). The study of Harnish et al (2002) is most relevant, because of its specificity to cycling. The authors investigated the validity of lab-based 5- and 40-km time-trials to predict the maximal lactate steady state. In addition to the time-trials, subjects completed a series of 30 min submaximal trials to establish maximal lactate steady state. Maximal lactate steady state was $92.1 \pm 1.2\%$ of the average speed of the 5-km time-trial and $99.6 \pm 1.1\%$ of the 40-km time-trial. These findings suggest that the average speed associated with a lab-based 40-km time-trial may be a good estimate of actual maximal lactate steady state in cyclists.

In summary, a variety of terms exist for lactate accumulation kinetics during exercise and the merits of the measure itself are uncertain in some investigators opinions (Gladden, 2004; Philp et al., 2005). A large body of research into blood and ventilatory threshold measures suggests that while there is no exact measure for lactate anaerobic threshold (W. G. Hopkins et al., 2001) the long-established measure of 4 mmol/L is more reliable and sensitive to change than that of ventilatory measures (W. G. Hopkins et al., 2001; Jacobs, 1986). With recent interest in single visit, non-invasive testing authors suggest that a 40 km time trial is a suitable predictor of maximal steady state in cyclists (Harnish et al., 2001).

Cycling Efficiency/Economy

Efficiency of movement refers to the ability to convert metabolic energy into mechanical work (McArdle, Katch, & Katch, 1996). Metabolic energy is estimated from oxygen consumption and respiratory exchange ratio (which indicates the proportion of fat and carbohydrate oxidized), and efficiency is the mechanical work (measured on an ergometer) expressed as a percent of the metabolic energy (Bijker, de Groot, & Hollander, 2001). A measure of efficiency can also be defined by the ratio of mechanical work to oxygen consumption and is known as exercise economy (E. W. Faria, Parker, & Faria, 2005a). For cycling, economy can be expressed as the watts produced per litre of oxygen consumed per minute (Coyle, 2005). Alternatively, efficiency and economy can be expressed as 'gross' or 'delta'. Gross efficiency (GE) is defined as the ratio of power output to power input (Horowitz, Sidosis, & Coyle, 1994). Delta efficiency (DE) is the increase in power output per increase in energy expenditure (Coyle, Sidosis, Horowitz, & Beltz, 1992) and therefore does not include resting metabolism in the equation (Moseley & Jeukendrup, 2001).

Improvement in economy can be a major factor in the success of endurance athletes, as exemplified by the seven time winner of the Tour de France, Lance Armstrong. In a recent case study, Coyle (2005) documented an 8% increase in efficiency for this athlete, after weight loss was taken into account. While the mechanisms for improvement of economy are yet to fully understood and require further research (Jones & Carter, 2000), extensive years of high volume endurance training (Coyle, 2005; Jones, 1997) and improved neuromuscular function (Jung, 2003; Paavolainen, Hakkinen, Hamalainen, Nummela, & Rusko, 1999) are thought to be responsible.

Anaerobic Capacity

Anaerobic capacity refers to the ability to perform work without a substantial contribution from aerobic metabolism (Green & Dawson, 1993). Moderate to high dependence on the anaerobic system is not limited to sprint events, because anaerobic mechanisms are used intermittently throughout short- to moderate-distance road-based events (Vogt et al., 2006). Track-based cycling events of less than one minute rely predominantly on the anaerobic system (Jeukendrup et al., 2000) particularly in the 'all out effort' for maximal power output at the start of the race (Craig & Norton, 2001). To measure these high intensity powers several tests have been developed (Finn, Gastin, Withers, & Green, 2000). While there is no gold standard measure for anaerobic capacity (Finn et al., 2000) the Wingate anaerobic test (Inbar et al., 1996) and the maximal accumulated oxygen deficit test (Medbo et al., 1988) are two cycling-specific tests are used for assessment.

The Wingate anaerobic test is accepted as a reliable and valid method to measure anaerobic power (Inbar et al., 1996). A multitude of values has been reported for athletic and non-athletic populations (Gastin, Costill, Lawson, Krzeminski, & McConell, 1995). An all out 30-s Wingate test is reported to have contributions of aerobic, phosphocreatine and glycolytic energy of 16%, 28% and 56% respectively. The contribution from the aerobic system is not trivial as it reacts quickly to energy demand and VO_2 measures reaching 90% of VO_{2max} during this 30 s all-out test (J. C. Smith & Hill, 1991). Competitive cyclists are advised to take note of the relative energy contributions across this 30-s bout in preparation for a final sprint for the line (E. W. Faria et al., 2005b). Traditional Wingate tests for cyclists have used 8.5% of the cyclist's mass as the resistance with a flying start. A comparison between untrained subjects at loads of 6.5%, 7.5%, 9.5% and 11.5% of subject's body mass demonstrated that peak and mean power output for a 30 s Wingate test

was optimal at 7.5% of subjects body weight (Kerner & Kurrant, 2004). Davies et al (1989) compared anthropometric variables and power indices in track sprinters, pursuit riders and a student population using an 80 s all out test. Maximal average power output was highest in sprint cyclists (1241 ± 266 W) followed by pursuit cyclists (962 ± 206 W) and students (1019 ± 183 W). There was a significant difference in maximal average power output between sprint vs pursuit cyclists and sprint cyclists vs students. Sprint cyclists also recorded both the highest cadence and anaerobic capacity. Maximal average power output and anaerobic capacity were also influenced by subjects' body size and muscularity.

The maximal accumulated oxygen deficit test is used commonly as a measure of anaerobic capacity (Spencer & Gastin, 2001; Weber & Schneider, 2001, 2002) and is the difference between the oxygen equivalent of the work performed and the oxygen consumed during an anaerobic capacity test (Bangsbo, 1996). The maximal accumulated oxygen deficit assumes that the mechanical efficiency of supra-maximal work is the same as sub-maximal work (Finn et al., 2000). In an attempt to establish the reliability and validity of the maximal accumulated oxygen deficit at various intensities of $VO_2\text{max}$, Gastin et al (1995) conducted a comparative study with semi-trained subjects. The study included $VO_2\text{max}$ measurements, 90 s all-out exhaustive cycling, constant work tests at 110% and 125% of $VO_2\text{max}$, and muscle biopsy of the vastus lateralis. Exercise intensity and anaerobic energy usage in the first 30 s were greatest in the all-out 90 s test than in the 125% and 110% tests. Peak blood lactate was greatest in the 90 s all-out exhaustive test. The authors suggested that due to the high lactate concentrations and the strong correlation between exercise intensity and anaerobic energy release in the first 30 s, the 90-s all-out test provided a better assessment of anaerobic ability. Craig et al (1993) reported on the

relationship between maximal accumulated oxygen deficit, VO_2max and lactate threshold in 18 high-performance endurance and sprint cyclists. Post performance blood lactates and the other variables measured were compared to 4000 m individual pursuit performance. The highest correlations existed between 4000 m pursuit time and VO_2max ($r=-0.79$), power output at lactate threshold ($r=-0.79$), half time of VO_2 response while cycling at 115% of VO_2max ($r=0.48$) and maximal accumulated oxygen deficit over 5 min ($r=-0.50$). Given the energetic demands of track sprinting (Jeukendrup et al., 2000) the need for a substantial anaerobic and aerobic capacity is obvious (Craig et al., 1993); hence the need for a test that simulates the requirements of the event itself (Paton & Hopkins, 2001).

A two-part study involving cyclists training at sub- and supra-maximal levels demonstrated that maximal accumulated oxygen deficit did not change with 6 wk of sub-maximal training at 5 sessions/wk but supra-maximal training at 7 to 8 sets of 20-s bouts at $\sim 170\%$ VO_2max enhanced anaerobic capacity by 28% (Tabata et al., 1996). In a second study using high intensity exercise, untrained subjects trained 3 d/wk for 8 wks. The initial week of training consisted of 3 x 2 min constant load cycling bouts at 82.5% of VO_2max with a 6 min rest between sets. Training intensity increased by 2.5% on a weekly basis so that by the final week of training the subject rode at 100% of pre-training VO_2max . Maximal accumulated oxygen deficit measures at mid- and post-intervention revealed increases in anaerobic capacity for both males ($14.3 \pm 5.2\%$) and ($6.6 \pm 1.9\%$) and females ($14.3 \pm 3.0\%$) and ($5.1 \pm 2.3\%$) respectively (Weber & Schneider, 2002). These between gender values were not significantly different. The results suggest that maximal accumulated oxygen deficit is sensitive to enhancements in anaerobic capacity as a result of short-term high intensity training in both male and female subjects.

Given the paucity of data available on elite or semi-elite cyclists, it is difficult to estimate the ability of the Wingate anaerobic test or maximal accumulated oxygen deficit to measure anaerobic capacity (Bangsbo, 1996). Clear testing methodologies for testing athletes (E. W. Faria et al., 2005b) and further research into the area is required (Bangsbo, 1996). The length of the maximal accumulated oxygen deficit should be ~2 min as this is the length of time required to exhaust the anaerobic system (Medbo, 1996). Researchers consider that the maximal accumulated oxygen deficit is currently the most accurate measure of anaerobic capacity due to the test's ability to isolate performance to purely anaerobic mechanisms (Finn et al., 2000; Medbo, 1996). Conversely Graham (1996) suggested that the role of maximal accumulated oxygen deficit in assessment of anaerobic capacity is still in question. The maximal accumulated oxygen deficit test was one of three measures considered necessary in evaluating 4000-m individual pursuit cyclists (Craig et al., 1993). Maximal accumulated oxygen deficit has been shown to be sensitive in measuring anaerobic capacity changes as a result of interval training programs that were prescribed at intensities above (Weber & Schneider, 2002) and below $-VO_{2max}$ (Tabata et al., 1996). However, data provided by Gustin (1995) suggested that a 90-s maximal test gives a better indication of anaerobic capacity than maximal accumulated oxygen deficit at either 110% or 120% of VO_{2max} , due to a strong association between Wingate and anaerobic variables such as peak blood lactate and anaerobic energy output. Similar findings were reported using an 80-s all out test, where maximal mean power output and anaerobic capacity were highest in sprint cyclists (Davies & Sandstrom, 1989). A maximal all-out effort is important in sprint-based track events, where anaerobic systems contribute substantially to performance outcome (Craig & Norton, 2001; Jeukendrup et al., 2000); however, longer track events of >1000 m place a greater reliance on strategy than all-out pacing (Jeukendrup et al., 2000). These findings suggest maximal accumulated oxygen

deficit may be a more sensitive measure where longer distances and greater reliance on the aerobic system is evident, whereas the 30-s Wingate test is more appropriate where an all-out effort is required.

Summary

Of great interest to sport scientists is identifying a lab-based test that accurately predicts performance (S. R. Hopkins & McKenzie, 1994; Lucia, 2004; Paton & Hopkins, 2001; Tan & Aziz, 2005). Researchers of cycling performance have a range of physiological tests to choose from for identification of thresholds, peak power and $VO_2\text{max}$ (W. G. Hopkins et al., 2001; Paton & Hopkins, 2001). The outcome of cycling performance is influenced by a range of physiological demands, differing energy requirements, environmental conditions, aerodynamic factors of bike and rider, type of terrain, road surface and race tactics (E. W. Faria et al., 2005a; S. R. Hopkins & McKenzie, 1994). Elite road cyclists display superior measures of $VO_2\text{max}$, an ability to ride at higher percentages of anaerobic threshold for longer and greater anaerobic power than non-elite cyclists. $VO_2\text{max}$, per se, may not be a sensitive enough measure to track improvement in fitness especially in elite cyclists but should be regarded as necessary in monitoring physiological status in developing athletes. Research into blood and ventilatory threshold measures suggest that the long-established measure of 4-mM is more reliable and sensitive to change than that of ventilatory measures. Exercise economy appears to improve with training over many years and enhancement of this measure is pivotal in improving performance. Measures such as average peak power in all-out tests of 80 to 90 s are representative of all out strategy as used by sprint cyclist in distances of 1000 m or less. The maximum accumulated oxygen deficit test, or variations of it, may be more representative of anaerobic capacity in supra-

maximal events such as the 4000 m individual pursuit, where anaerobic processes play a key role.

Tests chosen to evaluate performance should have high reliability (W. G. Hopkins et al., 2001) and closely replicate competitive performance and test performance (Paton & Hopkins, 2001). These factors are best served through the use of mobile power ergometers which enable field based testing of athletes and provide reliable, specific feedback on training and performance measures (Gardner et al., 2004; Paton & Hopkins, 2001) partly due to the fact that athletes are able to use their own bike during testing (W. G. Hopkins et al., 2001). Competitive cyclists should be assessed using constant work protocols i.e. time-trials, ideally utilising a mobile power ergometer within an indoor velodrome to minimise variables (Paton & Hopkins, 2001; Schabort, Hawley, Hopkins, Mujika, & Noakes, 1998).

CHAPTER ONE – PART B

Training Methods to Improve Physiological Measures and

Cycling Performance – A Review

Abstract

Coaches of endurance athletes incorporate phases of endurance, interval and resistance training into periodized training plans aimed at developing the athlete towards targeted performance goals. Endurance training, defined as activity of at least 20-min duration in which the heart rate is elevated to 60 – 80% of maximum heart rate causes changes in peripheral and central systems thus improving aerobic function. Interval training is considered important for enhancements of anaerobic capacity especially where “all-out” sprint efforts are required. Interval training is characterized by “supra-maximal” intensities of short time durations and extensive rest periods, thus enabling peripheral adaptation in sport-specific muscles. This type of training is used when recovery from repeated sprint efforts is critical to success or when an athlete’s performance is limited by a reduced anaerobic threshold. Manipulation of work, rest, intensity, reps and sets are factored into interval training to maximise training effects and enhance both the central and peripheral systems of an athlete. Resistance training has been used to improve force production and improve neuromuscular capabilities in endurance athletes. While there has been much debate over the use of resistance training, explosive sport-specific movements and high-intensity interval training appear to have a positive influence on performance in endurance athletes. Technological innovations such as mobile power ergometers provide accurate feedback of actual power output thus enabling coaches, researchers and sport scientists to monitor training and performance of athlete with greater accuracy. Similarly, training techniques will become more refined as coaches, sport scientists and researchers investigate different methods of enhancing performance.

