FACULTY OF HEALTH

The relationship between the preferred rate of movement and the most optimal cadence in the skill of cycling

by

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A thesis completed in fulfilment of the requirements of the degree of Doctor of Philosophy
30th October 2017
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Certificate of Authorship and Originality of Thesis

I certify that the work in this thesis has not previously been submitted for a degree nor has it been submitted as part of the requirements for a degree except as fully acknowledged within the text.

I also certify that the thesis has been written by me. Any help that I have received in my research work and in the preparation of the thesis itself has been acknowledged. In addition, I certify that all information sources and literature used are indicated in the thesis.

This research is supported by an Australian Government Research Training Program Scholarship.

_____________________________________________________
Anthony Gerard Whitty

30/10/2017
Date
Acknowledgements

I am going to start by thanking my supervisor Associate Professor Mark Watsford for everything that he has done for me over these past years. Without your expertise, assistance and guidance I would not have been able to do this. I really appreciate all the editing, reading and suggestions, but above all I am so thankful for your sense of humour and friendship that has allowed this journey to be completed. I honestly could not have got through this without all your assistance and hard work and it is something that I will be eternally grateful for. You are a ripping bloke who continually inspires others to achieve.

I also would like to thank Professor Aron Murphy for giving me this opportunity and for being so patient. You have always given me such amazing support both personally and with the project itself. I am really thankful for your hard work and guidance especially early on when framing the thesis and generating outside expertise in areas that was required.

I also thank Professor Aaron Coutts for all his work and time on this project. Aaron provided a huge amount of support in developing my writing and academic skills required to complete this thesis. I also thank Aaron for his support and honesty that was needed at times throughout the thesis. Aaron was always able to continually motivate me with his quick wit and sense of humour.

The completion of this thesis would not have been possible without the love and support of my family, especially during the challenging times. I would like to thank my children, Finn and Hollie for their constant support and unbridled positivity. I
would also like to thank my wonderful, beautiful and supportive wife Mandy. Her patience and support was what made the completion of this thesis truly possible. This is a journey that we definitely completed together and shared every hurdle. I would also like to thank my dog Ben for keeping me company between the early morning hours when most of the work for this thesis was completed.

I would also like to thank all the cyclists and fitness enthusiasts who participated in my studies. Again, without them this would not have been possible.

Finally, I would also like to thank Professor Justin Kemp for his support, expertise and time over the last 5 years. Justin was always willing to assist me and provided wonderful support and positivity.
List of Publications

Refereed journal publications arising from the work undertaken in this thesis:


Conference presentations arising from the work undertaken in this thesis:


2. Whitty, A. G., Murphy, A. J., Coutts, A. J. & Watsford, M. L (2014). The training effect on the freely chosen cadence, optimal pedaling frequency and
Preface

This thesis for the degree of Doctor of Philosophy is in the format of published or submitted manuscripts and abides by the ‘Procedures for Presentation and Submission of Theses for Higher Degrees – University of Technology, Sydney; Policies and Directions of the University’. All manuscripts included in this thesis are closely related in subject matter and form a cohesive research narrative.

Based on the research design, four manuscripts have been submitted for publication, with two having been accepted and published in peer-reviewed journals. These papers are initially brought together by an Introduction, which provides background information, an extension overview of the literature pertaining to all aspects of the thesis, and defines the research problem and the aims of the series of studies. The Literature Review, which is formed as a publication, provides a specific overview of previous knowledge regarding the relationship between the preferred rate of movement and the most optimal in locomotive skills. This review also provides a summary of the literature pertaining to the selection of the preferred pedalling rate in cycling.

The body of the research is presented in manuscript form (Chapter 3 to Chapter 5), in a logical sequence following the development of research ideas in this investigation. Each manuscript separately outlines and discusses the individual methodology and the findings of each study. The Discussion chapter provides an interpretation of the collective findings and practical applications from the series of investigations conducted as part of the thesis. This chapter also suggests directions for future research.
Abstract

Research examining the relationship between the preferred rate of movement and the most optimal in locomotive sports has demonstrated that both novice and well-trained participants select a preferred rate of movement that minimises the metabolic demands of the task. Referred to as the metabolic demand hypothesis, it has been suggested that novices will initially produce a movement pattern that is unstable, inaccurate and high in metabolic demand when compared to a well-trained participant. However, after a period of practice, novice participants will adopt a refined movement pattern with increased metabolic efficiency and reduced internal mechanical work required to coordinate and control the limbs.

In cycling, the preferred rate of movement is commonly referred to as the freely chosen cadence (FCC). Previous cycling research has demonstrated that elite and novice cyclists select a FCC that is significantly higher than the most optimal metabolic cadence. Instead, the FCC may be attributed to mechanisms other than the need to minimise the metabolic demands of the task, such as mechanical, psychological or physiological factors. However, other cycling studies have shown that the optimal metabolic cadence in well-trained cyclists increased as power output was elevated at higher exercise intensities and more closely resembled the FCC than previously shown. Therefore, to date, there remains conflicting findings as to whether the skill of cycling adheres to the metabolic demand hypothesis and exactly what variables directly influence cadence selection.

The aims of this thesis were to firstly determine whether the skill of cycling adhered to the metabolic demand hypothesis. Secondly, if this was not the case, the research
sought to investigate variables or mechanisms responsible for influencing cadence selection. Finally, the research aimed to determine the impact of a specific cadence-based interval training protocol on the FCC and performance. These aims were investigated using separate studies.

In study 1, a group of non-cyclists completed a series of tests at varying workloads, measured in relative terms of each participant’s fitness level, to determine their FCC and optimal pedalling frequency. The findings revealed that non-cyclists preferred to cycle well above the most optimal metabolic cadence, possibly in order to decrease muscle strain and mechanical load rather than the need to minimise aerobic demand.

In studies 2 and 3, non-cyclists and well-trained cyclists completed a 6-week cadence-based interval training program to determine whether the FCC could be altered with specific training. These studies were also conducted to determine if the selection of the FCC in both cohorts was related to minimising the metabolic demands of the task, and to assess the impact of the interval training program on performance. Collectively, the findings from these studies demonstrated that both well-trained and non-cyclists selected a FCC that was significantly higher than the most metabolically optimal cadence suggesting that the skill of cycling did not adhere to the metabolic demand hypothesis. Unlike other cycling research, the findings from these studies did not support the notion that cadence selection was solely based on minimising muscular effort or reducing the perceived exertion of the task. However, the findings were able to provide evidence to suggest that cycling cadence selection is different to other locomotor activities and may be under the control of central pattern generators (CPG). This was evidenced by the fact the FCC was highly
individualised, recorded strong between-day reliability in all participants, and was shown to be impacted by internal and external factors such as increases in power output and mechanical loading. The findings from studies 2 and 3 also revealed that regardless of the training stimulus, both well-trained and non-cyclists preferred to pedal at higher cadences and that low cadence interval training has the potential to have a greater impact on performance outcomes than high cadence training.
**List of Abbreviations**

beats·min\(^{-1}\) : beats per minute

DP\(_{\text{bot}}\): bottom dead point of the crank cycle

DP\(_{\text{top}}\): top dead centre of the crank cycle

FCC: freely chosen cadence

GE: gross efficiency

NE: Net efficiency

WE: Work efficiency

DE: Delta efficiency

iEMG: integrated electromyography

m: metres

min: minutes

n: number

\(\text{VO}_2\text{max}\): maximal oxygen uptake

RE: running economy km·h\(^{-1}\) – kilometres per hour

RPE: rating of perceived exertion

RPM: revolutions per minute

\(T_{0\text{deg}}\): torque at 0°

\(T_{135\text{deg}}\): torque at 135°

\(T_{180\text{deg}}\): torque at 180°

\(T_{45\text{deg}}\): torque at 45°

\(T_{90\text{deg}}\): torque at 90°

\(T_{\text{mean}}\): mean torque

\(T_{\text{peak}}\): peak torque

\(W_{\text{max}}\): maximal work capacity
Chapter 1:

Introduction
1.1 Background

1.1.1 Motor learning and locomotive skills

When completing motor tasks, individuals are known to self-select a preferred rate of movement that is unique to their physiology, biomechanics and skill level (Sparrow, Hughes, Russell, & Le Rossignol, 1999). Research has demonstrated that when performing locomotive skills, humans will inherently self-select a rate of movement that minimises the metabolic demands of the task (Lay, Sparrow, Hughes, & O'Dwyer, 2002), with the most optimal rate of movement for performance typically defined as one that minimises the rate of energy turnover (Hansen, 2015). This has been referred to as the metabolic demand hypothesis and is supported by evidence which has shown that superior efficiency is often associated with higher levels of success in laboratory and field-based tests (Brisswalter, Hausswirth, Smith, Vercruyssen, & Vallier, 2000; Coyle, 1995; Lopez Calbet et al., 1993; Vercruyssen et al., 2002).

1.1.2 Metabolic demand hypothesis

Traditionally, the primary focus of motor learning research has been the goal-directed nature of motor skill, with accuracy, consistency, and certainty of outcome the skill-defining dependent variables (Lay et al., 2002; Newell, Morris, & Scully, 1985; Rogers, 1974; Schmidt, 1975; Van Rossum, 1990; Wulf, Schmidt, & Deubel, 1993). Sparrow (1983) suggested a different view of learning, in that individuals constrain their pattern of limb movements to effectively meet the demands of the task. It was suggested that the metabolic energy expended in the learning of motor skills might occur according to the principles of economy, which was based on the premise that humans who were able to freely choose their work rate had lower metabolic costs than
those that worked at a rate imposed on them by the researcher (Corlett & Mahadeva, 1970; Salvendy, 1972; van der Walt & Wyndham, 1973; Zarrugh, Todd, & Ralston, 1974). Following this earlier work, motor learning research began to address the issue of economy and limb movements (Sparrow, 1983; Sparrow et al., 1999; Sparrow, Hughes, Russell, & Le Rossignol, 2000; Sparrow & Irizarry-Lopez, 1987; Sparrow & Newell, 1994a, 1994b, 1998), which led to the establishment of the theory of 'least amount of effort' or 'the minimisation of energy theory'. Also referred to as the 'metabolic demand hypothesis', it states that one defining characteristic of performance of motor skills is to complete the task with the least energy expenditure (Lay et al., 2002; Sparrow & Irizarry-Lopez, 1987), and that when performing motor tasks, humans naturally adopt a movement pattern that minimises metabolic energy expenditure through a process referred to as "self-optimisation" (Brener, 1986; Brener & Mitchell, 1989; Freeman, 1948; Salvendy, 1972; Sparrow & Irizarry-Lopez, 1987; Sparrow & Newell, 1994a, 1994b, 1998).

