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Review article

Optimal cadence selection during cycling

[*1, 2, 3]Dr Chris R Abbiss, PhD, [4]Dr Jeremiah J Peiffer, PhD, [1]Associate Professor Paul B Laursen, PhD

[1]School of Exercise, Biomedical and Health Sciences, Edith Cowan University, Joondalup, WA, Australia
[2]Department of Physiology, Australian Institute of Sport, Belconnen, ACT, Australia
[3]Division of Materials Science and Engineering, Commonwealth Scientific and Industrial Research Organisation, Belmont, Vic, Australia
[4]Centre of Excellence in Alzheimer's Disease Research and Care, Vario Health Institute, Edith Cowan University, Joondalup, WA, Australia

Abstract

Cadence or pedal rate is widely accepted as an important factor influencing economy of motion, power output, perceived exertion and the development of fatigue during cycling. As a result, the cadence selected by a cyclist's could have a significant influence on their performance. Despite this, the cadence that optimises performance during an individual cycling task is currently unclear. The purpose of this review therefore was to examine the relevant literature surrounding cycling cadence in order provide a greater understanding of how different cadences might optimise cycling performance. Based on research to date, it would appear that relatively high pedal rates (100-120rpm) improve sprint cycling performance, since muscle force and neuromuscular fatigue are reduced, and cycling power output maximised at such pedal rates. However, extremely high cadences increase the metabolic cost of cycling. Therefore prolonged cycling (i.e. road time trials) may benefit from a slightly reduced cadence (~90-100rpm). During ultra-endurance cycling (i.e. >4h), performance might be improved through the use of a relatively low cadence (70-90rpm), since lower cadences have been shown to improve cycling economy and lower energy demands. However, such low cadences are known to increase the pedal forces necessary to maintain a given power output. Future research is needed to examine the multitude of factors known to influence optimal cycling cadence (i.e. economy, power output and fatigue development) in order to confirm the range of cadences that are optimal during specific cycling tasks.

Keywords: pedal rate, economy, efficiency, power output

***Dr Chris R Abbiss, PhD**

Dr Abbiss is a post-doctoral research fellow in high performance cycling at Edith Cowan University, Australian Institute of Sport and the Commonwealth Scientific and Industrial Research Organisation, Australia. His primary research interests centre on human physiology and exercise performance, with focuses on cycling, fatigue, thermoregulation, pacing strategies and training. His work in this area has resulted in the publication of numerous peer-reviewed scientific articles.

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[*] Corresponding author. Address at the end of text.

Dr Jeremiah Peiffer, PhD

Dr Peiffer is a post-doctoral research fellow at the Centre of Excellence for Alzheimer's Disease Research and Care in the School of Exercise, Biomedical and Health Sciences and Vario Health Institute at Edith Cowan University in Perth, Australia. His research interests focus on the influence of physical activity on ageing, chronic disease, and Alzheimer's disease as well as cycling research focusing on thermoregulation, recovery, and fatigue.
Email address: j.peiffer@ecu.edu.au

Associate Professor Paul B Laursen, PhD

Dr Laursen is an Associate Professor of Exercise Physiology in the School of Exercise, Biomedical and Health Sciences at Edith Cowan University, Perth Australia. His research interests centre on various aspects of human physiology, with focuses on fatigue, high-intensity training, thermoregulation, hydration, muscle damage and recovery kinetics.
Email address: p.laursen@ecu.edu.au

Introduction

Understanding factors that affect cycling performance is of interest to scientists, coaches and cyclists alike. Accordingly, a vast body of literature has examined how various environmental, physiological and biomechanical factors influence cycling performance (for review, see references [23, 24]). From this work, cycling performance would appear to be dictated largely by the ability of the cyclist to produce high power outputs at minimal metabolic costs. As pedal rate (i.e. cadence) can influence both the ability to produce power, as well as rate of energy consumption, cadence selection could have a significant impact on cycling performance. For instance, the adoption of a high cadence (~90rpm) has been shown to reduce myoelectrical activity, muscle force and neuromuscular fatigue [64]. In contrast, high cadences (80-120rpm) have also been found to be less economical than lower cadences (≤60rpm) [15]. Indeed, Bieuzen et al. [9] observed a difference between energetically optimal cadence and neuromuscular optimal cadence (63.5 and 93.5rpm, respectively), in well trained cyclists. In addition, optimal and self-selected cadences have been found to be influenced by cycling intensity [46], course geography (grade) [43], muscle fibre composition [18, 33, 52] and cycling experience [46]. While information concerning pedal rate selection during cycling exists, a comprehensive review of the present literature is not currently available. As such, the cadence that results in the best possible performance outcome during the vast array of cycling events and conditions remains unclear. Therefore the purpose of this review is to 1) examine the literature pertaining to self-selected, forced and optimal cadences, 2) determine the factors that are responsible for the self-selection of cadence, and 3) provide a greater understanding of cadences that optimise performance during the variety of tasks performed by cyclists.