Introduction

Pate (1992) has suggested that the reason for continued improvement in world endurance records since the 1960's is predominantly due to improved athlete genetics and refined training practices. Training has been defined as the systematic and regular participation in exercise to enhance sports performance (Billat, 2001a). Use of lactate (Jacobs, 1986; Pyne et al., 2001; Thompson et al., 2006) and heart rate (Lucia et al., 2000) profiles to provide athletes with specific training zones has enabled regular self-monitoring and greater accuracy of prescribed workloads (Achten & Jeukendrup, 2003). Likewise, the use of mobile power ergometers, such as Power Taps and SRM Power Cranks have allowed a greater application of scientific principles to training and competition (E. W. Faria et al., 2005b; Gardner et al., 2004; Hill & Rowell, 1997; Schumacher & Mueller, 2002). This has enabled specific and almost instant feedback to coaches and athletes (Vogt et al., 2006). Also, athletes can continually improve athletic performance when modelling training targets on key event times (Basset et al., 1999; Ennis, 1985; Jeukendrup & Martin, 2001; Vogt et al., 2006).

Optimising physical training to increase cycling performance or to enhance physiological measures that are important to endurance performance i.e $VO_2\text{max}$ (Hoogeveen, 2000), lactate threshold, exercise economy and oxygen kinetics (Grassi, 2000; Kawaguchi, Tabusandani, Sekikawa, Hayashi, & Onari, 2001) is the primary focus of coaches, sport scientists and researchers alike. Endurance training, defined as activity of at least 20-min duration in which the heart rate is elevated to 60 – 80% of heart rate maximum (Carter, Bannister, & Blaberm, 2003), causes both central and peripheral physiological adaptations to occur. More specifically, changes in the pulmonary (Wilmore et al., 1980), cardiovascular (Blomqvist & Saltin, 1983) and neuromuscular (Carter et al., 2003; Jones &

Carter, 2000) systems interact to enhance the delivery of oxygen from the atmosphere to the mitochondria and increase metabolic control within the cell (Astrand & Rodahl, 1986). The literature suggests that aerobic endurance markers such as VO_2max (Fox et al., 1975), capillary density (Andersen & Henriksson, 1977), oxidative enzyme activity (Ingjer, 1979), and blood plasma volume (Convertino, 1991) are all substantially enhanced after sub-maximal training in moderately active athletes (Jones & Carter, 2000). The expected magnitude of change in these measures after training appears to be reduced, especially for athletes at the elite level (Weston et al., 1997). With regards to elite road cyclists, the reduced expected change in measures could be attributable to the all year round extensive competing and training volume of up to 35,000 km per year (Lucia, Hoyos, Santalla, Earnest, & Chicharro, 2003; Mujika & Padilla, 2001).

Variety of Approaches

Given the diverse nature of cycle racing (Jeukendrup et al., 2000), endurance training strategies for cycling includes a diversified training regime where manipulation of volume, duration and intensity is evident (Pate & Branch, 1992). For example, at the elite level, track sprints of <1000 m in length are typically completed between 10.1 s and 65 s for 200 m and 1000 m events respectively (Craig & Norton, 2001; Jeukendrup et al., 2000). An event of this duration requires a high anaerobic capacity for success (Jeukendrup et al., 2000). A training approach for this duration would be to include very high ‘event-specific’ intensity intervals of short duration to develop the anaerobic capacity and optimal recruitment of Type IIb fibres. Conversely, a 40-km time trial of ~60 min duration requires a large aerobic capacity due to the aerobic contribution of ~95% (Jeukendrup et al., 2000). Much longer ‘sustained’ intervals would be necessary to invoke the required cardiovascular

and metabolic adaptations for optimal performance in this event (Laursen & Jenkins, 2002). Clearly, some of the training approaches will differ.

Despite the spectrum of competitive cycling events (from the shortest track sprint of 200 m to the longest road tour cyclists (4000 km or greater) most cyclists regardless of competitive distance will train over long distances (Schumacher & Mueller, 2002). Sprint cyclists typically compete in wide variety of multiple day races in preparation for short duration events. A documented example of this approach is provided by Atkinson et al, (2003) who reported that a track cyclist competed in a major 3 wk tour of ~ 4000 km as preparation for a World Championship track based event of 4000 m lasting ~ 4min (Atkinson et al., 2003). Similarly, the German 4000 m pursuit team who achieved a world record at the 2000 Sydney Olympics are reported to have ridden between 29,000 and 35,000 km in a calendar year preparing for the competition which lasted fractionally over 4 min (Schumacher & Mueller, 2002). These studies suggest that even cycling events that are short in nature (~4 min) may still require a high volume of endurance training for success.

Interval training is utilised in sports when a mixture of anaerobic and aerobic mechanisms contribute to performance (Billat, 2001a, 2001b; Daniels & Scardina, 1984). Interval training is thought to be of most benefit when training volume is no longer sufficient to cause necessary adaptations (E. W. Faria et al., 2005b) by way of adaptations in skeletal muscle (Billat, Flechet, Petit, Muriaux, & Koralsztien, 1999; T. P. Smith, McNaughton, & Marshall, 1999) and an increase in exercise economy (Hickson, Heusner, & van Huss, 1975; Weston et al., 1997).

A variety of training methods including continuous distance training (Barbeau et al., 1993; Lucia et al., 2000), interval training (Esbjornsson, Hellsten-Westing, Balsom, Sjodin, & Jansson, 1993; Fox et al., 1975; Lindsay et al., 1996), strength training (Hickson, Dvorak, Gorostiaga, Kurowski, & Foster, 1998; Hickson, Rosenkoetter, & Brown, 1980) and plyometric training (Bastiaans, van Dieman, Veneberg, & Jukendrup, 2001; Paton & Hopkins, 2005) are all used in to enhance endurance cycling performance. The magnitude of cardiovascular (Wenger & Bell, 1986) and biochemical (Hickson, Hagberg, Ehsani, & Holloszy, 1981) adaptations to endurance training is influenced by several factors including: training volume i.e frequency (Hickson et al., 1981) and duration (Fox, Bartels, Klinzing, & Ragg, 1977; Hickson et al., 1975), intensity (Harms & Hickson, 1983), the length of the training program and the subjects initial state of fitness (Wenger & Bell, 1986). Typically, training studies have used sedentary or only moderately-trained endurance athletes with minimal studies conducted using elite level performers (Laursen & Jenkins, 2002). Only a few training studies exist which report relevant findings in subjects that can be considered elite-level performers (Lindsay et al., 1996; Weston et al., 1997). The following section identifies the various central and peripheral adaptations following the variety of training methods outlined above.

Volume of Training – Physiological Purpose

Continuous, sub-maximal training results in central (Fox et al., 1975; Giada et al., 1998) and peripheral (Andersen & Henriksson, 1977; Fox et al., 1975; Holloszy, 2004; Weston et al., 1997) adaptations which interact to improve the delivery, diffusion and utilisation of oxygen to the exercising muscle (Holloszy & Coyle, 1984). These adaptations and the mechanisms that cause them have been extensively studied in both non-athletic

(Wasserman, van Kessel, & Burton, 1966; Whipp et al., 1981; Wilmore et al., 1980) and athletic populations (Costill, Fink, & Pollock, 1976; Coyle et al., 1992).

Central Adaptations to Volume/Long Distance Cycle Training

Specifically, central adaptations result from an improvement in the heart's ability to pump blood, mainly by increasing the stroke volume which occurs because of an increase in end-diastolic volume and an increase in left ventricular mass (Astrand & Rodahl, 1986). These changes are induced by the increased volume and load placed on the heart during endurance exercise being stressful enough for adaptation to occur (Astrand & Rodahl, 1986). Subsequently, these adaptations result in an increased Q_{max} , which, according to the Fick equation, will increase VO_{2max} (Laffite, Mille-Hamard, Koralsztien, & Billat, 2003). Under intense exercise maximum cardiac output is limited by heart rate and stroke volume (Sutton, 1992).

The central adaptations that occur as a result of large volumes of training have been well-documented (Fox et al., 1977; Hickson et al., 1981; Hoogeveen, 2000; Jones, 1997; Wilmore et al., 1980). Increases in training volume have been shown to reduce body mass (Hoogsteen, Hoogeveen, Schaffers, Wijn, & van der Wall, 2003), increase aerobic power (Blomqvist & Saltin, 1983; Hickson, Bomze, & Holloszy, 1978; Hoogeveen, 2000), enhance the cardiovascular system (stroke volume and cardiac output) (Hoogsteen et al., 2003), and decreased event performance time (Jones, 1997). Missault et al (1993) compared the cardiac anatomy and left ventricular filling rates of elite cyclists to that of a non-athletic (control) population. The cyclists had at least 5 yr extensive endurance training (600 – 800 km.wk) in comparison to the control groups >1 hr.wk of activity. At rest, relative to the control group, elite cyclists displayed a lower heart rate ($73 \pm 9.4 \text{ b}\cdot\text{min}^{-1}$

¹ v $52 \pm 8.2 \text{ b}\cdot\text{min}^{-1}$), greater left atrial dimensions ($37 \pm 5 \text{ mm}$ v $41 \pm 5 \text{ mm}$). In a two-part study into effects of training and detraining Giada et al (1998) measured cyclists cardiac dimensions and classified subjects into a “young” age range (19 – 25 yr) and an “older” age range (50 – 65 yr). The groups were matched against two similarly age-, mass- and height-matched sedentary control groups. The younger subjects had ridden competitively for ~9 yr and the older subjects ~21 yr. Both groups of athletes displayed lower heart rates and less body fat mass relative to their control group counterparts. Measures of heart dimensions showed that older cyclists had the largest left ventricular dimensions and younger subjects showed greater hypertrophy of the left ventricular wall.

The effects of detraining were measured after a 2-month period of detraining (Giada et al., 1998). Younger cyclists had a reduction in thickness of the left ventricular wall in the order of 9% and older cyclists showed reduced ventricular dimensions of 20%. During this time reductions in incremental peak power in the older group (10%) and younger group (4%) were seen. Relative VO_2max was also reduced by ~20% in both cycling groups. Coyle et al (1986) studied the effects of detraining in previously trained subjects and found that to compensate for a decrease in blood volume, stroke volume increased in order to maintain cardiac output at the same level of exercise prior to the detraining intervention.

Hoogsteen (2003) reported that atrial dimensions of 35 professional cyclists were 22% larger than well-trained amateur counterparts. Despite the limited training volume, the well-trained group showed signs of hypertrophy in left ventricular and left atrial dimensions suggesting that initial changes happen quickly. The authors state the difference in groups was probably due to the extensive training background of the professional cyclists. It is thought that elite cyclists benefit predominantly from peripheral adaptations in working

musculature as opposed to central adaptations (E. W. Faria et al., 2005b) and that these changes in elite cyclists can only be induced through high intensity training (Laursen & Jenkins, 2002).

Prolonged, high-volume, moderate intensity training results in central adaptations which include cardiovascular alterations to the thickness of the left ventricular wall allowing a greater flow of blood to the working muscles (Giada et al., 1998 ; Missault et al., 1993), changes in blood plasma mass (Convertino, 1991), increase in time to fatigue at sub-maximal exercise (work capacity) and greater oxygen uptake (Blomqvist & Saltin, 1983), a lowered resting and sub-maximal heart rate (Carter et al., 2003; Missault et al., 1993). Effects of detraining cause reductions in cardiac anatomy, increased adipose tissue (Giada et al., 1998) a reduction in blood volume and an increase in stroke volume (Coyle et al., 1986). The combinations of these factors reduce peak incremental power and relative VO_2max (Giada et al., 1998).

Peripheral Adaptations to Distance Cycle Training

It is well-established that high volumes of endurance training result in major adaptations in skeletal muscle (Holloszy, 1975; Matoba & Gollnick, 1984; Taylor & Bachman, 1999). Such changes include: 1) increased myoglobin (Hickson et al., 1981); 2) increased mitochondrial size and number (Harms & Hickson, 1983; Kiessling, Piehl, & Lundquist, 1971); 3) increased oxidative enzyme activity (Gollnick et al., 1973); 4) altered muscle fibre composition (Henriksson & Rietman, 1977); and 5) preferential use of free fatty acids as an energy substrate (Holloszy & Coyle, 1984). These peripheral adaptations may be of limited importance for whole-body VO_2max , since maximum oxidative power (defined as the maximum rate of oxidative phosphorylation in muscle) is in excess of what is required

during two-legged exercise (Andersen & Saltin, 1985). It is likely that an increase in muscle aerobic potential plays a major role in the increased endurance and the reduced metabolic perturbation observed after aerobic training (Saltin & Gollnick, 1983).

Longitudinal studies have shown that the increased oxidative potential of a muscle, by augmentation of mitochondrial enzyme activity (Harms & Hickson, 1983; Holloszy, 1967), increase in capillary proliferation and density (Andersen & Henriksson, 1977; Soares, 1992) and enhancement of free fatty acid oxidation (Holloszy, 1975; Matoba & Gollnick, 1984; Taylor & Bachman, 1999) is localised in the fibres most active in the training programme, and can occur in both type I and type II fibres (Henriksson & Rietman, 1977). In order to maximise these changes, amateur cyclists would ride ~25,000 km each year (Atkinson et al., 2003), and elite professional cyclists have been reported to ride between 25,000 to 35,000 km each year (training and competition) (Lucia et al., 2003; Mujika & Padilla, 2001). In most instances, a large proportion of this volume is performed at moderate intensity (below the lactate threshold) and therefore adaptations are likely to occur predominantly in the Type I fibres.

The mitochondrial density and activity of type I (slow twitch) fibres in endurance trained athletes is elevated (Howald, Hoppeler, Claassen, Mathieu, & Straub, 1985) which is suggested to benefit oxidative energy production (Holloszy, 1975; Taylor & Bachman, 1999). The magnitude of change in mitochondrial enzyme concentration in skeletal muscle after training varies between >100% (Gollnick & Saltin, 1982; Holloszy, 1975) to none at all (Holloszy, 1975). Other peripheral adaptations due to endurance training are increases in myoglobin content, intra-muscular content and lipoprotein lipase activity (Taylor & Bachman, 1999). A decrease in the use of carbohydrate as a fuel source (i.e greater use of

fat during sub-maximal exercise) and hence less depletion of glycogen is also seen following a period of endurance training (Holloszy, 1975; Taylor & Bachman, 1999). Many of these adaptations are regulated by changes in specific enzyme activity (Holloszy, 1975). Typically, while carbohydrate intake can make up 60 to 70% or 8 to 10g/kg of an endurance athletes daily intake (Costill & Hargreaves, 1992) adaptations caused from long duration training suggest that fat utilisation is enhanced enabling the sparing of carbohydrate as a fuel source for energy (Holloszy, 1975; Matoba & Gollnick, 1984; Taylor & Bachman, 1999). Elite cyclists are said to benefit predominantly from peripheral adaptations in working musculature as opposed to central adaptations (E. W. Faria et al., 2005b) and that these changes such as these in elite cyclists can only be induced through high intensity training (Laursen & Jenkins, 2002).