As demonstrated in Figure 1, when an organism is continually presented with a number of equally reinforced alternative responses to a certain task, the response that requires the least amount of metabolic energy expenditure will become the dominant response (Brener & Mitchell, 1989; Freeman, 1948; Hull, 1943; Sparrow & Newell, 1998). Furthermore, when learning a skill, the novice will initially produce a movement pattern that is unstable, inaccurate and high in metabolic demand when compared to a highly trained participant. However, after a period of practice, novice participants will adopt a refined movement pattern with increased metabolic efficiency, reduced heart rate, reduced ratings of perceived exertion and internal mechanical work required to coordinate and control the limbs in the absence of an
increase in physical fitness (Cavanagh & Williams, 1982; Lay et al., 2002; Umberger & Martin, 2007).

In regards to the skill of cycling, earlier motor learning research examined university students on a bicycle ergometer to determine the relationship between the most preferred rate of movement and efficiency. When participants were asked to perform the task at a frequency either faster or slower than the preferred rate, metabolic energy cost relative to work output was increased (Benedict & Cathcard, 1913; Salvendy,
Alternatively, when pedalling at their freely chosen rate, participants were able to maximise their efficiency (Salvendy, 1972; Salvendy & Pilitsis, 1974). As a result, it was concluded that a freely chosen rate of work exists, for each individual, around which region the physiological costs and errors in performance are lowest and efficiency is highest.

1.1.3 The preferred and optimal rate of movement in cycling

In cycling, the preferred rate of movement is commonly referred to as the freely chosen cadence (FCC). Both laboratory and field-based testing have demonstrated that the FCC is task dependant with differences reported for high mountain passes (71.0 ± 1.4 rpm), flat mass start stages (89.3 ± 1.0 rpm) and time-trials (92.4 ± 1.3 rpm) (Emanuele, Horn, & Denoth, 2012; Foss & Hallen, 2005; Leirdal & Ettema, 2009; Lucia, Hoyos, & Chicharro, 2001; Mora-Rodriguez & Aguado-Jimenez, 2006; Nesi, Bosquet, & Pelayo, 2005; Nimmerichter, Eston, Bachl, & Williams, 2011). It has been demonstrated that the FCC can vary significantly between non-cyclists and well-trained cyclists and also within elite cycling cohorts that share similar physical and performance characteristics (Hopker et al., 2009; Hopker, Coleman, & Wiles, 2007).

Research has revealed that elite and non-cyclists select a FCC of approximately 80-110 rpm and 70-90 rpm when cycling between 100 and 250 W, respectively (Burke, 2002; Chavarren & Calbet, 1999; Coast, Cox, & Welch, 1986; Coyle, Sidossis, Horowitz, & Beltz, 1992; Hagberg, Mullin, Giese, & Spitznagel, 1981; Heil, Derrick, & Whittlesey, 1997; Le Chevalier, Vandewalle, Thépaut-Mathieu, Stein, & Caplan, 2000; Lucia et al., 2001; Marsh & Martin, 1993; Marsh, Martin, & Foley, 2000).
However, the cadence that minimises metabolic energy expenditure for elite and non-cyclists has been reported as between 50-80 rpm and 50-60 rpm when cycling at similar workloads (Chavarren & Calbet, 1999; Coast et al., 1986; Gaesser & Brooks, 1975; Marsh & Martin, 1993, 1997). Thus it appears that regardless of fitness level or cycling experience, individuals tend to pedal at a FCC that is higher than the optimal metabolic rate (Coast et al., 1986; Hintzy, Belli, Grappe, & Rouillon, 1998; Marsh & Martin, 1993), suggesting that the skill of cycling may not adhere to the principles of the metabolic demand hypothesis.

In direct contrast however, evidence collated on well-trained cyclists has demonstrated that the most economical cadence increases with elevated exercise intensity, and actually merges with the FCC at higher exercise intensities (Brisswalter et al., 2000; Hansen, Anderson, Nielsen, & Sjøgaard, 2002a; Nielsen, Hansen, & Sjøgaard, 2004). This suggests that at higher workloads (> 300 W), the selection of a FCC may actually be more closely related to the metabolically optimal cadence than previously postulated (Nielsen et al., 2004). However, limitations of this previous research include the use of lower power outputs that were not reflective of a real-world cycling environment (< 200 W) and the use of absolute workloads that were not able to account for any variations in fitness levels between participants. As a result, it remains unknown if the FCC and metabolic efficiency in cycling would actually merge at higher workloads. Therefore, research that includes a range of efficiency measurements, participants of varying cycling experience, and uses relative workloads that are reflective of a real-world cycling environment, would provide a unique insight into the relationship between the FCC and the metabolically optimal cadence.
Interestingly, the optimal pedalling frequency in cycling is not limited to the metabolic demands of the task, and has been defined as being either the most comfortable, maximal power producing, metabolically efficient, or best for performance (Foss & Hallen, 2005; Marsh & Martin, 1997; Patterson & Moreno, 1990). The relationship between the optimal cadence and the FCC is yet to fully encompass its complexity and this is supported by the fact that there remains uncertainty surrounding the exact variables or factors that are directly responsible for influencing cadence selection. Accordingly, it is recommended that research analysing the relationship between the FCC and the optimal pedalling frequency should include an array of variables that have been proposed to influence cadence selection in cycling and their domains of origin, as demonstrated in Figure 2.
Figure 2: The domains and their relevant variables that have been reported to influence the FCC and optimal pedalling frequency.

There are a number of different physiological variables that have been reported to influence cadence selection in cycling. These are economy and efficiency (Marsh, 1996; Moseley & Jeukendrup, 2001; Sidossis, Horowitz, & Coyle, 1992), the minimisation of neuromuscular fatigue (Neptune & Hull, 1999) reducing glycogen depletion (Ahlquist, Bassett, Sufit, Nagle, & Thomas, 1992; Coyle et al., 1992), optimising the application of force on the pedals (Ericson & Nisell, 1988; MacIntosh, Neptune, & Horton, 2000; Patterson & Moreno, 1990), muscle fibre composition, (Coyle et al., 1992; Pedersen, Sorensen, Jensen, Johansen, & Levin, 2002) and the
frequency of muscle activation and relaxation (Chavarren & Calbet, 1999; Coast et al., 1986; Londere, Moffitt-Gerstenberger, Padfield, & Lottmann, 1997; McDaniel, Durstine, Hand, & Martin, 2002).

1.1.4 Metabolic Efficiency

Research analysing the relationship between cycling cadence and metabolic efficiency has been detailed and complex. For example, Gaesser and Brooks, (1975) outlined and defined four different efficiency measures that researchers could choose from:

1) Gross efficiency (GE), the ratio of work accomplished to energy expended, that is, the effectiveness of converting chemical energy into mechanical work;

2) Net efficiency (NE), the ratio of the work accomplished to the energy expended above that during rest, that is the cost of resting metabolism is subtracted from the denominator in the computation;

3) Work efficiency (WE), the ratio of the work accomplished to the energy expended above that during cycling with no load, calculating by subtracting from the denominator the cost of moving the legs plus the resting metabolism, and

4) Delta efficiency (DE), the ratio of the change in the power output to the change in the energy expended at each power output.

Research has demonstrated that at a constant power output, GE decreased as cadence increased (Brisswalter et al., 2000; Chavarren & Calbet, 1999; Coast et al., 1986; Hintzy, Belli, Grappe, & Rouillon, 1999; Lepers, Millet, Maffiuletti, Hausswirth, &
Brisswalter, 2001b). However, not all studies reported these relationships. Faria (1992) reported that with trained cyclists pedalling at low power outputs (140 W), GE decreased from 18% to 14% as cadence increased from 68 to 132 rpm; but at approximately 290 W, GE remained constant at approximately 22%. Similarly, Sidossis, Horowitz, & Coyle (1992) found that when analysing well-trained cyclists, GE was similar at cadences of 60, 80, and 100 rpm during cycling at power outputs corresponding to 80% (280 W) and 90% (300 W) of an individual’s maximal aerobic power. However, at 50% and 60% of W_max, the GE at 100 rpm was significantly lower than either 60 or 80 rpm. To explain the difference between their results and previous research, it was speculated that the skill level of the participants might have played a role (Faria, 1992). Previous studies that have revealed a decrease in GE as cadence increases have tended to use less skilled riders. It has been suggested that these participants may have engaged in non-specific muscle groups, especially during the higher cadences and power outputs resulting in increased oxygen consumption without any increase in useful work.

In conjunction with these conflicting issues surrounding the effect that GE has on cadence and workload, it has also been speculated that GE is not the optimal measure of efficiency, as it includes energy that does not directly contribute to the actual work accomplished (Chavarren & Calbet, 1999; Faria, Sjojaard, & Bonde-Petersen, 1982). Alternatively, DE has been considered a more appropriate measurement as it determines true muscular efficiency (Chavarren & Calbet, 1999; Gaesser & Brooks, 1975; Lucia et al., 2004; Sidossis et al., 1992). As demonstrated in Figure 3, early research elucidated that DE decreased as cadence increased (Gaesser & Brooks, 1975), however, Sidossis et al. (1992) reported that DE increased from 21% to 24.5%
as cadence increased from 60 to 100 rpm. Again, these authors suggested that differences between their data and previous work may have been due to the use of unskilled riders in previous studies. Furthermore, Chavarren & Calbet (1999) demonstrated the differences between GE and DE and argued that DE was a more useful predictor of performance in road cyclists, since there was a strong relationship between DE and the percentage of type I fibres, as well as between the percentage of type I fibres and endurance. They reported that DE increased with pedalling rate in road cyclists, while in contrast, GE deteriorated with increasing pedalling frequency. These authors also stated that the principle advantage of the use of DE is that it provided a more valid estimate of the true muscular efficiency than GE. This was due to the change in energy expended being calculated relative to the change in actual work accomplished, discounting more of the metabolic processes that do not contribute to the actual work (Coyle et al., 1992; Stainbsy, Gladden, Barclay, & Wilson, 1980).
Figure 3: Conflicting results on delta efficiency values while pedalling at a constant power output at varying cadences. Adapted from (Chavarren & Calbet, 1999; Gaesser & Brooks, 1975; Sidossis et al., 1992).

Moseley & Jeukendrup (2001) conducted research on the reliability of cycling efficiency and indicated that efficiency seemed to be related to the exercise intensity and it was specifically improved at the higher work rates. They reported that no definition of efficiency is completely satisfactory as both GE and DE both have flaws in their calculations. It is generally agreed that GE is a poor measure of the efficiency of muscular work (Coyle et al., 1992; Gaesser & Brooks, 1975). It has been thought that GE distorts the essentially linear relationship between work rate and energy expenditure to make it appear that efficiency increases with work rate. This distortion occurs due to the reduced proportion of energy expenditure that is used to maintain homeostasis as total energy expenditure increases (Moseley & Jeukendrup, 2001). Conversely, DE was reportedly not the most reliable measure of efficiency. Interestingly, it has been suggested that GE provides a superior measure of whole body efficiency and may also be relevant from a practical point of view. Therefore, a
research design that encompasses both GE and DE, and includes a range of participant abilities, would provide essential evidence to assist in the understanding of the relationship between the FCC and the optimal cycling cadence.