Understanding self-selected/freely chosen cadence

Publications on cycling cadence often comment on the unusually high pedal rate (>90rpm) adopted during both level and uphill cycling by seven time Tour de France champion Lance Armstrong [17, 41]. Based on the success of this cyclist it seems reasonable to propose that such high pedal rates might optimise performance during the most influential phases of professional cycling events (i.e. uphill and time trials). However, successful elite cyclists have also been observed to adopt significantly lower cadences during uphill mountain accents (≤75rpm) [43, 74]. As such, the effect of such high cadences on performance during cycling is unclear. It has been suggested that a high mechanical efficiency and maximal aerobic capacity ($\dot{V}O_{2max}$) may allow particular cyclists to increase power output (475 – 500W) using noticeably higher pedal rates [42]. Alternatively, other cyclists may choose to cycle at lower cadences in order to minimise oxygen cost, since higher cadences appear to be less efficient (see section on Efficiency and economy). If this hypothesis is correct, then any one single cycling cadence is not likely to be beneficial for all cyclists [42]. Instead, the optimal cadence to adopt during cycling will depend on the central (i.e. $\dot{V}O_{2max}$) and peripheral (i.e. muscle fibre contribution) physiological characteristics of each individual. Such a notion could explain the close association observed between an athlete's cycling experience and a freely chosen pedal rate. Indeed, well-trained cyclists typically adopt higher cadences compared with their lesser trained counterparts [16, 29, 46]. However, as with optimal cadences, the factors affecting self-selected pedal rate remain unclear.

To date, very few studies have examined the effects of training on self-selected and optimal pedalling cadences. Hansen et al. [32] found that following 12 weeks of strength training, self-selected cadence during submaximal cycling was significantly reduced. In this study, it was suggested that the decline in self-selected pedal rate may be related to a reduction in perceptions of force associated with increased strength [32]. Indeed, it has been shown that when cycling at constant power outputs (90-180W), perceived exertion is negatively related to pedal rates in the range of 40-80rpm [56]. Despite this, no research has examined the influence of cadence training on self-selected and optimal pedal rates in trained cyclists. As a result it is unknown whether cyclists habitually adopt their own optimal pedalling cadence, mimic the pedal rate of successful cyclists, or both. Further research is needed in order to examine the influence of training at various cadences on optimal and preferred cadence selection.

Defining optimal cadence

For many years, scientists, coaches and athletes have attempted to determine the optimal pedal rate to apply during a variety of cycling tasks. While numerous investigations have been conducted [25, 28, 59, 66, 69], the best possible cycling cadence remains unclear. This uncertainty may be due to methodological differences and variations in the precise definition of the term 'optimal' used within cadence research. Indeed, previous research in this area has focused on the effects of various cadences on cycling mechanics [38, 49, 66], cycling efficiency [44], hemodynamics [28, 69], neuromuscular fatigue [37, 64, 65, 72] and more recently cycling performance [25, 75]. Therefore the ideal cycling cadence may differ, dependent on whether the term refers to the most economical, powerful, fatigue-resistant or comfortable cadence [25, 57]. For the purpose of this review on cadence, the term 'optimal' refers to the pedal rate resulting in the best possible performance outcome. The cadence that optimises performance under a variety of conditions experienced by cyclists is likely to be dictated by the trade-off between cycling economy, power output and the development of fatigue. Thus throughout this review each of these variables will be discussed with respect to various cycling disciplines.

Cycling power output

Pedal force and joint moments

Recent advancements in strain-gauge technology have led to improved understanding of the interaction between pedal force and resultant crank torque [7, 38, 49, 57]. Studies examining pedal force during cycling have revealed both effective and ineffective pedal loads [11, 22, 61]. Further, effective and ineffective pedal loads can be separated, by force, into normal (force applied perpendicularly to the pedal surface) and tangential (force applied along the surface of the pedal) components. Typical effective pedal loading at various cadences and power outputs are shown in Figure 1.