Fibre Type

The structured periods of endurance or base training that cause aerobic adaptation, and increase stamina enable greater recovery from intense bouts of training (I. E. Faria, 1984). This type of training causes changes in working musculature towards expression of slow-twitch properties (Holloszy, 1975). Fibre types have been classified as type I (slow twitch) and type IIa and IIb (fast twitch) (Taylor & Bachman, 1999) and while further sub-types exist for this nomenclature for the purposes of this review the three aforementioned fibre type classifications will be used. Fibre type alterations resulting from endurance training studies show that non-athletic populations are able to positively alter the percentage of type I fibres by 12% and reduce the percentage of type II fibres by 24% (Howald et al., 1985). Type I fibres demonstrate greater utilization of aerobic metabolic pathways, broader capillarization networks, larger mitochondria concentration and distinctly different substrate utilization (Taylor & Bachman, 1999) and are most common in endurance trained

athletes (Costill et al., 1976; Gollnick, Armstrong, Saubert IV, & Saltin, 1972). Gollnick et al (1973) studied the effects of 5-months of moderate intensity cycling on non-endurance trained subjects. Following the training intervention subjects displayed an increase in the size of type I fibres as well as the relative area that these fibres occupy within the muscle. This enhancement occurred without a reduction in type II fibre types. Conversely, a 24 wk endurance training study on active females showed no significant change in type I fibres and a 37% reduction in type IIb fibres (Ingjer, 1979). In an evaluation of fibre types in recreational, endurance trained and strength trained athletes Tesch (1985) found that the percentage of type I fibres in the vastus lateralis muscle of runners was greatest among all groups of athletes. The authors determined that long-term training is the cause of these adaptations.

Coyle (1992) suggests that concentration of type I fibres influences cycling economy and gross efficiency, however; it is also thought that successful competitive road cycling is not dependant on the total percentage of type I or type IIa fibres (Burke et al., 1977). Cyclists riding at 80 min^{-1} demonstrated a positive relationship ($r=0.75$) between cycling efficiency and type I fibres, suggesting that a cadence of 80 min^{-1} is closely related to the peak efficiency of type I fibres (Coyle et al., 1992). This agrees with the findings of Bosco et al (1980) who stated that the cadence and load of any test of economy should be related to the optimum rate of movement of the muscle fibre. The effects of prolonged cycling at an intensity of 65% VO_2max at self-selected cadences, have shown that cyclists cadence decreases from 87 to 69 rpm representing a 21% decrease (Lepers, Hausswirth, Maffiuletti, Brisswalter, & van Hoecke, 2000). The authors suggest that type II fibres were increasingly recruited over the type I fibres possibly due to the decrease in cycling cadence. The implications for muscular performance are an increase in lactate production, increased

metabolic damage to the muscle and shorter time to fatigue resulting in lowered cycling economy (Leperc et al., 2000; Woolford et al., 1999).

Collectively, peripheral and central adaptations brought about by a high volume of training have a positive effect on increasing VO_{2max} (Astrand & Rodahl, 1986), economy and lactate threshold (Knehr, Dill, & Neufeld, 1942). Together, these aerobic measures largely determine the performance potential of a cyclist. Metabolic changes in skeletal muscle are well documented, the question of whether endurance training can bring about similar substantial changes in fibre composition remains unknown (Taylor & Bachman, 1999).

Intervals/Tempo/Threshold - Physiological Purpose

In addition to continuous (high volume) training, the majority of competitive endurance athletes include some form of high-intensity interval training into their training plan (Hawley, Myburgh, Noakes, & Dennis, 1997; Paton & Hopkins, 2005). This form of training is commonly used to overload the training stimulus by using maximal or supra-maximal sport specific activity to induce a training response (Laursen, Blanchard et al., 2002; Lindsay et al., 1996; Paton & Hopkins, 2005). A variety of definitions exist for interval training. According to Daniels and Scardina (1984), interval training involves repeated bouts of exercise at 95 to 100% of VO_{2max} , lasting between 30 s to 5 min, with rest periods the same length or slightly shorter than the work period (Daniels & Scardina, 1984). When defining interval training, albeit for runners, Billat (2001a) stated that interval training is repeated short to long bouts of high-intensity exercise (equal or superior to the maximal lactate steady-state velocity) interspersed with recovery periods of light exercise or rest. Similarly, high intensity training has been defined as repeated bouts of short-to- moderate duration exercise lasting between 10 s and 5 min completed at an

intensity that is greater than anaerobic threshold with the rest period allowing for a small amount of recovery prior to the next repetition beginning (Laursen & Jenkins, 2002). Regardless of slight differences in definition, the purpose of high intensity training is to repeatedly stress the physiological systems that will be used during a specific endurance type exercise (Daniels & Scardina, 1984).

Peripheral Adaptations to Interval Training

Adaptations following training are dependant on the intensity, duration and frequency of the training bout (Laursen & Jenkins, 2002). Training at intensities above VO_{2max} has been shown to increase both glycolytic and oxidative enzymes (MacDougal et al., 1998). Researchers' attention on the effects of high-intensity interval training has focused on the response of phosphocreatine, the anaerobic enzyme adenosine triphosphatase and mitochondrial enzymes such as succinate dehydrogenase, citrate dehydrogenase and malate dehydrogenase as well as glycolytic enzymes such as hexokinase and phosphofructokinase to maximal intensity exercise (Bogdanis, Nevill, Boobis, Lakomy, & Nevill, 1995; Burgomaster, Heigenhauser, & Gibala, 2006; Gaitanos, Williams, Boobis, & Brooks, 1993; MacDougal et al., 1998). In maximal intensity cycling where maximal power-output is reached within 6 s, phosphocreatine and anaerobic glycolysis provide similar contributions to the energy requirement to achieve peak power (Gaitanos et al., 1993; McCartney et al., 1986). A maximal bout of 10 s will exhaust phosphocreatine availability (McCartney et al., 1986), with the subsequent resynthesis of phosphocreatine and removal of by-products dependant on duration of the rest period (Bogdanis et al., 1995). Resting periods of 4 min following 30 s maximal intensity bouts of cycling found that ATP and phosphocreatine recovered to close to resting levels (McCartney et al., 1986).

The majority of studies using high-intensity training have shown enhancement in both glycolytic and mitochondrial enzyme activity (Burgomaster et al., 2006; MacDougall et al., 1998) although others have reported no change in the measures (Weston et al., 1997). A study on recreational athletes by MacDougall et al (1998) using intensive 30-sec on a cycle ergometer demonstrated increases in oxidative mitochondrial and glycolytic enzyme activity. The protocol of the study can be seen in Table 5. Following the seven wk training bout of sprint training the glycolytic enzymes phosphofructokinase and hexokinase was 49% and 56% higher than prior to training. Oxidative enzymes malate dehydrogenase, succinate dehydrogenase and the mitochondrial enzyme citrate synthase increased by 29%, 65% and 36% respectively. Similar sprint duration, intensities, subjects and mode of training was used in a recent study by Burgomaster et al (2006). An 11% increase in citrate synthase activity was found following the six training sessions along with enhancements in peak and mean power in 30-s sprint (5.4% and 8.7% respectively) and time-trial performance (9.6%). A study utilising well-trained cyclists (average $\text{VO}_2\text{max} \sim 66 \text{ ml.kg.min}^{-1}$) by Weston et al (1997) reported no change in either phosphofructokinase or citrate synthase, conversely peak incremental power (3%), 40 km time-trial time (2%) and time to fatigue at 150% peak incremental power (21%) all showed a positive change following the intervention. These changes were related to an increase in muscle buffering capacity of the cyclists. The training protocol, which can be seen in Table 3, was performed at the lower intensity of 80% incremental peak power and is substantially lower than the sprint protocols of either MacDougall et al (1998) or Burgomaster et al (2006). Weston et al (1997) also used experienced cyclists as opposed to a recreationally trained population. It is apparent that intensity of training influences alterations in enzyme activity. It is unclear whether higher training intensities will cause changes in the enzyme activity of experienced cyclists as large as those seen in recreational subject groups.

A high percentage of type I fibres is found in endurance athletes with an extensive training background (Gollnick et al., 1972). These fibres contain significant amounts of mitochondria with large respiratory capacities (Holloszy & Coyle, 1984) recruited under low to moderate loads (Lucia, Hoyos, & Chicharro, 2001b) thus enhancing their aerobic capabilities (Gollnick et al., 1972) and efficiency (Coyle et al., 1992). In contrast, type II fibres typically display a lower mitochondrial number (Tesch & Karlsson, 1985) and are only recruited in periods of high-intensity activity (Holloszy & Coyle, 1984). A comparative study by Jansson et al (1977) on orienteer's and 16 – 18 yr old males concluded type II fibres have the metabolic ability to adapt to high oxidative demands as a result of higher intensity work-rates. This is assisted by a conversion from IIB to IIA fibre type expression. Alterations in fibre composition are evident in repeated bouts of high-intensity interval training (Esbjornsson et al., 1993). It was found that three-weekly maximal-intensity cycling sessions of 15 reps at 10 s duration decrease the proportion of type I fibres and increase type IIa. When high-intensity interval training increased to 2 daily sessions every day over 7 days, the proportion of type I fibres increased and type IIa decreased. Alleimeier (1994) reported that a two, or three-weekly maximal-intensity cycling protocol of 3 reps of 30-s sprint bouts with 20 s rest between bouts did not alter fibre distribution but did alter myosin chain expression in type IIb towards that of IIA fibres. The authors concluded that these findings support the changes in type II fibres in response to sprint training. Therefore, it would appear that the degree to which type II fibres alter is largely dependant on the intensity and volume of high-intensity training.

Maximal and Supra-Maximal Intensity Training Studies

Investigators of high intensity interval training have used moderate (Stepsto, Hawley, Dennis, & Hopkins, 1999), maximal (Westgarth-Taylor et al., 1997; Weston et al., 1997)

and supra-maximal (Creer, Ricard, Conlee, Hoyt, & Parcell, 2004; Laursen, Blanchard et al., 2002; Laursen, Shing, Peake, Coombes, & Jenkins, 2002) intensities as a basis for training. Creer et al (2004) investigated the effects of four wk of supra-maximal sprint training on neural, metabolic and performance adaptations in trained cyclists with at least 2 yr cycling experience divided into two groups. Post intervention increases of 6% and 4% for peak aerobic power and 6% and 3% in mean power of 4 x 30 s Wingate sprints were recorded for the sprint and control groups respectively.

Several authors have reported enhancement in 40-km time-trial performance high intensity interval training (Hawley et al., 1997; Laursen, Shing et al., 2002; Stepto et al., 1999). Perhaps the most comprehensive study was conducted by Stepto (1999) who investigated the effect of varying the intensity of interval training on 40-km time-trial performance in male endurance cyclists. Briefly, subjects (n=20) were divided into five groups who each performed a different training regime for 3-wk (see Table 3) and training protocols applied using the 'dose response' method and data was evaluated using polynomial function. Authors stated that work bouts of 4-min duration at 85% intensity of VO_2 max (race pace) resulted in the greatest enhancement in 40-km time-trial performance and the incremental peak power test (Stepto et al., 1999). In the same study, supra-maximal interval training (175% peak power) also resulted in improvements in time-trial performance and peak incremental power.

Table 3 displays the experimental training methods of cycling based training studies utilizing moderate, maximal and supra-maximal intensities on trained cyclists and triathletes.

Table 3. Experimental training protocols of cycling based training studies utilizing maximal and supra-maximal intensities on competitive cyclists and triathletes. Adapted from Paton & Hopkins (2004).

Author	Subjects	Training Protocol	Training Phase	Intensity
Maximal based interval training studies				
Hawley et al (1997)	Male cyclists >3yr cycling experience	Between 6 & 12 sessions consisting of 6 – 9 5 min bouts at 1 min rest periods	Base endurance	80% PPO
Laursen et al (2002)	Male cyclists and triathletes >3yr cycling experience	G1 = 8 x 2.4 min with 4.8 min recoveries at 2 sessions/wk G2 = 8 x 2.4 min with 2- to 3- min recoveries at 2 sessions/wk	Base and pre-comp	G 1 & G2 = Pmax
Laursen et al (2002)	Male cyclists >3yrs cycling experience	12 – 19 x 1 min, 2 sessions/wk	Base endurance	VO ₂ max PPO
Lindsay et al (1996)	Male cyclists >4yrs cycling experience	6 – 8 x 5 min with 1 min recoveries, 1 – 2 sessions/wk	Base endurance	80% PPO
Paton et al (2005)	Male cyclists >3yr cycling experience	3(5 x 0.5 min) with 20 step ups at end of each set, 2 min recoveries, 2 – 3 sessions/wk	Within competitive season	“maximal” sprints
Stepito et al (1999)	Male provincial endurance cyclists >3yr cycling experience	4 x 8 min, rest 1 min; 8 x 4 min, rest 1.5 min; 12 x 2 min, rest 3 min; 12 x 0.5 min, rest 4.5 min; 2 sessions/wk	Unspecified training phase	4 x 8 min = 80% PPO 8 x 4 = 85% PPO 12 x 2 min = 90% PPO 12 x 1 min = 100% PPO
Westgarth-Taylor et (1997)	Male cyclists with previous training history	6 – 9 x 5 min with 1 min recoveries, 2 sessions/wk	Base endurance	80% PPO
Weston et al (1997)	Male cyclists >4yrs cycling experience	6 – 8 x 5 min with 1 min recoveries, 1 – 2 sessions/wk	Base endurance	80% PPO
Supra-maximal based interval training studies				
Creer et al (2004)	Trained cyclists with >2yrs cycling experience	4 – 10 x 30 s, 2 sessions/wk for 4 wk	‘Maintenance’ training phase	“all-out” sprints
Laursen et al (2002)	Male cyclists and triathletes >3yr cycling experience	G3 = 12 x 30 s with 4.5 min, 2 sessions/wk	Base and pre-comp	175% PPO
Stepito et al (1999)	Male provincial endurance cyclists >3yr cycling experience	12 x 0.5 min, rest 4 min, 2 sessions/wk	Unspecified training phase	12 x 0.5 min = 175% PPO

PPO = peak power output, Pmax = minimal power output to elicit VO₂max

More recently, similar work was conducted by Laursen et al (2002). Three groups trained at various intensities of their peak incremental power and time at peak power. In order to set training intensity researchers tested subjects from groups 1 and 2 using their peak incremental power establishing what length of time they were able to hold their peak power for. For groups 1 and 2 time at peak power for training was based on 60% of the time that a subject held peak power. Group 3 trained at 175% of peak incremental power for 30 s. The authors' found that optimization of 40-km time-trial performance was greatest in groups training at 60% of time at peak power. They suggested that training at these intensities enhance time-trial performance, peak power output and VO₂max in trained cyclists. Table 4 displays the changes in average speed during the 40-km time-trial over the course of the 4-wk high intensity training program.