1.1.5 Crank and pedal force, cycling experience, and muscular coordination

Force production is another physiological variable that has been researched extensively in reference to cadence selection (Davis & Hull, 1981; Ericson & Nisell, 1988; Hansen et al., 2002a; MacIntosh et al., 2000; Patterson & Moreno, 1990; Pedersen et al., 2002; Sanderson, Hennig, & Black, 2000; Takaishi, Yasuda, Ono, & Moritani, 1996; Wilkie, 1950). According to many researchers, the force applied on the pedals has a direct effect on cycling economy, pedalling rate, and coordination (Hunter, St Clair Gibson, Lambert, & Noakes, 2002; Kautz, Feltner, Coyle, & Baylor, 1991; Lafortune & Cavanagh, 1983; MacIntosh et al., 2000; Patterson & Moreno, 1990; Patterson, Pearson, & Fisher, 1983; Sanderson, 1991; Sanderson et al., 2000; Smak, Neptune, & Hull, 1999; Takaishi et al., 2002). Therefore it would seem that the more skilful and co-ordinated an individual, the more efficient they are at applying the forces to the pedals.

Research has demonstrated that there is an optimal combination of pedalling rate and force development at the pedals whereby a cadence that is too low or too high does not permit an efficient force production pattern (Faria, 1992). Force production that is not optimal hinders the appropriate recruitment of muscle fibres. For example, pedalling force on the pedals is greater at 60 than 100 rpm and results in the recruitment of different muscles fibres. Cycling at 60 rpm has been shown to recruit a greater amount of Type II muscle fibres and depletes relatively more glycogen.
compared to pedalling at 100 rpm, where more Type I muscle fibres are recruited which have a greater fatigue resistance (Ahlquist et al., 1992; Coyle et al., 1991; Coyle et al., 1992). More recent research has demonstrated that there is a limit to the FCC. Mora-Rodriguez et al. (2006) reported that lactate accumulation was greater at 120 rpm than 80 or 100 rpm, possibly due to the increased shortening velocity of the muscle contraction that may elicit greater recruitment of FT muscle fibres. Therefore, pedalling at 120 rpm may have the same disadvantages as cycling at 50-60 rpm. As a result, cyclists may select a FCC that is higher than the optimal metabolic cadence in order to reduce the level of force on the pedals and possibly reduce the development of fatigue in the working muscles.

Muscular coordination is reportedly influenced by the skill level of the performer (Neptune, Kautz, & Hull, 1997), and suggested to play a role in cadence selection. Accordingly, the level of coordination of well-trained cyclists should be superior to their novice counterparts and also improve with practice and training. It has been proposed that more experienced cyclists select high cadences due to a high level of coordinative properties (Ericson, Nisell, Arborelius, & Ekholm, 1985). These include minimising both the net joint forces on the pedals and the magnitude of muscle activity, along with a difference in the timing of muscular activation in the crank cycle (Neptune et al., 1997). A number of studies have compared the level of cycling ability and the use of higher pedalling cadences (Belli & Hintzy, 2002; Marsh & Martin, 1997; Takaishi et al., 2002). Some researchers have reported that elite cyclists pedal at higher cadences than non-cyclists, most likely due to a superior efficiency of force production and co-ordination developed through years of training (Neptune et al., 1997). Others have suggested that cycling experience, per se, is not a pre-requisite
to the selection of a higher preferred cadence, and that there is reason to suspect that
cadence selection is commonly controlled by fundamental underlying mechanisms
common to all people (Hagberg et al., 1981). Again, the discrepancies between these
studies may have been due to inconsistencies with their methodologies. Therefore,
there remains a need to compare the FCC and factors associated with the optimal
pedalling frequency utilising a consistent methodological approach that utilises
workloads that resemble a real-world cycling environment and account for variations
in fitness levels and cycling experience.

The level of neuromuscular coordination in cycling can be measured by analysing
both the timing and the magnitude of muscular excitation at selected pedalling rates
for constant workloads (Ericson et al., 1985; Hunter et al., 2002; Jameson & Ring,
2000; Marsh & Martin, 1995; Neptune et al., 1997; Raasch, Zajac, Ma, & Levine,
1997). This has been quantified by both peak EMG activity and iEMG-based
measures in various muscles across a range of pedalling rates. The research findings
on the magnitude of neuromuscular coordination have been inconsistent and to date
there still remains no general consensus (Arkesteijn, Jobson, Hopker, & Passfield,
2013; Enders, V, & Nigg, 2015; Katona, Pilissy, Tihanyi, & Laczko, 2014; McGhie &
Ettema, 2011). It appears that muscular excitation must occur earlier in the crank
cycle as pedalling rate increases in order to develop the force in the same region
(Ericson & Nisell, 1988; Marsh & Martin, 1995; Takaishi et al., 2002; Takaishi et al.,
1996), however further research is needed to fully understand these aspects.

Along with considerations for muscular co-ordination and activation, it has been
suggested that cyclists prefer to pedal at higher cadences in order to minimize
peripheral muscle fatigue and lower crank force (Patterson & Moreno, 1990; Takaishi et al., 1996). Well-trained cyclists may select a higher cadence to reduce mean (T_{mean}) and peak (T_{peak}) torque along with peripheral muscular fatigue (Bertucci, Grappe, Girard, Betik, & Rouillon, 2005) as measured by the crank torque profile. It has been demonstrated that changes in cadence involved modifications in the crank torque profile (Bertucci et al., 2005). The crank torque profile represents the relationship between torque and crank angle and is based on the rationale that cycling at different cadences results in different muscular contraction velocities leading to the active muscles operating across different portions of their force–length and force–velocity relationship. It has also been suggested that cyclists may select a preferred cadence based on the contractile properties of the muscles as observed through an analysis of the crank torque profile (Bertucci et al., 2005; Bertucci, Grappe, & Groselambert, 2007; Bertucci, Betik, Duc, & Grappe, 2012). Interestingly, the effect of a change in cycling cadence on T_{mean}, T_{peak} and the crank torque profile has not been reported in non-cyclists. Therefore, research examining torque values at varying cadences and workloads in non-cyclists and then comparing them to well-trained cyclists would assist researchers in understanding if cadence selection is related to a need to minimise the muscular demands of the task. Furthermore, such research would enable the determination of differences in muscle recruitment during the crank cycle when comparing groups with different levels of cycling fitness and experience.

1.1.6 The most comfortable cadence

In addition to the physiological and biomechanical factors, cycling cadence selection has been attributed to psychological factors. One commonly assessed marker in
determining psychological factors that may influence cadence selection is the rating of perceived exertion (RPE). RPE assesses perceived intensity and is based on the physical sensations a person experiences during physical activity, including increased heart rate, increased respiration or breathing rate, increased sweating, and muscle fatigue. Although a subjective measure, RPE provides a valid estimate of the actual heart rate during physical activity (Borg, 1990).

It has been suggested that an individual’s perception of effort is an important factor when selecting a pedalling rate. Cues from active muscles may therefore be given more consideration than metabolic efficiency when selecting a preferred cadence. Ekblom and Goldbarg (1971) stated that “muscle strain”, defined as the strain placed on peripheral muscles and joints or local sensations, might provide feedback to the central nervous system, which strongly influences perceived exertion. It was suggested that the feelings individuals perceive in the periphery (legs) during cycling feed forward to the self-selection of pedalling rate in order to minimise the perceived effort of the task, even at the expense of a higher metabolic cost. It has also been suggested when cycling that at low pedalling rates where metabolic efficiency was maximised, the high levels of force on the pedals could cause an increase in sensation of exertion. Alternatively, at higher pedalling rates, when metabolic rate increases and the output becomes less efficient, RPE values may also increase. Therefore, it was suggested that in cycling it was important to differentiate in RPE values between central metabolic factors and peripheral cues from the active muscles involved in the task (Coast et al., 1986).
Coast et al. (1986) reported that perceived exertion was minimised at approximately 80 rpm and tended to be slightly higher than those minimising oxygen consumption. It has been demonstrated that perceived exertion remains relatively unchanged between 65 and 95 rpm but tended to increase at the extremes of the cadence range (50 and 110 rpm) (Coast et al., 1986). In another study depicted in Figure 4, Hansen, Jorgensen, Jensen, Fregly, & Sjogaard (2002b) investigated overall RPE in healthy males during treadmill cycling at 61 to 115 rpm at 40% and 70% of the power output at which VO$_2$max was attained. The RPE data revealed a parabolic relationship with minimum RPE values occurring at 63 and 72 rpm at the low and high power output, respectively. Although as in the research conducted by Coast et al (1986), RPE was not differentiated between central and peripheral factors. Further research that analyses RPE both centrally and peripherally in a range of participants at multiple cadences and workloads, before and after a training regime would provide a unique insight in determining if cadence selection is directly related to perceived exertion.
Figure 4: Group (mean ± SD) gross efficiency at low (open circles) and high (solid circles) submaximal power output as a function of pre-set pedal rate. Regression lines are extrapolated below 61 rpm. Pedal rates at maximum gross efficiency (open arrows) and at minimum RPE (arrows with horizontal lines) are pointed out as well as the mean freely chosen pedal rate (solid arrows) and the pedal rate at which maximum peak crank power occurred (broken arrow). Adapted from Hansen et al. (2002a).

1.1.7 Cadence and performance

Finally, it has also been argued that the ideal rate of movement for competitive cyclists is the cadence that optimises performance (Foss & Hallen, 2004a). To establish which cadence is optimal for performance, researchers have manipulated pedalling rates either in absolute terms or as a percentage of their FCC. Time trials over distances of approximately 8 to 24 km (Foss & Hallen, 2005; Watson & Swensen, 2006), and time to exhaustion tests ranging from approximately 5 - 11 minutes (Nesi et al., 2005; Nielsen et al., 2004) have been used to examine the relationship between FCC and performance, with results generally showing that
cadences of approximately 80–90 rpm were most optimal. It was suggested that the selection of the FCC was based on reducing peripheral fatigue of leg musculature in lieu of whole body metabolic efficiency (Nickleberry & Brooks, 1996).

