Master's thesis

NTNU
Norwegian University of Science and Technology
Faculty of Medicine and Health Sciences
Department of Circulation and Medical Imaging

Madison Taylor

The inclusion of sprint-interval training during the recovery period of competitive cyclists: immediate versus residual effects on endurance and sprint performance

Master's thesis in Exercise Physiology
Supervisor: Arnt Erik Tjønna and Prof. Øyvind Sandbakk
June 2018

NTNU
Kunnskap for en bedre verden

Madison Taylor

The inclusion of sprint-interval training during the recovery period of competitive cyclists: immediate versus residual effects on endurance and sprint performance

Master's thesis in Exercise Physiology
Supervisor: Arnt Erik Tjønna and Prof. Øyvind Sandbakk
June 2018

Norwegian University of Science and Technology
Faculty of Medicine and Health Sciences
Department of Circulation and Medical Imaging

NTNU
Norwegian University of
Science and Technology

ABSTRACT

Introduction: The annual training program of competitive cyclists is traditionally broken into the competitive-, recovery-, and preparatory period. During the recovery period, cyclists dramatically reduce their training volume and emphasis is placed on low intensity training (LIT). Previous research has shown a decline in endurance performance and loss of physiological training adaptations during this period. However, sprint-interval training (SIT) could be a potential time efficient strategy for maintaining endurance and sprint performance in trained athletes during the recovery period, with could provide benefits in the subsequent preparatory period. ***Aim*****:** The aim of the current thesis was to investigate the effects of incorporating one weekly SIT session versus focusing solely on LIT during the 3-week long recovery period on endurance and sprint performance in competitive cyclists. A secondary aim was to examine the effects of these two training strategies 6-weeks into the subsequent preparatory period. ***Methods:*** 11 competitive male cyclists completed a series of performance tests directly following the competition season (pre-test), immediately after a 3-week long recovery period (post-test), and 6-weeks into the subsequent season (re-test). The SIT group (SIT, $n = 5$) included one SIT session per week during the 3-week long recovery period, while the LIT group *(*LIT, $n = 6$) focused only on LIT during this period. There were no differences between groups in terms of training load leading up to the recovery period or in the subsequent preparatory period. ***Results:*** Both groups were equally able to maintain maximal oxygen uptake (VO_{2max}), peak aerobic power (W_{max}), power output @ 4 mmol L^- [La^-], and power output during a 20 minute all out trial (PO_{20min}) during the recovery period, and the inclusion of SIT provided no immediate advantage. However, in the absence of a high intensity training stimulus during the recovery period the LIT group experienced a significant decline to repeated sprint ability compared to the improvement seen in the SIT group following this period. 6-weeks into the subsequent preparatory period, the SIT group demonstrated a 7% improvement to PO_{20min} from their pre-test value, which was larger than the unchanged performance in the LIT group. ***Conclusion:*** The present findings suggest that the inclusion of one weekly SIT session during the recovery period provided a residual performance advantage 6-weeks into the subsequent preparatory period, increasing the likelihood of performance improvements from the end of the competitive season to the subsequent preparatory period.

ACKNOWLEDGEMENTS

I would first like to thank my two thesis supervisors; senior engineer Arnt Erik Tjønna and professor Øyvind Sandbakk for their invaluable support, guidance and wisdom throughout this project. Arnt Erik Tjønnas good humor, valuable feedback and unwavering trust throughout this thesis gave me the confidence to pursue this project whole-heartedly. The responsibility he placed on me was intimidating but vital for my growth as a student and researcher. And professor Øyvind Sandbakk, whose support during the writing process of this thesis was fundamental. He consistently allowed me to explore the research and data in a variety of directions while patiently steering me in the right course, faultlessly offering the perfect words of advice when things went just a little bit too far (i.e. two pages of text about blood volume). I am sincerely grateful for the privilege of working with both of you.

Besides my supervisors, I would also like to acknowledge Knut Skovereng for his support in the lab and during the processing and analyses of the raw data. He was incredibly patient and generous with his time throughout this project. Also, I would like to thank all of the employees and students at the Center for Elite Sports Research (SenTIF) and Olympiatoppen in Trondehim, Lillehammer, Bergen and Kristiansand, Norway for their involvement in the execution of this multi-center study. Thank you as well to the athletes who took part in this project. I hope that these findings may benefit you in the pursuit of your goals as an elite athlete and may be used by future generations of Norwegian champions.

Finally, I must express profound gratitude to my friends and family. Particularly, to my parents and brother for their constant, love, support and encouragement throughout this process. And in loving memory of my grandparents, Ruth and Harvey Zindler for their commitment to furthering my education and making this opportunity possible for me. I am forever grateful, and I dedicate this project to you.

With gratitude to everyone involved, I am completing this master's thesis, delivering a product I feel incredibly proud of and will move forward feeling inspired to continue researching and contributing to the understanding of athlete development.

Thank you.

TABLE OF CONTENTS

ABSTRACT .... **I**

ACKNOWLEDGEMENTS .... **III**

FREQUENTLY USED ABBREVIATIONS .... **VII**

1.0 INTRODUCTION **1**

1.1 Determinants of Cycling Performance 1
1.1.1 Endurance Performance *2*
1.1.2 Sprint Performance *5*
1.2 Training Load Quantification 6
1.3 Cycling Season 7
1.4 Reduced Volume Training Strategies 9
1.5 Aim and Hypothesis 11

2.0 METHODS **13**

2.1 Study Design 13
2.2 Subjects 14
2.3 Training 14
2.4 Experimental Procedures 16
2.5 Statistical Analysis 19

3.0 RESULTS **21**

3.1 Training Characteristics 21
3.2 Baseline Characteristics 22
3.3 Body Mass 22
3.4 VO2max and Wmax 24
3.5 Threshold and Gross Efficiency 25
3.6 Sprints 26
3.7 Endurance performance 27

4.0 DISCUSSION **29**

4.1 Main Findings 29
4.2 Recovery Period 29
4.3 Preparatory Period 32
4.4 Methodological Considerations and Future Perspectives 36
4.5 Practical Applications 37

5.0 CONCLUSION **38**

REFERENCES **39**

FREQUENTLY USED ABBREVIATIONS

GE	gross efficiency
HIT	high-intensity training
HR	heart rate
$[La^-]$	concentration of blood lactate
LIT	low-intensity training / low intensity training group
LT	lactate threshold
MIT	moderate-intensity training
PO	power output
PO_{6sec}	power output during 6-sec ‘all out’ sprint
PO_{20min}	average power output during 20-min ‘all out’ trial
PO_{Win4}	power output during 4 repeated 30-sec Wingate sprints
PRE-TEST	refers to the initial performance test following the end of the competition season
POST-TEST	refers to performance test following the 3-week long recovery period
RE-TEST	refers to the performance test 6-weeks into the subsequent preparatory period
SIT	sprint-interval training / sprint-interval training group
VO_2	oxygen uptake
VO_{2max}	maximal oxygen uptake
W_{max}	peak aerobic power output
W	watt

1.0 INTRODUCTION

Competitive road cyclists endure a very long and intense season, training up to 11 months a year and cycling about 35,000 km each season [1, 2]. The typical season of a competitive cyclist is broken into 3 distinct training periods; preparatory, competition and recovery (Figure 1). Preparatory training starts in the end of November or early December, and the competition seasons generally runs from July through to the end of September [1-4]. In the weeks after a competition, cyclists enter the recovery period, with the intention of promoting physical and mental recovery. During this period the athlete tends to decreased both training volume and intensity, while others may even adopt a nearly sedentary lifestyle [3, 5, 6]. Several investigators have observed lower performance levels, and the loss of physiological adaptations after the recovery period [1, 6-8], yet there are currently no accepted training recommendations specifically for this period.

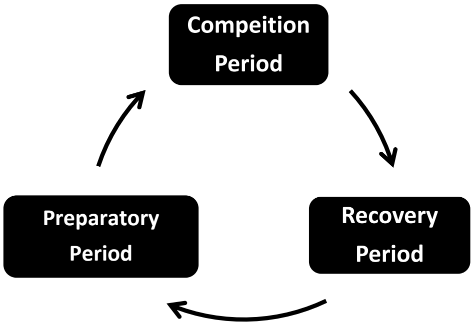

***Figure** 1.* Illustration of the annual training periods of a competitive cyclist.

1.1 Determinants of Cycling Performance

Cycling includes many competition styles, ranging from 1-day long classics to 3-week long tour races. Races require the athlete to endure long duration rides on both flat and uphill sections while also demanding many high intensity sprints for breakaways, starts and finishes [3, 9-11]. Competitive cycling performance involves a complex interaction of physiological (i.e VO_{2max}, LT, work economy), psychological (motivation), environmental (wind, temperature, altitude), mechanical (type of bicycle, wheels and tires) and tactical factors (sprinting and pacing strategies) [11]. While cycling is considered an aerobic endurance sport, it also requires a significant contribution from anaerobically derived energy to successfully perform the repeated sprints required for a winning performance. [3, 12-14]. For these reasons, this thesis will focus on the physiological adaptations associated with endurance and sprint performance. These variables have been summarized in Figure 2.

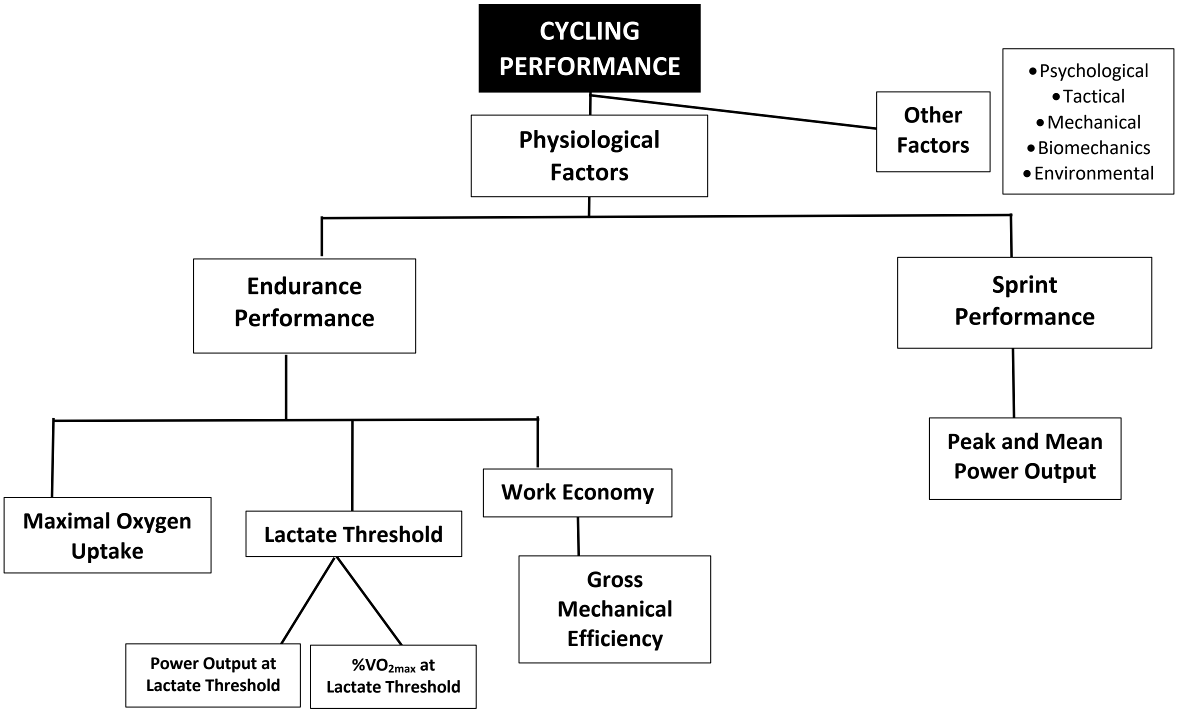

Figure 2. Hypothetical model of functional and physiological variables associated with endurance and sprint performance of competitive cycling. Adapted from Coyle et al (1995), Basset et al (2000), and Joyner and Coyle (2008).

1.1.1 Endurance Performance

At the core of endurance performance is the body's ability to produces and use metabolic energy. Specifically, the body's ability to supply the working muscles with oxygen, and those muscles ability to meet the demand for ATP via oxidative phosphorylation. Maximal oxygen uptake (VO_{2max}) describes the body's ability to use oxygen during maximal exercise and is one of the most common variables used in the literature to describe aerobic fitness and demonstrate training effect [15]. Elite endurance athletes often display VO_{2max} values 50-100% greater than those seen in healthy young subjects with male professional cyclists possessing values in the range of ~65-80 mL kg^{-1} min^{-1} [1, 11, 16]. The Fick equation defines VO_{2max} as the product of maximal cardiac output (Q_{max}) and arteriovenous oxygen difference ($a\text{-}vO_{2diff}$), describing the complex interrelationship between centralized 'supply' factors and peripheral 'demand' factors. Supply factors that could limit VO_{2max} include; maximal cardiac output and the oxygen carrying capacity of the blood, and demand factors refer to

Simplified Fick Equation

$$VO_{2max} = Q_{max} \bullet a\text{-}vO_{2diff}$$

Q_{max}= Stroke Volume • Heart Rate

$a\text{-}vO_{2diff}$ = arterial oxygen content – venous oxygen content characteristics of the skeletal muscle (such as capillary and mitochondrial density and muscle oxidative capacity)[15]. Given that there is much less variation in maximal HR and systemic oxygen extraction between trained and untrained individuals, it is generally agreed that limitations to VO_{2max} in trained subjects is a results of a supply limitation, as opposed to a peripheral demand limitation [15, 17, 18]. Specifically, stroke volume is largely considered the main physiological adaption contributing to the high VO_{2max} value of elite athletes, as many elite athletes have been observed to have ~50% greater stroke volume than their sedentary counterparts [15, 19]. Other 'trainable' physiological adaptions associated with VO_{2max} include; increased blood volume, capillary density and mitochondrial density, oxidative enzyme activity and muscle fiber type composition [15, 20-22].

While a high VO_{2max} is regarded a prerequisite for competing at a high level, it does not tell the whole story. Athletes with similar VO_{2max} values can have significant differences in performance. For example; Coyle and Coggan [23] observed a more than six-fold difference in performance (time to exhaustion at 88% of VO_{2max}) amongst a group of endurance trained cyclists who all had similar VO_{2max} values. In some cases, training interventions have improved performance without eliciting changes to VO_{2max} [24, 25]. It is important to recognize that cyclists do not actually spend much time competing at maximal VO_2. In fact, Fernandez-Garcia et al [14] reported that during the 1996 Tour de France cyclists only spent less than 20% of total race time at an intensity above 90% of VO_{2max}, and more than 60% of the competition was spent in an intensity range of 50-90% of VO_{2max} (Figure 3). While a high VO_{2max} explains an athletes upper limit for oxygen uptake, it is not strongly correlated with race performance at this level [15, 23, 26]. Instead, we should consider factors influencing the ability to sustain performance power over a long time-period such as the lactate threshold (LT) and work economy.