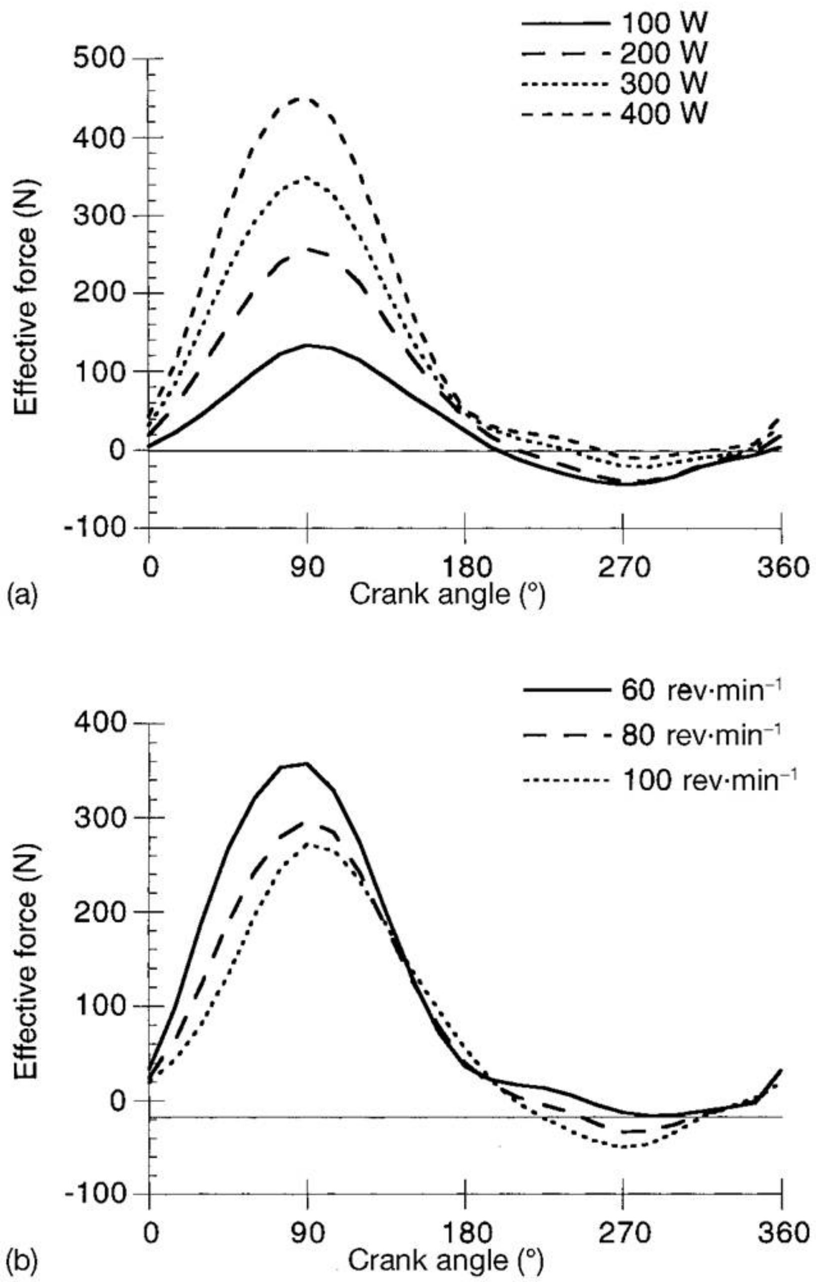

Figure 1: Effective pedal forces throughout the entire crank cycle during cycling at various power outputs (a) and cadences (b). 0° crank angle refers to top dead centre. Figure reproduced by permission of the publisher Taylor & Francis Ltd , http://www.tandf.co.uk/journals from Sanderson DJ, Hennig EM and Black AH. The influence of cadence and power output on force application and in-shoe pressure distribution during cycling by competitive and recreational cyclists. J of Sports Sci 2000. [61].

The effective pedal force acts perpendicularly to the bicycle crank, generating a torque which is transmitted through the bicycle chain to the wheel. From Figure 1 it can be seen that the effective pedal force and thus crank torque vary substantially throughout the pedal cycle. Indeed, peak torque typically occurs at approximately 100°, past top dead centre, whereas negative load occurs on the upstroke of the pedal cycle (Figure 1). Since power output is the product of crank torque and crank angular velocity, instantaneous power output also varies throughout a crank cycle [11].

Despite this, average power output produced over an entire revolution may be determined by the following equation:

Power (W) = average net effective pedal torque x average angular velocity (cadence) [11].

Based on the above formula, the average force/torque applied to the pedals over an entire pedal revolution at a fixed power output is reduced at higher cadences [71]. For example, at 350W the average effective force applied to the pedals is ~15% lower when cycling at 105rpm (184N) compared with 90rpm (215N). This reduction in average pedal force (i.e. force over an entire revolution) is predominantely due to a decrease in peak normal forces (Figure 1b; [60, 61]). This is important as the peak normal forces observed during maximal cycling are likely to be dictated by the force/torque-velocity relationship of muscle contractions [45, 63]. In short, the peak torque that can be applied to the pedals during short duration maximal cycling is reduced at faster contraction velocities (i.e. faster cadences; Figure 2).