1.1.8 Central pattern generators

More recently, it has been suggested that during rhythmic human movement, motor coordination is most likely delegated to neural networks, termed central pattern generators (CPG), located in the spinal cord (Zehr, 2005; Zehr & Duysens, 2004). Evidence that cycling cadence may be controlled by these CPG stems from the fact that the FCC in cycling is largely individual (50–100 rpm) and is robust to acute changes such as mechanical and cardiopulmonary loading (Hansen, 2015; Hansen & Ohnstad, 2008; Hartley & Cheung, 2013). In addition, both internal (e.g., experience) and external (e.g., performance type) factors are known to alter the FCC (Hansen, 2015; Hartley & Cheung, 2013; Sardroodian, Madeleine, Voigt, & Hansen, 2014; Zehr, 2005). Therefore, it has been suggested that the FCC in cycling represents a voluntary rhythmic leg movement frequency, under the primary influence of CPG (Hartley & Cheung, 2013; Zehr, 2005). However, it must be noted that the investigation of the idea of cadence being controlled by CPG in healthy humans is significantly challenged by limited access to the spinal cord, as compared with studies on animals however, there is sound rationale to consider the relevance of such control in cycling.
1.2 Statement of the Problem

For the majority of locomotive activities, there is widespread support for the metabolic demand hypothesis, which states that humans will self-select a preferred rate of movement with the purpose of minimising the metabolic demands of the task. In contrast, research into cycling has yielded conflicting findings in regards to cadence selection and the metabolic demands of the task. There is strong evidence that cyclists select a FCC that is significantly higher than the cadence that is most metabolically efficient. However, more recent work has demonstrated that the most economical cadence actually increases linearly with power output at high work-loads (>300 W), (Foss & Hallen, 2005; Lepers, Millet, & Maffiuletti, 2001a; Lepers et al., 2001b; Nielsen et al., 2004; Samozino, Horvais, & Hintzy, 2006), suggesting that cadence selection and metabolic efficiency may be more closely related than previously postulated (Vercruyssen & Brisswalter, 2010). Therefore, confusion remains as to whether the skill of cycling adheres to the principles of the metabolic demand hypothesis.

Despite an abundance of studies examining factors that directly influence cadence selection, it remains unclear as to exactly what causes cyclists of ranging abilities and fitness levels to select a preferred rate of movement. This task is made even more difficult given the array of variables that have been previously shown to have an impact on cadence selection. There also remains a number of methodological inconsistencies in the research which have the potential to impact the corresponding findings. Mainly, the use of absolute versus relative workloads, power outputs that do not reflect a real-world cycling environment, the use of only a single measurement of
efficiency, and a lack of direct comparison between groups of cyclists with varying fitness levels and experience.

Finally, the majority of studies that have examined the relationship between the FCC and the most optimal pedalling frequency in cycling have been limited to analysing the existing characteristics of a solitary cohort at a single point in time. Therefore, few studies have examined the effect of manipulating cycling cadence in a range of participants over an extended period of time, to determine its impact on the FCC and the optimal pedalling frequency. There are likely to be variations between training status and fitness level of the participant when any external stimulus is applied in an attempt to alter the preferred cadence. However, the way in which non-cyclists and well-trained cyclists respond to the application of any specific training stimulus is currently unknown. Interestingly, there is also limited research on the practical applications of interval-training at high and low cadences in order to improve performance in cycling.

Therefore, the current research will provide further insight into identifying the variables that may influence the FCC and the optimal pedalling frequency, and assist in determining whether cycling adheres to the metabolic demand hypothesis. This will be achieved through analysing participant’s preferred and optimal cadence at workloads relative to their fitness levels, and representative of a real-world cycling environment.
1.3 Aims and Hypothesis

1.3.1 What is known about the proposed topic area.

- For the majority of locomotor skills, the preferred rate of movement coincides with the rate of movement that minimises the metabolic demands of the task.
- Cyclists of varying experience and fitness level prefer to pedal at high cadences.
- The FCC in cycling is task dependant and may be influenced by a number of variables derived from a number of different domains.

1.3.2 What is unknown about the proposed topic area.

- Whether the preferred rate of movement in cycling coincides with the most metabolic optimal pedalling frequency.
- The exact variables that influence the selection of the FCC in cyclists of ranging abilities and fitness levels.
- The impact of training on the FCC, performance and the variables proposed to influence cadence selection.

This research was undertaken using three related studies as outlined in Figure 5, with each building on the results of the preceding work. Study 1 examined whether the skill of cycling adhered to the principles of economy and also investigated the relationship between the preferred pedalling rate and metabolic demand in non-cyclists. Study 2 examined whether the preferred pedalling rate in non-cyclists could be altered with training, as evident in other research analysing locomotive skill (Majed, Heugas, Chamon, & Siegler, 2012; Sparrow et al., 1999). Study 3 investigated whether the FCC could be altered in a more established movement
pattern as seen in well-trained cyclists and accordingly whether these changes were related to minimising the metabolic or muscular demands of the task. Furthermore, studies 2 and 3 investigated the impact of 6 weeks of high and low cadence interval training on performance and pedalling characteristics in well-trained and non-cyclists. Each of these studies are outlined below.

1.3.3 The relationship between the FCC and the most optimal rate of movement in non-cyclists

Aim: To determine the factors associated with cadence selection in a group of non-cyclists pedalling at varying workloads, measured in relative terms of each participant’s fitness level.

Overview: To date, no study has analysed both the FCC and the most economical pedalling rate at relative workloads in a group of non-cyclists. Additionally, no previous study has examined the crank torque profile in novices to determine whether the FCC is closely related to minimising the muscular demands of the task. The purpose of this study was to examine both the freely chosen cadence (FCC) and the physical variables associated with cadence selection in non-cyclists. Eighteen participants pedalled at 40, 50, and 60% of their maximal power output (determined by a maximal oxygen uptake test, $W_{\text{max}}$) whilst cadence (50, 65, 80, 95, 110 rpm, and FCC) was manipulated. Gross efficiency (GE), was used to analyse the most economical cadence whilst central and peripheral ratings of perceived exertion (RPE) were used to measure the most comfortable cadence and the cadence whereby muscle strain was minimised. Peak ($T_{\text{peak}}$), mean crank torque ($T_{\text{mean}}$) and the crank torque profile were analysed at 150 and 200 W at cadences of 50, 65, 80, 95, and 110 rpm in order to determine the mechanical load.
**Hypothesis:** It was hypothesised that (a) non-cyclists would select a FCC that was higher than the most economical cadence, and (b) that FCC would be closely related to variables associated with minimising the energetic demands of muscle and mechanical load.

**1.3.4 Study 2: The relationship between the preferred rate of movement and metabolic demands in non-cyclists**

**Aim:** The aim of study 2 was to analyse the relationship between the skill of cycling and the principles of economy. This was achieved through a two-part experiment. Part A determined whether non-cyclists selected a FCC that was significantly lower, and less efficient in metabolic terms, when compared to well-trained cyclists. Part B examined the influence of 6 weeks of interval training at either 20% above or below the FCC on the preferred cadence in a group of non-cyclists. Collectively, the aim of the study was to provide new evidence to determine if the skill of cycling adhered to the minimization of energy theory as demonstrated in other high-energy endurance based skills (Lay et al., 2002; Lay, Sparrow, & O'Dwyer, 2005; Sparrow et al., 2000; Sparrow & Newell, 1994b).

**Overview:** Sixteen male well-trained cyclists and sixteen male well-trained non-cyclists completed a series of submaximal cycling bouts at 60% maximal power ($W_{\text{max}}$) at cadences of 50, 70, 90, and 110 rpm, and their FCC to determine their preferred cadence, gross efficiency (GE), rating of perceived exertion, and crank torque profile. Performance was measured via a 15-min time trial, which was preloaded with a cycle at 60% $W_{\text{max}}$. Following the testing, the non-cyclists only were
then randomly assigned to a high-cadence (HC) (20% above FCC) or a low-cadence (LC) (20% below FCC) group for 18 interval-based training sessions over 6 weeks and then retested to assess any changes.

**Hypothesis:** It was hypothesised that in Part A of the experiment, well-trained cyclists would display superior values for efficiency at all tested cadences and prefer to pedal at a higher FCC than non-cyclists. It was also hypothesised that in Part B of the study, the FCC in non-cyclists would change in accordance with their training stimulus and that cadence selection would be more closely linked to muscular efficiency or centrally driven neuromuscular control than metabolic efficiency.

1.3.5 Study 3: The effect of low- vs high-cadence interval training on the freely chosen cadence and performance in endurance-trained cyclists

**Aim:** The aim of study 3 was to firstly determine whether a training protocol undertaken at either above or below the preferred cadence could alter the selection of the FCC in an already established movement pattern such as those seen in endurance-trained cyclists. A further aim of study 3 was to determine whether measurements of gross efficiency (GE), perceived exertion, and the crank torque profile could be altered with training. Finally, study 3 aimed to determine whether interval training with cadence manipulation could improve performance in a 15-min preloaded time trial (TT) in well-trained cyclists.

**Overview:** Sixteen male endurance-trained cyclists completed a series of submaximal rides at 60% maximal power (W\text{max}) at cadences of 50, 70, 90, and 110 rpm, and their FCC to determine their preferred cadence, gross efficiency (GE), rating of perceived
exertion, and crank torque profile. Performance was measured via a 15-min time trial, which was preloaded with a 15-minute cycle at 60% $W_{\text{max}}$. Following the testing, the participants were randomly assigned to a high-cadence (HC) (20% above FCC) or a low-cadence (LC) (20% below FCC) group for 18 interval-based training sessions over 6 weeks and then retested to assess any changes.

**Hypothesis:** It was hypothesised that the training protocol would alter the FCC of the highly skilled well-trained cyclists in the direction of the training stimulus that was undertaken. It was also hypothesised that the variables associated with minimizing the muscular demands of the task, as opposed to those related to the metabolic efficiency, would change significantly and therefore be more closely related to the selection of the FCC. Finally, it was hypothesised that regardless of the required cadence manipulation, performance in both groups would improve as a result of training for 6 weeks at 70% maximal power ($W_{\text{max}}$).
What factors influence cadence selection in non-cyclists?

Can the FCC in non-cyclists and well-trained cyclists be altered with training and if so what variables change in the process?

Review of literature
pertaining to the relationship between the preferred and most optimal rate of movement in locomotive sports

Study 1
The relationship between the FCC and the most optimal rate of movement in non-cyclists (measured in relative terms).

Study 2
The relationship between the preferred rate of movement and metabolic demands in non-cyclists (a cadence-based interval-training intervention).

Study 3
The effect of low vs high-cadence interval training on the FCC and performance in endurance-trained cyclists.

Practical Applications and consideration of the relevance of the metabolic demand hypothesis for the skill of cycling

Figure 5: Flow diagram of the progression of studies one, two and three
1.4 Significance of the Project

There have been numerous attempts to determine the variables that directly influence cadence selection in cycling (Ettema & Loras, 2009; Faria, Parker, & Faria, 2005; Hansen, 2015). However, research analysing the optimal pedalling frequency and its relationship with the FCC in cycling remains inconclusive. Very few of these studies have examined coordinative, physiological, psychological and motor learning factors simultaneously, thus, the current series of studies allow multiple variables to be investigated concurrently.

The physiological domain has dominated research in the area of cycling efficiency and self-selected pedalling rates. In contrast, results from this thesis could assist in determining whether motor control and coordination principles could also be applied to source the mechanisms that cause cyclists to shift to higher cadences. In addressing the skill of cycling from a learning perspective, certain changes in the rate at which the task is performed over time could be beneficial to athletes, coaches and exercise scientists. This may assist in furthering our understanding of why cycling could in fact be a skill that is not performed in accordance with the metabolic demand hypothesis.

