Case Presentation

Intrinsic and Extrinsic Factors that Determine an Appropriate Pedalling Cadence for the Elite Cyclist

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Abstract

Cycling performance is determined either by the ability to achieve a very high power output over a short period of time or the ability to sustain a more moderate power output over several hours. In both cases the factors that influence power production have been examined from the perspective of optimizing aerodynamics, in pursuit of reducing the cyclists drag, through to improving musculoskeletal power production. The current review is focused on musculoskeletal power output with reference to the effects that pedal cadence play on muscle function. Based on the evidence a wide range of pedalling cadences are adopted by elite cyclists that are a function of the type of event and typography that the cyclist encounters. In events that require sustained power production over several hours the preferred pedal cadence ranges from 80-100 rpm, the data suggest that lower cadences are adopted during hilly events and higher cadences adopted for flatter stage events. During track pursuit cycling pedal cadences of ~100 rpm are adopted and during sprint events the observed pedal cadence is between 120 and 160 rpm. From a musculoskeletal and cardio respiratory perspective the balance between velocity of movement and force generation is important during road race events because of the effects of gross and delta efficiency in relation to power output and energy turnover. In track cycling the higher cadences are more a function of the velocity-power relationship of the exercising musculature such that the pedal cadence is close to the peak power velocity relationship for muscle with a 50:50 ratio of fast and slow muscle. During all-out sprinting the highest pedal cadences are beneficial because of the higher reserves in power generating capacity that such a strategy confers.

Keywords: Power Output; Cadence; Cycling Efficiency; Muscle Energetics

Introduction

The achievements of human powered locomotion demonstrate the remarkable ability of athletes to generate sustained high-power output. Between 1964 and 2011 the average velocity for the 4 kilometer individual cycling pursuit increased from 49.32km/h to 57.49km/h. The power output required to sustain 49km/h for 4 minutes is about 400 watts, which increases to over 630 watts for speeds over 57km/h. The typical power profile during a track-based 4000m pursuit is illustrated in (Figure 1) and demonstrates an initial peak power output and subsequent maintenance at ~500W for a male cyclist and 350-400 W for a female.

The average power output required to set the current 1 kilometer record is over 850 watts, which equates to an average speed of 64km/h (UCI world records, 2015). In professional road cycling the average speed to complete the Tour De France is equally impressive. Over the last 100 years the average speed to complete the Tour de France has improved by >65%, in 1906 it was 24.5km/h and this had increased to an average of 40.8km/h by 2006 (letour http://www.letour.fr/HISTO/fr/TDF/records/palmares.html). Taking into account the improvements in road conditions, bicycle technology and the changes in rules that allows riders to receive assistance, a more realistic comparison of the average speed could be made from the 1950's to the current record. In 1950 the average speed for the winner

to complete the Tour was 32.8km/h and the current record of the winner was 40.8km/h (2006), which represents a 24% improvement. There is, of course, considerable variation in the demands to generate power that will be a function of the terrain that the riders encounter during road cycling events. Using the SRM-Training system crankset [1], measured power production of 6 elite cyclists during a six-day stage race and reported that the average power output varied between 190 and 390 W with an average of 220watts for 5 days of the mass start races, the additional day consisted of an individual time trial The highest average power output (392 ± 60 W) was observed during the
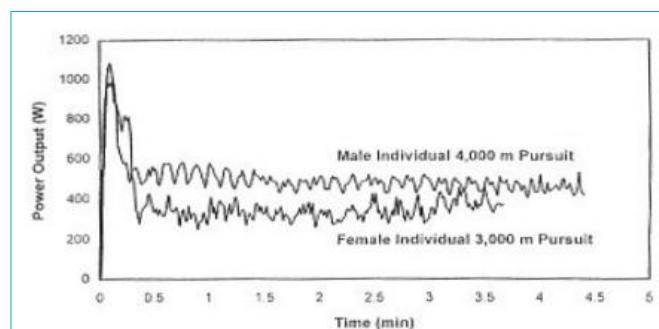

Figure 1: Power output of a male cyclist during completion of a 4000 m pursuit and female cyclist completing a 3000 m pursuit (Jeukendrup et al, 2000).

Table 1: Mechanical power required to travel at different cycling velocities with zero wind speed and road gradient. Environmental conditions (wind and gradient) required to produce 150W at various velocities (NB negative values denote downhill or tailwind) Umberger, 2003.

Velocity (m/s)	Power with zero wind and grade (W)	Wind producing 150W (m/s)	Gradient producing 150W (m/s)
4	23.1	10.2	3.5
6	55.3	5.33	1.75
8	112.2	1.57	0.52
10	202.1	-1.65	-0.58
12	333.2	-4.58	-1.69

uphill time trial, while the lowest average power output (220 ± 22 W) was generated during mass start stages that had an average distance of 149km and an energy expenditure of 11.9MJ.