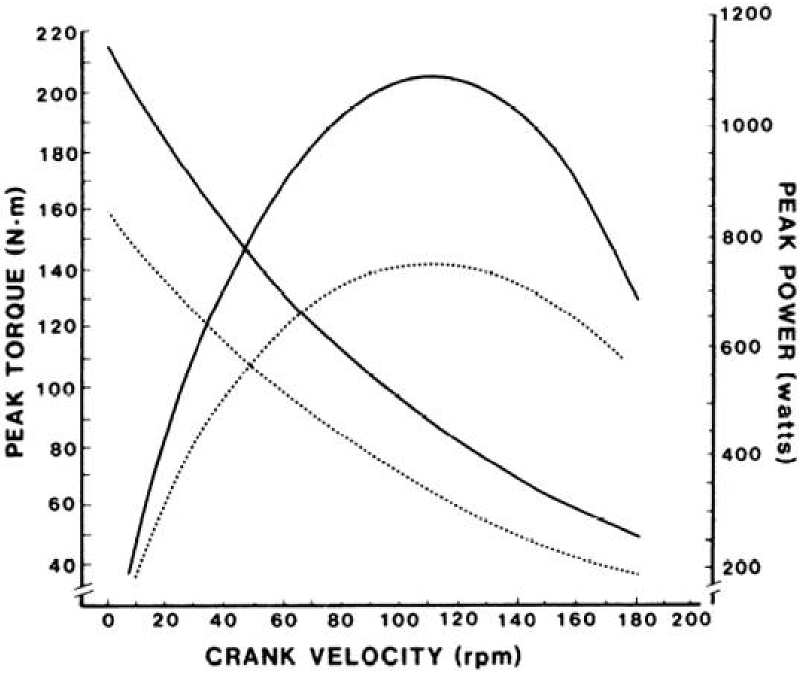

Figure 2: Relationship between peak crank torque, crank velocity (i.e. cadence) and power output during short duration (<10s) maximal cycling in two separate subjects (solid and dashed lines). Figure used with permission from J Appl Physiol. [51]

Based on the contractile properties of human muscle it has been shown that maximal cycling power output is achieved at approximately 120-130rpm (Figure 2; [8, 50, 51, 62, 78]). Such high cadences may be important to maximal sprint cycling performance. Indeed, track and bicycle motorcross (BMX) cyclists typically perform short duration events (≤1000m) at average cadences equal to or greater than 120 rpm [19, 20]. However, Zoladz et al. [78] found that when pedalling above 100rpm there was a decrease in the power output delivered at any given oxygen cost, which was in turn associated with an earlier onset of anaerobiosis [77, 78]. Such findings highlight the disadvantage of adopting such high cadences (>100rpm) during prolonged high-intensity exercise, such as competitive road cycling.

With regards to prolonged submaximal performance, optimal cycling cadence is one that typically maximises global power output (i.e. effective pedal force) from the musculature of the lower limb [14] at low metabolic cost [23]. In an attempt to gain insight into cadence optimisation over prolonged exercise durations, researchers have examined the influence lower extremity net [49] and individual [21, 53] joint moments on muscular effort and its association with the preferred [49] or optimal [59] cadence. While it appears that the relative contribution of the joint moments at the ankle, knee and hip remain fairly constant at various cadences and cycling power outputs [53], the average absolute moments (i.e. moment-based mechanical cost function) across these joints may decrease with increasing cadences in the range of 50-95rpm, with a subtle but noticeable increase from 95-110rpm [49]. Further, Marsh et al. [49] found that the cadence which minimises the sum of these moments increases at higher power outputs. These findings and those of others [36, 59], suggest that the moment-based mechanical cost functions may be reduced in the range of 90-110rpm and could be important in determining the preferred or optimal cadence during cycling.

Inertial load and momentum

To further understand the mechanical cost associated with cadence, researchers have quantified both the muscular and non-muscular components that dictate pedal forces and crank torques [7, 54]. Muscular components refer to forces or torques that are produced by muscular activity, whereas non-muscular components refer to other factors that may influence pedal or crank forces, such as gravity or inertia [7]. While muscular pedal forces are reduced with higher cadences (as described in the previous section), non-muscular pedal forces increase linearly with pedal rate [7, 54]. As a result, overall pedal forces at fixed power outputs follow a quadratic relationship with increases in cadence (Figure 3).