The research design of this thesis also allows the adoption of a novel approach in determining the FCC and the most optimal cadence for performance. These were achieved by manipulating the FCC via an interval-training program over an extended period of time and examining its impact on cadence selection, the optimal cycling cadence and performance. Therefore, the findings from these studies also have the potential to influence the practice of sport scientists and cycling coaches at all levels.
of competition. This research also has the potential to identify individual characteristics that may influence the optimal cadence selection and the outcomes of this thesis may also inform coaches and sport scientists as to whether a low or high cadence interval-training regime may impact performance in a unique manner.

1.5 Limitations and Assumptions

The following limitations and assumptions apply to the studies reported in this thesis:

- All bicycle tests were performed on an SRM ergometer and not on the participants’ own bicycle.
- All bicycle-training sessions were performed on a Monark ergometer and not on the participant’s own bicycle.
- Participants were asked to refrain from physical activity 24 hours prior to testing sessions however this was dependent on participant compliance and honesty.
- The selection of participants for this research was not randomised, rather, relied on targeted recruitment.
- The results and implications of the research can only be directed at the specified population that were used.
- It was assumed that the well-trained cyclists that participated in this research, underwent their normal training regime outside their direct involvement with the interval training.

1.6 Delimitations

The following delimitations apply to the studies reported in this thesis

- The measurement of cycling performing was delimited to a pre-loaded time trial of 15 min followed by a 15 min maximal effort time trial.
• The cadence-based interval training program was restricted to a six-week period.

• The cadences selected for the six-week interval training program were restricted to representing either 20% above or below each participants FCC.

• Submaximal testing was restricted to 6-8 min periods.

• The study was delimited to the assessment of the following variables: physiological (VO₂max, DE, GE, lactate threshold), psychological (RPEcentral, RPEperipheral) and biomechanical (crank torque profile) testing, with the assessment of kinetic components of the crank-leg system and the use of dynamical system approach to cadence selection being beyond the scope for the research.

• All participants performed an individualised yet consistent warm-up prior to the performance trial based on their maximal power output measured on the preceding day.

• Testing times for each participant were not held constant and there may be some diurnal variation in results.
Chapter 2: Do the metabolic demands of a task determine the rate of performance? A review of the preferred rate of movement in cycling and other locomotive skills

As per the journal article under review in *Sports Medicine*.

Abstract

The relationship between the preferred rate of movement and the metabolic demands of the task in locomotive skills has received considerable attention, specifically in regards to the optimal rate for performance. It has been proposed that when performing these skills, humans will inherently self-select a rate of movement to minimise the metabolic demands of the task. Alternatively, it has been suggested that the preferred rate of movement may be attributed to other mechanisms, such as mechanical, psychological or other physiological factors. More recently, it has been speculated that the preferred rate of movement may be under control of central pattern generators residing in the nervous system, with research analysing the skill of cycling generating most of the attention in this area. To date, researchers remain divided as to the mechanism that influences the preferred rate of movement in locomotive skills and their impact on performance. The purpose of this article is to review the available literature pertaining to the preferred rate of movement, metabolic demands of the task, and performance in locomotive skills, with specific reference to the skill of cycling and the variables proposed to influence the freely chosen cadence.
Chapter 3: Factors associated with the selection of the freely chosen cadence in non-cyclists

Based on the published journal article in the European Journal of Applied Physiology.

Abstract

The purpose of this study was to examine both the freely chosen cadence (FCC) and the physical variables associated with cadence selection in non-cyclists. Eighteen participants pedalled at 40, 50, and 60% of their maximal power output (determined by a maximal oxygen uptake test, $W_{\text{max}}$) whilst cadence (50, 65, 80, 95, 110 rpm, and FCC) was manipulated. Gross efficiency (GE), was used to analyse the most economical cadence whilst central and peripheral ratings of perceived exertion (RPE) were used to measure the most comfortable cadence and the cadence whereby muscle strain was minimised. Peak ($T_{\text{peak}}$), mean crank torque ($T_{\text{mean}}$) and the crank torque profile were analysed at 150 and 200 W at cadences of 50, 65, 80, 95, and 110 rpm in order to determine the mechanical load. FCC was found to be approximately 80 rpm at all workloads and was significantly higher than the most economical cadence (50 rpm) ($p < 0.05$). At 60%$W_{\text{max}}$, RPE peripheral was minimised at 80 rpm, which coincided with the FCC. Both $T_{\text{peak}}$ and $T_{\text{mean}}$ significantly decreased as cadence increased and, conversely, significantly increased as power output increased. An analysis of the crank torque profile showed that the crank angle at both the top ($DP_{\text{top}}$) and the bottom ($DP_{\text{bot}}$) dead point of the crank cycle at 80 rpm occurred later in the cycling revolution when compared to 50 rpm. The findings suggested that the FCC in non-cyclists was more closely related to variables that minimise muscle strain and mechanical load than those associated with minimising metabolic economy.

Keywords: muscle strain · pedalling force · relative intensity

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Chapter 4: The impact of low vs high cadence interval training on the freely chosen cadence in non-cyclists. (A comparison of preferred pedalling rates in well trained and non-cyclists).

As per the requirements for a manuscript under review at *Human Movement Science*.

Abstract

The aim of this two-part study was to determine whether the skill of cycling adhered to the metabolic demand hypothesis. In Part A, 16 male non-cyclists (NC) and 16 well-trained cyclists (WTC) pedalled at 60%\(W_{\text{max}}\) at varying cadences to determine their freely chosen cadence (FCC), crank torque profile and the most optimal metabolic cadence. There were no differences in the FCC between the WTC (93 ± 8 rpm) and NC (86 ± 10 rpm) with both groups selecting a FCC that was significantly higher than the most optimal metabolic cadence (50 rpm). Furthermore, there were no differences in the crank torque profile between NC and WTC. Part B of the experiment examined the effects of high (HC) and low cadence (LC) interval training on the FCC and the most optimal pedalling frequency in NC. Sixteen male NC pedalled at 60%\(W_{\text{max}}\) at cadences of 50, 70, 90, 110 and the FCC to determine their preferred and most optimal metabolic cadence, perceived exertion (RPE) and performance prior to and at the completion of a 6-week interval-training program. Findings from Part B revealed that the FCC increased in the HC group, whereas the LC group remained unchanged. The only reductions in the metabolic demands of the task following training were seen at 50 rpm for the HC group and 70 rpm for the LC group. Following training, both the HC and LC group increased the total distance covered in the performance test, with the LC group demonstrating a greater improvement. Collectively, the findings from Part A and B provided evidence for the rejection of the metabolic demand hypothesis for the skill of cycling. Alternatively, the current findings demonstrated that the FCC is highly individual, has strong day to day reliability and is impacted by external factors such as an increase in workload and may be linked to central pattern generators (CPG). The findings from Part B also
revealed that interval training with either high or low cadence both groups improved time trial performance.

**Key words**

Metabolic efficiency, cadence, central pattern generators

**Highlights**

- No differences recorded in freely chosen cadence between well-trained cyclists and non-cyclists.
- The freely chosen cadence was significantly higher than the most optimal metabolic cadence in both well-trained cyclists and non-cyclists.
- 6 weeks of high cadence interval training increased the freely chosen cadence in non-cyclists but it was unchanged for non-cyclists participating in low cadence interval training.
- Findings provided evidence for the rejection of the metabolic demand hypothesis for cycling but showed support for the proposal that cadence selection may be under the influence of central pattern generators.
- Low cadence interval training improved performance to a greater extent than high cadence interval training for non-cyclists.

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Chapter 5: The effect of low vs high cadence interval training on the freely chosen cadence and performance in endurance-trained cyclists.

Based on the published journal article in *Applied Physiology Nutrition and Metabolism*.

Abstract

The aim of this study was to determine the effects of high (HC) and low cadence (LC) interval training on the freely chosen cadence (FCC), and performance in endurance trained cyclists. Sixteen male endurance-trained cyclists completed a series of submaximal rides at $60\% W_{\text{max}}$ at cadences of 50, 70, 90, 110 rpm and their FCC to determine their preferred cadence, gross efficiency (GE), rating of perceived exertion (RPE) and crank torque profile. Performance was measured via a 15-min time trial, which was preloaded with a cycle at $60\% W_{\text{max}}$. Following the testing, the participants were randomly assigned to a HC, (20% above FCC) or LC, (20% below FCC) group for 18 interval training sessions over 6 weeks. The HC group increased (p=0.01) their FCC from 92 to 101 rpm after the intervention whereas the LC group remained unchanged (93 rpm). GE increased from 22.7 to 23.6% in the HC group at 90 rpm (p=0.05), from 20.0 to 20.9% at 110 rpm (p=0.05) and from 22.8 to 23.2% at their FCC. Both groups significantly increased total distance and average power output during the 15-minute time trial (TT) following training, with the LC group recording a greater performance measure. There were minimal changes to the crank torque profile in both groups following training. This study demonstrated that the FCC can be altered with HC interval training. Furthermore, LC interval training may significantly improve time trial results of short duration due to an increase in strength development or possible neuromuscular adaptations.

**Keywords:** metabolic efficiency · central pattern generators· muscular demands

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Chapter 6: 
Discussion
6.1 Introduction

The primary purpose of this thesis was to analyse the relationship between the preferred and optimal rate of movement in locomotive skills. Prior to undertaking this research, there were conflicting views regarding the nature of this relationship. The outcomes of one sub-section of the literature suggested that when performing locomotive skills, humans will inherently self-select a rate of movement in order to minimise the metabolic demands of the task. Referred to as the metabolic demand hypothesis, this concept suggests that when initially performing skills, humans produce a movement pattern that is unstable and high in metabolic demand when compared to well-trained counterparts. However, with practice the coordinative movement pattern will be more stable and be produced in a more metabolic efficient manner requiring significantly less metabolic demand (Cavanagh & Kram, 1989; Cavanagh & Williams, 1982; Lay et al., 2002; Umberger & Martin, 2007).

In contrast, others questioned whether the preferred rate of movement in locomotive skills was based solely on minimising the metabolic demands of the task (Hansen, 2015; Hunter et al., 2010; Monsch et al., 2012). Accordingly, it was suggested that the preferred rate of movement may be attributed to other mechanisms, such as mechanical or muscular effort, performance, muscle fibre type, psychological factors such as comfort mode, or more specifically, may be controlled by rhythmic movement output from the nervous system known as central pattern generators (CPG) (Hansen, 2015; Moore, 2016; Sparrow, 1983; Zehr, 2005). The sequence of studies in this thesis aimed to firstly identify and summarise the literature pertaining to the relationship between the preferred rate of movement and the optimal in locomotive skills. Secondly, this research aimed to summarise the findings related to the factors
that contribute to the freely chosen cadence (FCC) and the optimal pedalling frequency in cycling. Thirdly, the thesis also aimed to identify whether the skill of cycling adhered to the metabolic demand hypothesis and if not, determine the variables or mechanisms that may be attributed to cadence selection in cyclists of ranging abilities and fitness levels. Finally, the research aimed to determine the impact of a specific cadence-based interval-training program on performance well-trained and non-cyclists.