Table 4. Changes in average speed of 40-km time-trial over the course of a 4-wk high intensity program Laursen et al (2002).

TT ₄₀ Speed (km·hr ⁻¹)	Pre	Mid	Post
G1	42.2 ± 2.4	43.2 ± 2.3	44.4 ± 2.8**
G2	41.4 ± 2.5	42.9 ± 2.1	43.7 ± 2.4**
G3	41.9 ± 2.6	42.6 ± 2.7	43.7 ± 2.1*
G _{con}	41.8 ± 1.4	41.4 ± 1.3	41.4 ± 1.5

* P < 0.05 vs Pre measure.

Hawley et al (1997) studied the acute effects of high intensity training on 40-km time-trial performance and incremental peak power output. The authors reported that after four to six sessions at 80% incremental peak power output over the course of 2-3 weeks, peak aerobic power increased by 5% and 40-km time-trial performance by 2 to 3%. Following a further six sessions where the 80% training load changed based on the subject's newly established incremental peak power output, no improvement was seen in 40-km time-trial performance

or incremental peak power output. The authors suggest that the high intensity training sessions led to muscle adapting to the training and thus becoming fatigue resistant to high levels of intensity.

MacDougal (1998) studied 12 healthy subjects to gauge their response to sprint interval training. In a similar training regime to that of Creer (2004) subjects trained on alternate days three times a week for seven weeks. The initial bout of training was four sets of 30-s maximum sprint efforts interspersed with four min of rest between sets. Table 5 displays the training protocol.

Table 5. Seven week training regime for subjects in high intensity study (J. D. MacDougal et al., 1998).

	Week 1	Week 2	Week 3	Week 4	Week 5	Week 6	Week 7
Set/session	4	6	8	10	10	10	10
Rest between sets (min)	4.0	4.0	4.0	4.0	3.5	3.0	2.5

Anaerobic measures included 4 x 30-s sprint test at 7.5 g/kg body mass in which power output ($W \cdot s^{-1}$), peak power output, total work over 30 s and percent of fatigue were recorded over the course of the 4 x 30-s Wingates with 4 min of recovery separated each Wingate bout. Pre-intervention peak aerobic minute power (VO_2max) was measured at $3.73 L \cdot min^{-1}$ (± 0.13). Post-intervention measures of VO_2max resulted in an increase of 7% while peak power output and total work over sets 2, 3 and 4 of the Wingate test had significant increases (data not reported) in comparison to the pre-assessment. The authors suggest that intense sprint interval training of relatively brief periods can result in an increase in maximum short term power and peak aerobic power. A limitation was that the

subjects were non-cyclists at the time of the study which may have contributed to any learning and training effect for the athletes.

Training at both maximal and supra-maximal intensities has the potential to enhance sprint performance (MacDougal et al., 1998), time-trial performance (Hawley et al., 1997; Laursen, Shing et al., 2002; Stepto et al., 1999) and incremental peak power (Creer et al., 2004; Hawley et al., 1997; Laursen, Shing et al., 2002; Stepto et al., 1999). In all but one of the studies presented in table 3 on experienced competitive cyclists, training interventions were carried out in the 'base' or lower intensity phase of the cyclists periodization. In the study of MacDougal et al (1979), a non-athletic population was used which limits the usefulness of the findings to trained (and elite) cyclists. It would appear that exercise economy (Paton & Hopkins, 2005), peak power (Stepto et al., 1999; Westgarth-Taylor et al., 1997), time-trial performance (Lindsay et al., 1996; Stepto et al., 1999; Westgarth-Taylor et al., 1997), fibre type (Esbjornsson et al., 1993), muscle buffering capacity (Weston et al., 1997) glycolytic and mitochondrial enzyme activity (MacDougal et al., 1998) are all enhanced with either maximal or supra-maximal high intensity training (Kubukeli, Noakes, & Dennis, 2002). The relevance of these findings are significant for competitive cyclists as bouts of short duration high intensity work are witnessed in track (Broker et al., 1999; Craig & Norton, 2001), road (Coggan, 2006; Ebert et al., 2005) and mountain bike (Baron, 2001; Stapelfeldt et al., 2004) events. Training for such events should involve a range of power outputs to represent the array of power outputs in such competitions (Coggan, 2006).

Resistance Training

The two primary factors that contribute to strength gains are neural adaptation and muscle hypertrophy (Staron et al., 1994). The combination of endurance and resistance training or

“concurrent training” is common practice in athletes who are seeking an edge over their opponents (Gravelle & Blessing, 2000). The end result of concurrent training is largely dependant upon the volume and frequency of training (Hakkinen et al., 2003) and training specificity (Dudley & Fleck, 1987). Much interest and debate surrounds the simultaneous use of endurance training and strength training (Dolezal & Potteiger, 1996; Dudley & Fleck, 1987; Kraemer, Deschenes, & Fleck, 1988; Sale, MacDougall, Jacobs, & Garner, 1990). Concurrent training has been thought to interfere with the adaptation to endurance training due to differential training stimuli (Dudley & Fleck, 1987) and typically strength training shows alteration of muscle fibre from type I towards type IIa and IIb fatigable fibres (Kraemer et al., 1988). Despite this, the enhancement of neuromuscular efficiency, through muscular disinhibition and increased muscle co-ordination, are said to be key factors in support of strength training for athletes training for aerobic based events (Dolezal & Potteiger, 1996; Kraemer et al., 1988). Table 6 summarises the effects of resistance training on endurance performance in competitive athletes from a range of sports.

Table 6. Summaries of experimental and control training in studies of the effects of resistance training on endurance performance in competitive athletes. Studies ordered alphabetically. (From Paton and Hopkins, 2000, with permission).

Study	Experimental group training	Control group training
Bastiaans et al (2001)	Explosive weights (sets of 30 reps of squats, leg presses, single-leg step ups) replacing 37% of control	8.9 h.wk ⁻¹ endurance in pre-competition phase
(Bishop, Jenkins, MacKinnon, McEniery, & Carey, 1999)	Normal weights (3-5 sets of 2-8RM squats)	? h.wk ⁻¹ endurance in off-season
(Hoff, Helgerud, & Wisloff, 1999)	Normal sport-specific weights (3x 6RM), 7%; general strength, 2%; endurance, 70%; total 8.5 h.wk ⁻¹	Endurance, 72%; general strength, 13%; total 9.2 h.wk ⁻¹ in basic preparation phase
(Creer et al., 2004)	4-10x 30-s sprints, 2 session.wk ⁻¹ for 4 wk plus 5 h.wk ⁻¹ endurance training	8 h.wk ⁻¹ endurance training
(Hoff, Gran, & Helgerud, 2002)	Normal sport-specific weights (3x 6RM), 7.5% plus endurance; total 9.6 h.wk ⁻¹	Mainly endurance with strength endurance; total 10.1 h.wk ⁻¹ in pre-season phase
(Johnston, Quinn, Kertzer, & Vroman, 1997)	Normal weights (2-3 sets of 6-20RM)	32-48 km.wk ⁻¹ endurance in pre-competition season

(Laursen, Blanchard et al., 2002)	High-intensity cycling intervals (12-19x 1 min), plus 8 h.wk ⁻¹ base training	Low intensity in base phase, ~10 h.wk ⁻¹
	High-intensity cycling intervals (8x 2.4 min with 4.8-min recoveries)	~10 h.wk ⁻¹ in off and pre-competition phases
	High-intensity cycling intervals (8x 2.4 min with 2- to 3-min recoveries)	
	Very high-intensity cycling intervals (12x 30 s with 4.5-min recoveries)	
(Osteras, Helgerud, & Hoff, 2002)	Normal sport-specific weights (3x 6RM), 5% of total of 15 h.wk ⁻¹	Endurance ± strength-endurance, total 15 h.wk ⁻¹ in pre-competition phase
(Paavolainen, Hakkinen, & Rusko, 1991)	Explosive strength and sport-specific weights, 34-42%; endurance, 66-58%; total 6-9 sessions wk ⁻¹ in base preparation phase	Endurance, 85%; strength-endurance, 15%; total 6-9 sessions wk ⁻¹ in base preparation phase
(Paavolainen et al., 1999)	Explosive sport-specific strength (sprints, jumps, low-load weights), 32%; endurance and circuit, 68%; total 9.2 h.wk ⁻¹	Endurance and circuit, 97%; sport-specific explosive strength, 3%; total 9.2 h.wk ⁻¹ in post-competition phase

Traditional resistance training, which involves lifting moderate-to-heavy loads at relatively slow movement speeds, has been shown to be ineffective in improving long duration physical performance in competitive female cyclists (Bishop et al., 1999) or VO₂max in recreational male and female runners and cyclists (Hickson et al., 1998). Regular resistance based strength training results in hypertrophy of type II muscle fibres (Kraemer et al., 1988) although adaptation of the muscle to a strength training program will depend heavily on the mode of exercise, the type of movement(s) and muscle action(s) that are utilized (Kraemer, 1992; Kraemer et al., 1988). Staron et al (1994) showed a significant decrease in the percentage of type IIb fibres with a trend towards a non-significant increase in type IIa after just two weeks of a high-intensity lower body training program in a “healthy” population. Endurance athletes with an extensive training background have been found to have a high percentage of type I fibres (Tesch & Karlsson, 1985). Several researchers have reported that endurance performance can be substantially improved by

incorporating explosive strength training into runners' (Jung, 2003; Paavolainen et al., 1999) and cyclists' (Paton & Hopkins, 2005) programs.

Hakkinen (2003) studied the efficacy of combining concurrent strength and endurance training (n = 11) against strength training only (n = 16) for a period of 21 wk on recreationally active subjects. The strength component involved both maximal and explosive facets of resistance training with the aerobic portion of the program divided into 3 periodized training phases increasing in intensity at weeks 7 and 14. Training intensities for the strength and endurance group were based on the results of the peak aerobic power test with blood lactate measure taken every second minute of the test. Neural based assessments included rate of force development and EMG recording of the leg extensors. Metabolic determinants of the training included muscle biopsy of the vastus lateralis muscle. Cross sectional area of the right quadriceps femoris was taken using magnetic resonance imaging.

At the conclusion of the 21 wk of training integrated EMG results showed that increases of 26% and 29% occurred in the right VL during the maximal bilateral isometric leg extension action for the strength and strength endurance groups respectively while the left vastus lateralis increases were 19% and 22% for strength and strength endurance groups respectively. Rate of force development within the first 500 ms increased only in the strength group. Strength measures of leg extension significantly improved by 21% and 22% in the strength and strength endurance groups respectively. Increases in muscle cross-sectional area were found to the magnitude of 6% and 9% in the strength and strength endurance groups respectively. Unfortunately, the strength group did not carry out the peak aerobic assessment but authors reported that the strength endurance group increased

VO₂max by 18.5% and the wattage at the conclusion of the peak aerobic power test by 17%.

Of more relevance to application to competitive performance, several studies have investigated the effects of resistance training on performance in athletes with endurance backgrounds (Bishop et al., 1999; Hickson et al., 1998). Hickson et al (1998) investigated the impact of resistance training on seven cyclists and one runner. Six of the subjects were male and two were female with all subjects from an endurance background and not having weight trained for at least six months prior to the study. Three sessions of periodized strength training was performed on a weekly basis for 10-wk while endurance training continued according to the subjects own previous intensities and volumes. Resistance training involved various leg exercises and was always completed >1 hr prior to endurance training. Measures were taken of VO₂max, short term performance (high intensity specific exercise until fatigue occurred within 5 to 8 min) and long term performance (exercising to exhaustion at 80 to 85% of VO₂max). Muscle samples taken from the vastus lateralis muscle showed no change in type I or type II fibres at the conclusion of the study. There was an overall increase in leg strength of 30%, while thigh girth, fibre type and mitochondrial activities were unchanged. Short term endurance increased by 11% and 13% in cycling and treadmill running respectively. Long term cycling to exhaustion at 80% of VO₂max increased from 72 to 85 min. No significant change was found for 10 km run to exhaustion or VO₂max. The authors state that weight training may assist short term endurance capacity in trained endurance athletes, and does not impair or assist maximal aerobic power.

In a similar investigation on endurance athletes Bishop et al (1999) studied the effects of 21 female cyclists who were assigned to a resistance training (n = 14) or control (n = 7) group. The 12-wk program was performed twice weekly and consisted of parallel squats of 2 – 8 repetition maximum lifts of five sets to failure. Between sets rest periods included three min rest. Measures included muscle biopsy of the vastus lateralis, average power output over a 1-hr maximal cycle test, blood lactate and VO₂max, 1RM leg strength and muscle enzyme activity. Training resulted in a significant increase in 1RM in the resistance training group of 36% while the control group increased by only 4%. The resistance trained group reported no change in average power output in lactate or VO₂max response and no alteration of fibre type or muscle enzyme activity. Mean power in the resistance trained group decreased by 1.8%. The authors concluded that increased leg strength training does not improve endurance performance in female cyclists.