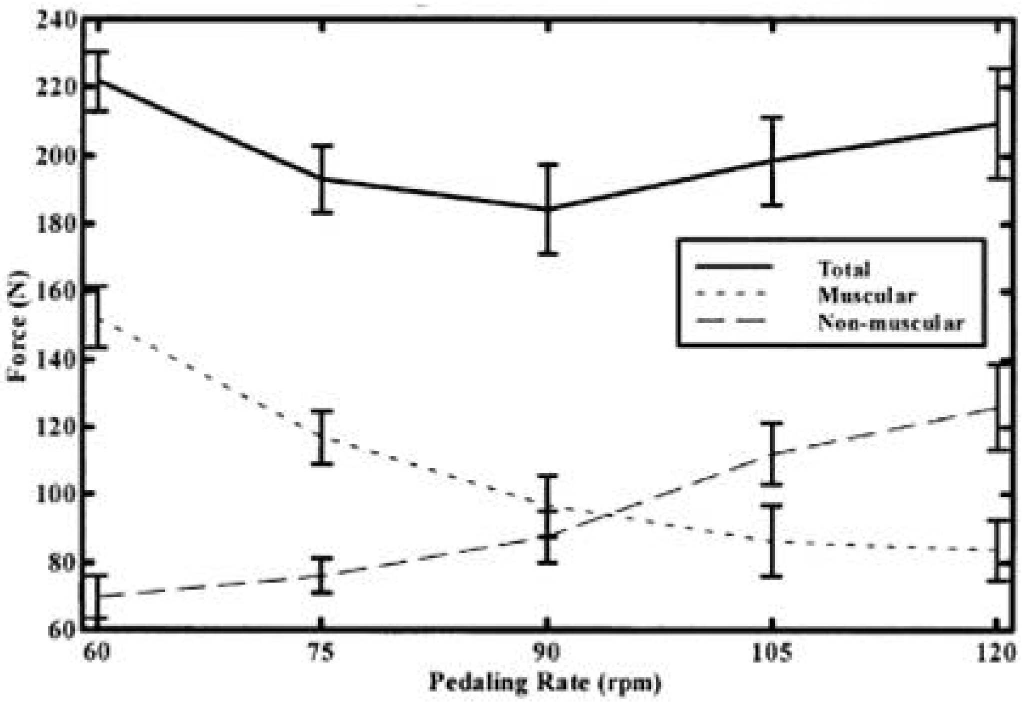

Figure 3: Muscular, non-muscular and total pedal forces while cycling at 120W and at 60, 75, 90, 105 and 120rpm. Reprinted from: J Biomech, Vol.32, Neptune RR and Hertzog W. The association between negative muscle work and pedaling rate, pp.1051-1026, 1999, with permission from Elsevier. [54].

Examining this relationship, Neptune and Herzog [54] found that when cycling at 260W, a minimum pedal force of 190N was observed at 90rpm, compared with higher (105 and 120rpm) and lower (60 and 75rpm) cadences. Since gravitational forces are largely unaffected by changes in cadence [7, 12], increasing non-muscular pedal forces that occur with higher cadences are primarily due to the influence of inertial load (i.e. increased inertia of the crank) (kg m^2) [7]. Indeed, by increasing crank inertial loads, self-selected cadence has been found to significantly increase, possibly an attempt to reduce peak crank torque [31]. It has therefore been suggested that changes in inertial properties associated with increasing cadence may influence lower extremity neuromuscular coordination [7, 38, 40].

Neuromuscular fatigue and myoelectrical activity

The influence of inertial properties on neuromuscular coordination during cycling has previously been examined [7, 40, 55]. Through the examination of muscle activation burst patterns and the coordination of mono- and bi-articular antagonists, it has been shown that higher cadences result in a forward shift (i.e. earlier in the crank cycle) in the activation of gluteus maximus, vastus lateralis, and tibialis anterior [38, 39]. Further, the magnitude of this shift decreased in proximal (hip) to distal (ankle) limb segments [39]. Since increases in pedalling rate can influence neuromuscular recruitment patterns, it seems plausible to presume that variations in cycling cadence might induce the development of neuromuscular fatigue. Nevertheless, research on this topic has produced conflicting results [37, 44, 64-66, 72]. Studies have shown that the self-selection of relatively high pedalling rates (~80–90rpm) may reduce muscle activation of vastus lateralis [44, 64, 72]. Therefore it has been suggested that cyclists may spontaneously select a high cadence in order to prevent the development of neuromuscular fatigue, regardless of the energy cost [64]. In support of this, Takaishi et al. [72] found that integrated electromyography (iEMG) of vastus lateralis as a function of time (i.e. slope of the iEMG) followed a quadratic relationship with cadence and was minimised at 80-90rpm. The authors concluded that cyclists tend to adopt such cadences in order to minimise muscular fatigue, and not metabolic demand, since lower cadences (60-70rpm) were associated with reduced oxygen consumption [71, 72]. In contrast to these findings, Sarre et al. [65] found that when cycling at constant power outputs (60%, 80% and 100% of maximal aerobic power output) neuromuscular activation of vastus lateralis and vastus medialis were unaffected by varying cadence (70 – 130% of self-selected pedal rate). Further, with the use of femoral nerve electrical stimulation, it was shown that similar variations in cadence (± 20% of self-selected cadence) during prolonged cycling had no effect on the occurrence of either central or peripheral fatigue development of the leg extensors [37, 66]. Inconsistencies in findings within this research area may be related to methodological differences relating to the functional role of the muscles examined, training level of the subjects, and the range of power outputs/cadences used [64].