6.1.1 An overview of the literature relating to the preferred rate of movement and the optimal in endurance based sports

The initial aim of this thesis was to review the literature pertaining to the relationship between the optimal and preferred rate of movement in locomotive skills. This review summarised research that had been conducted;

1. On a range of locomotive skills, including participants of varying expertise and fitness levels.
2. That specifically focussed on analysing the metabolic demands of the task, the preferred rate of movement and performance.
3. That implemented training or practice designs that manipulated the rate of movement of the task to determine its impact on performance and the preferred rate of movement.

It was identified that in a range of locomotive skills such as running, walking and swimming, there was strong support for the metabolic demands hypothesis. Interestingly, in other skills such as uphill and downhill walking, it was proposed that
the preferred rate of movement might not coincide with the one that minimises the metabolic demands of the task. The majority of the research that questioned whether the metabolic demand hypothesis could be applicable to all locomotive skills was directly related to cycling. However, within the skill of cycling, there were conflicting arguments as to whether participants prefer to pedal at a rate that minimises the metabolic demands of the task, or indeed adopt a preferred rate of movement due to other mechanisms. Hansen et al. (2009) suggested that cycling research demonstrated that when pedalling at high power outputs, well-trained cyclists chose a FCC that was metabolically optimal, however, pedalling at high cadences during low-to-moderate intensity efforts was uneconomical and may have a negative impact on performance.

The review identified a need to conduct a more comprehensive analysis of the relationship between the preferred rate and the optimal rate of movement for the skill of cycling. This would need to include an analysis of participants of ranging abilities and fitness levels at varying levels of intensity, as well as a more consistent and validated methodological approach. Moreover, as seen in research on other locomotive skills, there was a distinct need to determine the impact of intervention studies that manipulated the rate of movement of the task, on the preferred rate of movement, metabolic demand and performance in cycling.

Following on from the identification of these areas requiring additional enquiry, the purpose of this thesis was to conduct a series of studies to analyse the relationship between the FCC and the optimal pedalling rate in both well-trained and non-cyclists. Collectively, these studies provide evidence to assess the efficacy of the metabolic demand hypothesis in relation to cycling and provide alternative mechanisms that
may be considered to influence cadence selection. These studies specifically focused on the following key aspects:

1. The determination of the relationship between the FCC and the optimal cycling cadence in non-cyclists. This would be measured using relative workloads, at a range of exercise intensities, and by adopting a more valid and reliable research design than previously implemented.

2. A comparison of the FCC and the optimal cycling cadence between well-trained and non-cyclists.

3. The application of a cadence based interval training study to determine whether the FCC in both well-trained and non-cyclists can be altered. Furthermore, if the FCC could be modified, the research sought to identify the factors that were associated with such changes.

4. The determination of the efficacy of interval training with cadence manipulation on performance in cycling.

### 6.1.2 The FCC and the optimal cadence in non-cyclists

Study 1 of the present thesis analysed the relationship between the FCC and the optimal cadence in untrained non-cyclists. The results highlighted that untrained non-cyclists selected a FCC of 80 ± 7 rpm and were unaffected by changes in workload. Previous research analysing “well trained” non-cyclists at constant workloads (150-200 W) reported that the FCC was affected by changes in workload and ranged from approximately 91 rpm (Marsh & Martin, 1993) to 60-75 rpm (Takaishi et al., 1996). In contrast, research with “untrained” non-cyclists demonstrated that the FCC decreased (80 to 69 rpm) as power output increased (75-150 W) (Marsh, Martin, &
Foley, 2000). The findings obtained from study 1 demonstrated that unlike previous research, when cadence selection was determined in terms relative to the participant’s fitness level, the FCC for non-cyclists remained unaffected by external variables such as increases in power output. The reasons for the discrepancies between previous work and study 1 may have been due to inconsistencies in the methodological approaches adopted in previous studies. For example, Marsh and Martin (1993), used an 8 minute test incorporating an absolute workload (200 W), whereas Takaishi (1996) simply asked the participants which cadence they preferred (Takaishi et al., 1996). The current study was the first to use relative workloads to assess the FCC in non-cyclists, which may account for any variations in the participant’s fitness levels. This is an important aspect of the interpretation of the results, especially when involving untrained participants with various fitness levels. Previous research in this area that adopted the use of absolute workloads were not able to account for variations in fitness levels and selected relatively low power outputs that were not reflective of a real world cycling environment.

Study 1 also demonstrated that the FCC (80 rpm) for non-cyclists was significantly higher than the most metabolically economical cadence (50 rpm) at all workloads. This was in agreement with previous studies that demonstrated that the preferred cadence in cycling was higher than the most economical, with some proposing that this was due to the need to optimise power output and minimise peripheral stress (Hopker et al., 2007; Marsh & Martin, 1993, 1995, 1997; Takaishi et al., 2002; Takaishi et al., 1996). When interpreted in the context of previous studies, the current findings suggest that, unlike other locomotive skills such as running and walking; non-cyclists selected a preferred rate of movement that did not coincide with the rate
that minimised the metabolic demand of the task. In summary, study 1 demonstrated that cycling cadence selection could be attributed to mechanisms other than the need to minimise the metabolic demands of the task.

Research has suggested that cyclists pedal at higher cadences in order to minimise peripheral muscle fatigue and to reduce crank force as shown by measurements of $T_{\text{peak}}$ and $T_{\text{mean}}$ (Patterson & Moreno, 1990). This was confirmed in study 1, which demonstrated that $T_{\text{peak}}$ decreased as cadence increased, and $T_{\text{mean}}$ at 80 rpm (FCC) was 39% lower than at 50 rpm (most economical cadence) at 200 W. In support of minimising the muscular demands of the task, research has also reported that cadence changes involved modifications in the crank torque profile (Bertucci et al., 2005). The rationale is that cycling at different cadences may result in different muscular contraction velocities, leading to the active muscles operating across different portions of their force–length relationship. Research with well-trained cyclists has revealed that the crank angle at $D_{\text{top}}$ and $D_{\text{bot}}$ were significantly lower at 80 rpm compared to 100 rpm suggesting that the $D_{\text{top}}$ and $D_{\text{bot}}$ occurred later in the cycling revolution (Bertucci et al., 2005). Uniquely, study 1 demonstrated that the crank angle at $D_{\text{top}}$ and $D_{\text{bot}}$ at 50 rpm was significantly lower compared to both 95 and 110 rpm at all workloads. These changes in $T_{\text{peak}}$, $T_{\text{mean}}$, and the crank torque profile, have been suggested to reflect a shift in muscle fibre recruitment from fast to slow twitch, which have greater fatigue resistance and a higher mechanical efficiency (Takaishi et al., 1996). These findings propose that non-cyclists may in fact increase their pedal rate to reduce the mechanical load, thus reducing the $T_{\text{mean}}$ and $T_{\text{peak}}$. Although not conclusive, the findings from study 1 indicate that additional research is required to
analyse the crank torque profile in cyclists of ranging fitness levels and experience at a range of cadences and workloads.

Research concerning the electromyographic (EMG) analysis of cycling has demonstrated how the pattern of muscle activation during pedalling can be analysed in terms of muscle activity level and timing. Muscle activity level is generally quantified with root mean square or integrated EMG values (Hug & Dorel, 2009). Muscle activation timing is studied by defining EMG signal onset and offset times that identify the duration of EMG bursts and, more recently, by the determination of a lag time maximizing the cross-correlation coefficient. Future research analysing EMG activity and the crank torque profile at a range of cadences and workloads including participants of varying cycling experience and fitness level in a single study may provide new evidence in understanding cadence selection in cycling.

The findings from study 1 revealed that the FCC may be related to perceived level of comfort, with peripheral RPE minimised at 80 rpm (the FCC) and significantly lower than 50 (most economical) and 110 rpm at 60%Wmax. Indeed, this shows that perception of effort may be an important factor to consider when selecting a FCC and that peripheral input from active muscles are important regulating factors for choosing FCC. These findings support the speculation that muscle strain is important to an individual’s comfort level and may therefore influence preferred cadence selection. Whilst the present study was the first investigation to uncover this relationship in non-cyclists, such findings have been consistently shown in studies performed on well-trained cyclists (Capostagno, Lambert, & Lamberts, 2016; Lollgen et al., 1975; Marsh
Collectively, the findings from study 1 highlighted that untrained non-cyclists prefer to pedal at cadences that were significantly greater than optimal metabolic pedalling frequency. Furthermore, the data collected on RPE and crank torque profile demonstrate that untrained non-cyclists may prefer to pedal at higher cadences because they felt these more comfortable and easier to maintain, required less muscular effort and resembled more closely the pedalling rate they would likely to select in a real-world situation. Study 1 also demonstrated that non-cyclists preferred to cycle well above the most economical cadence, possibly in order to increase perceived comfort levels, and decrease muscle strain and mechanical load, rather than a need to minimise metabolic demand. These findings suggest that unlike other locomotive skills, cycling may not adhere to the metabolic demand hypothesis.

However, in order to more substantially reject the metabolic demand hypothesis for the skill of cycling, research needed to address two primary aspects. Firstly, it was necessary to compare the FCC and metabolic and muscular demands of the task in well-trained and non-cyclists determined at relative workloads. Secondly, as demonstrated in other locomotive skills which support the metabolic demand hypothesis, there was a need to undertake research that manipulated the rate of movement of the task and assess the impact on the FCC, the metabolic and muscular demands of the task, as well as performance in both well-trained and non-cyclists.
In an attempt to address this paucity of research, this sequence of studies implemented cadence-based interval training interventions for both well-trained and non-cyclists in order to investigate the applicability of the metabolic demand hypothesis for the skill of cycling. The main purpose of this strategy was to combine elements of previous research from other locomotive skills researching the metabolic demand hypothesis to elucidate the relevance in cycling, and secondly to determine whether the FCC in cycling could be altered and the factors associated with any applicable changes. Finally, the purpose of these studies was to determine the impact of the cadence-based interval training performance in well-trained and non-cyclists and the practical applications of such findings.

6.1.3 The impact of training on FCC selection and performance

One of the primary aims of this thesis was to determine whether the preferred rate of movement in both trained and untrained cyclists could be altered with training, as demonstrated in other locomotive skills (Sparrow et al., 2007; Sparrow & Newell, 1994a, 1994b). For example, Sparrow et al. (1999) instructed novice participants to row at their preferred stroke rate as well as at ± 20% of the preferred rate over consecutive days of practice. Their findings demonstrated that firstly, HR and RPE declined over days of practice and secondly, HR, oxygen consumption and RPE were significantly lower when rowing at the preferred rate when compared to values that represented ± 20% of their preferred rate.

Study 2 of the current thesis revealed that after undertaking a 6-week cadence-based interval training program, non-cyclists who trained at higher cadences increased their FCC whilst those that pedalled at lower cadences had a FCC that remained
unchanged. Although it was initially proposed that both groups would alter their FCC in accordance with their training cadence, the findings from study 2 demonstrated that irrespective of the training stimulus, non-cyclists prefer to pedal at higher cadences (Chavarren & Calbet, 1999; Lucia et al., 2001).