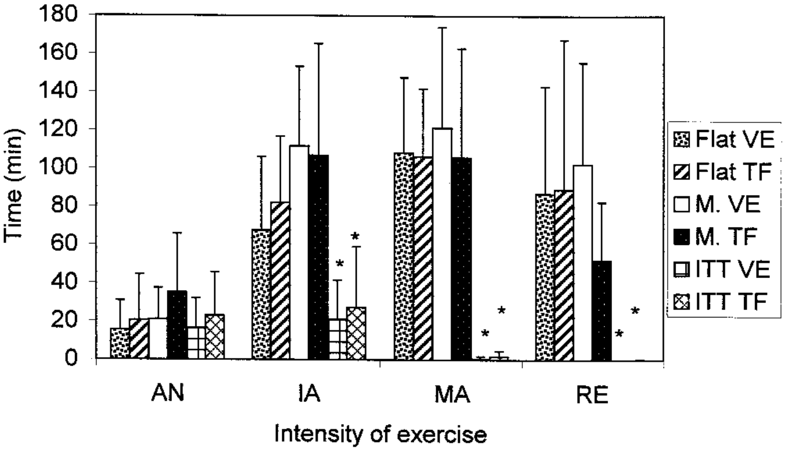

Figure 3. Intensity of exercise during Vuelta (VE) and the Tour de France (TF) in flat, mountainous (M), and individual time trial (IIT). Intensity zones; Anaerobic (AN), Intense Aerobic (IA), Moderate aerobic (MA) and Recovery (RE). Borrowed from Fernández-García et al (1999).

The LT refers to the moment at which the production of lactate exceeds its rate of removal. The exponential rise in blood lactate signals a shift toward anaerobic energy production once oxygen supply is no longer sufficient to meet the needs of the working muscles [27]. While the exact effects of lactate accumulation are subject to ongoing debate it is clear that the accumulation of hydrogen ions negatively affect the muscles ability to contract and ultimately results in fatigue [27]. Long term endurance training can induce improvements to power output, speed or fractional utilization of VO_{2max} ($\%VO_{2max}$) at LT. These improvements are linked to increases in mitochondrial enzyme activity, increased number of mitochondria or use of a larger muscle mass [15, 22, 23]. While maximal effort (i.e. VO_{2max}) is generally limited by centralized adaptations, submaximal performance variables are linked primarily to peripheral adaptions in the muscle [22].

The absolute value of blood lactate does not tell us much about an individual's potential for endurance performance, but when LT values are expressed relative to VO_{2max}, velocity or PO it is seen to be strongly correlated to endurance performance [15, 23, 27, 28]. Untrained individuals experience the LT around 50-60% of VO_{2max} while elite cyclists have been reported to have a LT around 80-90% of VO_{2max} [16, 29, 30]. The ability to maintain a high $\%VO_{2max}$ at LT is manifested as the capacity to meet the energy demands of high intensity work through aerobic pathways, which provides sustainable and long lasting energy [15]. When VO_{2max} was controlled for Coyle et al [23] found that endurance performance was most significantly related to $\%VO_{2max}$ at LT ($r = 0.90$), suggesting that $\%VO_{2max}$ at LT is a more accurate means of predicting performance than reporting solely on VO_{2max}. This relationship has been further established in more recent investigations such as; Borszcz et al [28] who identified a strong correlation between PO at LT and 60-minute time trial ($r = 0.82$), and Clark et al [31] who established a similar relationship on a stimulated 20-km rolling terrain course ($r=0.80$). Both LT and VO_{2max} interact to determine how long one can perform at a given intensity.

Work economy describes the oxygen cost of performing at a given submaximal speed or PO and also helps explain some of the variability in cycling performance. When cycling at a given PO oxygen cost can vary by as much as 15 – 20% between individuals [32]. Exercise performance is greatly influenced by economy as those who are able to generate more power or speed for the same oxygen cost (or inversely, those who use less oxygen to produce the same power) will have a performance advantage. Similarly, gross mechanical efficiency (GE), describes the bodies efficiency at converting ATP in physical work, and is expressed as the ratio of work accomplished to energy expended [16]. A high mechanical efficiency is manifested as a lower rate of ATP utilization, and thus lower VO_2 during a submaximal activity [32]. Generally speaking approximately 80% of chemical energy is lost as heat, while ~20% can be used for physical work [29]. It has been reported that the GE of endurance trained cyclists can vary from ~18% to ~26%, with professional cyclist likely displaying a higher GE [33-36].

1.1.2 Sprint Performance

Cycling is unique in that it is not strictly an aerobic endurance sport, performance velocity and PO are highly variable during competitions [13]. A cyclists ability to produce explosive power is essential for climbing, sprinting, starting and finishing a race [2, 3, 11, 13]. PO varies dramatically throughout the race, requiring riders to produce maximal PO for a race-specific periods of time, with many races being decided with a sprint finish [37]. As seen in Figure 4, each race component requires multiple high intensity sprints above maximal power output, and PO can range from 0 to 1665 W throughout the race [13]. In fact it is not uncommon that the winner of multi week long tours finishes in first by only 200 – 400 seconds, which equates to only 0.07-0.13% of the total race time [11], suggesting that high level competitive races can be won or lost with a strong sprint capacity.

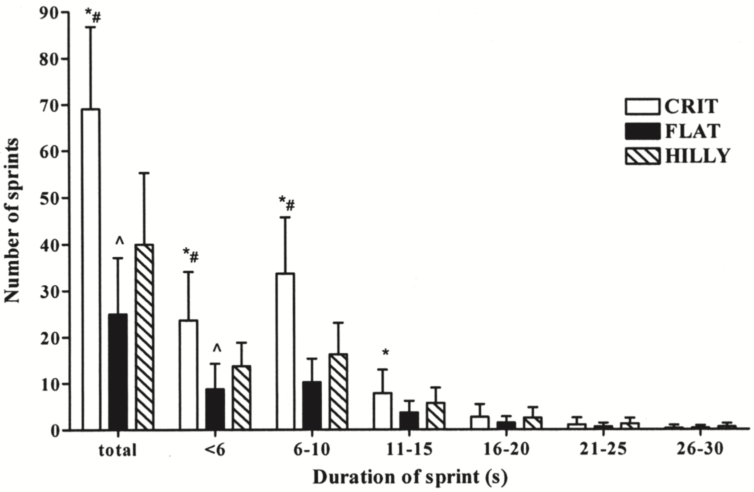

Figure 4. Duration and number of sprints above maximum aerobic power output for short circuit races (CRIT), flat (FLAT) and hilly (HILLY) stages of the the Tour Down Under. (*) CRIT > FLAT. (#) CRIT > HILLY. (^) HILLY > FLAT. $p < 0.05$. Borrowed from Ebert et al (2006).

These moments of intense efforts stress the anaerobic system, with energy being supplied from two main energy sources; phosphocreatine (PCr), and anaerobic glycolysis. PCr provides the most readily accessible energy source. The peak PO of the PCr system (~10 – 18 W kg^{-1}) is reached within the first 2-5 seconds of maximal effort, and becomes depleted within 10 – 30 seconds resulting in a steady decline in peak PO the longer the effort continues [38-40]. ATP can also be readily supplied via anaerobic glycolysis at a slightly lower PO. It is assumed there is a fixed amount of energy available through these anaerobic pathways, and this energy is likely maximally expended within a few minutes [39, 40]. Thereafter, the accumulation of lactate and hydrogen ions decreases the intracellular pH of the cell and ultimately affect the muscles ability to contract and generate force [27, 41]. For this reason, a cyclist must carefully consider the initiation of a sprint as there will be a gradual reduction of power the longer they sustain the sprint [42, 43]. Improved endurance fitness is associated with enhanced PCr resynthesis, which is further linked to the recovery of peak power output (PO) during repeated sprints [38]. This endurance adaptation enables the cyclists to have repeated moments of enhanced PO and is essential for fast paced breakaways and strong finishes during competition.

Anaerobic capacity is traditionally assessed using short duration, supramaximal sprints. The most common of these test is the Wingate test, a 30-sec supramaximal test against a predetermined resistance [2, 39, 44]. From the Wingate test peak and mean PO can be determined [44]. Surprisingly, Wingate test results on trained cyclists are quite limited in the literature, especially considering it is a sport-specific test [45-47]. The United States Cycling Federation reported peak PO values during a Wingate between 12.8 to 13.9 W/kg and mean PO between 10.4 to 11.2 W/kg, with higher values attributed to higher ranked cyclists [45]. Interestingly, when the peak and mean Windgate PO values of competitive male cyclists are compared with other well-trained athletes competitive cyclists routinely produce the highest Wingate test results, ranking in the 'elite' category for peak anaerobic PO [48]. This further highlights the importance of a high PO to cycling performance.

With the advancement of power meters in the recent years there has been a dramatic shift towards the use of PO variables for describing the demands of cycling [13, 49, 50], as well as prescribing and monitoring training [13, 49, 50]. This has led to an increased interest for published research on power variables in professional cycling. Some recent studies have shown correlations with anaerobic capacity and cycling performance [51-53]. Notably Davison et al [53] found that the Windgate average PO per unit of body mass was the strongest individual predictor of hill climb performance (6 km with 6% incline, r= –0.90; 1 km with 12% incline, r = –0.92), and Inoue et al [52] found significant correlations between the peak and mean power of a repeated Wingate test and race time in mountain bike cross country performance (r= 0.79 and 0.63 respectively). However there is a general lack of current research exploring the relationship between anaerobic capacity and endurance performance, so further research in this area is highly encouraged.

1.2 Training Load Quantification

In order to achieve the best performance, a cyclist must develop an annual training strategy that carefully manipulates the training load over the course of the season, combining periods of low, moderate and high intensity training with periods of rest and recovery. Understanding the stress that a training session puts on an athlete is critical to designing, monitoring and manipulating training programs both with respect to peaking performance but also to reduce the risk of overtraining [54].

Heart rate (HR) based methods for monitoring training load the most are common method for monitoring training intensity, as HR equipment is inexpensive and reliable, and HR_{max} remains fairly stable throughout the season [8]. Various HR-based methods have been proposed to quantify training load, one of the most widely used being the training impulse (TRIMP) method originally proposed by Banister [55]. The TRIMP method has been used as a means for quantifying an elite athletes response to training load [56-59]. The TRIMP score is computed from exercise duration and average HR achieved during the session.

$$\text{TRIMP (AU)} = \text{time} \times \Delta\,\text{HR} \times y$$

The change in HR (ΔHR) (expressed as; ($HR_{exercise}$ − HR_{rest} / HR_{max} − HR_{rest})) is weighted by a multiplying factor (*y*) to reflect exercise intensity. The product, expressed as arbitrary units (AU), can then be used to characterize exercise intensity and training load over the course of a training session, competition or season [60]. The TRIMP method was further advanced by Manzi et al [60] to be more sensitive to individual variations by introducing an individual weighting factor (y_i) which is calculated for each subject as a reflection of their HR response and blood lactate response curve. *i*TRIMP have been shown to be an effective means of quantifying training load for improving fitness and has a strong relationship to performance.

1.3 Cycling Season

The annual training program of a competitive cyclists is traditionally comprised of three distinct periods; the competition period, the recovery period, and preparatory period.

Competitive cyclists have a long competitive season, generally competing from July through to the end of September, during with a competitive cyclist may accumulate over 90 days of competition [1, 2, 4]. Lucia et al [1] reported that during the competition season competitive cyclists trained an average of 810 km/week, with an intensity distribution of 76.8% LIT, 15.1% MIT, and 8.1% HIT (Figure 5). During the competition period cyclist must sustain a high level of peak fitness, so they are

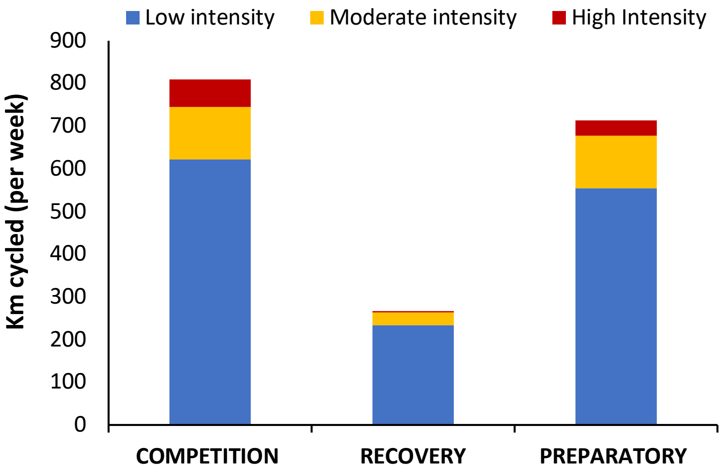

Figure 5. Graphical representation of training volume and percentage of time spent at each intensity during the different periods of the cycle season of competitive cyclists. Low intensity; heart rate lower than 150 beats min^{-1}. Moderate intensity; 150 to 175 beats min^{-1}. High intensity; heart rate higher than ~175 beats min^{-1}. Adapted from data presented by Lucia et al [1].

adequately prepared for the numerous races they will compete in each season.

Following the competition season, competitive cyclists are encouraged to take 3-6 weeks of rest to promote physical and mental recovery. Traditionally they decrease training volume by 60-80% and execute most training at a low intensity [1, 3, 4]. Some authors have even suggested that cyclists take on a sedentary lifestyle during these periods of recovery [1, 6]. It is common to see a performance decline following periods of reduced training. Several investigators have observed lower fitness levels after the recovery period then the end of the pervious competition season [1, 6, 8, 59, 61]. For example; in a recent report Maldonado-Martin et al [6] found that after 5 weeks of training cessation, top level road cyclists experienced significant declines to most physiological performance markers such as; VO_{2max} (-10.8%), maximal power output (-8.5%) and power at LT (-13.4%). Figure 6 summarizes some of the physiological changes associated with the cessation of training. These changes include; an immediate decline of blood volume and stroke volume [21, 62, 63] which can result in up to a 20% reduction to VO_{2max} [6, 21, 59, 62, 64], reduced oxidative capacity [62], arterio-venous VO_2 difference [21], declines to peak aerobic PO [6, 62, 65, 66] and other important performance markers (i.e time to exhaustion or endurance capacity) [4, 7, 64, 67-70]. Athletes can also experience higher blood lactate concentrations following submaximal and maximal exercise [67, 68, 70-73] and an increase in respiratory exchange ratio (RER) [62, 69, 71, 72], indicative of a shift towards decreased reliance on fat oxidation and an increased reliance on carbohydrates which could have significant performance implications on road cyclists as substrate utilization is critical for successful pacing strategies.

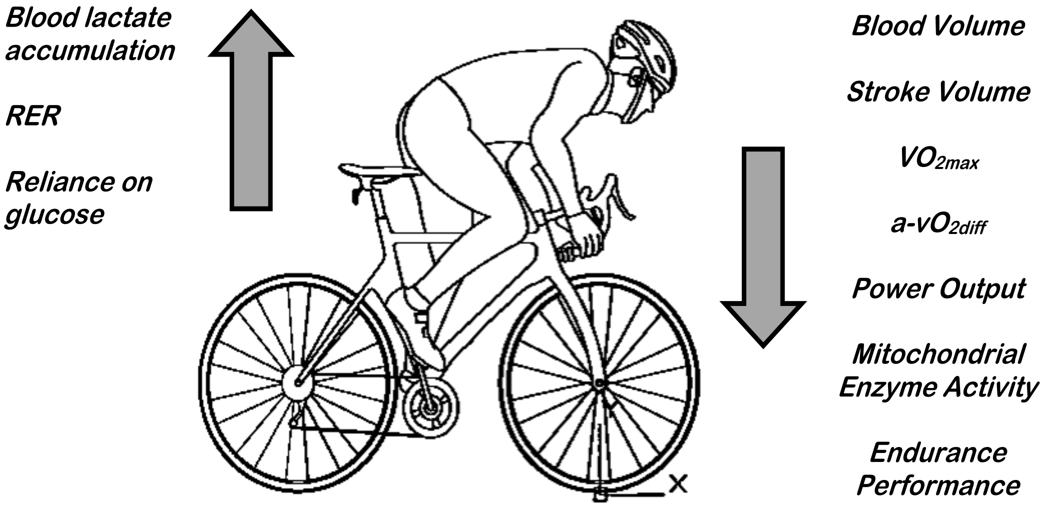

Figure 6. The potential cardiorespiratory, neuromuscular and metabolic effects associated with the cessation of training for athletes. Directions of arrows indicates increase or decrease of each physiological component.