While muscle activation of the knee extensors (i.e. vastus lateralis and vastus medialis) has been found to be reduced [44, 64, 72] or unaffected [65] by increases in cadence, muscle activation of gastrocnemius lateralis and biceps femoris has been shown to increase at faster pedal rates [45, 47, 71]. It is thought that such increases in muscle activation allow for a greater delivery of forces during the downstroke and reduced negative forces during the upstroke of the cycle pattern [64]. Negative force refers to the counterproductive force typically observed during the upstroke of the pedal action (Figure 4).

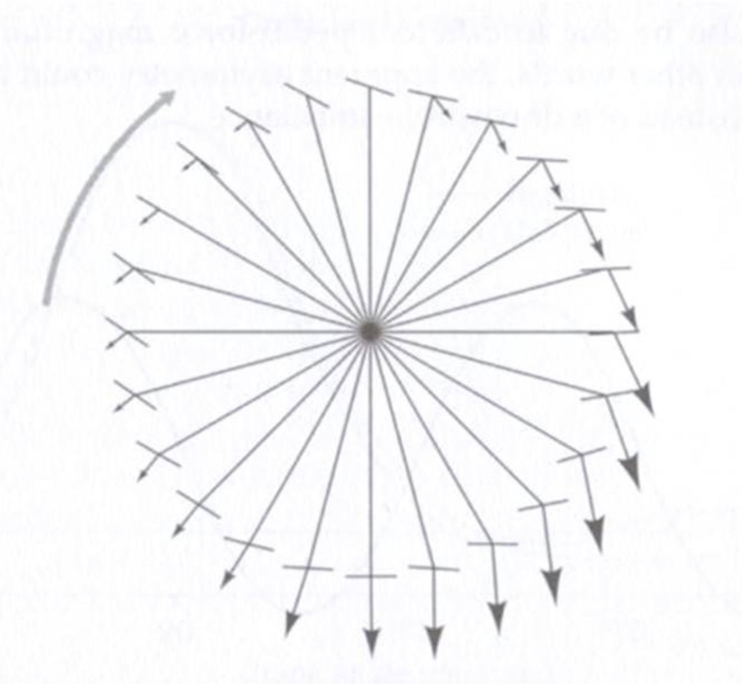

Figure 4. Diagram demonstrating the direction and magnitude of pedal forces throughout a typical clockwise pedal cycle. Note counterproductive (negative) pedal forces during the upward phase of the pedal cycle. Reprinted, with permission, from J.P. Broker, 2003, Cycling Biomechanics: Road and Mountain. In: High-Tech Cycling: The Science of Riding Faster, edited by E.R. Burke, 2nd ed. (Champaign, IL: Human Kinetics, 125, figure 5.4.[11].

This negative force is generated by the insufficient speed of the rear leg during the upstroke of the pedal cycle [57, 66]. Despite an increase in activation of biceps femoris at higher cadences, the increase in pedal rate and thus crank speed/momentum may still result in greater negative work. Thus in order to overcome this increase in negative work, it has been suggested that the front leg may be required to perform greater positive work during the downstroke, resulting in increased fatigue (especially at high power outputs) [66].

In addition to affecting neuromuscular coordination, alterations in cadence may also influence muscle fibre recruitment patterns [2]. Such recruitment patterns are thought to be in response to a reduction in muscle force development when cycling at higher cadences, rather than an increase in the velocity of contraction (see section on Pedal force and joint moments). It is believed that a reduction in myoelectrical activity observed during high cadence cycling may indicate less recruitment of Type II muscle fibres [2] or, conversely, greater recruitment of Type I muscle fibres [2, 64]. Supporting this, Ahlquist et al. [2] found that when cycling at a constant metabolic cost (~85% maximal aerobic capacity), a low cadence (i.e. high force; 50rpm) resulted in significantly greater Type II muscle glycogen depletion compared with a higher pedal rate (100rpm). In addition, Sarre et al. [64] examined the electromyographic signal of vastus lateralis using spectral analysis and found that the median power frequency was minimised during the cyclist's freely chosen pedal rate (88rpm). Since the mean power frequency reflects the action potential velocity of motor units [3, 4], it has been suggested that a higher mean power frequency could represent a greater recruitment of fast twitch motor units [30]. The optimal cadence to adopt during prolonged submaximal cycling may therefore be based on the rate at which recruitment of fast twitch motor units is minimised [63, 64], although this does not appear to be the case for all activated muscles of the lower extremities [64]. Indeed, the role and contribution of each individual muscle should be appreciated when examining factors influencing self-selected and optimal cadences. Minimising the recruitment of fast twitch motor units may be important for prolonged submaximal cycling, since Type II muscle fibres are typically more metabolically demanding than the Type I subtype [18, 33].