Training studies examining cadence selection in non-cyclists have been limited. Hirano et al. (2015) reported that two weeks of training at either high or low cadences increased the work completed at lactate threshold in the low cadence group but not the high cadence group. Alternatively, Hansen et al. (2015) determined that non-cyclists decreased their FCC by 8 and 10 rpm on average following 12 weeks of heavy strength training when pedaling at 37 and 59% of $W_{\text{max}}$, respectively. Study 2 was the first of its kind to demonstrate that HC interval training increased the FCC for non-cyclists whereas LC training had no impact when utilizing a range of power outputs and crank inertial loads. The combined findings for study 1 and 2 of this thesis demonstrated that when determined in relative terms of their fitness levels, non-cyclists prefer to pedal at cadences that are higher than the metabolically optimal at a range of different workloads and have a FCC that is only altered by high cadence interval training.

Study 3 of the thesis replicated the cadence-based interval training conducted in study 2 with a cohort of well-trained cyclists, in order to determine if a more established movement pattern could also be altered with training. Study 3 revealed that well-trained cyclists who completed 6 weeks of interval training at 20% above (HC) their preferred cadence increased their FCC; whereas those that trained at 20% below (LC) demonstrated no changes in cadence selection. These findings were observed in both
the submaximal FCC test at $60\% W_{\text{max}}$ as well as in the preloading component of the performance test at the same workload. These results suggest that as seen with non-cyclists performing a novel task, an established movement pattern in a group of well-trained cyclists can also be altered with six weeks of specific high-cadence training. These findings support previous research which demonstrated that well-trained cyclists prefer to pedal at high cadences in lab and field based studies over a range of exercise intensities and terrains (Foss & Hallen, 2004b, 2005; Lepers et al., 2001a; Lucia et al., 2001; Lucia et al., 2004). A strength of studies 2 and 3 was the individual nature of the cadences utilised in training, meaning that all participants were cycling at an equal percentage either above or below their FCC. This was also demonstrated in study 1 whereby all testing conditions were undertaken in relative terms of the participant’s fitness levels. The individualised nature of cadence selection in well-trained cyclists has previously been highlighted as an important characteristic to identify when undertaking research on cadence selection in cycling (Hansen, 2015). It could be argued that any further research analysing cycling cadence should also consider this application.

A further key finding of study 3 was that that both training groups demonstrated a significant improvement in performance after six weeks of training, with the LC training group improving to a greater extent as supported by a moderate effect size. Notably, these findings support previous research which has shown that training and performing at low cadences may be more beneficial to improving performance in endurance-trained cyclists over shorter distances than at higher cadences (Hirano et al., 2015; Nimmerichter et al., 2011; Paton et al., 2009; Stebbins et al., 2014). It is possible that the performance improvements induced by low-cadence training in
previous research along with the current study may be due to the use of higher crank forces, which could have a positive benefit by either improving strength or generating specific neuromuscular adaptations.

In contrast to the findings of the current study, Kristoffersen and colleagues (2014) reported no improvement in performance for veteran cyclists following 12 weeks of low cadence interval training when all participants pedalling at an absolute rate of 40 rpm. Such a finding may have been due to the use of an absolute, rather than relative power measure and that 40 rpm is significantly lower than the pedalling rate that an endurance cyclist would adopt under any conditions. Study 3 utilised relative measures of cadence for the interval training sessions and were only 20% lower than their FCC and therefore similar to a cadence they may utilise when negotiating uphill terrain (Kristoffersen et al., 2014). Low cadence training to improve cycling performance is becoming increasing popular with coaches and sports scientist and may warrant further research to better understand the mechanisms responsible.

6.1.4 The metabolic demand hypothesis and the skill of cycling

According to the metabolic demand hypothesis, when initially performing skills, the novice will select a preferred rate of movement that changes with practice to become similar when compared to their well-trained counterparts. In contrast to other locomotor skills, the findings from study 2 revealed that there were no differences in the FCC between well-trained and non-cyclists during submaximal cycling conditions measured at relative workloads. Previously, differences in FCC between trained runners and cyclists (90-100 rpm) when compared to less trained non-cyclists (65-80 rpm) had been reported, however, this research utilised absolute workloads, with
variations in power output between groups and therefore perhaps not sufficiently accounting for variations in individual fitness levels (Marsh & Martin, 1998). Through the adoption of relative workloads, study 2 was able to compare the FCC and associated variables between well-trained and non-cyclists with increased precision. Those in support of the metabolic demand hypothesis have also demonstrated that both novice and well-trained participants select a rate of movement that coincides with the rate whereby the metabolic demands of the task are minimised. Study 2 also revealed that the FCC in both non-cyclists (86 rpm) and well-trained cyclists (93 rpm) were significantly higher than the most metabolically efficient (50 rpm), which supports previous cycling research (Chavarren & Calbet, 1999; Takaishi et al., 2002; Takaishi et al., 1996). In further support for the rejection of the metabolic demand hypothesis, study 3 also demonstrated that well-trained cyclists selected a FCC before and after the 6-week training period that was significantly higher than the optimal metabolic cadence (50 rpm).

Finally, supporters of the metabolic demand hypothesis have repeatedly demonstrated that experts will perform tasks with superior movement efficiency or economy when compared to the novice. If the skill of cycling adhered to the metabolic demand hypothesis, then it would have been expected that well-trained participants would exhibit superior efficiency levels than their novice counterparts at all cadences. Study 2 of the thesis demonstrated that this was not the case and although this has been shown previously, (Marsh & Martin, 1993), these studies were limited by implementing a methodology that either used absolute workloads, relative workloads at high intensities, or only analysed GE at one cadence (Hopker et al., 2007; Marsh & Martin, 1993; Moseley et al., 2004; Nickleberry & Brooks, 1996). Therefore, when
taken collectively, the results from the original studies in this thesis provided evidence to reject the metabolic demand hypothesis for the skill of cycling.

Interestingly, the findings from study 1 which suggested that cadence selection in non-cyclists may be attributed to reducing the muscular demands of the task by improving perceived effort were not replicated in either study 2 or 3 of the thesis. Indeed, neither study 2 or 3 revealed any significant changes to the crank torque profile or to $T_{\text{peak}}$ and $T_{\text{mean}}$, nor were there any consistent changes to either $\text{RPE}_{\text{central}}$ or $\text{RPE}_{\text{peripheral}}$. However, in support of Lay (2002), study 3 demonstrated that well-trained cyclists in the HC group recorded their lowest value for $\text{RPE}_{\text{peripheral}}$ at 90 rpm following the training period as opposed to 70 rpm at the commencement of training. Further, the HC group displayed a significant reduction in $\text{RPE}_{\text{peripheral}}$ at both 90 and 110 rpm following the training whilst the lowest value for $\text{RPE}_{\text{peripheral}}$ for the LC group changed from 70 rpm to 50 rpm after training. These results provide support for the role of perception in selecting cadence (Garcin et al., 1998; Jameson & Ring, 2000). However, the collective findings this thesis provided evidence to reject the metabolic demand hypothesis for the skill of cycling.

6.1.5 Support for the role of Central Pattern generators in cadence selection in cycling

As an alternative to the metabolic demands hypothesis, several authors have proposed that the FCC in cycling is an innate voluntary rhythmic leg movement, possibly controlled by CPG located in the spinal cord (Hansen, 2015; Zehr, 2005; Zehr & Duysens, 2004). A suggested model for this control is that oscillating neural circuitry (half-centres) reside in the lumbar spinal cord (Stang et al., 2016) and that discrete
rhythm or pattern generating networks are responsible for producing the basic locomotor rhythm and muscle activity seen in locomotion (Hansen, 2015; Hartley & Cheung, 2013; Zehr, 2005; Zehr & Duysens, 2004). Evidence in support of this theory has revealed that in cycling, the FCC is largely individual, and is robust to acute changes such as mechanical loading and cardiopulmonary loading (Hansen, 2015; Hansen & Ohnstad, 2008; Hartley & Cheung, 2013). The findings from studies 2 and 3 provided support that the selection of a preferred cadence in cycling may be linked to CPG, with the FCC being demonstrated as being highly individualised. For example, the FCC in non-cyclists in study 2 ranged 68-105 rpm in submaximal testing and 64-108 rpm in the performance test. Similarly, in study 3, the FCC in well-trained cyclists ranged from 80-103 rpm on submaximal testing and 78-106 rpm on the performance test.

CPG theorists have also suggested that cycling may be under the control of CPG due to the fact that it is a robust movement with strong day to day reliability. In further support of CPG, both study 2 and 3 demonstrated that there was strong day to day variations in the FCC. For example, in study 2, non-cyclists recorded a FCC on day 2 of testing at 60%W_{max} of 86 rpm and also recorded an average of 83 rpm at the same workload on day 3. These findings were supported when observing the well-trained cyclists in study 3 of the thesis in both the submaximal conditions on day 2 as well as in the performance test on day 3.

CPG theorists have also suggested that evidence for FCC to be under control of CPG is demonstrated by the fact that both internal (e.g., age, experience) and external (e.g., road gradient, crank inertial load, performance type) factors are known to alter the
In support of this notion, participants in both study 2 and 3 selected higher cadences in the performance test conducted on day 3 when compared to the submaximal test (day 2) and pre-loading (day 3) aspect of the performance test. In both the NC (17%) and the WTC (22%) there was a significant difference in the power outputs and thus external loads in these two testing conditions. Therefore, the evident increase in cadences observed in both groups may have been due to the elevation in power which in turn may have caused an increase in mechanoreceptor stimulation, heightening perceived exertion (Hansen, 2015). To counteract this both groups may have therefore increased their FCC to reduce peak torque and concomitantly decrease RPE. Alternatively, the change in FCC may have been due to higher power outputs causing an elevation in rate of force development requiring enhanced muscle activation, including increased common drive from supraspinal centres to the CPG, contributing to larger net excitability of the CPG.

Study 3 also revealed that the LC group had a FCC that remained unchanged in the TT from pre to post training, and a performance measure superior to that recorded by the HC group. Similar findings have been observed in well trained cyclists following heavy strength training, with FCC remaining the same while performance increased (Hansen, 2015; Hansen & Ohnstad, 2008; Hansen & Smith, 2009). It is possible that the LC training with the use of higher forces in the current study could elicit strength training responses for the cycling muscles when compared to the lower peak forces experienced by the HC group. The subsequent improvements in performance may have been due to similar mechanisms provided by CPG theorists in that heavy strength training may provide enhanced neuromuscular efficiency (Hansen, 2015;
Hansen et al., 2002b; Hansen & Smith, 2009; Hartley & Cheung, 2013; Zehr, 2005). One of the limitations of this study was that the crank torque profile and GE data was not collected in the 15 min TT and may have provided further support for CPG control as this would have enabled the comparison of the crank torque profile at different power outputs. However, a recommendation for future research was to conduct an analysis of both GE and the crank torque profile at a range of cadence and cycling environments.