The preparatory period follows the recovery period and is very important part of an athlete's season. Training volume increases significantly, and the athlete works to regain their performance status. The athlete spends more time training time at a high intensity, and increases total training time to 10+ hours per week [5, 59]. Sassi et al [4] reported that VO_{2max}, maximal aerobic power output (W_{max}) and predicted time to exhaustion improved significantly from the end of the recovery period to the competition season [4]. Lucia et al [1], Paton and Hopkins [61], and Zapico [74] have also shown steady improvements to performance variables from the end of the recovery period through to the competition season. It has previously been suggested that following periods of training cessation there is likely an initial rapid fitness improvement upon retraining, which will inevitably slow, so that retaining to an athletes previous competitive status could take up to twice the amount of time that was spent detraining [65, 70]. While, it is quite clear that the preparatory period serves as an important time for the athlete to regain (and ideally improve) their physical fitness from the past competition season, it remains unclear how training strategies during the recovery period could affects an athlete's ability to recapture performance in the subsequent season.

1.4 Reduced Volume Training Strategies

It has long been suggested that the performance decline should be minimized during periods of reduced volume training [62, 66], yet there are no accepted recommendations of reduced training strategies during the recovery period and there is a general lack of information on the effects of reduced training on endurance and sprint performance. Currently it is common for cyclists to adopt a low volume, low intensity strategy during this period [1, 4, 61]. However, it appears that the low volume required for proper recovery does not provide enough stimulus for the athlete to maintain key physiological adaptations associated with cycle performance [1, 4, 59]. In a recent study [59], well-trained cyclists were randomized into either a traditional low intensity (LIT) group or an experimental group that did one high intensity (HIT) session every 7-10 days during an 8-week long recovery period. It was observed that the LIT group experienced declines to VO_{2max}, W_{max}, $\%VO_{2max}$ at 4 mmol L^{-1} [La^{-}] and performance (40-minute all out power), while the HIT group was able to maintain or improve these variables during the same time period. Interesting, they also found those who were able to maintain 40-minute all out cycle performance (40-minute all out power) during the recovery period were able to improve their performance from before the recovery period to the beginning of the subsequent season, while those who experienced a performance decline over the recovery period did not see the same improvement (Figure 7). García-

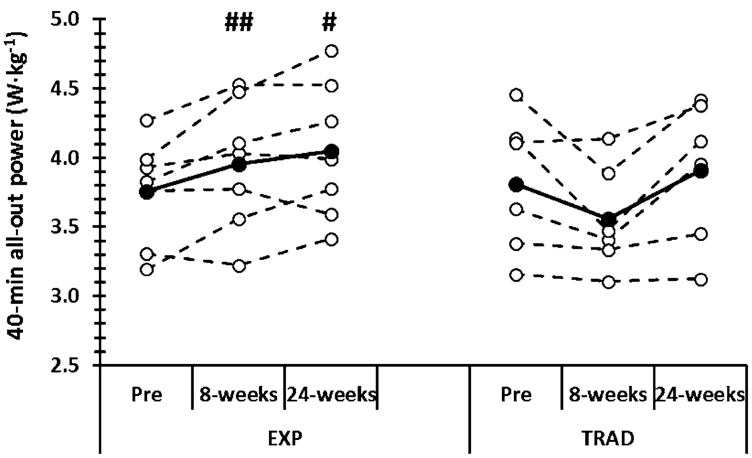

Figure 7. Graphical representation of individual data points and mean values (solid line) before the recovery period, after the recovery period (8 weeks), and 16 weeks into the subsequent season (24 weeks) in a group performing 1 HIT session every 7-10 days (EXP) and a group that focused on low intensity training (TRAD). (#) likely between group difference from pre-test. (##) very likely between group difference from pre-test. Borrowed from Rønnestad et al (2014).

Pallares et al [64] introduced a reduced volume training strategy of two weekly 40 minute moderate intensity (~80% of VO_{2max}) training sessions during a 5-week long recovery period of top level kayakers, and observed these athletes experienced a decline to VO_{2max}, and important performance markers (i.e. paddling speed and power). This suggests that the moderate intensity stimulus was not strong enough to maintain aerobic performance in highly trained athletes, and further highlights the importance of incorporating high intensity training into the reduced training strategy of well-trained athletes.

Sprint-interval training (SIT) is characterized by short (~30 seconds) and repeated supramaximal, or 'all-out' efforts at an intensity equal to or greater than VO_{2max} [75, 76]. The purpose of SIT is to repeatedly stress the physiological systems to a greater extent than what would actually be required for a specific exercise in order to induce central and peripheral adaptations that improve performance [77]. SIT significantly stresses both the aerobic and anaerobic system, and induce improvements to endurance and sprint performance variables in groups of highly trained athletes [24, 77-79]. Both Laursen et al [78] and Stepto et al [79] reported improvements to VO_{2peak}, W_{max} and 40-km TT following a 3 or 4 week SIT intervention (12 x 30 seconds at 175% peak PO) in groups highly trained cyclists. Interesting, Rønnestad et al [80] reported greater improvements to VO_{2max}, peak and mean PO during a 30-sec Wingate test and mean PO during a 40-min all out TT following a 10-week SIT intervention compared to an effort matched HIT group with competitive male cyclists. SIT interventions have been shown to increase oxidative enzyme activity [25, 81], decreased VO_2 at submaximal intensities [24], improve motor unit recruitment and muscle coordination [82] peak and mean aerobic PO [78-80], and endurance performance [83]. Given the success of HIT as a low volume training strategy it seems appropriate to consider how the addition of a low volume supramaximal sprint intervention (SIT) during the recovery period could support the maintenance of performance adaptations in highly trained athletes.

A commonly cited advantage of SIT training is that it involves a relatively low time commitment [24, 25, 76, 79, 81, 84, 85]. Iaia and Bangsho [24] found that endurance trained runners were able to maintain performance (10-km run time) with the inclusion of 30-second sprint intervals despite a 65% reduction in total training volume during a 4 week intervention. And Gibala et al [84] observed a decrease in time to complete a 50kJ and 740kJ time trial (-10.1% and -4.1%) as well as increase in W_{peak} during the 50 kJ and 740 kJ time trial (+ 10.4 and 4.4%) with just 6 SIT sessions over 2 weeks. These results were similar to those observed in the matched LIT group, despite a 90% difference in total training volume (6500 kJ vs 630 kJ) and a 130% difference in total training time (630 mins vs 135 mins). And recently, Paquette et al (2017) concluded that SIT training resulted in identical improvements to VO_{2max} and W_{max} despite requiring only half the total time at the target intensity as the HIT intervention [85].

While the scale for performance improvement in endurance-trained athletes is quite low, it appears that SIT training provides a sufficient and time efficient stimulus to generate important improvements for trained cyclists. The cited improvements associated with SIT show the potential to serve as an adequate training stimulus for the maintenance of critical endurance and sprint performance variables during the recovery periods. To the best of my knowledge, the inclusion of SIT has never been investigated in regard to the recovery period of athletes, and it remains unclear how this training strategy could affect long-term performance once the training volume increases again during the preparatory period.

1.5 Aim and Hypothesis

The primary aim of the present study was to investigate; (1) the effect on endurance and sprint performance of incorporating one weekly SIT session into the training strategy of competitive cyclists during the 3-week long recovery period compared to the traditional approach of focusing solely on low-volume LIT; (2) the effect these two training strategies have on endurance and sprint performance 6-weeks into the subsequent preparatory period.

Based on previous findings, the hypothesis of the present study is that the inclusion of 3 SIT sessions during the recovery period would result in a better maintenance of performance and physiological factors associated with endurance and sprint performance during the recovery period, and this will be further reflected by the SIT group experiencing larger performance improvements 6-weeks into the subsequent preparatory period.

2.0 METHODS

2.1 Study Design

The present study was completed in two phases over a 13-week period (Figure 8). Phase one monitored the athletes training load for the final 4-weeks of the competitive season (lead in period) during the month of September. An initial performance test (pre-test) was completed in late September within the first week following the last competitive race of the season. The subjects were allocated to a sprint training group (SIT) or low intensity group (LIT) for the 3-week long intervention period, during which both groups reduced their training load by 60 to 80%. Following the recovery period a second performance test was completed (post-test). Phase two continued to monitor the cyclists training for an additional 6-weeks into the subsequent preparatory period. These training sessions were recorded; however no instructions were given to the coaches or athletes in regard to training load, intensity or recommended sessions.

The current study was executed concurrently at four Olympic Training Centers in Norway, Trondheim, Lillehammer, Bergen and Kristiansand. The same equipment was used at all four centers (details below), with standardized procedures. Each participant was tested on the same equipment, by the same test lead following identical test protocol for the pre, post and re-tests at their respective location.

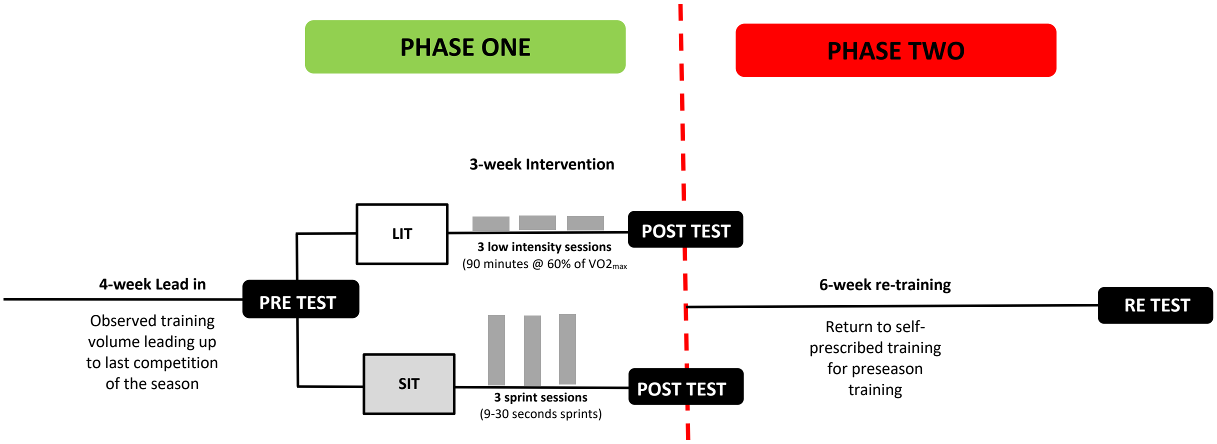

Figure 8. Illustration of study design. Phase one, initial 7 weeks of the study. Pre-test; initial performance test at the end of the competitive season. Post-test, performance test following 3-week recovery period. Phase two, monitored athlete for an additional 6-weeks into the subsequent preparatory period. Re test, final performance test. SIT, sprint interval group. LIT, low intensity group

2.2 Subjects

Twenty-one competitive male cyclists were recruited for this study, sixteen completed phase one and twelve agreed to participant in phase two; eleven road cyclists and one mountain biker. Subject inclusion is presented in Figure 9. Cyclists were considered well trained based on the recommendations of Jeukendrup et al [11], which include a high $VO_{2max,}$ W_{max}, power to weight ratios and training frequency. All cyclists had a competed for a minimum of 3 years and had previously performed similar or identical tests in the laboratory. After giving informed written consent the cyclists were allocated into the sprint (SIT) group, or a low intensity (LIT) group. Subject characteristics are presented in Table 1.

The study was performed according to the ethical standards established by the Helsinki Declaration of 1976, approved by the Norwegian Social Science Data Services (NSD) and the local ethical committee at Lillehammer University College, and the participant provided written informed consent to participate in the study.

Table 1. Anthropometric data for SIT group, LIT group and total group.

	SIT *(n=5)*	**LIT** *(n=6)*	**Total** *(n=11)*	**Range**
Age (years)	23.1 ± 3.1	21.0 ± 4.3	22.0 ± 3.8	[17.8 – 26.9]
Weight (kg)	73.7 ± 6.7	72.4 ± 5.6	73.0 ± 5.8	[63.2 – 83.9]
$\mathbf{VO_{2max}}$ ($L\ min^{-1}$)	5.4 ± 0.3	5.0 ± 0.5	5.2 ± .5	[4.2 – 6.0]
$\mathbf{VO_{2max}}$ ($mL\ min^{-1}\ kg^{-1}$)	74.5± 5.4	69.3 ± 3.7	71.7 ± 5.1	[64.4 – 80.1]

Data presented as mean ± standard deviation and range [minimum value – maximum value]. n, Number of participants. VO_{2max}, maximal oxygen uptake. SIT, sprint interval group. LIT, low intensity group.