The majority of traditional strength training studies presented show increased improvement in tests of neuromuscular efficiency (Hickson et al., 1998; Turner, Owings, & Schwane, 2003) and short term performance (Bastiaans et al., 2001) for cyclists in a test to exhaustion (Hickson et al., 1998). No change was shown in type I or type II fibres muscle fibre samples taken from the vastus lateralis during a study utilising concurrent resistance and endurance training (Bishop et al., 1999). Subjects from a non-competitive population have shown large increases in VO₂max of 18.5% (Hakkinen et al., 2003) while athletic populations appear not to increase VO₂max; thus weight training appears neither to enhance nor impair maximal aerobic power in moderately trained endurance athletes, but still has the potential to increase performance (Bastiaans et al., 2001; Bishop et al., 1999; Hickson et al., 1998).

Explosive Resistance Training

Current literature suggests that traditional resistance training is ineffective in enhancing performance measure in endurance athletes (Bastiaans et al., 2001; Bishop et al., 1999; Hickson et al., 1998). A novel approach to address the limitation of resistance training has been to use explosive resistance or “plyometric” activities to enhance measures of performance (Hakkinen et al., 2003). The impact of six-weeks of periodized plyometric training program on regular but not highly trained distance runners was carried out on a mixed gender group (Turner et al., 2003). Subjects were assigned to two mixed gender groups (control and experimental). The experimental group carried out periodized plyometric training program three times a week over the course of six-weeks concurrent with the subjects normal training of 10 mile at three times/wk. After six weeks of plyometric training the runners did not improve jump performance measure suggesting that the ability of the muscles ability to store and return elastic energy was not influenced. There was no change reported in VO_2 max of either group although experimental subjects were found to be more economical in running performance at the speed of 11 km/hr which was the average of all speeds used. Authors suggest that while the improvement of economy of two to three percent in the plyometric group was small this change would be worthwhile to competitive athletes (Turner et al., 2003).

Due to the high volume of training and performance events over the course of a season (Schumacher & Mueller, 2002) it has been suggested that the only way for elite cyclists to enhance performance is through high-intensity training (Laursen & Jenkins, 2002). A study on experienced cyclists by Bastiaans et al (2001) investigated the use of various resistance and plyometric exercises to enhance various measure including short term power, time-trial performance and efficiency. The resistance training represented 37% of

control group training time of the nine-week pre-competition study. Training methodology followed a cycle-weights-cycle pattern. Measures were taken preceding training intervention and at week four and at the conclusion of the intervention. Time-trial performance increased in both groups (experimental 10.8% and control = 7.7%) but not significantly enough for a by training-group effect, however at week four of training the experimental group demonstrated a significant increase in time-trial performance that was significantly different from the control group (4.2% vs 3.2% respectively). Despite the variation in group measures, between groups were not significantly different, but once again a significant difference existed at week four for experimental compared to the control group. Measures of short-term power showed a significant difference between groups at week -four and -nine of 4.4% and 4.2% increase in the experimental and a 5.4% and 6.3% for the control groups in short-term power respectively. This was significantly different between groups at week nine caused by the decrease in performance of control. There were no significant changes in either measures of efficiency over the course of the study. The authors concluded that replacing a portion of cycling program with explosive strength training, prevents a decrease in short-term power without compromising gains in endurance performance of trained cyclists.

In a recent study, Paton and Hopkins (2005) investigated the effects of replacing a portion of road cycle training with 30 min of 'cycling specific' high-intensity ballistic training, interspersed with high-resistance cycle sprints. Unlike any other high-intensity training study this was carried out in the competitive phase of the cyclist's season. The protocols for each session are summarised in Table 3. Uniquely, the experimental group used explosive single-leg jumps (20 each leg) as part of their training. Performance measures included 1 km and 4 km time-trial performance and peak power output. Twelve sessions of

high intensity training resulted in major increases in 1 km- ($8.7\% \pm 2.5\%$) and 4 km- ($8.4 \pm 4.1\%$) sprint performance with peak power also increasing ($6.8\% \pm 3.6\%$) when compared against changes in the control group. These changes were attributed to improvements in exercise efficiency and the anaerobic threshold which improved by $3.7 \pm 4.8\%$ in comparison against the control group. Clearly this study suggests that significant improvements in performance are able to be made on cyclists during the competition season. These changes can be effected in as little as four weeks.

Endurance Training vs Resistance Training Interventions

The recent finding of Paton & Hopkins (2004) suggest that in-season improvements can be made through use of sport specific high intensity training and explosive body weight resistance. Previous to this numerous studies have found that resistance training has performance benefits for cyclists (Bastiaans et al., 2001). Traditional resistance has been shown to be ineffective in improving long duration physical performance (Bishop et al., 1999) or $VO_2\text{max}$ (Hickson et al., 1998). Researchers have reported that endurance performance can be substantially improved by incorporating explosive strength training into runners (Jung, 2003; Paavolainen et al., 1999) and cyclists (Paton & Hopkins, 2005) programs. Bastiaans (2001) found that replacing a portion of cycling program with explosive strength training prevents a decrease in short term power without compromising gains in endurance performance of trained cyclists. Therefore, it is possible that further gains could be achieved by adopting a more specific resistance based programme. Jones et al (2000) suggest that further research is required into the mechanisms of resistance training for endurance athletes with particular focus on plyometrics and the role of neuromuscular recruitment.

Summary

Coaches of endurance athletes incorporate phases of endurance, speed, interval and resistance training into periodized training plans aimed at developing the athlete towards targeted performance goals. As coaches, sport scientists and researchers investigate different methods of enhancing performance training techniques have become more refined (Jeukendrup & Martin, 2001; Jones, 1997).

Traditionally coaches have relied upon volumes of endurance training in the lead up to a competitive season (Pate & Branch, 1992) with the results are well documented (Fox et al., 1977; Jones, 1997; Wilmore et al., 1980). The mechanisms behind the central (Blomqvist & Saltin, 1983; Carter et al., 2003; Wilmore et al., 1980). and peripheral (Gollnick et al., 1973; Henriksson & Rietman, 1977; Hickson et al., 1981) adaptations to endurance training are well understood. In comparison to the non-elite cyclist, continuous moderate tempo aerobic training is less likely to enhance the performance of elite cyclist due to the large volume of training and racing that elite road cyclists do on an annual basis (Laursen & Jenkins, 2002). Athletes that have increased training volume and who have been able to improve performance event time despite decreasing in some measure of aerobic fitness (Jones, 1997).

Despite the necessity of a well-developed aerobic system in road racing, cyclists also require a substantial anaerobic capacity for short sprints or races that are predominated by high-intensity efforts. Sprint- or interval-training is characterized by maximal and supra-maximal intensities of short time durations and extensive rest periods (Daniels & Scardina, 1984). Interval training is used when recovery from repeated sprint efforts is critical to success (Schumacher & Mueller, 2002) or when an athlete's performance is limited by a

reduced anaerobic threshold. Interval training enables changes in the peripheral systems of an athlete (Burgomaster et al., 2006; Esbjornsson et al., 1993). The purpose of high-intensity training is to repeatedly stress the physiological systems that will be used during a specific endurance type exercise (Daniels & Scardina, 1984). This is carried out by altering training protocols such as number of repetitions and sets, length of rest period and alteration of intensities (Laursen & Jenkins, 2002; Pate & Branch, 1992). Researchers have studied alterations in muscle fibre type (Alleimeier et al., 1994; Esbjornsson et al., 1993), enzyme activity (Burgomaster et al., 2006; MacDougall et al., 1998), time-trial performance (Stephens et al., 1999) and various other fitness parameters in order to identify the mechanisms behind change in performance from interval training. The nature and magnitude of increases in performance as a result of periods of interval training appear to be dependant on the training state of the individual as well as the intensity and volume of the training.

Resistance training has been used to improve force production and neuromuscular capabilities in endurance athletes. Studies of traditional methods of resistance training in recreational subjects has shown an increase in $VO_2\text{max}$ (Hakkinen et al., 2003) on the other hand, endurance trained runners and cyclists have not shown these same improvements (Hickson et al., 1998). A number of authors have investigated the use of explosive sport-specific movements to improve parameters of fitness in athletes (Bastiaans et al., 2001; Turner et al., 2003). These studies have shown great improvements in only a short time period and very few training sessions (Paton & Hopkins, 2005). A unique approach to combining explosive resistance training and high-intensity interval training was carried out recently by Paton et al (2005). Investigators found that the combination of high-intensity interval cycling and explosive resistance training produced large increases in performance.

The role of neural and enhanced economy is said to have contributed to a large part of these performance increases. While the results of Paton et al (2005) are very clear, the extent to which explosive resistance training contributed to these changes is unknown. Therefore, further research should focus on the role of explosive resistance training in association with high-intensity interval training.

CHAPTER TWO

The Effect of Power Training Interventions on Cycling

Performance in Competitive Trained Male Cyclists

Abstract

In a recent study competitive road cyclists experienced substantial gains in sprint and endurance performance (4-9%) when sessions of high-intensity interval training (HIT) consisting of sets of continuous cycling and explosive jumps were added to their usual training in the competitive phase of a season. In the current study we investigated the contribution of the leg jumps to various measures of performance. Fifteen cyclists were randomized to a control or experimental group for 4-5 wk of training during their competitive season. Both groups replaced part of their usual competitive-phase training with 10 30-min sessions consisting of four sets of high-intensity intermittent cycling against high resistance (4 30-s maximum efforts at a cadence of 50–60 min⁻¹ alternating with 30-s recovery). Between each set of 4 30-s sprints the control group carried out one set of explosive single-leg jumps (20 for each leg), while the experimental group cycled at high intensity for 20 s at 50–60 min⁻¹. Before and after the training period all cyclists completed a 30-s sprint test, a 20-km time-trial, and an incremental test for assessment of peak power, VO₂max, lactate threshold and exercise economy.

The control group produced enhancements of performance power similar to those seen previously (up to 6%), but enhancements in the experimental group were less marked. Relative to the control group the mean percent changes ($\pm 90\%$ confidence limits) in the experimental group were: power at 4-mM lactate, -4.2 (± 6.3); VO₂max, -3.1 (± 3.7); mean time-trial power, -0.7 (± 4.5); peak incremental power, -1.7 (± 5.0); power at 80% max heart rate, -2.8 (± 5.6); power at 80% VO₂max, 0.8 (± 4.3); metabolic efficiency at 80% VO₂max, -3.8 (± 3.9); 30-s mean power, 2.3 (± 2.1); and 30-s peak power, -4.2 (± 7.8). The addition of sets of explosive jumps to sessions of high-intensity continuous cycling

intervals in the competitive phase of a cyclists' season may produce greater gains than the cycling intervals alone.

Introduction

The majority of endurance athletes incorporate some form of high-intensity interval training into their regular training plan (Hawley et al., 1997; Paton & Hopkins, 2005). High-intensity interval training overloads the adaptive stimulus through maximal or supra-maximal sport specific activity, thus inducing a desired training response (Laursen, Blanchard et al., 2002; Paton & Hopkins, 2005) when an increase in training volume no longer brings about a desired response (Dennis & Noakes, 1998). According to Daniels et al (1984) interval training involves repeated bouts of exercise at 95 to 100% of VO_2 max lasting between 30 s to 5 min with rest periods the same length or shorter than the work period. Changes in performance are primarily thought to be through adaptive response in muscle enzyme activity (Alleimeier et al., 1994) and enhancement of skeletal muscle buffering capacity (Laursen & Jenkins, 2002). Similarly, high intensity training (HIT) has been defined as repeated bouts of short to moderate duration exercise lasting between 10 s and 5 min completed at an intensity that is greater than anaerobic threshold with the rest period following a repetition allowing for a small amount of recovery prior to the beginning of the next repetition (Laursen & Jenkins, 2002).

Mechanistic explanations for the observed performance improvements following HIT include an increase in exercise economy (Billat et al., 1999; T. P. Smith et al., 1999) and adaptations such as increased enzyme activity and alterations in skeletal muscle fibre (Kubukeli et al., 2002). Extensive reviews have highlighted the enhancements in performance and physiological capacities of trained and untrained subjects using HIT (Kubukeli et al., 2002; Laursen & Jenkins, 2002). Reported improvements in ventilatory thresholds (6%), peak power output (4%) have been observed after as little as four sessions of HIT (Laursen, Blanchard et al., 2002). Importantly, improvements in 40 km time-trial

performance of between 4.4 to 5.8% in three groups of competitive cyclists after eight HIT sessions (Laursen, Shing, Peake, Coombes, & Jenkins, 2005) have been shown. Typically, HIT studies involving endurance athletes have been carried out in the preparatory phase of the season (Paton & Hopkins, 2005).

The impact of resistance training on endurance parameters has been investigated with mixed results (Paton & Hopkins, 2005). Improvement of neuromuscular efficiency (Hickson et al., 1998; Turner et al., 2003) short term sprint performance, (Bastiaans et al., 2001) and time to exhaustion (Hickson et al., 1998) have been found after resistance training interventions. Several authors have reported resistance training having neither a positive nor negative influence on maximal aerobic power in moderately trained competitive endurance athletes (Bastiaans et al., 2001; Bishop et al., 1999; Hickson et al., 1998; Turner et al., 2003). However, resistance training has been shown to increase $VO_2\text{max}$ in a non-competitive population by 18.5% (Hakkinen et al., 2003). This suggests that resistance training in moderately-trained endurance cyclists has the potential to increase performance while not influencing $VO_2\text{max}$. Further research is required into the mechanisms of resistance training for endurance athletes with particular focus on plyometrics and the role of neuromuscular recruitment (Jones & Carter, 2000).

A recent HIT study conducted by Paton and Hopkins (2005) reported major gains (4-9%) in several measures of sprint performance, peak power and exercise economy. The athletes involved were well-trained cyclists who completed 12 x 30-min sessions, over a 4- to 6-week period, consisting of sets of explosive leg jumps alternating with sets of high resistance cycling sprints. Hamilton et al (2006) performed a similar study using competitive endurance runners. While the gains in performance were not as substantial as

those reported by Paton and Hopkins, enhancement in predicted 800-m speed ($3.6 \pm 1.8\%$), predicted 1500-m speed ($3.7 \pm 3.0\%$) and peak incremental speed ($1.8 \pm 1.1\%$) relative to the control group indicated worthwhile improvements. Interestingly, both of these studies were completed in the subjects' competitive season using a control and training group. There is a significant amount of data showing that both HIT training and the combined HIT and explosive resistance training enhances performance, but as yet no study has compared the relative contribution of explosive resistance training to high intensity training. The purpose of the current study was to determine the contribution of explosive resistance training to HIT as measured by a variety of physiological and performance tests in competitive cyclists.