### 6.1.6 Summary

The outcomes from this thesis highlighted a number of key findings in relating to the relationship between the optimal metabolic cadence and the FCC in cycling. Firstly, it was demonstrated that non-cyclists selected a FCC that was significantly higher than the optimal metabolic cadence when undertaking, maximal, submaximal and performance tests conducted at varying relative workloads. Rather than a need to minimise the metabolic demands of the task, it appears that non-cyclists prefer to pedal at higher cadences in order to decrease muscle strain and mechanical load. The findings also demonstrated that the FCC for non-cyclists could be altered with a 6-week cadence-based interval-training program, which further supported the propensity for non-cyclists to select high cadences. Although requiring further research, the findings from this thesis support the notion that cadence selection in non-cyclists is different to other locomotor activities and may be under the control of CPG. This was due to the observation that the FCC for non-cyclists was shown to be highly individualised and recorded strong between-day reliability in all participants.
The thesis also demonstrated that the FCC for well-trained cyclists could be altered with high-cadence interval training but was unaffected by low-cadence interval training. Training with a relatively low cadence led to a tendency to improve performance to a greater extent than high-cadence training possibly due to neurological adaptations, suggesting that low cadence interval training may significantly improve time trial results of short duration. The thesis also provided evidence to demonstrate that well-trained cyclists select a FCC that is higher than the optimal metabolic cadence and provided further support for the rejection of the metabolic demand hypothesis. Alternatively, as seen with non-cyclists, the thesis provided evidence that the FCC in well-trained cyclists may be under the control of CPG. However, it should also be noted that the notion of the existence of CPG controlling the pedalling action in cycling and the metabolic demand hypothesis need not be mutually exclusive of one another.

6.2 Practical applications

This thesis has identified a series of practical applications from the studies conducted that would be of benefit to cycling coaches and sport scientists;

- The FCC is task specific, with different values reported for steady state testing, performance tests or maximal aerobic capacity testing.
- The FCC is highly individual and a one-size fits all policy approach to selecting a FCC should be avoided. Therefore, sport scientists should consider allowing their athletes to select cadences that are individualised and change from one aspect of cycling to another.
• The FCC in both well-trained and non-cyclists can be altered with high-
cadence interval training of values of 20% above their preferred cadence.
• Low cadence interval training may lead to a greater improvement in short
duration time trial performance when compared to high cadence interval
training.
• Specific cadence based interval training can change the maximal aerobic
capacity and performance within a 6–week, period even in well-trained
cyclists with multiple years of experience.
• Sport scientists and coaches should be aware that the FCC in cyclists of range
abilities and fitness level may not coincide with the rate of movement that
minimises the metabolic demands of the task.

6.3 Directions for future research

To expand upon the findings of this thesis, and further develop the applications of
cycling cadence selection efficiency and performance, it is recommended that future
research explores the following areas:

• Conducting more extensive training studies (12+ wks) to determine a
longer-term training effect on metabolic or muscular aspects associated
with cadence selection. Although it must be noted that this could be
challenging to ensure adherence in a well-trained cohort.
• Consider research designs that implement performance tests that are
longer in duration, conducted at relative workloads, and allow cadence
to be self-selected rather than being fixed.
• Conducting experiments that directly test for the existence of central
pattern generators in cadence selection. For example, researchers could
attempt to compare cadence selection in the field where both internal and external factors that contribute to cadence selection are manipulated systematically.

- Consideration should be given to outdoor testing due to advances in portable devices where cyclists can use their own bicycles for assessment. Many bicycles are now equipped with unique gearing systems that enables them to either manipulate the gear or cadence depending on the terrain, degree of fatigue, or purpose of the test.

- Future research analysing EMG activity and the crank torque profile at a range of cadences and workloads including participants of varying cycling experience and fitness level in a single study may provide new evidence to assist in the understanding of cadence selection in cycling.

- Future research analysing the relationship between cadence selection, metabolic efficiency and kinetic contributions would also provide useful information regarding the FCC in cycling.
Reference List


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Sardroodian, M., Madeleine, P., Voigt, M., & Hansen, E. A. (2015). Freely chosen stride frequencies during walking and running are not correlated with freely chosen pedalling frequency and are insensitive to strength training. *Gait Posture, 42*(1), 60-64. doi: 10.1016/j.gaitpost.2015.04.003


Appendices
Appendix 1

CONSENT FORM Study One

I ______________________________ agree to participate in the research project, Effects of cycling practice and preferred rate of pedalling on efficiency and movement control being conducted by Anthony Whitty, School of Leisure, Sport and Tourism, 9514 5178, of the University of Technology, Sydney.

I understand that the purpose of this study is to examine the changes to efficiency and economy levels when power output and rate of pedalling are manipulated. Subjects will be asked to pedal at maximal efforts at stages in the testing period.

I understand that my participation in this research will involve coming into the university over a six-week period. This will consist of three visits a week for 60 minutes at a time. There will not be risks to any subject and privacy will be upheld in the process of testing subjects.

I am aware that I can contact Anthony Whitty on 0410 487 349 or his supervisor Aron Murphy on 9514 5294 if I have any concerns about the research. I also understand that I am free to withdraw my participation from this research project at any time I wish without giving a reason. I also understand that my academic progression will not be affected by my decision to participate in the research or not.

I agree that Anthony Whitty has answered all my questions fully and clearly.

I agree that the research data gathered from this project may be published in a form that does not identify me in any way.

_________________________  _____/_____/_____
Signed by

_________________________  _____/_____/_____  
Witnessed by

NOTE:
This study has been approved by the University of Technology, Sydney Human Research Ethics Committee. If you have any complaints or reservations about any aspect of your participation in this research you may contact the Ethics Committee through the Research Ethics Office, Ms Susanna Davis (ph 9514 1279). Any complaint you make will be treated in confidence and investigated fully and you will be informed of the outcome.
Subject Information Sheet for Cycling Efficiency Testing (Study 1)

1. There has been a great deal of research on cycling efficiency and optimal cadence, force production and preferred cadence. This study will aim to assist the research in determining both the preferred and most optimal cycling cadence.

2. Test 1 will test your VO₂ max.

3. Test 2-4 will examine your efficiency levels at different power outputs (relative to your VO₂ max).

4. Test 5 will examine your force production throughout the cycling revolution at two different power outputs.

5. Test 6 will examine your most preferred level of pedalling at three different workloads.

Overall these tests will give you your own cycling profile and from this we will be able to compare your results to that of others of the same fitness level and cycling experience and to the elite and well trained cyclists.
Appendix 3

Data collection sheet for Submaximal testing for Study 1, 2 and 3

Efficiency Test Week 1 (50 % of max)

Subject Name: ______________________

Weight: ________ Height: __________

Temperature: ________ Humidity: ________ Barometric Pressure: ________

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Efficiency Test Week 2 (40 % of max)

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Temperature: ________ Humidity: ________ Barometric Pressure: ____________

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Efficiency Test Week 3 (60% of max)

Subject Name: ______________________

Weight: _______ Height: _______

Temperature: _______ Humidity: _______ Barometric Pressure: _______

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<td>5</td>
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</tbody>
</table>
**Cycling training example schedule for Study 2 and 3**

Name:

Complete the following session 3 times a week

For the entire session your cadence will be ____________.

The first 5 mins of the warm up will be at 100 w or _____ kp
The second 5 mins of the warm up will be at 150 W or ____ kp

In the hard effort phases you we be pedalling at _____ W which is equal to ______ kp
In the recovery phases you will be pedalling at _____ W which is equal to _____ kp

**Session: (Remember your cadence is always _________)**

First 5 minute warm up at ________
Second 5 mins warm up at ________

Followed immediately by

4 mins hard effort at _______ and 2 mins easy at _____________

Repeat this interval 4 times with no extra rest in between the intervals

This is followed by a 5 min cool down at ________

Total pedalling time = 39 mins

**Post session: (That means after the session)**

30 mins after each of the cycling training sessions are completed I want to rate how hard you thought the session was and record it in your training diary. For example if you thought it was a very hard session you would score it a 7.

<table>
<thead>
<tr>
<th>Rating</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>Rest</td>
</tr>
<tr>
<td>1</td>
<td>Very, Very Easy</td>
</tr>
<tr>
<td>2</td>
<td>Easy</td>
</tr>
<tr>
<td>3</td>
<td>Moderate</td>
</tr>
<tr>
<td>4</td>
<td>Somewhat Hard</td>
</tr>
<tr>
<td>5</td>
<td>Hard</td>
</tr>
<tr>
<td>6</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>Very Hard</td>
</tr>
<tr>
<td>8</td>
<td></td>
</tr>
<tr>
<td>9</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>Maximal</td>
</tr>
</tbody>
</table>
CONSENT FORM Study 2 and 3

I __________________________________ agree to participate in the research project, Effects of cycling practice and preferred rate of pedalling on efficiency and movement control being conducted by Anthony Whitty, School of Leisure, Sport and Tourism, 9514 5178, of the University of Technology, Sydney.

I understand that the purpose of this study is to examine the changes to efficiency and economy levels when power output and rate of pedalling are manipulated. Subjects will be asked to pedal at maximal efforts at stages in the testing period.

I understand that my participation in this research will involve coming into the university over a twelve-week period. This will consist of three visits a week for 60 minutes at a time. There will not be risks to any subject and privacy will be upheld in the process of testing subjects.

I am aware that I can contact Anthony Whitty on 0410 487 349 or his supervisor Aron Murphy on 9514 5294 if I have any concerns about the research. I also understand that I am free to withdraw my participation from this research project at any time I wish without giving a reason. I also understand that my academic progression will not be affected by my decision to participate in the research or not.

I agree that Anthony Whitty has answered all my questions fully and clearly.

I agree that the research data gathered from this project may be published in a form that does not identify me in any way.

___________________________________                _____/_______/______
Signed by

________________________________________              _____/_______/______
Witnessed by

NOTE:

This study has been approved by the University of Technology, Sydney Human Research Ethics Committee. If you have any complaints or reservations about any aspect of your participation in this research you may contact the Ethics Committee through the Research Ethics Office, Ms Susanna Davis (ph 9514 1279). Any complaint you make will be treated in confidence and investigated fully and you will be informed of the outcome.
Subject Information Sheet for Cycling Efficiency Testing and Training Study 2 and 3.

The purpose of this study is to determine if your preferred cadence and the optimal cycling cadence can be changed with training.

You will be required to complete the following tests both before and after participation in a 6-week training study.

1. Test 1 will test your VO₂ max.
2. Test 2-4 will examine your efficiency levels at different power outputs (relative to your VO₂ max).
3. Test 5 will examine your force production throughout the cycling revolution at two different power outputs.
4. Test 6 will examine your most preferred level of pedalling at three different workloads.

After completion of these tests you will be required to complete 18 interval training sessions conducted at UTS over a 6 week period.