2.3 Training

The cyclists recorded all training sessions during the 13-week period using their personal HR monitors. HR monitors were set up to automatically sync each session to TrainingPeaks.com with second by second recordings of their HR response for each session. Total training load, expressed in arbitrary units (AU), was calculated based on Manzi et al [60] approach of individualized training impulse (iTRIMP) analysis. iTRIMP was computed from the HR response, as the average value of each 5 seconds, exercise duration and weighted against an individual weighting factor (y_i) which is calculated for each subject as a

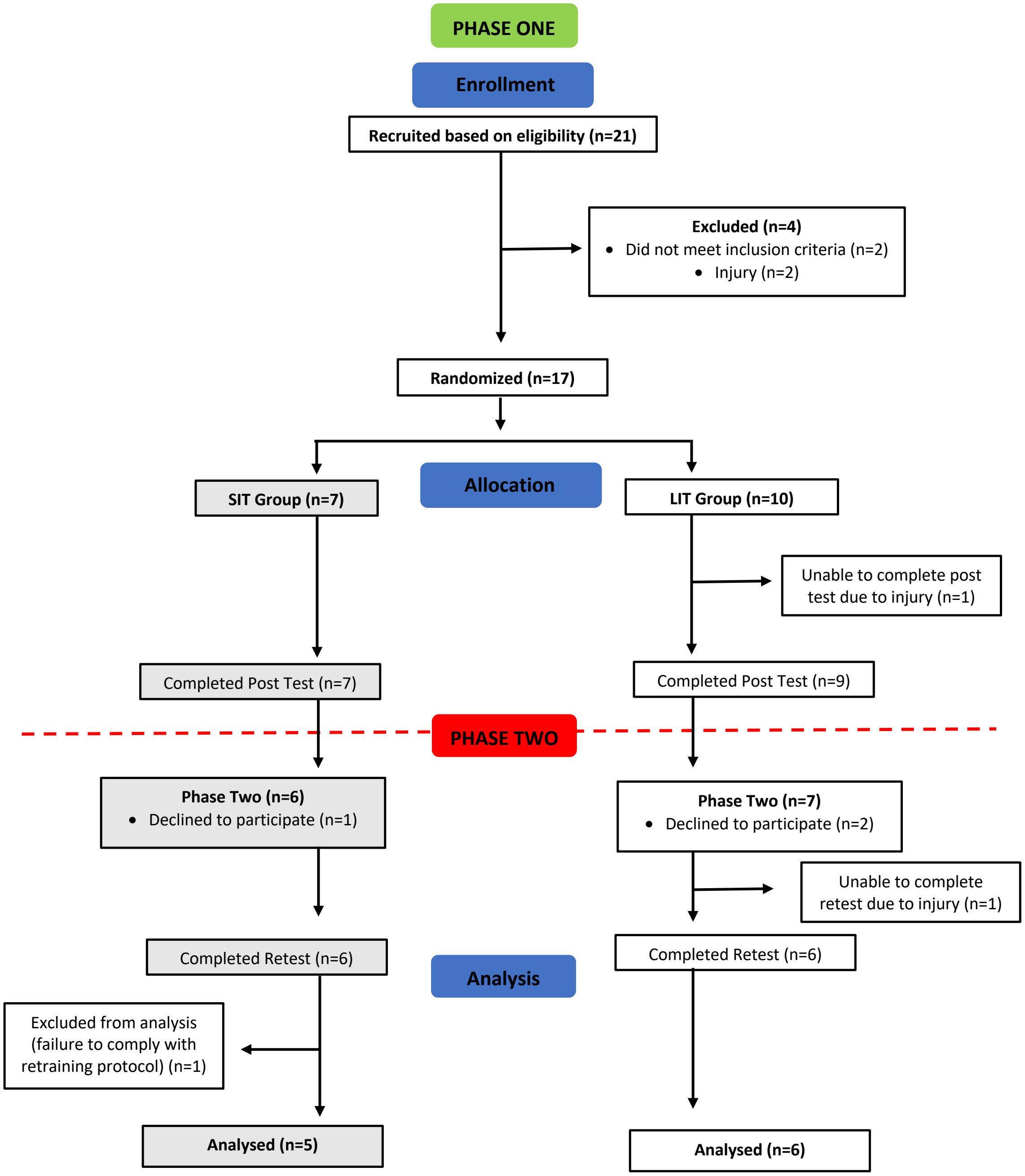

Figure 9. Flow chart of subject inclusion. Phase one, initial 7 weeks of the study (final 4-weeks of the competitive season and 3-week intervention). Phase two, additional 6-weeks into the subsequent preparatory period. SIT, sprint interval group. LIT, low intensity group.

reflection of their blood lactate response curve. The total iTRIMP score for each session is found as the sum of the results for each 5-second average for the duration of the training session.

During the 3-week long intervention period cyclists were instructed to reduce their training load by 60-80%. The LIT group performed one 90-min session at the PO corresponding to 60% of $VO_{2max,}$ as determined from results from the pre-test per week. The SIT group performed 3 supervised sessions on the Lode cycle ergometer in the laboratory (one per week). The session began with a 20-min warm up at a wattage corresponding to 60% of VO_{2max}, followed by 3 bouts of four 30-sec repeated Wingate sprints with 4-min between each sprint, and 10-min recovery between each bout, followed by a 10-min cool down at 60% of VO_{2max}. Both groups were allowed to incorporate additional LIT sessions to their weekly training. Training load was analyzed daily by the test lead and participants were given constant feedback to ensure they maintained the required reduction to their training load throughout the recovery period

During phase two both groups were free to optimize their training load in order to prepare for the subsequent competition season. No instructions or feedback was given with regard to training load, intensity or recommended sessions during this 6-week period.

2.4 Experimental Procedures

The cyclists arrived at the laboratory between 12.00 and 16.00 on the day of their performance test. Two days before the first test session the participants were asked to record their food intake were asked to adopt an identical food regimen for the subsequent test sessions in order to reduce the fluctuations of muscle glycogen between the trials. Cyclists were not allowed to consumed caffeine on the day of the test. All tests were performed under similar conditions (18 – 21 °C). Verbal encouragement was given throughout all tests to encourage maximal effort. All tests (pre-test, post-test, re-test) were performed at the same time of day (± 1 hour). All tests were performed on the Lode Excalibur Sport Cycle ergometer (Lode BV, The Netherlands). During the initial test session, the subject was instructed to set the cycle ergometer to their preferred settings. These settings were recorded, and identical settings were used for all subsequent tests. Throughout each test HR was monitored on the subjects' personal HR monitor, with the same monitor being at each test.

2.4.1 Warm up and Kaiser test

The subject warmed up on the cycle ergometer for 10-mins at 175 W ± 25 W. The same resistance was used in the post and re-test warm up. The subject then moved to the Kaiser and removed their shoes. The heels were placed at the bottom of the plates and the seat position was adjusted so the knee angle was no more than 90 degrees. The seat position was noted and used for the post and re-tests. The Kaiser was set to 10 sets at 250 kg. The participant was instructed to kick as explosively as possible and drive until failure.

2.4.2 Blood Lactate Profile

Directly following the Kaiser test the subject moved back to the cycle ergometer and cycled for 10-mins at 150 W to help clear the legs. The lactate profile tests started at 175 W and the power output was increased by 50 W every 5-mins until a blood lactate concentration ([La-]) of 3 mmol was observed. Thereafter resistance was increased by 25 W. HR response and a rating of received exertion (RPE) were recorded during the fourth minute of each bout and a blood sample was taken from the fingertip at the end of each 5-min bout. The sample was analyzed for whole blood [La^-] using the Biosen C-Line Sport lactate measurement system (EKF Industrial Electronics, Magdeburg, Germany*)*. The test was terminated when a [La-] of 4 mmol L^{-1} [La-] or higher was reached. VO_2 and RER were measured during the last 2 minutes of each bout using a computerized metabolic analyzer with a mixing chamber (Oxycon Pro, Erich Jaeger, Hoechberg Germany). The gas analyzers were calibrated before every test. Data from this test was used to calculate power output and VO_2 at 4mmol L^{-1} [La-].

2.4.3 Six second sprint

Following the lactate profile, the subject spent 5-mins cycling at 100W. The sprint started from a stopped position with the right foot 45° down from the top and the hands on the down bars. The subject was instructed to remain seated and pedal ‘all out’ for the 6-sec duration of the test. The tester counted the subject in for 10-secs and clapped to signal the start and end of the sprint. A braking resistance of 0.8 Nm/kg body mass was applied to the flywheel and remained constant throughout the 6—sec. After the 6-sec sprint the subject was allowed 5-mins of active recovery at 100 W.

2.4.4 VO_{2max}

The VO_{2max} test was started at either 200 or 250 W depending on results from previous from previous tests. PO was increased by 25 W every minute until exhaustion. Maximal HR (HR_{max}), PO on the last load, and total test time were recorded. A blood sample was taken from the fingertip 1-min after termination and analyzed for [La$^-$]. VO_2 and RER were measured throughout the test on the metabolic gas analyzer. VO_{2max} was calculated as the highest 30-sec average of VO_2 measurements (5-second sampling time). W_{max} was calculated as the mean PO during the last minute of the incremental VO_{2max} test.

2.4.5 60-minutes at 60% of VO_{2max} with 4-repeated Wingate sprints

Following the VO_{2max} test the subject had a 10-min passive break. At the pre-test participants were offered an energy gel and one energy drink, both without caffeine. Intake was recorded, and the same intake was replicated at the post-test and re-test. Using data from the previous tests the PO corresponding to 60% of VO_{2max} was calculated and used for the duration of the test. The PO from the pretest was used in the post and retest. VO_2 and RER were measured from minute 5-10 and from minute 30-35 on the metabolic gas analyzer. During the test the subject was instructed to maintain a constant cadence and to remain seated as much as possible.

For the repeated Wingate sprints braking resistance was set to 0.8 Nm/kg body mass. A protocol was designed into the Lode software in advance as follows; at minute 35.5 the PO was adjusted to 200 W and the subject was instructed to find a cadence of 80 rpm. A 30-sec Wingate sprint was initiated at minute 40 with a 5-second verbal count down, the braking resistance was applied to the flywheel and remained constant throughout the 30-sec. The subject remained seated throughout the test, and strong verbal encouragement was given. Cyclists then recovered with 1-min passive recovery (either stationary or pedaling backwards), then 3-mins active recovery at 100 W before the next test. A total of 4 repeated Wingate sprints were completed with this protocol. After the last sprint the subject had 3-mins of active recovery at 100 W and resistance was then increased back to the PO eliciting 60% of VO_{2max} for the remaining 7-mins of the test.

2.4.6 20-minute 'all out' trial

Before the 20-min all-out began, the starting load was determined between the test lead and the subject based on the results from the VO_{2max} test and perceived exertion. Following the 60-min protocol the Lode was put into manual mode, and the load was set to the agreed upon PO. During the 20-min trial the cyclists were instructed to cycle at as high average PO as possible. Performance was measured as the average PO during the trial. The subject was allowed to manually control the PO on the external terminal throughout the test. The cyclists were allowed to occasionally stand, and could drink water as desired. The cyclist received no feedback about HR, or cadence but were aware of the remaining time and their current PO. VO_2 and RER were measured from minute 4 – 5, 9 – 10 and 15 – 20 on the metabolic gas analyzer. HR, RPM and RPE were recorded every 5 minutes. A lactate sample was taken at minute 10 and 1 minute after the completion of the test. Figure 10 provides a visual illustration of the performance test protocol.

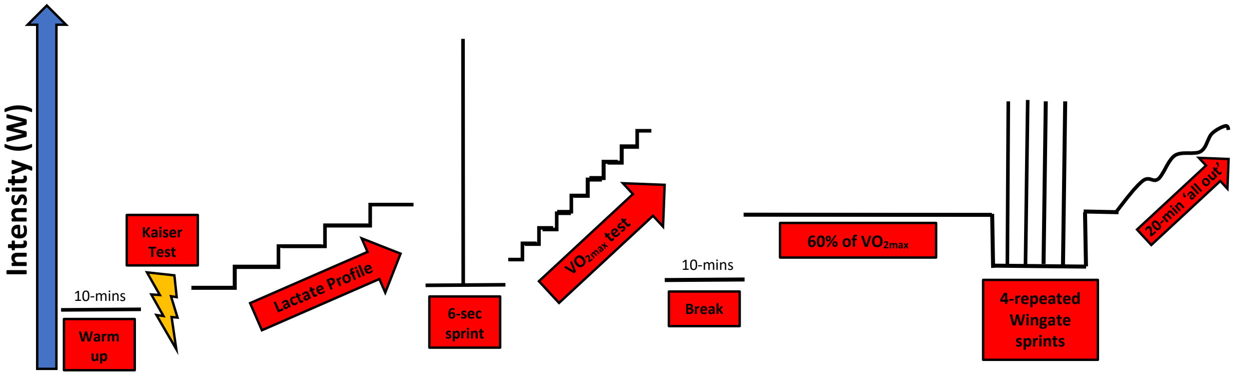

Figure 10. Performance test protocol

2.5 Statistical Analysis

All descriptive data are presented as mean ± standard deviation (SD). Raw data were visually inspected to check for possible measurement errors prior to further analysis. Data were then assessed for assumptions of normality using the Shapiro-Wilk test and were visually inspected via box plot. To check for differences between the groups at the pre-test variable means were compared using a one-way ANOVA. Two-way repeated measures analysis of variance was used to investigate changes within or between the groups the over the three time points (pre-test, post-test, re-test). Percent change was calculated using the formula [(post-test mean – pre-test mean) / pre-test) x 100]. Correlation analyses were performed using Pearson correlation coefficients. A p-value of less than or equal to 0.05 was regarded as significant. All statistical analyses were conducted using SPSS 25.0 (SPSS, Chicago, USA) for Mac. All figures were generated with Microsoft Excel for Mac (Version 16.23: Microsoft, Bloomsbury Publishing Plc.).

3.0 RESULTS

3.1 Training Characteristics

Training characteristics are presented in Table 2. There were no statistically significant differences in average weekly training load (iTrimp per week) or total training time (hours per week) between groups during the lead in period, recovery period or preparatory period.

During the recovery period average training load, training time, and session quantity was significantly reduced. Average weekly training load was reduced by 64 ± 5 % and 65 ± 10 % in the SIT and LIT group respectively. There were no significant differences between the groups with respect to the reduction of training load, number of sessions per week or average training hours per week during the recovery period. As intended training intensity distribution was markedly different between groups during this period, as the SIT group spent significantly more time at high intensity, while the LIT group completed almost all of their training as LIT (Figure 11).

There was no significant difference in training load between the lead in period and the preparatory period across groups (p = 0.111).

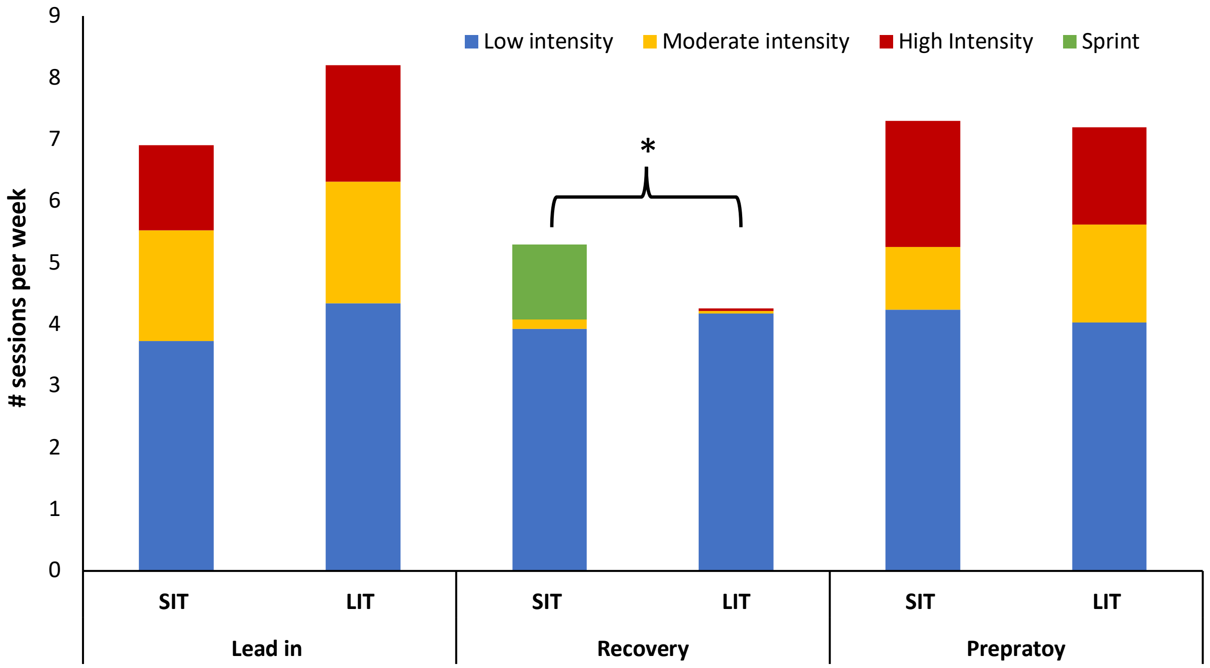

Figure 11. Graphical representation of mean session quantity and percentage of total session quantity spent training at Low intensity, Moderate intensity and High intensity during the different periods of the cycle season for the SIT, sprint group and LIT, low intensity group. * significant difference in training distribution between groups ($p < 0.05$).