Methods

Design

The study was a controlled trial in which pair-matched subjects were assigned to either an experimental or control group based on peak power output from a pre-training incremental exercise test to exhaustion. Subjects performed a set of pre-intervention laboratory-based performance tests in the two weeks before and two after a 5-wk training period. The study was performed during the competitive phase of a summer cycling season.

Subjects

Cyclists were recruited from local road cycling and triathlon clubs in the Auckland region. Several criteria for involvement in the study were required: male road cyclists or triathletes aged 17-50 yr, have had no previous resistance training in the 6 months before the study start date, currently competing in at least one cycling race a week and riding a minimum of 200 km each week. After being informed of any risks associated

with participation, 16 cyclists gave their written informed consent to participate, in accordance with the ethics committee of AUT University. Although there were no withdrawals from the study, one subject dramatically reduced his training following the completion of a major tour. The subjects data was not included in the final analysis. Subject characteristics and baseline measures are shown in Table 7.

Table 7. Subject characteristics, training history and pre-test measures.

	Control	Experimental
Age (y)	31.8 ± 8.0	39.4 ± 10.0
Body mass (kg)	82.8 ± 10.4	78.1 ± 4.5
Height (cm)	180 ± 7	177 ± 2
Sum of 8 skinfolds (mm)	80 ± 28	72 ± 22
Body fat (% body mass)	13.6 ± 5.1	11.5 ± 3.6
Calf girth (mm)	39.9 ± 2.2	37.9 ± 1.6
Quadriceps girth (mm)	55.5 ± 3.9	54.8 ± 2.5
Training (h.wk-1)	9.8 ± 2.9	9.2 ± 4.3
Peak power (W)	390 ± 31	394 ± 22
VO ₂ max (L.min-1)	4.51 ± 0.37	4.45 ± 0.24
Power at 80% VO ₂ max (W)	268 ± 28	260 ± 19
Power at 4 mmol.L-1 lactate (W)	303 ± 35	298 ± 28
Power at 80% HRmax (W)	326 ± 39	325 ± 18
Metabolic efficiency at 80% VO ₂ max (%)	22.1 ± 1.3	22.5 ± 1.4
Wingate mean power (W)	763 ± 81	727 ± 38
Wingate peak power (W)	941 ± 105	902 ± 68
Mean time-trial time (min)	31.1 ± 1.3	30.7 ± 0.9
Mean time-trial power (W)	302 ± 27	307 ± 24
10-km blood lactate (mmol.L-1)	6.8 ± 2.9	7.5 ± 2.0
20-km blood lactate (mmol.L-1)	11.4 ± 2.1	10.2 ± 2.7
Time-trial mean heart rate (min-1)	162 ± 12	167 ± 15

Data are mean ± between-subject standard deviation. VO₂max, maximum oxygen uptake; HRmax, maximum heart rate.

Exercise Performance Tests

All laboratory tests were performed on an electro-magnetically controlled cycle ergometer (Velotron, Racermate, Seattle, Washington) in a temperature-controlled laboratory (19 - 20°C, ~50% humidity). Cyclists were instructed to refrain from hard physical activity for the 24 h prior to each test. The tests completed were a 20-km time-trial, an incremental peak aerobic power test and a 30-s Wingate assessment. The incremental test was followed by 20 min of recovery prior to the start of the warm-up phase preceding the Wingate assessment. Prior to each incremental test, a two-point calibration procedure was carried out: Gas 1 = Ambient Air (20.93% O₂ and 0.03% CO₂); Gas 2 = alpha standard gas (BOC, Auckland, NZ) consisting of 15.00% O₂ and 5.00% CO₂. The flow-volume transducer was calibrated using a 3-L syringe (Hans Rudolph, Kansas City, Missouri) and checked, post-calibration, over a range of flows.

For the incremental test, cyclists initially performed a 10-min warm-up at a power no greater than 150 W. Thereafter, cyclists performed a maximal incremental peak aerobic power test with the initial 3-min stage starting at 180 W with 30 W increases occurring at each 3-min stage. Blood lactate was measured during the last 15 s of each stage using a Lactate Pro analyser (Akray, Kyoto, Japan). Heart rates were recorded using a Polar 725x device (Polar Electro, Kempele, Finland) at the same time. The cyclist continued with the incremental stages until either their cadence dropped below 40 min⁻¹ for 5 s or more or the cyclist stopped due to volitional exhaustion. Peak power output (W) was determined as the power of the final completed stage plus the nearest 5 s fraction of the following stage if required. Fractions of stage were measured in 5 W increments, so for every 30 s completed the cyclists gained 5 W in addition to their last completed stage.

During the pre- and post-training incremental test, oxygen uptake was continuously measured using an automated breath-by-breath system (Metamax 3B, Cortex, Leipzig, Germany). Maximum oxygen consumption was determined as the highest 30 s average recorded during the test. Two other measures of performance were derived from the incremental test. Power at a blood lactate concentration of 4 mmol.L^{-1} was predicted from log-log plots of blood lactate vs running speed using the trend function in Microsoft Excel separately for the pre- and post-training data. Power at a fixed heart rate was determined in a similar fashion from linear plots of heart rate vs cycling power. The fixed heart rate was determined for each cyclist as the average heart rate during the final minute of the middle 3-min stage of the pre-training incremental test (or the mean of the two middle stages for cyclists who completed an even number of stages).

Two to four days after the incremental peak aerobic power test and following a similar warm-up procedure as described for the incremental test, cyclists performed a laboratory based 20-km performance time-trial. During the 20-km time-trial the mid- and end-distance blood lactate concentration was measured. Heart rate was measured continuously throughout the test. At the conclusion of 20-km the Velotron software calculated total time, average power and average heart rate.

Anthropometry

Prior to the 20 km performance time-trial, pre- and post-intervention, subject's body mass, height, skinfolds, mid-thigh and mid-calf girth were measured using the International Society for the Advancement of Kinanthropometry (ISAK) eight skinfold site protocol. All measures were taken by the primary researcher who is an ISAK L1 anthropometrist. All measures were taken in accordance with ISAK guidelines (Norton et al., 2004). In all

anthropometric calculations the mean of each site was taken from two trials to be used in data analysis.

Training

Prior to the initial incremental peak power test, baseline training in the 2 wk prior to the study was taken from the cyclists' response to question in the pre-exercise questionnaire. For the training intervention period, all cyclists were issued with a Polar heart rate monitor recording strap (Polar Team, Kempele, Finland) which they were requested to wear during all training and competitions. The straps recorded the date, time and duration of exercise as well as heart rate at 5-s intervals. Data from the heart rate strap were to be used to determine each cyclist's weekly training volume and intensity, but due to lack of adherence there were insufficient data for analysis.

High Intensity Resistance Training Intervention

Training was performed in a controlled laboratory environment under the supervision of the primary researcher or a research assistant. The training sessions were preceded by either a 5-min warm-up on a separate cycle ergometer or following a training ride. Each session was performed 1-3 times per week, depending on the cyclists' availability. Both groups of cyclists were instructed to continue their training and competition program but reduce their current training by 1-h each week during the time of the intervention. On average the subjects reported that prior to the start of the study they were cycling between 8 to 14 hours on a weekly basis. The ~5 h that were taken out of the subjects' normal training program was replaced by 10 x 30 min of the lab-based HIT sessions. Both groups carried out high-resistance interval training sets which consisted of four sets of cycling at 50–60 min⁻¹ on a friction-loaded cycle ergometer (Monark 824E, Varberg, Sweden). Initial

resistance was applied to the basket based on 7.5% of the subject's body weight with further increases in increments ranging between 0.1 and 0.5 kg over the remaining nine sessions.

Following a set of 4x 30-s efforts interspersed with 30-s rest the experimental group remained on the bike and carried out another 20 s of cycling with no change in the weight from the previous set. In a modified prescription described by Paton and Hopkins (2005), the control group subjects dismounted the bike, changed into sports shoes and completed a set of maximal effort single-leg jumps. The jump sets consisted of subjects performing 20 explosive one-leg step-ups off a 45-cm box with the right leg followed by 20 jumps with the left leg over durations of between 90 and 120 s. Figure 1 displays the jump procedure. Briefly, the cyclists' placed one foot on a 45-cm box and jumped with as much force as possible in a vertical direction. Instructions were given that each jump should be separated by ~3 s to minimize the eccentric component of the following jump. Paton and Hopkins (2005) stated that the aim of their explosive jump training protocol was to develop a sport-specific strength training routine that athletes would be prepared to use in the competitive phase of the season.



Figure 1. Concentric phase of the explosive jump

Lab-based Training Analysis

A custom made infra-red device was attached to the right front fork of the Monark 824E ergometer in order to measure the number of revolutions during each 30-s exercise bout. The Monark wheel was divided by nine equally sized black segments separated by nine silver patches of the same dimension. As the wheel turned the black segment was recorded as 'off' and the silver as 'on'. The angular distance between markers on the wheel rim was known; therefore, the on and off signals measures by the system could be converted to total angular displacement. There was no need for filtering the data, because we did not differentiate the raw signal. The analogue signal output from the sensor was sampled at 1000 Hz with a National Instruments data acquisition card (National Instruments, Austin, Texas). The programme for analysing the data was written in Labview 6.1 (National Instruments, Austin, Texas).

Statistical Analyses

Inferential statistics were based on interpretation of magnitude of effects (Batterham & Hopkins, 2006), as follows. Mean effects of training and their 90% confidence limits were estimated with a spreadsheet (W. G. Hopkins, 2003) via the unequal-variances t statistic computed for change scores between pre- and post-tests in the two groups. For statistical purposes the ballistic group (interval training plus jumps) was used as the control for the continuous (experimental) group. Each subject's change score was expressed as a percent of baseline score via analysis of log-transformed values, to reduce bias arising from non-uniformity of error. Errors of measurement expressed as coefficients of variation were also estimated with the spreadsheet. The spreadsheet also computed quantitative and qualitative chances that the true effects were beneficial, trivial and harmful, when a value for the smallest worthwhile change was entered. The value chosen for the smallest substantial

change in the various measures of power was 1.25% (Paton & Hopkins, 2006). For the anthropometric measures, the smallest substantial change was 0.20 of the baseline between-subject standard deviation (W. G. Hopkins, 2003). An effect was considered to be unclear if its confidence interval overlapped the smallest substantial positive and negative values (that is, if the chances of the effect being beneficial and harmful were both >5%). See Appendix 1 for the changes in performance and anthropometry over the course of the study.

Results

Training

Figure 2 shows the mean sprint power over the 10 training sessions in both groups. One subject recorded a major increase in Wingate peak power output following training which was determined to be an equipment fault therefore the data for this subject has been removed from the Wingate peak power analysis.

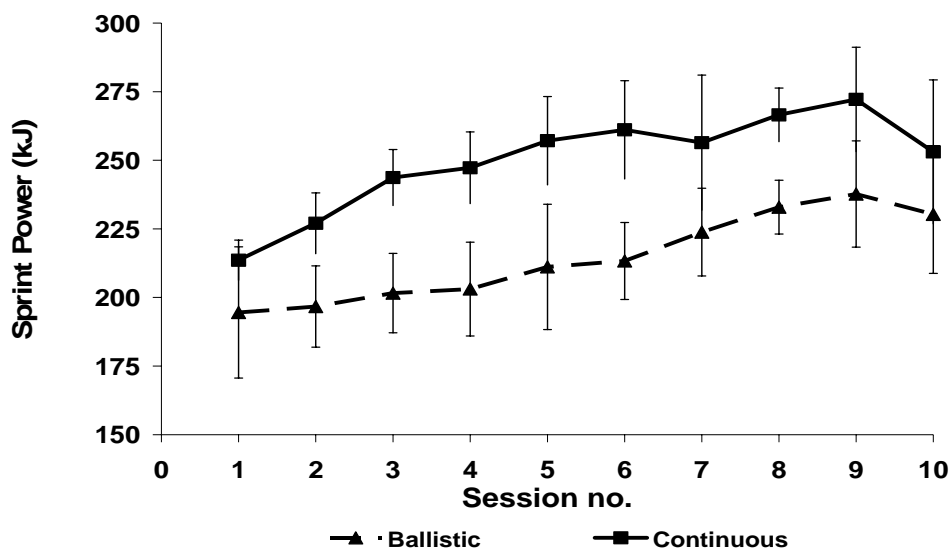


Figure 2. Sprint power over 10 training sessions

Effects on Performance

Table 8 shows the mean changes in the performance and related measures for experimental and control groups, and statistics for the difference in the changes.

Table 8. Changes in performance and anthropometry in experimental (continuous) and control (ballistic) groups and qualitative inferences about the difference (experimental minus control) in the changes.

	Change in measure (%)			Qualitative inference
	Experimental mean \pm SD	Control mean \pm SD	Difference; \pm 90%CL	
Peak incremental power	3.2 \pm 4.8	5.1 \pm 6.0	-1.7; \pm 5.0	Unclear
VO ₂ max	-0.1 \pm 2.2	3.1 \pm 5.3	-3.1; \pm 3.7	Harmful
Power at 80% VO ₂ max	2.2 \pm 5.4	3.1 \pm 4.1	-0.8; \pm 4.3	Unclear
Power at 4-mM lactate	2.1 \pm 3.8	6.4 \pm 8.9	-4.2; \pm 6.3	Unclear
Power at 80% HRmax	2.8 \pm 4.6	5.8 \pm 7.5	-2.8; \pm 5.6	Unclear
Metabolic efficiency at 80% VO ₂ max (%)	0.6 \pm 4.1	4.5 \pm 3.7	-3.8; \pm 3.9	Unclear
Wingate mean power	1.5 \pm 2.3	-0.8 \pm 2.1	2.3; \pm 2.1	Benefit likely
Wingate peak power	-1.5 \pm 10.3	2.8 \pm 5.0	-4.2; \pm 7.8	Unclear
Time-trial mean power	4.9 \pm 5.9	5.6 \pm 3.7	-0.7; \pm 4.5	Unclear
Body mass	-1.0 \pm 2.2	-0.1 \pm 1.3	-0.8 \pm 1.8	Trivial
Sum of 8 skinfolds	-2.4 \pm 13.5	-3.3 \pm 6.6	0.9; \pm 10.3	Unclear
Quadriceps girth	-0.4 \pm 2.1	0.3 \pm 0.9	-0.6; \pm 1.6	Trivial

90%CL, 90% confidence limits; VO₂max, maximum oxygen uptake; HRmax, maximum heart rate.