Efficiency and economy

Numerous studies have examined the influence of pedalling frequency on the efficiency and economy of cycling [6, 27, 44, 46, 48, 71, 72]. Generally, when cycling at constant power outputs, lower cadences have been found to result in reduced oxygen cost (i.e. improved gross efficiency) compared with higher cadences [6, 15, 27]. Improved efficiency of cycling observed at lower pedalling rates is likely to be dictated by the relationship between muscle shortening velocity and the efficiency of muscle contractions (percent Type I and Type II active fibres). For instance, under *in vitro* conditions, it has been observed that the efficiency of skeletal muscle contractions is augmented with increasing speed of contraction, until a maximum is reached (i.e. an economically optimal shortening velocity) [35]. The most economical cadence appears to be extremely low (~50-60rpm) when cycling at low power outputs (≤200W), but increases to approximately 80-100rpm with increasing workloads (~350W) [26, 44, 58]. The cause of the rise in the economically optimal cadence is unclear, but is again likely to be due to the power-velocity relationship of muscle contraction and the additional recruitment of fast twitch muscle fibres with increases in exercise intensity. As previously mentioned (see section on Pedal force and joint moments), an increase in cadence at higher exercise intensities may optimise the power-velocity relationship, and as a result reduce the metabolic cost of cycling. Indeed at lower cadences, greater force per pedal stroke is required to maintain a given power output, which requires additional muscle fibre recruitment and thus a higher energy expenditure [58, 67]. Supporting this, myoelectrical activity of vastus lateralis is reduced at higher cadences (see section on Neuromuscular fatigue and myoelectrical activity).

In addition to reducing the average pedal force per revolution, a faster pedal rate might reduce the oxygen cost associated with high intensity cycling since the mechanical efficiency of both fast and slow twitch muscle is improved at high and low contraction velocities, respectively [34, 35, 63, 68]. It has therefore been suggested that a cyclist's ability to improve their efficiency at high cycling cadences might be dictated by a cyclist's individual muscle fibre composition [33]. Indeed, human muscle containing high levels of slow twitch muscle fibre composition has been found to be more efficient during cycling than muscle with fast twitch muscle fibre predominance [18, 33]. In the light of this, Hansen and Sjøgaard [33] suggest that when individuals with low levels of slow twitch muscle fibres increase pedal rate (especially at higher workloads), muscular efficiency will be either unchanged or possibly reduced due to significant involvement of less efficient fast twitch muscle fibres. However, in cyclists with greater percentages of slow twitch muscle fibres, an increase in pedal rate could minimise fast twitch fibre recruitment and enhance slow twitch fibre use [2, 33]. Within this framework, fatigue of Type I muscle fibres that may occur during prolonged constant intensity exercise might result in a progressive recruitment of additional fast twitch fibres, resulting in an increase in the energetically optimal cadence [10, 76]. In support of this, Brisswalter et al. [10] showed that following 30min of constant pace cycling (80% of $\dot{V}O_{2max}$), the energetically optimal cadence of trained triathletes increased from 70rpm to 86rpm. Conversely, others have shown that energetically optimal cadences remain relatively stable during prolonged cycling [5, 73]. In addition, self-selected cadence during prolonged cycling is typically found to decrease [1, 5] or remain relatively constant [43], rather than increase. The influence of fatigue on muscular power development and thus self-selected and optimal cadences is currently unclear. However, it seems plausible that variations in pedal rate that occur during prolonged cycling may be related to alterations in muscle fibre recruitment strategies and thus related to exercise intensity, duration and muscle fibre composition. Further research examining the influence of metabolic and neuromuscular fatigue on self-selected and optimal cadences throughout a range of cycling durations (e.g. sprint, prolonged and ultra-endurance) is warranted.

Hemodynamic/blood flow

While numerous studies have investigated the influence of cadence on oxygen consumption, power output and fatigue development (described above), few studies have examined the hemodynamic changes associated with different pedal rates [13, 28, 67, 69, 70]. As with oxygen consumption, it has been observed that when cycling at a constant power output, heart rate may increase both above and below the ideal cadence [67]. Further, the pedal rate that minimises heart rate rises linearly with increasing power output [13, 67]. The close relationship between the energetically optimal cadence (i.e. cadence which minimises $\dot{V}O_2$) and the cadence which minimises heart rate may be related to the oxygen (see section on Efficiency and economy) and thus blood flow demands of working muscle. Gotshall et al. [28] have shown increases in heart rate, stroke volume and cardiac output with higher pedal cadences ranging from 70-110rpm. However, in this study the elevated cardiac output observed at higher cadences was associated with a disproportionately lower rise in oxygen consumption, as shown by a reduction in the arterial-venous oxygen difference [28]. Consequently, this study showed that increases in cardiac output observed at higher cadences were not solely due to elevated oxygen demands. Instead the authors suggested that the higher cardiac output could have been due to the enhanced effectiveness of the skeletal muscle pump resulting from the faster cadences [28]. Indeed, the greater contraction rate occurring at higher cadences would facilitate venous return, augment ventricular preload, and elevate cardiac output.