Table 2. Average training distribution for high-level competitive cyclists during 3 distinct training periods.

	SIT (n=5)			**LIT** (n=6)		
	Lead in	Recovery	Preparatory	Lead in	Recovery	Preparatory
Total Training (Weekly)						
iTrimp	847 ± 291	307 ± 129	679 ± 295	661 ± 224	236 ± 102	611 ± 227
Sessions	6.9 ± 0.3	5.3 ± 1.7	7.3 ± 0.7	8.2 ± 4.7	4.3 ± 1.4	7.2 ± 1.4
Hours	12.4 ± 3.9	6.9 ± 2.0	8.9 ± 1.5	13.7 ± 7.8	6.3 ± 3.0	9.0 ± 4.3
Training Mode (%)						
Cycle	89 ± 7	73 ± 11	72 ± 13	87 ± 14	86 ± 15	70 ± 16
Strength	5 ± 7	12 ± 12	14 ± 10	9 ± 14	6 ± 10	20 ± 10
Other	5 ± 8	15 ± 11	14 ± 6	4 ± 5	8 ± 11	11 ± 12
Intensity Distribution (%)						
LIT	54 ± 14	74 ± 4	58 ± 10	53 ± 16	97 ± 4	56 ± 11
MIT (%)	26 ± 10	3 ± 24	14 ± 7.0	24 ± 10	1 ± 3	22 ± 6
HIT/SIT* (%)	20 ± 8	23 ± 7*	28 ± 6.6	23 ± 13	1 ± 2	22 ± 8

Data is represented as mean ± standard deviation. Percentages represented as percentage of total session quantity. Individualized training impulse (iTrimp). Lead in, last 4-weeks of the competition season. Recovery, 3-week intervention period. Preparatory, 6-weeks into the preparatory period. Low intensity training (LIT); Moderate intensity training (MIT); High intensity training (HIT); Sprint interval training (SIT). * sessions completed as sprint intervals.

3.2 Baseline Characteristics

There were no significant differences between the groups at the pre-test with respect to body mass, VO_{2max}, W_{max}, PO at 4 mmol L^{-1} [La], %VO_{2max} at 4 mmol L^{-1}, PO_{20min}, 6-sec or 30-sec sprints. The mean VO_{2max} of the SIT group was slightly higher than that of the LIT group, however it was not statistically significant (p = 0.164). See Table 3.

3.3 Body Mass

Both the SIT and LIT group experienced a small but significant increase in body mass of 0.7 ± 0.7 kg and 0.5 ± 1.0 kg respectively during the recovery period. This was significant within groups (p = 0.041)

Table 3. Changes to physiological and performance variables through 3 different training periods

	SIT (n=5)			**LIT** (n=6)		
	PRE	POST	RE	PRE	POST	RE
Mass (kg)	73.7 ± 6.7	74.2 ± 7.5 *	73.6 ± 6.4	72.4 ± 5.6	73.1 ± 5.6 *	73.3 ± 4.4
MAX VALUE						
VO_{2max} (mL min^{-1})	5469 ± 384	5333 ± 453	5373 ± 664	5023 ± 554	5111 ± 642	5176 ± 711
VO_{2max} (mL min^{-1} kg^{-1})	74.5 ± 5.4	72.1 ± 4.3	72.5 ± 6.4	69.3 ± 3.7	69.8 ± 5.6	70.8 ± 9.7
W_{max} (W)	453 ± 35	448 ± 41	436 ± 50	430 ± 50	439 ± 43	456 ± 57
W_{max} (W kg^{-1})	6.2 ± 0.3	6.0 ± 0.3	5.9 ± 0.5	5.9 ± 0.4	6.0 ± 0.4	6.2 ± 0.5
THRESHOLD						
PO @ 4 mmol L^{-1}	338 ± 62	319 ± 57 *	339 ± 65 †	307 ± 45	299 ± 51 *	307 ± 43 †
% VO_{2max} @ 4 mmol L^{-1}	81.9 ± 6.5	81.5 ± 3.5	86.9 ± 4.9	84.2 ± 3.7	81.0 ± 7.8	82.5 ± 4.2
SUBMAXIMAL						
GE (%)	20.4 ± 1.9	19.7 ± 1.2	19.7 ± 1.5	20.1 ± 0.3	20.2 ± 1.1	19.7 ± 0.8
SPRINTS						
6-sec peak (W)	1371 ± 190	1373 ± 202	1421 ± 206 *†	1340 ± 74	1362 ± 68	1411 ± 91 *†
6-sec peak (W kg^{-1})	18.7 ± 2.7	18.6 ± 2.4	19.2 ± 2.8	18.5 ± 0.7	18.8 ± 1.7	19.3 ± 1.2
30-sec mean (W)	665 ± 58	683 ± 71	679 ± 88	684 ± 83	665 ± 78	659 ± 72
30-sec mean (W kg^{-1})	14.5 ± 2.8	14.0 ± 2.6 $^{\#}$	14.0 ± 2.7	16.0 ± 1.0	15.7 ± 2.4 $^{\#}$	15.2 ± 2.5
PERFORMANCE						
20 min (W)	295 ± 60	295 ± 44	316 ± 57 $^{\#}$	292 ± 44	287 ± 3.9	291 ± 45 $^{\#}$
20 min (W kg^{-1})	4.0 ± 0.6	4.0 ± 0.4	4.3 ± 0.5 $^{\#}$	4.0 ± 0.4	3.9 ± 0.4	4.0 ± 0.4 $^{\#}$

Values are mean ± SD and percent (%). PRE, first test at the end of the competition season. POST, second test after 3 weeks of reduced training in the recovery period. RE, third test 6 weeks into the preparatory period. VO_{2max}, maximal oxygen uptake. W_{max}, maximum power output, measured as average power output during final minute of VO_{2max} test. PO @ 4 mmol, power output at 4 mmol L^{-1} [La-]. %VO_{2max} at 4mmol, fractional utilization of VO_{2max} at 4 mmol L^{-1} [La-]. GE, gross efficiency. 6-sec peak, peak power output during 6 second 'Wingate style' sprint. 30-sec mean, average mean power output of 4 repeated Wingate sprints. 20 min, average intensity during 20 minute all out. (*) significant within groups change from pre-test ($p < 0.05$). (#) significant between groups change from pre-test ($p < 0.05$). (†) significant within group change from post-test ($p < 0.05$).

but there no difference between groups during this period (p = 0.648). Body mass remained stable during the preparatory period, and there was no significant difference in body mass from the pre-test to re-test in either group.

3.4 VO2$_{max}$ and W$_{max}$

No significant differences to mean VO_{2max} or $W_{max,}$ were found at any of the three time points, neither when expressed in absolute terms (mL min^{-1}) or relatively (mL kg^{-1} min^{-1}) (taking into account changes to body mass). The VO_{2max} of the subjects averaged ~73.0 and ~ 70.0 mL kg^{-1} min^{-1} throughout the test in the SIT and LIT group respectively. Changes to VO_{2max} can be seen in Figure 11.

With the exception of one outlier, all subjects were within ± 4% of their pre-test VO_{2max} following the recovery period. There were no significant changes to VO_{2max} during the preparatory period neither between groups (p = 0.607) or between groups (p = 0.901). At the re-test the absolute VO_{2max} of the SIT group was –1.8 ± 7.1% lower than their pre-test value, and the LIT group showed a + 3.0 ± 8.9% improvement from their pretest value. The changes within group (p = 0.825) and between groups (p = 0.342) were statistically insignificant. There was one outlier in the SIT group. When this subject was omitted from the analysis the SIT group still had an average decline to their VO_{2max} value at the post test (– 0.5 ± 2.5%) (between group; p = 0.480, within group; p = 0.197), but a small average VO_{2max} improvement (+1.2 ± 2.7%) at the re-test (between group; p = 0.372, within group; p = 0.708). The results remained statistically insignificant at both time points.

There was no change to W_{max} in either group during the recovery period (p = 0.701), or 6-weeks into the preparatory period (p = 0825). W_{max} ranged from 366 W to 538 W (5.1 to 6.8 W kg^{-1}) with a mean of 443 W (6.0 W kg^{-1}) over the three time periods.

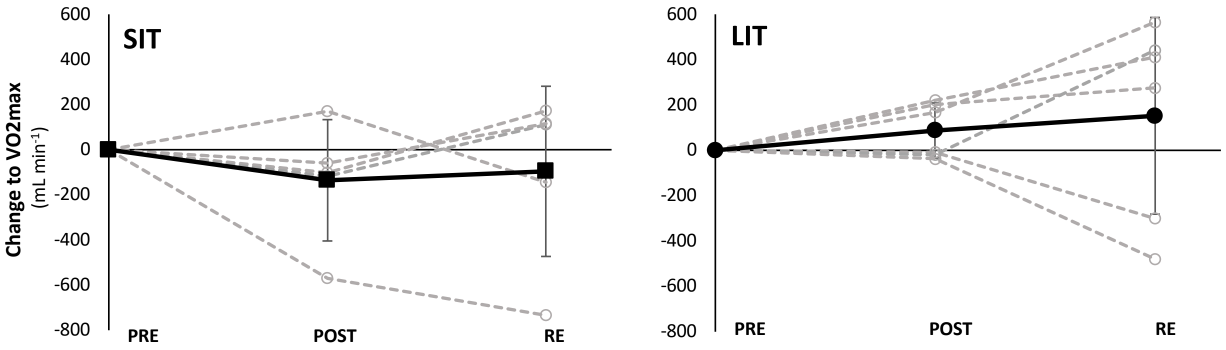

Figure 11. Individual data points (marked line), mean values (solid line) and standard deviations for change to maximal oxygen uptake (VO_{2max}), directly following the competitive season (PRE), after the 3-week recovery period (POST), and 6-weeks into the preparatory period (RE) in the low intensity training group (LIT), and the sprint interval training group (SIT).

3.5 Threshold and Gross Efficiency

During the recovery period, PO at 4 mmol L^{-1} [La^{-}] decreased by – 5.7 ± 1.1%, and – 2.6 ± 6.3% in the SIT and LIT group respectively. These changes were significant over time ($p = 0.01$) but not significantly different between groups ($p = 0.239$). During the preparatory period both groups experienced a significant increase in PO at 4 mmol L^{-1} [La] ($p = 0.02$), but there was no difference between groups ($p = 0.208$). The improvement seen during the preparatory period offset the decline experienced during the recovery period. Nine out of 11 athletes were within ± 2.5% of their pretest score after the preparatory period at the retest. There was no significant difference between pretest and retest values across groups ($p = 0.928$) or between groups ($p = 0.735$) (Figure 12).

With respect to %VO_{2max} @ 4mmol L^{-1} [La^{-}] (Figure 13), there were no statistically significant changes in either group at any time point. However, 4 out of 5 SIT subjects experienced an improvement to their %VO_{2max} at 4 mmol L^{-1} [La^{-}] at the re-test from their pre-test value (+ 6.2 ± 9.4%). In contrast, 4 out 6 LIT subjects experienced a decline to %VO_{2max} at 4 mmol L^{-1} [La^{-}] from the pre-test to the re-test(– 2.1 ± 5.1%). There were significant outliers in both groups. This result was not statistically significant ($p = 0.086$), but does represent a trend in the findings.

Gross efficiency scores ranged from in the range of 18.1 to 22.6% over the three time periods. There were no statistically significant changes to GE in across groups following the recovery period ($p = 0.472$), or 6-weeks into the preparatory period ($p = 0.333$).

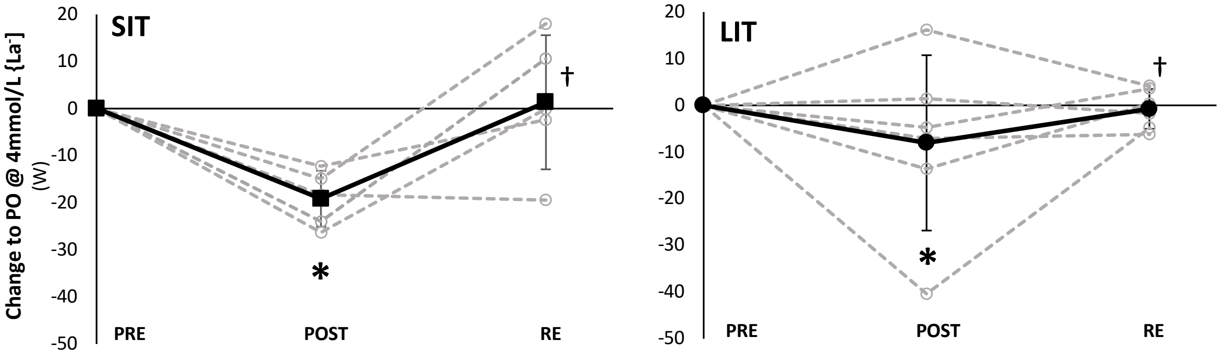

Figure 12. Individual data points (marked line), mean values (solid line) and standard deviations for change to power output at lactate threshold (PO @ 4 mmol L^{-1} [La^{-}]), directly following the competitive season (PRE), after the 3-week recovery period (POST), and 6-weeks into the preparatory period (RE) in the low intensity training group (LIT), and the sprint interval training group (SIT). (*) significant change ($p < 0.05$) from pre-test. (†) significant within group change from post-test ($p < 0.05$).

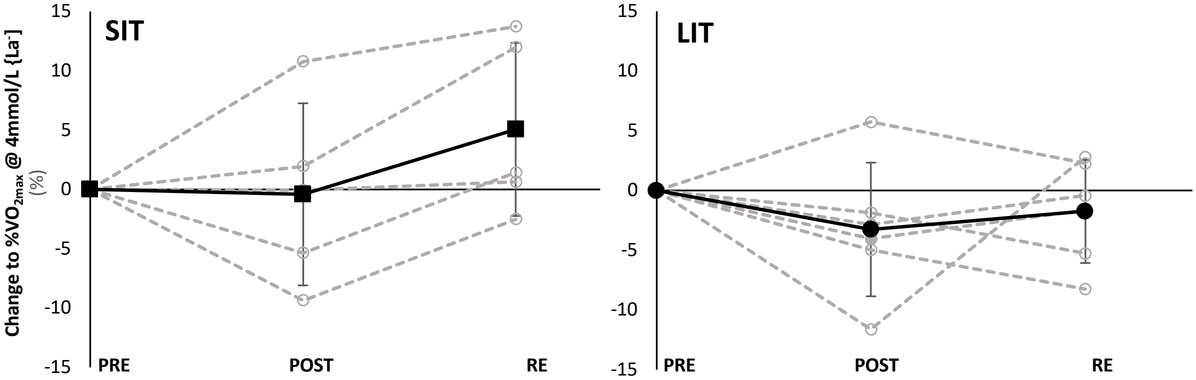

Figure 13. Individual data points (marked line), mean values (solid line) and standard deviations for change to fractional utilization of VO_{2max} at lactate threshold (%VO_{2max} @ 4 mmol L^{-1} [La^-]), directly following the competitive season (PRE), after the 3-week recovery period (POST), and 6-weeks into the preparatory period (RE) in the low intensity training group (LIT), and the sprint interval training group (SIT).