Standard errors of measurement for the control group between pre and post tests, in order of increasing error, were: Body mass, 0.9%; Quadriceps girth, 0.6%; Wingate mean power, 1.5%; mean time-trial power, 2.6%; metabolic efficiency at 80% VO₂max, 2.7%; power at 4-mM lactate, 2.7%; Wingate peak power, 3.5%; VO₂max, 3.7%; power at 80% VO₂max, 3.8%; incremental peak power 4.2%; sum of eight skinfolds, 4.6%; power at 80% maximum heart rate, 4.9%. The 90% confidence limits for the true values of the error of measurement were $\times/\div 1.5$ for all performance measures.

Discussion

The major finding of this study was 10 sessions of high-intensity training (HIT) combined with explosive resistance training produced greater gains in performance than HIT only. Enhancement in power in the 20-km time-trial performance test of the ballistic group and continuous group demonstrated the effect on performance from concurrent and HIT treatments respectively. The largest worthwhile change in the experimental group was Wingate mean power. Relative to pre-intervention measures the largest worthwhile change in the control group was VO_2 max. While these findings are not as large as those reported in Paton and Hopkins (2005) they are still larger than the minimal worthwhile change for competitive cyclists (Paton & Hopkins, 2006). The gains were unlikely to be due to a placebo effect, as the change on one of the submaximal measures of performance (4-mM lactate power) showed improvement in both groups, despite being qualitatively unclear, with the control group showing the greatest enhancement. The estimate of the effect was unlikely to be biased by any differences in fitness between the groups, which showed similar mean values at baseline for most measures. Finally, the standard error of measurement in a non-intervention control group would be expected to be smaller, however, in the present study both groups were exposed to a treatment. Therefore, individual responses to the treatment will inflate the error of measurement, which will partially explain why some effects are not clear.

Enhancements with the combination of continuous cycling and ballistic jumps in this current study were generally a little less than the 3.7–8.7% observed by Paton and Hopkins (2005). There may be several explanations for the smaller changes in performance observed between the present study and the study of Paton and Hopkins (2005) from where the control group protocol was taken. The majority of cyclists were already competing

weekly in criterium cycling events. This style of racing requires riders to sprint at regular intervals for points. Racing takes place within an enclosed circuit of ~1 km with cyclists racing for periods of 20 to 60 min in duration. The intermittent nature of this style of competition is similar to prescriptions of interval training described by previous reviewers (Daniels & Scardina, 1984; Laursen & Jenkins, 2002). It is possible that the effects of the HIT would be minimized by the intermittent sprint nature of criterium racing.

A second reason for the difference in responses could be due to the difference in training protocol employed by the current study. Paton and Hopkin (2005) used a 5 x 30 s period for cycling based training then 2 min for jumps and 2 min rest prior to the start of the next set. This equates to ~9 min for each set of cycling and jumps. In the present study, cyclists in the control group dismounted the bike at 3.5 min and had the same time period to complete their allotted jumps prior to the start of the next bout of cycling. Therefore, a cycle and jump set lasted 7 min. It is plausible that the extra 2 min of rest in the former study allowed a greater repayment of resynthesis of phosphocreatine (Bogdanis et al., 1995). However, this would only account for the initial rep of each of the 5 x 30 s effort as subsequent 30 s bouts would have a similar anaerobic energy cost to the cyclists in either study. Following a maximal sprint, cyclists would have reduced their phosphocreatine content to ~20% of resting levels and after 1.5 min of recovery, phosphocreatine would have returned to ~64% of initial levels (Bogdanis et al., 1995). Rest periods of three and six min show a decrease in the rate of phosphocreatine repayment to 74% and 85% respectively (Bogdanis et al., 1995). The availability of phosphocreatine for maximum sprint performance is considered vital to achieve peak powers (Casey, Constantin-Teodosiu, Howell, Hultman, & Greenhaff, 1996).

Effect of HIT on 20-km Time-Trial Performance

Performance time-trials have been widely used by sport scientists in high-intensity training studies (Laursen & Jenkins, 2002). In the current study mean 20-km time-trial power increased which is in agreement with several researchers who used a variety of sub-, maximal- and supra-maximal training protocols to enhance 40-km time-trial performance (Hawley et al., 1997; Laursen, Shing et al., 2002; Stepto et al., 1999). Recent evidence from Paton and Hopkins (2005) also shows that 1-km (8.7%) and 4-km (8.4%) tests are enhanced after a period of concurrent training. The enhancements in the control group are not as great as that of the former study however a change in performance of ~5% for both experimental and control group is substantial. Evidence presented from the current study and previous studies suggest that both explosive resistance training and various protocols of HIT will improve time-trial performance of distances between 1 km and 40 km. Various mechanisms have been postulated as being responsible for improving time-trial performance including increased economy by way of neural enhancement (Paton & Hopkins, 2005) greater use of fatty acids for fuel (Westgarth-Taylor et al., 1997) and an increase in peak incremental power (Stepto et al., 1999). The explosive resistance training of the concurrent group has previously contributed to enhanced economy in runners (Paavolainen et al., 1999) and cyclists (Paton & Hopkins, 2005). The concurrent group also increased peak incremental power ($5.1 \pm 6.0\%$). In the current study a combination of these changes may have assisted the increase in time-trial performance in the concurrent group. Incremental peak power showed a smaller change in continuous group, however, this may have contributed to an increase in time-trial performance. As with the ballistic jump group it is unknown if sparing of carbohydrate for fuel was responsible.

Effect of HIT on VO₂max and Economy

The qualitative inference of VO₂max suggests a possible benefit from the explosive resistance intervention used in this study. No change was witnessed in the continuous group but the ballistic group showed a positive change that is large enough to be considered worthwhile for competitive cyclists (Paton & Hopkins, 2006). Previous literature has reported an increase of VO₂max following strength training in untrained subjects but no change in VO₂max of a cycling population carrying out strength training (Bishop et al., 1999). A number of studies have shown periods of high-intensity training of untrained (MacDougall et al., 1998) and endurance trained subjects enhancing VO₂max (Acevedo & Goldfarb, 1989; Laursen, Shing et al., 2002; Stepto, Martin, Fallon, & Hawley, 2001). The reported increase in VO₂max in the current study would suggest that enhancements within the central and/or peripheral aerobic system had taken place during the explosive resistance training. Given that the cyclists in the current study were in a competition phase and had presumably undertaken extensive endurance training in the lead up to competition racing, it is unlikely that the enhancement occurred in the central system. However, the absolute VO₂max scores of the subjects would be considered to be at the lowest level of Jeukendrup et al (2000) definition of “trained cyclists” or those with an absolute VO₂max of 4.5 – 5.0 L·min⁻¹. Hence, the enhancement in VO₂max may be attributed to an increase in cardiovascular ability via cardiac output through an increased stroke volume (Hoogsteen et al., 2003) or an increase in haemoglobin (Astrand & Rodahl, 1986). Given that the experimental group did not increase VO₂max this would suggest that explosive jumps played a role in enhancing VO₂max. If this was to be the case it is thought that an improvement in economy, through an enhancement of the neural system is responsible (Paton & Hopkins, 2005). One of the two primary adaptations from resistance

training is an improvement in economy (Staron et al., 1994) which is said to benefit endurance athletes (Dolezal & Pottelger, 1996; Kraemer et al., 1988).

Economy in high-intensity training studies using competitive athletes has been measured by oxygen cost of exercise (Paavolainen et al., 1999; Paton & Hopkins, 2005), lactate response at a given speed or power output (Hamilton et al., 2006; Paton & Hopkins, 2005) and fuel utilization at various intensities of power output (Hawley et al., 1997). In the current study power at 4-mM lactate demonstrated the greater change in the control group, suggesting that the explosive resistance training employed by the control group enhanced exercise economy. Enhanced economy through a reduction in lactate have been reported in runners (Hamilton et al., 2006) using high-intensity training in association with resistance training and cyclists using high-intensity training only (Laursen, Blanchard et al., 2002) through enhancement of the anaerobic threshold. We chose metabolic efficiency of VO_2max and power at 80% VO_2max as our measures of economy. Relative to the control group both measures for the experimental group were unclear. The control group showed improvement in economy at 80% VO_2max to be unclear. Possible reasons for these changes have been discussed above, but as the greatest alterations were witnessed in the ballistic group it is thought that the explosive resistance training component was responsible for economy enhancement. Previous research using similar training techniques have shown clear effects in VO_2max and economy (Hamilton et al., 2006; Paavolainen et al., 1999) and cyclists (Paton & Hopkins, 2005) who used resistance training to enhance economy and performance. It is thought that due to the use of a non-conventional control group, i.e. one that carried out the training in the current study findings were not as clear as in the studies of previous researchers.

Effect on HIT Body Composition

It is beneficial for cyclists to maintain lean body mass throughout the season in order to maximize power to weight ratio (Lee et al., 2002). The best example of this is seen in uphill specialists who retain minimal lean body mass enabling greater climbing ability (Padilla et al., 1999). Changes that were seen in the groups in relation to skinfold, thigh girth or calf girth were trivial. While addition of muscle mass is often a direct result of strength training (Staron et al., 1994) explosive resistance training will only add ~1%, which has been suggested to be the addition of muscle mass (Paton & Hopkins, 2004). While the addition of extra mass may not be beneficial for the majority of cyclists (Padilla et al., 1999) greater muscle mass has been associated with improved short-term power performance and greater anaerobic capacity (Davies & Sandstrom, 1989).

Effect on HIT Anaerobic Power

Wingate mean power showed a likely benefit for the experimental group relative to the control group, while the difference between groups in Wingate peak power output was unclear following the training intervention. Alleimeier et al (1994) found that a training intervention of 3 bouts of supra-maximal 30 s sprints with 20 min rest between bouts resulted in no change of peak or mean 30 s power. However, a more recent study by Burgomaster et al (2006) demonstrated improvements in mean power (8.7%) and peak power (5.4%) when using a 30 s Wingate test as the training protocol. The main difference between studies was the rest periods and frequency of training bouts. The training protocol for the later study used 4 min rest between bouts with 4–7 bouts performed each session for the seven sessions. This may be related to the lower cadences (50–60 min⁻¹) in the current training protocol. Peak cadences in Wingate assessments are well in excess of 100 min⁻¹ (Inbar et al., 1996).

Track cyclists require high anaerobic capacities for success in events (Craig & Norton, 2001) and although endurance cyclists typically compete at more moderate intensities, a well developed anaerobic system is often required for sprinting during and at the end of a race. Endurance athletes with an extensive training background have been found to have a high percentage of type I fibres (Tesch & Karlsson, 1985) and the introduction of resistance training has been reported to interfere with the adaptation to endurance training due to differential training stimuli (Dudley & Fleck, 1987). Typically introduction of strength training shows alteration of muscle fibre from towards type IIa and IIb fatigable fibres (Kraemer et al., 1988). Staron et al (1994) showed a significant decrease in the percentage of type IIb fibres with a trend towards non-significant increase in type IIa after just two weeks of a high-intensity lower body resistance training program. Alterations in fibre composition are evident in repeated bouts of HIT (Kubukeli et al., 2002). For example, the introduction of 3 sessions each week of 10 s duration, maximal intensity sessions of HIT have been reported to decrease the proportion of type I fibres and increase type IIa. When HIT increased to 2 daily sessions every day for 7 days, the proportion of type I fibres increased and type IIa decreased (Esbjornsson et al., 1993).

Limitations/Weaknesses

Lack of data from regular training sessions meant that there was minimal chance of measuring the impact of training volume and intensity outside the lab. This meant that cyclists could have been doing very little over the time of the study but we would have no way of knowing or quantifying that drop in volume. However, given that it was the competition season it is unlikely that volume and intensity of cycling was reduced. As this study was performed in the competitive season, it was assumed that the subjects were in a stable phase of training. An increase in $VO_2\text{max}$ in the control group suggests that this was

intervention-related rather than by mechanisms outside the control of the researchers. The experimental group showed no change in VO_2max suggesting that the resistance portion of the explosive resistance training benefited the control group. However, lack of training data for sessions outside the lab does not assist this conclusion.

An increase in sample size would have given greater power to the study. Vigorous advertising of the study and recruitment of subjects was carried out for over a month prior to the start of the study. The training intervention was designed to fit in with the subjects racing commitments and as such there was a tight time-line on when the study could be carried out.

An increase in repetitions or duration of cycling may have had a greater effect on overall performance, however, monitoring of the in-lab training showed that all subjects progressed incrementally over the 10 sessions of high intensity training.

Future Directions/Research

Further research into the area of both high-intensity training and explosive resistance training in competitive athletes is required. Current literature on the mechanisms that lead to performance improvement is unclear. The means by which improvement occurs is likely to be founded on enhanced economy via improved neural mechanisms, muscle enzyme adaptation and greater use of free-fatty acids for energy thus sparing carbohydrate. Alterations of fibre type transformation due to HIT and resistance training is undecided. Studies that assess muscle biopsy alongside performance changes would serve to clarify this area. If the combination of intensity, duration and frequency is to be explored the dose-response method would be an effective way to address this limitation. The dose

response method requires a substantial number of subjects and sufficient resources for a successful outcome. The combination of high-intensity cycling and explosive resistance training has been shown to produce worthwhile effects in both runners and cyclists' therefore, further study into sports such as duathlon and triathlon is warranted. Further research should also focus on the optimal combination of high intensity cycling and explosive resistance training. Again, the most effective way to address this question is by way of the dose-response method or by carrying out a longitudinal study with regular interventions and effective wash-out periods between interventions.

Conclusion

The combination of high-intensity cycling and explosive resistance training over 5 wk at 2–3 sessions/wk (a total of 10 sessions) provided greater performance gains than high-intensity cycling alone. This suggests that within a competitive season well-trained cyclists can produce worthwhile gains in performance in a short time period. The inclusion of explosive resistance training with high-intensity cycling over 5 wk is overall of greater benefit, however a number of the variables measured have shown a an unclear or trivial result suggesting the need for further research on the role of explosive resistance training and high-intensity cycling in enhancing cycle performance.