In addition to increasing venous return, higher cadences might also reduce the period of blood flow occlusion that occurs in the microvessels of skeletal muscle during cycling. With the use of near infrared spectroscopy (NIRS), Takaishi and co-workers [69, 70] found that when cycling at 75% $\dot{V}O_{2max}$, muscle blood flow and oxygenation of vastus lateralis was significantly reduced during the initial pedal downstroke (first third of the crank cycle; Figure 5), presumably due to high intramuscular pressure associated with muscle contraction.

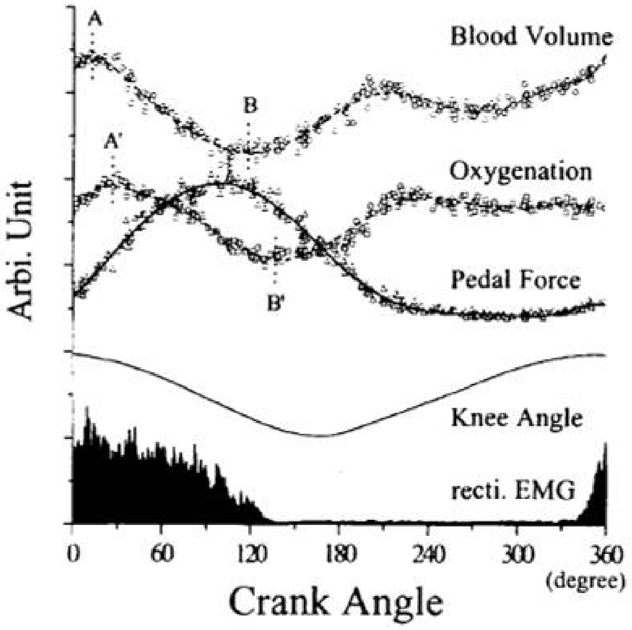

Figure 5: Changes in muscle blood flow (circle), muscle oxygenation (square), pedal forces (triangle), knee angle and rectified electromyography (EMG) throughout a pedal cycle. 0° crank angle refers to top dead centre. Figure reprinted with permission from Lippincott Williams & Wilkens for Takaishi T, Sugiura T, Katayama K, et al. Changes in blood volume

and oxygenation level in a working muscle during a crank cycle, Med Sci Sports Exerc, Vol.34 No.3, 2002, pp.520-528 [70].

Further, in untrained individuals, this deoxygenation (i.e. the minimum blood volume and oxygenation reached) was more sever at low (50rpm) compared with high (85rpm) cadences [69]. It is therefore plausible that higher cadences could improve oxygen delivery to working muscles by limiting blood flow occlusion. Such findings may be especially important during the forceful contractions (i.e. during high power outputs) typically achieved by professional/elite cyclists. Despite this, further research is needed in order to determine the influence of hemodynamics on preferred and optimal cadence selection during cycling.

Conclusion

A vast body of literature has examined various factors that may influence the optimal pedal rate to adopt during a variety of cycling tasks. Despite this research, the cadence which maximises performance during cycling remains unclear. It is possible that much of the uncertainty surrounding optimal cadences could be due to methodological inconsistencies between studies. In particular, the term ‘optimal’ may be used to describe the most economical, powerful, fatigue-resisting or comfortable pedal rates. As a result, the cadence that results in the best possible performance during the variety of cycling tasks experienced by cyclists appears to be multifaceted. Consequently, future research exploring the best possible cadence to select during cycling should examine a number of factors (i.e. power, neuromuscular fatigue, efficiency, blood flow and comfort) that may be associated with maximising performance outcomes. In particular, the influence of training at various cadences on performance and physiological adaptations requires further examination. Based on previous research, it would appear that muscle force and neuromuscular fatigue might be reduced, and cycling power output maximised, with relatively high pedal rates (100-120rpm). However, such high pedal rates increase the metabolic cost of cycling, especially at low power outputs (≤ 200W). As a result, short duration sprint cycling performance might be optimised with the adoption of fast pedal rates (~120rpm). Due to the influence that fast pedal rates have been shown to impart on cycling mechanics, cycling efficiency and fatigue development, performance in longer duration events might be enhanced from use of slightly slower cadences (~90-100rpm). During ultra-endurance cycling, performance might be improved by using relatively low cadences (70-90rpm), since cycling economy is improved and energy demands are lowered. Future research examining a multitude of factors known to influence optimal cycling cadence (i.e. economy, power output and fatigue development) is needed to confirm these hypotheses.

Address for correspondence:

Dr Chris R Abbiss, School of Exercise, Biomedical and Health Sciences, Edith Cowan University, 100 Joondalup Drive, Joondalup, WA, Australia 6027
Tel.: +61 8 6304 5740
Fax: + 61 8 6304 5036
Email: c.abbiss@ecu.edu.au

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