3.6 Sprints

Following the recovery period, the SIT group experienced a significant improvement to average mean PO during 4-repeated Wingate sprints (PO_{Win4})(+ 2.3 ± 4.5%) (Figure 14). In contrast the LIT group experienced a decline to average mean PO_{Win4} (– 3.4 ± 2.5%). This difference between groups was statistically significant when expressed relative to body mass (W kg^{-1}) ($p = 0.027$), but not. At the re-test all 6 LIT subjects had an average mean PO_{Win4} less than or equal to their pre-test value with an average decline of -5% from their pre-test values. In contrast, the SIT group had a small decline to average mean PO_{Win4} during the preparatory period, but finished the re-test with a 1% improvement from their pre-test score. While the current between group difference from pre-test to re-test was not statistically significant it does represent a trend in the findings ($p = 0.061$).

No statistically significant changes were seen to peak PO_{Win4} at any of the time points neither when expressed in absolute terms or relative to body mass. Peak PO_{Win4} values ranged from 636 to 1348 W (10.0 to 16.6 W kg^{-1}) over the 3 time periods.

During the recovery period peak 6-sec PO (PO_{6sec}) did not differ in either group with no significant differences within ($p = 0.614$) or between groups ($p = 0.680$) when expressed in relative to body mass (Figure 14). Following the preparatory period (at the re-test) significant improvement to peak PO_{6sec} from pre-test values when expressed relative to body mass was observed in both groups (+ 2.7 ± 2.9% and +

4.0 ± 5.3 % in the SIT and LIT group respectively) (p = 0.016), there was no difference between groups (p = 0.619) (Figure 14). Values ranged from 1048 to 1567 W (14.8 to 21.8 W kg^{-1}) throughout the 3-tests.

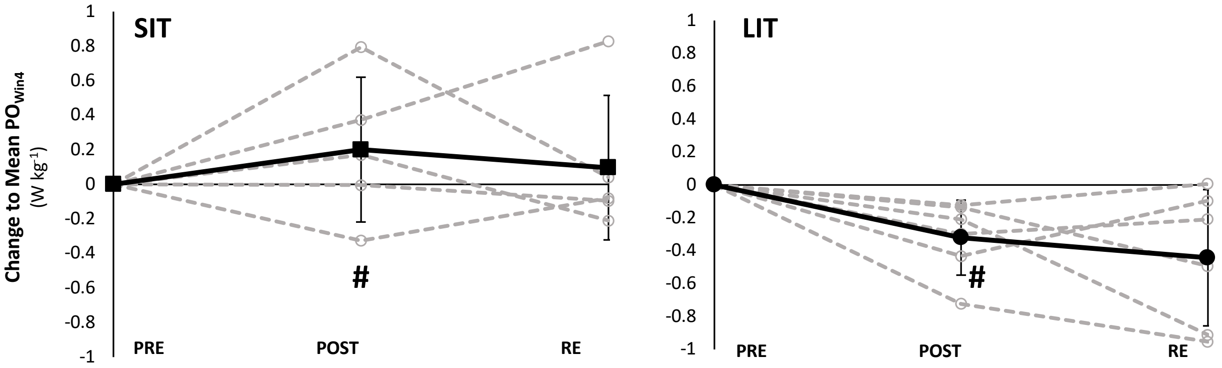

Figure 14. Individual data points (marked line), mean values (solid line) and standard deviations for change to average mean power output during 4 repeated Wingate sprints (mean PO_{Win4}), directly following the competitive season (PRE), after the 3-week recovery period (POST), and 6-weeks into the preparatory period (RE) in the low intensity training group (LIT), and the sprint interval training group (SIT). (#) significant difference between groups from pre-test ($p < 0.05$).

3.7 Endurance performance

Following the recovery period the SIT group had no change to their average PO during the 20 minute 'all out' (PO_{20min}) (0.0 ± 8.4%), while the LIT group experienced a 1.6 ± 3.6 % reduction to average PO. These changes were statistically insignificant both within groups (p = 0.637) and between groups (p = 0.641). Six weeks into the subsequent preparatory period, the SIT group exhibited a + 7.2 ± 7.5% improvement to their average PO_{20min} compared to their pre-test results (Figure 15). Four out of 5 SIT subjects had performance improvements in the ranged of 4 – 14%, and one SIT subject had a –3% decrease to average PO_{20min} from their pretest scores. This was significantly greater than the unchanged average PO_{20min} from the pre-test to the re-test (0 ± 3.6%) seen in the LIT group. The change to PO_{20min} between groups was statistically significant both when expressed in absolute values (W)(p = 0.047) and when expressed relative to body weight (W kg^{-1}) (p = 0.048).

The performance improvement seen in SIT group was mirrored by significant increase in average VO_2 consumption throughout the 20-min trial from pre-test to the re-test (4255 ± 632 to 4552 ± 673 mL min^{-1}). The LIT group saw no significant change to their VO_2 during the 20-min trial at any time point. This

VO_2 response was a statistically significant difference between the two groups from pre-test to post-test ($p = 0.042$). No significant changes were observed to average RPM throughout the 20-min trial or [La-] at the end of the test at any of the time points.

Across groups there was a significant correlation between the percent change to $\%VO_{2max}$ at 4 mmol L^{-1} [La^-] and average PO_{20min} from the pre-test to the retest ($r = 0.61$, $p < 0.05$). No other significant correlations were observed.

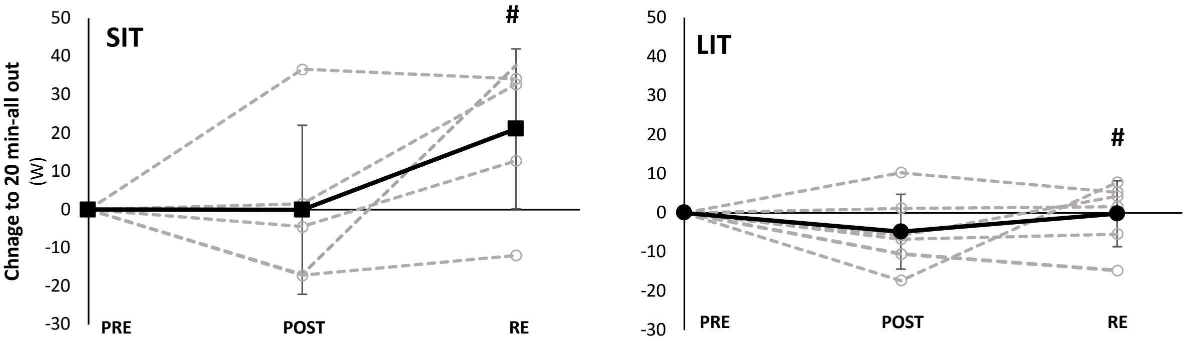

Figure 15. Individual data points (marked line), mean values (solid line) and standard deviations for change to average power output during 20-min all out trial (PO_{20min}) directly following the competitive season (PRE), after the 3-week recovery period (POST), and 6-weeks into the preparatory period (RE) in the low intensity training group (LIT), and the sprint interval training group (SIT). (#) significant difference between groups from pre-test ($p < 0.05$).

4.0 DISCUSSION

4.1 Main Findings

The main findings of the current study were as following:

(1) The SIT intervention provided no immediate advantage over the traditional LIT stimulus for the maintenance of VO_{2max}, W_{max}, body mass, PO at 4 mmol L^{-1} [La], GE or PO_{20min} following a 3-week long recovery period.
(2) In the absence of a high intensity training stimulus the LIT group experienced a significant decline to average mean PO_{Win4} when scaled to body mass (W kg^{-1}) following the 3-week long recovery period compared to the SIT group that experienced a significant improvement during this time.
(3) Six-weeks into the subsequent preparatory period the SIT group was able to significantly improve their PO_{20min} from the end of the end of the previous competition season which was considerably a considerably larger improvement than the unchanged PO_{20min} seen in the LIT group.

4.2 Recovery Period

The first significant finding of the current study was that following the 3-weeks of reduced training both groups had a similar increase in body mass and decreased PO at 4 mmol L^{-1} [La], and were equally able to maintain their VO_{2max}, W_{max}, GE and PO_{20min}. These findings were in contrast to the hypothesis of the current study, as it was predicted that the inclusion of 3 SIT sessions during the recovery period would result in a superior maintenance of the physiological factors associated with endurance performance than the low intensity strategy traditionally used during this period. This was based on previous findings showing that low intensity training during periods of reduced volume training has consistently resulted in declines to endurance performance [1, 4, 7, 64]. And while SIT has never been investigated as a strategy during the recovery period, it has routinely been suggested as a beneficial, and time efficient strategy for improving and maintaining endurance performance in trained athletes [24, 47, 78, 82, 85]. However, we observed no differences between the two groups with respect to any of the measured endurance variables, and a general maintenance of endurance fitness and performance in both groups during the 3-week recovery period.

In the present study, it was found that the mean $VO_{2max,}$ $W_{max,}$ GE and PO_{20min} could be maintained for a period of 3-weeks despite a ~65% reduction to total training load. The VO_{2max} of both groups was virtually unaffected during the recovery period, despite the training intervention. All, but one participant, were within ± 4% of their pretest VO_{2max} values following the recovery period, and the cohort maintained a mean VO_{2max} of ~71 mL kg^{-1} min^{-1} over all three test periods. The cyclists included in the current study all had VO_{2max} values in agreement to VO_{2max} values seen in other studies on competitive cyclists [1, 6, 7], and were in accordance with recommendations for selecting well-trained cyclists [11]. To date, there remains some controversy about the rate of decline to VO_{2max}, and the stimulus required to maintain a high VO_{2max} value. Some authors have reported declines in VO_{2max} following periods of reduced volume training strategies [7, 86]. Rønnestad et al [7] reported a likely decline to VO_{2max} of 3% following an 8-week period focusing on low volume LIT with highly trained cyclists, and Garcia-Pallares et al [64] reported a decline of 3.3% to VO_{2max} following a 5-week low volume MIT intervention. Greater declines have been reported when the training stimulus is completely removed, with declines in the range of – 4 to – 20% following 4 weeks of training cessation [21, 62, 64, 65]. In contrast, others have reported no change to VO_{2max} during periods of training cessation or reduced volume [1, 67-69, 87]. For example, Rietjens et al [87], reported that VO_{2max} was maintained for a period of 3-weeks in well trained cyclists when total training volume was halved and intensity was reduced to < 70% VO_{2max}. And Lucia et al [1, 8] has reported no significant difference to mean VO_{2max} during any period of the cycle season in groups of elite male cyclists over the 3 distinct periods of the cycling season, and the cyclists maintained an average VO_{2max} of ~74 mL kg^{-1} min^{-1} throughout the season [1, 8].

It is generally agreed that fluctuations to VO_{2max} of trained individuals are the result of centralized adaptations [15, 17, 18, 21]. For example, Coyle et al [21] suggested that the entire decrease to VO_{2max} during a 3-week period of detraining could be attributed to a decrease in Q_{max}, which was likely the result of an immediate decline in BV following the cessation of training. Coyle et al. [20] later went on to show that that if BV was maintained at a similar level in the detrained state as in the trained state VO_{2max} could be maintained within 2 – 4% of trained values, suggesting that the reduction in BV is highly associated with declines in cardiovascular function during the periods of training cessation [63]. Thus, it could be interpreted that a 65% reduction to total training load and the decreased intensity associated with the current LIT intervention (< 60% of VO_{2max}) was sufficient to maintain the central adaptations in these well-trained cyclists over a 3-week period. Furthermore, we detected no change to W_{max} or PO_{20min} following the recovery period in either group. Seeing as W_{max} is considered a strong predictor or performance homogenous groups of cyclists [28, 31, 88, 89], and PO_{20min} can be considered a direct measure of cycling endurance performance this provides further evidence that the high-intensity stimulus of the SIT training had no immediate advantage over LIT during the recovery period.

Certainly, aerobic performance cannot only be considered in terms of maximal performance variables (i.e. VO_{2max} or W_{max}), but also the physiological response to submaximal exercise. In the current study, there was a significant – 6% and – 3% decline to PO at 4 mmol L^{-1} [La-] in the SIT and LIT group respectively during the recovery period (with no difference between groups). Recently Maldonado-Martin et al [6] showed declines of ~12% to LT1/LT2 following 5-weeks of training cessation in a group of young top level cyclists, citing that the mean declines observed in the maximum data (i.e. VO_{2max} and W_{max}) showed smaller declines than the mean declines in submaximal values (i.e. values for the LT1/2). A similar trend was observed in the current study in that no significant changes to VO_{2max} or W_{max} were observed in either group however both groups showed significant declines to PO at 4 mmol L^{-1} [La-] following the recovery period. Thus, the current findings support the notion that submaximal variables are more sensitive than maximal variables to training induced changes [1, 4, 6]. Furthermore, it suggests that SIT was not superior to LIT in protecting the athletes from such decline. It has repeatedly been shown that low and moderate aerobic capability dominate the competition time during elite cycling events, with large parts of the competition being spent near the LT [14, 49]. Thus, the declines PO at LT could have unwarranted consequences on the rider's performance in the subsequent season.

It could be argued that the 3-week long recovery period used in the current study was unusually short, which may explain why the fitness decline reported in this study was less severe than that which has been previously reported [4, 7, 21]. However, the 3-week recovery period was established based on the feedback from the athletes and coaches advocating for a 3-week recovery period citing this was their standard practice. Thus, while this intervention period is shorter than that which has previously been used [6, 7, 64] it was intended to mirror the real world practices. Future research may seek to further optimize the recovery period by investigating detraining effects associated with different lengths of the recovery period.

The second finding of the current thesis was that in the absence of a high intensity training stimulus the LIT group experienced a 3% decline to average mean PO_{Win4} during the 3-week long recovery period. In contrast the SIT group showed a significant 2% improvement to their average mean PO_{Win4} during the same period. Given that the SIT intervention used in the current study involved repeated Wingate sprints it should not be surprising that the SIT group experienced an immediate improvement to their sprint capacity. Previous studies have shown that SIT interventions can lead to improved peak and mean Wingate PO [47, 90, 91]. Rønnestad et al [47] reported a 5% increase in mean Wingate PO in a group of competitive cyclists following a 10-week SIT intervention (30-sec intervals separated by 15-sec recovery for 9.5-mins, 2x per week), which was notably greater than the insignificant 1% improvements associated with an effort matched HIT group (5-min work intervals separated by 2.5 minute recovery). They theorized that the observed Wingate PO improvements could be related to the repeated high-power acceleration phase present at the initiation of each sprint, which requires significant and repeated neuromuscular stimulation. In a recent meta-analysis of repeated sprint training Taylor et al [92] suggested that repeated sprints likely cause beneficial changes in the patterns of muscular activity via improved efficiency of the neural pathways, increased activity of relatively inactive muscle groups, and greater recruitment of the gluteus maximus muscle. Ultimately, they concluded that repeated sprint training could produce small to large improvements to power, speed, repeated sprint ability and endurance. It seems likely that the improvements to sprint performance seen in the current study could arise from overall improvements to the neuromuscular properties of the muscles [82, 92, 93].

It is an important finding that the low intensity training stimulus was not sufficient to preserve sprint capacity in these high-level cyclists following the recovery period. In the current study, all 6 the subjects in the LIT group decreased their average mean PO_{Win4} in the range of 0 to – 6% following the 3-week recovery period, while in contrast only 1 SIT subject had a decline to average mean PO_{Win4} (– 2%). This observable difference between groups emphasizes the significance of these results. Indeed other studies have reported changes to PO following periods of reduced training with regards to; aerobic peak power [1, 6-8, 64], sport specific performance markers [7, 64, 67, 72] and muscular strength [67], but to the best of our knowledge there are no studies reporting changes to peak or mean 30-sec Wingate PO during different periods of the season, or following periods of reduced training. Thus, the finding that in the absence of high intensity training repeated Wingate sprint capacity is reduced is a novel finding in the literature. Neither group experienced changes to peak PO_{Win4} or peak PO_{6sec} during the recovery period.