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CHAPTER THREE

Summary and Recommendations for Cyclists

Several variables influence cycling performance including distance, intensity, race tactics and environmental conditions. Together, these factors influence the physiological and energetic demands on the cyclist. The extremes of distances raced in competitive cycling are vast. In the majority of these events most of the energy is provided by the aerobic system, but events requiring an “all-out” strategy are heavily dependent on the anaerobic system. These track-based events are less than 1-km in length, are completed inside ~60 s by elite cyclists and at the longest distance require equal (50/50) contributions from the anaerobic and aerobic energy systems. Longer, road based events rely largely on the aerobic system with cyclists often riding at sub maximal intensities for long periods of time. However, time-trials, criteriums, sprint finishes or mid stage-primers and hilly or mountainous stages require the cyclist to ride at maximal or supra-maximal intensities for short to extended periods of time. Therefore, planning of the training and competition period should take into account the range of intensities that a cyclist will be exposed to.

Training programs are written in order to enhance athletic capabilities to match the physiological aspects of the performance event and typically involve performance testing prior to, and during training. Regular performance assessments assist the coach and athlete by identifying training intensity zones and tracking changes in fitness. Two of the most common assessments are VO_2 max and blood lactate threshold, both of which are regularly assessed in a range of athletes from semi-competitive to elite performers. In comparison to semi-competitive cyclists, elite cyclists display superior measures of blood lactate threshold and VO_2 max and possess a greater ability to ride at higher percentages of both of these measures. Despite the VO_2 max being a widely used and referenced physiological measure, doubt over its' validity exists. The usefulness of VO_2 max may lie in measurement of cyclist's performance in early phases of their career to monitor progress

and as a tool for talent identification. The VO_2max assessment also elicits ventilatory thresholds that have been used in the past for setting of training intensity zones. However, current data suggests that the use of the maximal lactate steady state or 4-mM of blood lactate is more accurate than ventilatory measures. The time commitment in identification of maximal lactate steady state is considerable, however time-trials at distances of 5 and 40 km have shown correlate highly with maximal lactate steady state. Therefore, it would be of use to coaches and athletes to use performance time-trials as a monitoring tool.

Endurance athletes incorporate phases of endurance, interval and resistance training into periodized training plans aimed at enhancing performance. Significant adaptations results from large volumes of aerobic training. When an increase in training volume no longer causes adaptations, training duration should be reduced in favour of an increase of training intensity. Interval training is considered important for enhancements of anaerobic capacity and is used when recovery from repeated sprint efforts is critical to success or when an athlete's performance is limited by a reduced anaerobic threshold. Manipulation of work, rest, intensity, reps and sets are factored into interval training to maximise training effects and enhance both the skeletal and peripheral systems of an athlete. Resistance training has been used to improve force production and improve neuromuscular capabilities in endurance athletes. There has been much debate over the use of resistance training, however; explosive sport-specific movements and high-intensity interval training appear to have a positive influence on performance in endurance athletes.

During our experimental investigation we examined the role of high-intensity cycling with and without explosive resistance training in competitive cyclists. The combination of high-intensity cycling and explosive resistance training for 10 sessions over 5 weeks provided

greater performance gains than high-intensity cycling alone, but in most cases the repeatability of the findings was unclear. This suggests that within a competitive season 10 sessions well-trained cyclists can produce worthwhile gains in performance in a short time period. The optimal limit for high-intensity training sessions is unknown at this stage, however; high-intensity training has been reported to enhance performance in as little as 4 sessions over the course of 2 weeks.

Recommendations

The combination of high-intensity training and explosive resistance training in cyclists produces worthwhile changes in performance. Coaches involved in high-intensity training should be aware that performance benefits resulting from this type of training are achieved within 8 – 12 sessions. Training protocols should be periodized into the training plan as with any other training component. Further research should focus on the optimal combination of high intensity cycling and explosive resistance training perhaps by use of the dose-response method. Studies that investigate the performance effect on triathletes would be of interest as the benefits of high-intensity and explosive resistance training has been shown to produce gains in both runners and cyclists.

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APPENDICES

Appendix 1. Changes in performance and anthropometric measures.

Experimental and control groups and qualitative inferences about the effects on competitive performance. The control group (Ballistic) is used as the reference.

	Change in measure (%)			Qualitative inference
	Experimental mean \pm SD	Control mean \pm SD	Difference; \pm 90%CL	
Power at 4-mM lactate (W)	2.1 \pm 3.8	6.4 \pm 8.9	4.2; \pm 6.3	Unclear likely
Power at 60% MHR	2.9 \pm 5.1	6.0 \pm 9.1	-2.9; \pm 6.7	Unclear
Power at 70% MHR	2.9 \pm 4.7	5.9 \pm 8.2	-2.8; \pm 6.1	Unclear
Power at 90% MHR	2.8 \pm 4.7	5.7 \pm 6.9	-2.7; \pm 5.4	Unclear
Metabolic efficiency 70%	3.1 \pm 6.5	3.9 \pm 3.1	-0.8; \pm 5.0	Unclear
Metabolic efficiency 75%	2.2 \pm 5.5	3.9 \pm 2.9	-1.6; \pm 4.3	Unclear
Metabolic efficiency 85%	0.3 \pm 4.4	3.7 \pm 3.3	-3.3; \pm 3.8	Harmful
Metabolic efficiency 90%	-0.6 \pm 4.5	3.6 \pm 4.0	-4.1; \pm 4.1	Harmful
Power 70% VO ₂ max	4.5 \pm 5.3	3.1 \pm 5.2	1.4; \pm 4.8	Unclear
Power 75% VO ₂ max	3.8 \pm 4.7	2.6 \pm 5.2	1.1 \pm 4.5	Unclear
Power 85% VO ₂ max	2.4 \pm 3.6	1.8 \pm 5.6	0.5; \pm 4.2	Unclear
Power 90% VO ₂ max	1.7 \pm 3.1	1.5 \pm 5.8	0.2; \pm 4.3	Unclear
Calf girth (mm)	-0.4 \pm 1.1	0.5 \pm 1.3	-0.9; \pm 1.1	Unclear
Lactate at 10 km (mM)	2.9 \pm 38.2	15.2 \pm 78	-10.7; \pm 53	Unclear
Lactate at 20 km (mM)	-0.7 \pm 25	-4.9 \pm 1.3	4.5; \pm 21.1	Harmful

Appendix 2. Participant Information Sheet

Study Title

The effect of high-intensity training on cycling performance in competitive trained male cyclists.

Invitation

As a competitive endurance trained cyclist, you are invited to participate in a study, which is investigating the influence of a five-week resistance training intervention. The study will consist of cycle-based resistance exercises previously shown to increase cycling performance.

What is the purpose of the study?

The purpose of this study is to identify which training regime results in maximum increases in physiological measures and cycling performance. The study is part of a masters qualification for one of the researchers, Joe McQuillan.

Can I join the study?

Yes, if you are an injury free competitive endurance-trained male triathlete. If you are cycle training 200km or greater each week and competing once a week at the time of the study you will be considered.

What happens in the study?

Before Training:

You will be one of 20 athletes who will undergo four assessments involving physiological and performance measure's to assess anaerobic power, aerobic fitness, time taken to cycle 20km. These tests will be completed prior to the beginning of the training period. The first day of testing will involve completing an Onset of Blood Lactate Accumulation (OBLA) assessment in order to gauge your blood lactate response to gradual cycle based exercise, this is followed by a incremental step-test to exhaustion to assess your peak cycle power. These assessments will be carried out on a stationary rig, on which your own bicycle will be mounted. Following a short rest period a 30s sprint test on a cycle ergometer will be completed. The second day of testing will involve the completion of a 20km cycling time trial on a stationary rig, on which your own bicycle will be mounted. During this time your VO₂ kinetics will be measured in response to exercise. Following the completion of this test, a blood sample will be taken from your finger.

Resistance Training:

Following the initial assessment of physiological measures and cycling performance, you will be required to complete a five week, supervised, cycle-based resistance training program. The frequency of training will be twice weekly.

The duration of each training session will be 30 minutes. You are expected to maintain your normal training load throughout the duration of this study.

Following Training:

The physiological and performance tests completed before training will be repeated in the same order to determine the effect of the resistance training programme.

What time commitment is needed from me for participation?

All participants are required to complete all tests before and after the training study (2 x 2hr sessions and 2 x 1-hour sessions). Over the five weeks of training, 10 training sessions, each lasting for 30 minutes will be completed (total 5 hours). Total time commitment of 13 hours

What are the discomforts and risks?

The study involves a small degree of discomfort and minimal risk. The nature of the testing procedure requires participants to produce a maximal effort at times during the various assessments. For comparison, the intensity will be similar to that felt at the end of a hard race.

What are the benefits?

Research into the area of resistance training and its effect of cycling and running is limited. The effects of high intensity cycling on stationary cycle ergometers has been proven to significantly increase the peak power output and cycle performance of in-season cyclists. Therefore, further study into the various components that have contributed to this increase in performance is useful for both coaches and cyclists. Personally, you will benefit from participation in this study by having your skinfold, weight, anaerobic cycle power, VO_{2max} , lactate threshold and cycle economy measured and have the opportunity to improve these important measures and your cycling performance via supervised resistance training.

How is my privacy protected?

Confidentiality will be maintained before, during and after the study. Your personal information (e.g. name, contact details and results) will not be disclosed to anyone outside the research team. Raw testing data from the study will be kept for use at a later stage if required. Only the researchers involved with the study will have access to this and participants will be unable to be identified.

Costs of Participating

There will be no costs incurred during the study.

Participant Concerns

If you have any concerns or questions about this study or your participation in it then please don't hesitate to contact the Principal Investigator (Professor Will Hopkins, Division of Sport and Recreation, AUT, Tel: 09 917 9793). If you have any concerns about the conduct of this investigation then contact Madeline Banda, AUTECH, Tel: 09 921 9999).

Appendix 3. Informed Consent

Project Title: The effect of high-intensity training on cycling performance in competitive trained male cyclists.

Principal Investigator: Professor Will Hopkins, Tel: 09 921 9793

Other Researchers:

Joe McQuillan and Andrew Kilding

I have read and understood the subject information sheet for the above titled research project to be conducted by Joe McQuillan at Auckland University of Technology.

This is to certify that I _____ hereby agree to participate as a volunteer in the study described.

- I have read and understand what is required of me as a participation in this study. YES NO (please tick)
- I am aware of the benefits and risks associated with my participation in this study. YES NO
- I am aware that I am free to withdraw my consent at any time without giving reason. YES NO
- I understand that my name will not be associated with the research.
YES NO
- I have been given the opportunity to ask whatever questions I desire and all such questions have been answered to my satisfaction.
YES NO

Participant: _____ Date:

Witness: _____ Date:

Researcher: _____ Date:

Appendix 4. Pre-test Screening Questionnaire

Personal Information

Name..... Date of Birth...../...../..... Gender M F
 Address.....
 Telephone HmWk Mob
 Emergency Contact Name Ph
 Doctors Name Ph

Physical/Medical History

Have you ever had any of the following (please circle):

Serious Infection	Yes/No	Epilepsy	Yes/No
*History of heart problems	Yes/No	Pregnancy	Yes/No
*Increased blood pressure	Yes/No	Asthma	Yes/No
*Heart disease/stroke in the family	Yes/No	Arthritis	Yes/No
*Recent surgery	Yes/No	Cramps	Yes/No
Dizziness/faintness	Yes/No	Physical disabilities	Yes/No
Diabetes	Yes/No	Haemophilia or Anemia	Yes/No
Allergies	Yes/No	Take medication	Yes/No

*Details/Comments.....

Do you currently/previously smoke? Yes/No

Any musculoskeletal injuries.....

Is there any other condition/illness or reason that may affect you ability to perform physical exercise?

Recent Exercise History

Please give details of current physical training. Include details of training type, time, frequency and intensity

What are your current goals?

All information given above shall remain strictly confidential among AUT exercise physiology staff.
 Occasionally information may be shared with medical professionals with your consent.

If the answer to any of the above questions is yes then:

Discuss with the Sport Performance Staff the nature of the problem

Questions indicated by * please provide further details

Signed Date/...../.....

Signature of guardian/parent (if under 18)

Signature of tester..... Date/...../.....

Appendix 5. Study Promotion Poster

WANT TO “**FINE TUNE**” and “**IMPROVE**”
YOUR TRAINING AND PERFORMANCE?

WANT **2 FREE** PHYSIOLOGICAL ASSESSMENTS
TO FIND OUT YOUR **VO₂MAX, LACTATE
THRESHOLD, CYCLING ECONOMY &
BODY COMPOSITION?**

WANT TO BE PART OF A **CUTTING-EDGE,
CYCLE-SPECIFIC, 5-WEEK, SUPERVISED
TRAINING STUDY?**

Are you:

- Male and free from injury?
- Aged 18 - 50?
- Cycling at least 200km/Week?
- Competing on a regular basis in **CYCLING SPECIFIC** events
- No resistance training for the last 6 months?

If you can answer '**YES**' to all of the above then you could be part of a research study at Auckland University of Technology between October and December 2005. If you are interested and would like more details then please contact (ASAP):

Joe McQuillan
Division of Sport & Recreation
Auckland University of Technology
Tel: 09 921 9999 ext 7119 or
Email: joe.mcquillan@aut.ac.nz



Appendix 6. Test Data Collection Sheet



Test: _____

Warm up: _____ Device/Site _____

Date: _____ Time: _____ Baro Pressure: _____ Humidity: _____ Room
Temp: _____

Name/I.D: _____ Age: _____ Weight: _____ Gender: _____

Comments: _____

Time	Power/Speed	Gradient	Lactate	HR	VO ₂	VCO ₂	RPE
Resting							

Appendix 7. Request for Petrol Vouchers

30 November 2005

RE: PETROL VOUCHERS FOR SUBJECTS

Hi Will

As discussed previously I'd like to request the following amount in petrol vouchers for the 16 subjects in my study titled The Effect of High Intensity Training on Competitive Male Cyclists. All the subjects receiving vouchers completed the full training study and all testing requirements. This meant that each subject made at least 16 visits to the AUT/MISH Sport Science Lab over the course of the study.

The breakdown for costs are based on the travel from the home address of the subject:

The allocation will be \$75 for the shore based subjects and \$125 for the city based subjects.

North Shore = 6 x \$75 = \$450

City = 10 x \$125 = \$1250

Total = \$1,700

Thanks for your help with this

Joe McQuillan