4.3 Preparatory Period

The third, and likely most significant finding of the current study was that 6-weeks into the subsequent preparatory period the SIT group experienced a 7% improvement to PO_{20min} from the end of the pervious competition season, which was significantly greater than the LIT group who showed no significant change to their PO_{20min} performance 6-weeks into the preparatory period from their pre-test performance. During the preparatory period both groups were free to optimize their training and there were no significant differences between two groups in terms of total weekly training (training load, number of sessions or hours), training mode, or training intensity distribution during the preparatory period. Based on previous findings showing improved endurance during the preparatory period [3, 4, 7, 61], and because we observed no differences between the two groups with respect to any of the measured endurance variables during the 3-week recovery period it was expected that both groups would experience similar performance improvements during the preparatory period. Thus, it is surprising that the SIT group appears to have experienced a residual performance advantage 6-weeks into the preparatory period that was not immediately apparent following the recovery period, and the LIT group was unable to improve their past season performance.

During the preparatory period there was no change to $VO_{2max,}$ W_{max} or GE in either group. Both groups were equally able to improve PO at 4 mmol L^{-1} [La-] from the post test to the re test, allowing them to recover the previous declines seen in the recovery period. At the re-test 9 out 11 subjects were within 2% of their pre-test PO at 4 mmol L^{-1} [La-] values. This is somewhat expected at PO at threshold intensity has previously been reported to increase during the preparatory period [61, 94]. There was also a trend for the SIT group to improve their $\%VO_{2max}$ at 4 mmol L^{-1} [La^{-}] at the re-test from their pre-test value (+ 5%), while the LIT group demonstrated a likely decline (– 2%). Submaximal threshold values are highly important for cycling success and have frequently been regarded as better predictors of cycling performance than VO_{2max} alone [3, 8, 12, 23, 35, 95]. Fittingly, there was also a significant correlation across groups between changes to PO_{20min} and $\%VO_{2max}$ at 4 mmol L^{-1} [La^{-}] from the pre-test to re-test ($r = 0.61$)

The PO_{20min} improvements observed in the SIT group from the pre-test to 6-weeks into the subsequent season were mirrored by a significant increase in absolute VO_2 uptake throughout the 20-minute trial, a change that was not apparent in the LIT group. There was no change to [La-] accumulation following the trial in either group at any time point, which would have suggested a shift toward anaerobic metabolism. An increased VO_2 at high intensity suggests increased availability of oxygen to the working muscles and/or improved oxygen utilization in the working muscles, both of which would allow for greater ATP production via aerobic glycolysis at a higher percentage of VO_{2max}.

It has long been suggested that peripheral adaptations are likely responsible for the increased exercise capacity following SIT interventions in groups of trained individuals [25, 75, 77, 84]. And multiple authors have demonstrated rapid changes to the skeletal muscle following SIT interventions [25, 75, 81]. Burgomaster et al [25] demonstrated that following just 6 SIT sessions over 2-weeks there was a significant increase to muscle oxidative function, and resting muscle glycogen content, and Iaia et al [24] found that with the inclusion of SIT, endurance trained runners were able to maintain their muscle oxidative capacity for four weeks despite a two thirds reduction in the total amount of training. This is an interesting finding as it has been demonstrated that muscle oxidative enzymes decline at a faster rate than VO_{2max} during the detraining period [21, 70], and are likely slower to regain in the subsequent retraining period [70]. Based on the current findings it could be suggested that the low volume SIT intervention used in the current study was a strong enough stimulus for the SIT group to maintain the peripheral adaptions (i.e. muscle oxidative capacity) accrued over the competition season during the recovery period and the cyclists could thus progress the development of these adaptions during the preparatory period which was exhibited by an improved performance at the re-test. Whereas the low intensity stimulus practiced in the LIT group was not enough to conserve such peripheral adaptions and the preparatory period allowed only for the recovery of past adaptions but not further improvement. This would explain why no further performance improvement from their past season performance was observed in the LIT group at the re-test. However, because the current study did not perform muscle biopsies we can do nothing more than speculate on the mechanisms involved, and future research should be executed exploring muscular and metabolic adaptations during the recovery period and subsequent seasons of endurance athletes. For a further review of skeletal muscle adaptations to interval training the reader is directed to the recent review by MacInnis and Gibala [75] for an in-depth discussion on potential mechanisms and markers for such adaptations.

It is worth mentioning that the only statistically significant difference observed between the two groups immediately following the recovery period was the improved ability to produce power during repeated Wingate sprints in the SIT group. During the preparatory period there were no significant changes to average mean PO_{Win4} in either group, but when focusing on the change from the pre-test to the re-test there was a trend for the LIT group to display a decline to average mean PO_{Win4} (– 5%), while the SIT group demonstrated a likely improvement (+ 1%). Interestingly Inoue et al [52] reported a significant correlation between peak and mean PO of a repeated Wingate test and mountain bike performance (r= 0.79 and 0.63 respectively), yet no significant correlations when only one Wingate was performed. They noted that it appeared that the ability to repeatedly produce anaerobic efforts seemed to be a more important determinant of performance than a single bout of maximal anaerobic power. While it was not directly measured, it is possible that the that neural adaptations associated with repeated sprint training may have also contributed to the enhanced performance observed in the SIT group. Potential neural adaptations include increased muscle fiber recruitment, muscle firing rate, and motor unit synchronization; all of which would result in the ability to produce more force [52, 82, 91, 92, 96, 97].

Additionally, with regards to the LIT group, it is interesting that these subjects were not able to 'catch up' to the average mean PO_{Win4} of the SIT group 6-weeks into the subsequent season despite no significant differences in training load or training intensity distribution (i.e. same amount of HIT training) during this time. In fact, none of the LIT subjects were able to improve their average mean PO_{Win4} from their pre-test score, further pointing towards the importance of incorporating SIT into the training strategy of well-trained athletes. This between group difference could imply that some adaptation (likely neuromuscular) was lost with the absence of high intensity training in the LIT group during the recovery period which was not recovered after 6-weeks of 'retraining', and could further explain the LIT groups inability to improve their endurance performance from the end of the competitive season. However, again, in the absence of muscle biopsies or EMG records, further speculation with regards to the mechanisms behind the current aerobic performance improvements are unwarranted, but it seems possible that the improvements to sprint capacity, observed in the SIT group during the recovery could have been involved in the delayed improvements to aerobic performance observed in the SIT group 6-weeks into the preparatory period.

Finally, despite no changes to peak PO_{6sec} during the recovery period, both groups demonstrated a small but significant improvement (+ 3%) to peak PO_{6sec} 6-weeks into the recovery period compared to their pretest values. Data on shorten sprints (less than 10-sec) with competitive cyclists is very limited in the current literature thus the 6-sec sprint results presented in the current thesis represent an under reported series of data in the literature. This type of short sprint is very applicable to cycling performance as success in a high level race will require the rider to produce a very high PO (greater than 1000 W) for short periods of time repeatedly throughout the race [11]. It has previously been shown that in-field results can be highly varied due to multiple factors influencing the riders PO (i.e. cadence, rider position (sitting vs. standing), drafting, fatigue and road gradient [98]), thus there is need for a standardized method for reporting such data. For this reason, the Windgate style protocol used in the current study could prove to be a very valuable measure in future research as it is highly reliable, controllable and easily replicated. Additionally, in contrast to a 30-sec sprint the peak 6-sec sprint value can provide researchers and coaches with the absolute peak PO possible for their athletes and is an essential piece for demonstrating an integrated measure of all aspects of the peak PO.

4.4 Methodological Considerations and Future Perspectives

It remains a challenge to do research in groups of such high-level competitive athletes as it is difficult to attract a large group of participants. The current study was originally planned with many more participants, including a group that would have executed HIT training. However, due to inflexible training regimes, injury, sickness and the high standards for participant inclusion many athletes were unable to be included in the current study and/or declined to move forward into the second phase of the study. For these reasons, the sample size of the current study became much smaller than intended and the intervention moved forward with only the LIT and SIT groups. Ultimately were able to include 11 competitive cyclists in the final analyses, most of which are currently competing at an international level. While this sample size is consistent with that which has been used in other studies involving similarly trained athlete populations, it is possible that the lack of statistical significance found in the current study may be due to the relatively low statistical power. It is also important to recognize that the current study used a very conservative approach to analysis. Significance from analyzing this homogenous group of athletes with similar VO_{2max} values (for example) may have been lost due to the small potential for fluctuation [15]. Therefore, definitive conclusions cannot be drawn about whether the changes (or lack thereof) observed in the current study were due the intervention or not. However, even with a limited sample size the results of the current study are still considerable as it provides valuable insight into the response of elite athletes, so researchers and coaches do not need to rely solely on investigations with less trained subjects. Regardless, further research should be done with larger group sizes in order to better understand the response to low volume training during the recovery period, and the residual effects this training has in subsequent parts of the season.

Additionally, there is little consensus in the literature about training load quantification and thus there are a variety of methods to consider when developing such a study (i.e. HR or PO ‘intensity zones’, total distance, Training Stress Score, ect.). Because so many different methods have been used to date in the current research, any quantification method has the potential to be considered a limitation to some degree. The current design used the iTrimp method, which has was previously validated by Manzi et al [60], and provides a means to standardized the highly individualized response of each athlete. However there remains few studies which have provided iTrimp scores in connection with training strategies [50, 60], making it difficult to contrast the current results with other such studies. Throughout the 13-week period of the current study, second by second HR recordings were collected for every training session of each subject. An in-depth analysis of this data was beyond the scope of the current thesis but could be of interest for future research- potentially contrasting longitudinal methods for quantifying training load.

Finally, the multicenter design of this project inherently had the potential to produce slight inconsistencies with regards to; equipment, test protocol, athlete explanations, etc. despite our best efforts to standardize it. However, because our analyses were pairwise these effects were less important for our analyses as long as each lab provided reliable results as per the standardized protocol.

4.5 Practical Applications

The findings of the current study may have important practical relevance for endurance athletes looking to optimize their training during the recovery period. It is critical to give the athlete sufficient time off during this period in order to promote physical and mental recovery, so low-volume, low time commitment training strategies are essential for these athletes. This study demonstrates that a highly trained endurance athletes can reduce their training load by more than 60% during the recovery period and still maintain their endurance performance for a period of 3-weeks. The low-volume, low time commitment SIT strategy presented in this thesis could be of considerable interest for competitive cyclists because it implies that including just one SIT session per week during a 3-week long recovery period could provide a significant performance advantage 6-weeks into the subsequent season over those who focused solely on low intensity training during the same period. While the current study had low statistical power, no negative side effects were observed or reported by the athletes from the inclusion of the single weekly SIT session, which provides further support for its viability as positive training recommendation.

From a coach or athlete perspective, it could be argued that the recovery period should be completely unstructured in order to provide the athlete with sufficient recovery time. To the best of our knowledge, there is no research on the mental and/or psychological response to different training strategies during the recovery period, thus decisions about training programing should be made by the coach on an individualized basis.

5.0 CONCLUSION

In conclusion, this thesis shows that well trained cyclists are able to reduce their training load by more than 60% for a period of 3-weeks and still maintain their endurance performance. However, in the absence of a high intensity training stimulus a decline to sprint performance during the recovery period is likely. Six-weeks into the subsequent preparatory period the SIT group showed a significantly greater endurance performance improvement from the end of the previous competitive season than the LIT group who was not able to improve their performance from the end of previous the season. This suggests that the addition of just one SIT session each week promotes an accelerated performance improvement in the subsequent training period.

Although the mechanisms for this performance improvement remain elusive, it is possible that the SIT stimulus allowed for the SIT group to maintain valuable peripheral and/or neural adaptions (i.e. muscle oxidative capacity or neuromuscular factors) obtained in the competitive season throughout the recovery period. Thus, allowing them to further the development of these adaptions in the subsequent season, and improve their previous performance. Whereas the LIT group likely required the preparatory period to regain past adaptations and were thus not able to improve on their past performance.

Despite being restricted by a small sample size, and a limited understanding of the mechanisms behind the current performance improvements, the SIT intervention used in the present study places no foreseeable risk on the athlete. Thus, the results of the current study in conjunction with that which has been previously reported supports the inclusion of 1-weekly SIT session during the recovery period of competitive cyclists as a means of improving performance in the subsequent season. However, additional investigation is needed to better understand the mechanisms of the resulting performance improvement in order to further maximize training during the recovery period in top-level endurance athletes.

REFERENCES

1. Lucia, A., et al., *Metabolic and neuromuscular adaptations to endurance training in professional cyclists: a longitudinal study.* Jpn J Physiol, 2000. **50**(3): p. 381-8.
2. Faria, E., D.L. Parker, and I. Faria, *The science of cycling - Physiology and training - Part 1*, in *Sports Med.* 2005. p. 285-312.
3. Lucia, A., J. Hoyos, and J.L. Chicharro, *Physiology of professional road cycling.* Sports Med, 2001. **31**(5): p. 325-37.
4. Sassi, A., et al., *Seasonal changes in aerobic fitness indices in elite cyclists.* Appl Physiol Nutr Metab, 2008. **33**(4): p. 735-42.
5. Tonnessen, E., et al., *The road to gold: training and peaking characteristics in the year prior to a gold medal endurance performance.* PLoS One, 2014. **9**(7): p. e101796.
6. Maldonado-Martin, S., et al., *Effects of long-term training cessation in young top-level road cyclists.* J Sports Sci, 2017. **35**(14): p. 1396-1401.
7. Ronnestad, B.R., A. Askestad, and J. Hansen, *HIT maintains performance during the transition period and improves next season performance in well-trained cyclists.* Eur J Appl Physiol, 2014. **114**(9): p. 1831-9.
8. Lucia, A., et al., *Heart rate and performance parameters in elite cyclists: a longitudinal study.* Med Sci Sports Exerc, 2000. **32**(10): p. 1777-82.
9. Cheung, S.S., Zabala, M. , *Cycle Science* 2017, United States Human Kinetics Inc.
10. Faria, E.W., D.L. Parker, and I.E. Faria, *The science of cycling: factors affecting performance - part 2.* Sports Med, 2005. **35**(4): p. 313-37.
11. Jeukendrup, A.E., N.P. Craig, and J.A. Hawley, *The bioenergetics of World Class Cycling.* J Sci Med Sport, 2000. **3**(4): p. 414-33.
12. Santalla, A., et al., *The Tour de France: an updated physiological review.* Int J Sports Physiol Perform, 2012. **7**(3): p. 200-9.
13. Ebert, T.R., et al., *Power output during a professional men's road-cycling tour.* Int J Sports Physiol Perform, 2006. **1**(4): p. 324-35.
14. Fernández-García, B., et al., *Intensity of exercise during road race pro-cycling competition.* Medicine & Science in Sports & Exercise, 2000. **32**(5): p. 1002-1006.
15. Bassett, R.D. and E.T. Howely, *Limiting factors for maximum oxygen uptake and determinants of endurance performance.* Medicine & Science in Sports & Exercise, 2000. **32**(1): p. 70-70.
16. Joyner, M.J. and E.F. Coyle, *Endurance exercise performance: the physiology of champions*. 2008: Oxford, UK. p. 35-44.
17. Saltin, B., *Hemodynamic adaptations to exercise.* The American Journal of Cardiology, 1985. **55**(10): p. D42-D47.
18. Wagner, P.D., *New ideas on limitations to VO2max.* Exerc Sport Sci Rev, 2000. **28**(1): p. 10-4.
19. Blomqvist, C.G. and B. Saltin, *Cardiovascular adaptations to physical training.* Annu Rev Physiol, 1983. **45**: p. 169-89.

20. Ekblom, B. and L. Hermansen, *Cardiac output in athletes.* Journal of Applied Physiology, 1968. **25**(5): p. 619-625.
21. Coyle, E.F., et al., *Time course of loss of adaptations after stopping prolonged intense endurance training.* J Appl Physiol Respir Environ Exerc Physiol, 1984. **57**(6): p. 1857-64.
22. Holloszy, J.O. and E.F. Coyle, *Adaptations of skeletal muscle to endurance exercise and their metabolic consequences.* J Appl Physiol Respir Environ Exerc Physiol, 1984. **56**(4): p. 831-8.
23. Coyle, E.F., et al., *Determinants of endurance in well-trained cyclists.* J Appl Physiol (1985), 1988. **64**(6): p. 2622-30.
24. Iaia, F.M., et al., *Four weeks of speed endurance training reduces energy expenditure during exercise and maintains muscle oxidative capacity despite a reduction in training volume.* J Appl Physiol (1985), 2009. **106**(1): p. 73-80.
25. Burgomaster, K.A., et al., *Six sessions of sprint interval training increases muscle oxidative potential and cycle endurance capacity in humans.* J Appl Physiol (1985), 2005. **98**(6): p. 1985-90.
26. Bassett, D.R. and E.T. Howley, *Maximal oxygen uptake: "classical" versus "contemporary" viewpoints.* Medicine and science in sports and exercise, 1997. **29**(5): p. 591.
27. Faude, O., W. Kindermann, and T. Meyer, *Lactate threshold concepts: how valid are they?* Sports Med, 2009. **39**(6): p. 469-90.
28. Borszcz, F.K., et al., *Physiological Correlations With Short, Medium, and Long Cycling Time-Trial Performance.* Res Q Exerc Sport, 2018. **89**(1): p. 120-125.
29. McArdle, W.D., Katch, F. I., & Katch, V. L., *Exercise physiology: nutrition, energy, and human performance*. 2015: Lippincott Williams & Wilkins.
30. Lucía, A.L., H.L. Joyos, and J.L. Chicharro, *Physiological Response to Professional Road Cycling: Climbers vs. Time Trialists.* International Journal Of Sports Medicine, 2000. **21**(7): p. 505-512.
31. Clark, B., et al., *The physiological correlates of variable gradient cycling performance*. 2015. Vol. 4. 2015.
32. Coyle, E.F., *Integration of the physiological factors determining endurance performance ability.* Exerc Sport Sci Rev, 1995. **23**: p. 25-63.
33. Lucia, A., et al., *Inverse relationship between VO2max and economy/efficiency in world-class cyclists.* Med Sci Sports Exerc, 2002. **34**(12): p. 2079-84.
34. Nickleberry, B.L., Jr. and G.A. Brooks, *No effect of cycling experience on leg cycle ergometer efficiency.* Med Sci Sports Exerc, 1996. **28**(11): p. 1396-401.
35. Coyle, E.F., et al., *Cycling efficiency is related to the percentage of Type I muscle fibers.* Medicine & Science in Sports & Exercise, 1992. **24**(7): p. 782-788.
36. Santalla, A., J. Naranjo, and N. Terrados, *Muscle efficiency improves over time in world-class cyclists.* Med Sci Sports Exerc, 2009. **41**(5): p. 1096-101.
37. Martin, J.C., C.J. Davidson, and E.R. Pardyjak, *Understanding sprint-cycling performance: the integration of muscle power, resistance, and modeling.* Int J Sports Physiol Perform, 2007. **2**(1): p. 5-21.

38. Bogdanis, G.C., et al., *Contribution of phosphocreatine and aerobic metabolism to energy supply during repeated sprint exercise.* J Appl Physiol (1985), 1996. **80**(3): p. 876-84.
39. Smith, J.C. and D.W. Hill, *Contribution of energy systems during a Wingate power test.* British Journal of Sports Medicine, 1991. **25**(4): p. 196.
40. Serresse, O., et al., *Estimation of the contribution of the various energy systems during maximal work of short duration.* Int J Sports Med, 1988. **9**(6): p. 456-60.
41. Hall, M.M., et al., *Lactate: Friend or Foe.* Pm r, 2016. **8**(3 Suppl): p. S8-s15.
42. de Jong, J., et al., *Pacing Strategy in Short Cycling Time Trials.* Int J Sports Physiol Perform, 2015. **10**(8): p. 1015-22.
43. Morton, R.H. and D.J. Hodgson, *The relationship between power output and endurance: a brief review.* European Journal of Applied Physiology and Occupational Physiology, 1996. **73**(6): p. 491-502.
44. Driss, T. and H. Vandewalle, *The measurement of maximal (anaerobic) power output on a cycle ergometer: a critical review.* BioMed research international, 2013. **2013**: p. 589361-589361.
45. Tanaka, H., et al., *Aerobic and anaerobic power characteristics of competitive cyclists in the United States Cycling Federation.* Int J Sports Med, 1993. **14**(6): p. 334-8.
46. Peveler, W.W., J.D. Pounders, and P.A. Bishop, *Effects of saddle height on anaerobic power production in cycling.* J Strength Cond Res, 2007. **21**(4): p. 1023-7.
47. Rønnestad, B.R., et al., *Short intervals induce superior training adaptations compared with long intervals in cyclists – An effort-matched approach.* Scandinavian Journal of Medicine & Science in Sports, 2015. **25**(2): p. 143-151.
48. Zupan, M.F., et al., *Wingate Anaerobic Test peak power and anaerobic capacity classifications for men and women intercollegiate athletes.* J Strength Cond Res, 2009. **23**(9): p. 2598-604.
49. Vogt, S., et al., *Power output during stage racing in professional road cycling.* Med Sci Sports Exerc, 2006. **38**(1): p. 147-51.
50. Sanders, D. and M. Heijboer, *Physical demands and power profile of different stage types within a cycling grand tour.* Eur J Sport Sci, 2018: p. 1-9.
51. Novak, A.R., et al., *Power Profiles of Competitive and Noncompetitive Mountain Bikers.* J Strength Cond Res, 2019. **33**(2): p. 538-543.
52. Inoue, A., et al., *Relationship between anaerobic cycling tests and mountain bike cross-country performance.* J Strength Cond Res, 2012. **26**(6): p. 1589-93.
53. Davison, R.C., et al., *Correlates of simulated hill climb cycling performance.* J Sports Sci, 2000. **18**(2): p. 105-10.
54. Smith, D., *A Framework for Understanding the Training Process Leading to Elite Performance.* Sports Medicine, 2003. **33**(15): p. 1103-1126.
55. MacDougall, J.D., H.A. Wenger, and H.J. Green, *Physiological testing of the high-performance athlete*. 2nd ed. ed. 1991, Champaign, Ill: Human Kinetics Books.
56. Padilla, S., et al., *Exercise intensity during competition time trials in professional road cycling.* Medicine & Science in Sports & Exercise, 2000. **32**(4): p. 850-856.
57. Padilla, S., et al., *Exercise intensity and load during mass-start stage races in professional road cycling.* Medicine and Science in Sports and Exercise, 2001. **33**(5): p. 796-802.

58. Rodriguez-Marroyo, J., et al., *Workload demands in professional multi-stage cycling races of varying duration*, in *Br. J. Sports Med.* 2009. p. 180-185.
59. Rønnestad, B., A. Askestad, and J. Hansen, *HIT maintains performance during the transition period and improves next season performance in well-trained cyclists.* European Journal of Applied Physiology, 2014. **114**(9): p. 1831-1839.
60. Manzi, V., et al., *Relation between individualized training impulses and performance in distance runners.* Med Sci Sports Exerc, 2009. **41**(11): p. 2090-6.
61. Paton, C.D. and W.G. Hopkins, *Seasonal changes in power of competitive cyclists: implications for monitoring performance.* J Sci Med Sport, 2005. **8**(4): p. 375-81.
62. Mujika, I. and S. Padilla, *Physiological and performance consequences of training cessation in athletes: detraining.* Rehabilitation of sports injuries: Scientific basis, 2003: p. 117.
63. Coyle, E.F., M.K. Hemmert, and A.R. Coggan, *Effects of detraining on cardiovascular responses to exercise: role of blood volume.* J Appl Physiol (1985), 1986. **60**(1): p. 95-9.
64. Garcia-Pallares, J., et al., *Post-season detraining effects on physiological and performance parameters in top-level kayakers: comparison of two recovery strategies.* J Sports Sci Med, 2009. **8**(4): p. 622-8.
65. Godfrey, R., et al., *The detraining and retraining of an elite rower: a case study.* Journal of Science and Medicine in Sport, 2005. **8**(3): p. 314-320.
66. Neufer, P.D., *The effect of detraining and reduced training on the physiological adaptations to aerobic exercise training.* Sports Med, 1989. **8**(5): p. 302-20.
67. Neufer, P.D., et al., *Effect of reduced training on muscular strength and endurance in competitive swimmers.* Medicine & Science in Sports & Exercise, 1987. **19**(5): p. 486-490.
68. McConell, G.K., et al., *Reduced training volume and intensity maintain aerobic capacity but not performance in distance runners.* Int J Sports Med, 1993. **14**(1): p. 33-7.
69. Madsen, K., et al., *Effects of detraining on endurance capacity and metabolic changes during prolonged exhaustive exercise.* J Appl Physiol (1985), 1993. **75**(4): p. 1444-51.
70. Houston, M., H. Bentzen, and H. Larsen, *Interrelationships between skeletal muscle adaptations and performance as studied by detraining and retraining.* Acta Physiologica Scandinavica, 1979. **105**(2): p. 163-170.
71. Smorawiński, J., et al., *Effects of 3-day bed rest on physiological responses to graded exercise in athletes and sedentary men.* Journal of Applied Physiology, 2001. **91**(1): p. 249-257.
72. Costill, D.L., et al., *Metabolic characteristics of skeletal muscle during detraining from competitive swimming.* Med Sci Sports Exerc, 1985. **17**(3): p. 339-43.
73. Londeree, B.R., *Effect of training on lactate/ventilatory thresholds: a meta-analysis.* Med Sci Sports Exerc, 1997. **29**(6): p. 837-43.
74. Zapico, A., et al., *Evolution of physiological and haematological parameters with training load in elite male road cyclists: a longitudinal study.* Journal of Sports Medicine and Physical Fitness, 2007. **47**(2): p. 191-6.
75. Macinnis, M.J. and M.J. Gibala, *Physiological adaptations to interval training and the role of exercise intensity.* Journal of Physiology, 2017. **595**(9): p. 2915-2930.

76. Gist, N., et al., *Sprint Interval Training Effects on Aerobic Capacity: A Systematic Review and Meta-Analysis.* Sports Medicine, 2014. **44**(2): p. 269-279.
77. Laursen, P.B. and D.G. Jenkins, *The scientific basis for high-intensity interval training: optimising training programmes and maximising performance in highly trained endurance athletes.* Sports Med, 2002. **32**(1): p. 53-73.
78. Laursen, P.B., et al., *Interval training program optimization in highly trained endurance cyclists.* Med Sci Sports Exerc, 2002. **34**(11): p. 1801-7.
79. Stepto, N.K., et al., *Effects of different interval-training programs on cycling time-trial performance.* Med Sci Sports Exerc, 1999. **31**(5): p. 736-41.
80. Rønnestad, B.R., et al., *Short intervals induce superior training adaptations compared with long intervals in cyclists - an effort-matched approach.* Scand J Med Sci Sports, 2015. **25**(2): p. 143-51.
81. MacDougall, J.D., et al., *Muscle performance and enzymatic adaptations to sprint interval training.* J Appl Physiol (1985), 1998. **84**(6): p. 2138-42.
82. Creer, A.R., et al., *Neural, metabolic, and performance adaptations to four weeks of high intensity sprint-interval training in trained cyclists.* Int J Sports Med, 2004. **25**(2): p. 92-8.
83. Esfarjani, F. and P.B. Laursen, *Manipulating high-intensity interval training: Effects on V˙O2 max, the lactate threshold and 3000m running performance in moderately trained males.* Journal of Science and Medicine in Sport, 2007. **10**(1): p. 27-35.
84. Gibala, M.J., et al., *Short-term sprint interval versus traditional endurance training: similar initial adaptations in human skeletal muscle and exercise performance.* J Physiol, 2006. **575**(Pt 3): p. 901-11.
85. Paquette, M., et al., *Effects of submaximal and supramaximal interval training on determinants of endurance performance in endurance athletes.* Scandinavian Journal of Medicine & Science in Sports, 2017. **27**(3): p. 318-326.
86. Garcia-Pallares, J., et al., *Performance changes in world-class kayakers following two different training periodization models.* Eur J Appl Physiol, 2010. **110**(1): p. 99-107.
87. Rietjens, G.J.W.M., et al., *A reduction in training volume and intensity for 21 days does not impair performance in cyclists.* British Journal of Sports Medicine, 2001. **35**(6): p. 431.
88. Hawley, J., T. Noakes, and J.A. Hawley, *Peak Power Output Predicts Maximal Oxygen Uptake And Performance Time In Trained Cyclists.* European Journal of Applied Physiology, 1992. **65**: p. 79-83.
89. Bentley, J.D., et al., *Peak power output, the lactate threshold, and time trial performance in cyclists.* Medicine & Science in Sports & Exercise, 2001. **33**(12): p. 2077-2081.
90. Hazell, T.J., et al., *10 or 30-s sprint interval training bouts enhance both aerobic and anaerobic performance.* European Journal of Applied Physiology, 2010. **110**(1): p. 153-160.
91. Vera-Ibanez, A., et al., *Neural adaptations after short-term wingate-based high-intensity interval training.* J Musculoskelet Neuronal Interact, 2017. **17**(4): p. 275-282.
92. Taylor, J., et al., *The effects of repeated-sprint training on field-based fitness measures: a meta-analysis of controlled and non-controlled trials.* Sports Med, 2015. **45**(6): p. 881-91.

93. Markovic, G., et al., *Effects of sprint and plyometric training on muscle function and athletic performance.* J Strength Cond Res, 2007. **21**(2): p. 543-9.
94. Hopker, J., D. Coleman, and L. Passfield, *Changes in cycling efficiency during a competitive season.* Med Sci Sports Exerc, 2009. **41**(4): p. 912-9.
95. Lucia, A., et al., *Physiological differences between professional and elite road cyclists.* Int J Sports Med, 1998. **19**(5): p. 342-8.
96. Paavolainen, L., et al., *Explosive-strength training improves 5-km running time by improving running economy and muscle power.* Journal of Applied Physiology, 1999. **86**(5): p. 1527-1533.
97. Kraemer, W.J., S.J. Fleck, and W.J. Evans, *Strength and power training: physiological mechanisms of adaptation.* Exerc Sport Sci Rev, 1996. **24**: p. 363-97.
98. Quod, M.J., et al., *The power profile predicts road cycling MMP.* Int J Sports Med, 2010. **31**(6): p. 397-401.

NTNU
Kunnskap for en bedre verden