Power production during cycling

Power production during cycling is the product of applied torque and angular velocity of the pedals. In general terms, the greater the power production the faster the cyclist will propel themselves although some caveats must be applied in relation to the terrain, size of the cyclist (i.e. frontal area and drag) and mass of the cyclist and bicycle. These factors are determined by the individual's power to weight ratio, the frontal area (and hence drag) of the cyclist and whether the cyclist is going up- or downhill and were described by [2] and further clearly illustrated by [3] (Table 1). With the wide spread use of power meters substantial focus has increasingly been placed on the athletes power output and the strategy that may be adopted to achieve or sustain a required power output. Since a cycling velocity of 30km/h could be achieved either through adopting a pedal cadence of 62rpm, a chainring gear of 50 and cassette gear of 13 or alternatively a cadence of 100, chainring of 50 and cassette gear of 21 (www.bikecalc.com), it is clear that the combination of pedal cadence and gearing can be adjusted to meet the demands of the required pace (and therefore power output). Interest on the pedal cadence adopted by cyclists of varying levels of expertise, from the trained cyclist through to the elite professional continues [4-10]. No single consensus exists regarding the most appropriate cadence for cyclists, which is likely to be due to the terrain, type of event and the physiology of the athlete. The following review discusses the factors that influence pedal cadence from the energetics required to sustain a given power output and the characteristics of muscle physiology and function that influence the velocity and force of contraction.

The energy turnover and velocity relationship during cycling can be described as exponential and is a function of two retarding forces that affect the power demands [11]. The first resistive force is rolling resistance, which is affected by both the cross-sectional area of a tyre and the pressure to which it is inflated. While rolling resistance creates a substantial resistive force at velocities less than 13km/h, at speeds greater than this wind resistance becomes the dominant factor [12]. Consequently, once cycling speed is greater than 13km/h the effects of wind resistance means that any increase in speed results in a cube increase in power demand and the relationship between speed and power is thus best explained as an exponential. Improving elite cycling performance could be focused upon better aerodynamics to reduce the effects of wind resistance and/or enhancing the peak or sustained power output by the athlete.
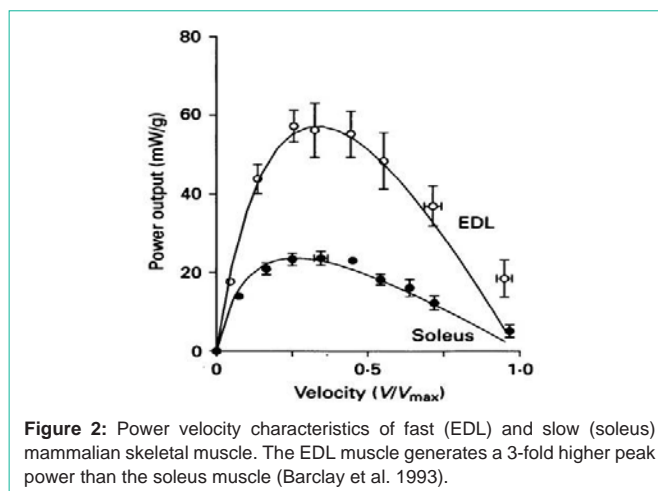

Figure 2: Power velocity characteristics of fast (EDL) and slow (soleus) mammalian skeletal muscle. The EDL muscle generates a 3-fold higher peak power than the soleus muscle (Barclay et al. 1993).
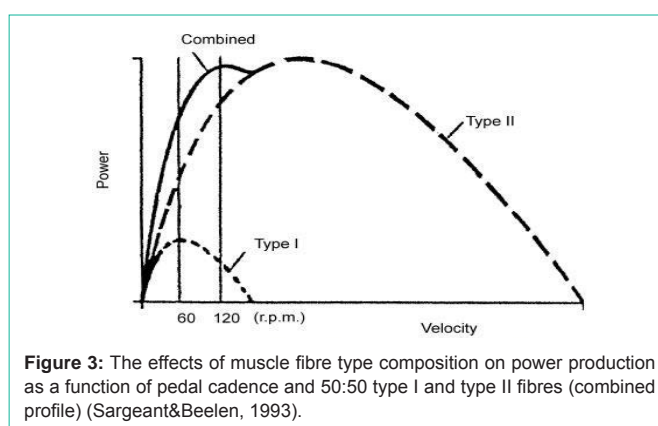

Figure 3: The effects of muscle fibre type composition on power production as a function of pedal cadence and 50:50 type I and type II fibres (combined profile) (Sargeant&Beelen, 1993).

Musculoskeletal factors in energy turnover

The force-velocity characteristics of skeletal muscle are a direct function of the twitch characteristics of the muscle fibres [13]. were able to demonstrate that the consequences of the differences in the power-velocity characteristics of Extensor Digitorum Lunges (EDL, fast twitch) and soleus (slow twitch) meant that the power output was at least double in the EDL compared with soleus (Figure 2). At the same time the rate of energy turnover was 5-times higher in EDL than soleus (calculation based on heat generation). The ability to produce power therefore will be a function of the fibre type composition of the exercising musculature [14]. Reported that cyclists that were either National or State class possessed a muscle fibre type distribution that was between 66 and 53% slow twitch and 33 and 46% fast twitch fibres. The higher preponderance of slow twitch fibres was observed in the National class of cyclists and whilst this might appear counterintuitive in terms of level of performance, the metabolic and fatigue resistant nature of slow twitch fibres would be beneficial in cyclists whose selection criteria was based upon performance in a 40km time trial [14,15]. Proposed a model of the effects of mixed muscle fibre composition on power output. Based upon a two compartment model he concluded that skeletal muscle with a 50:50 distribution of fast and slow muscle would generally result in the peak power occurring somewhere around 100-120 rpm (Figure 3). However, human single muscle fibres are generally a composition of a mix of different isoforms of myosin expression from type I (slow, oxidative) to type IIa- IIx (fast oxidative and fast glycolytic) fibres.
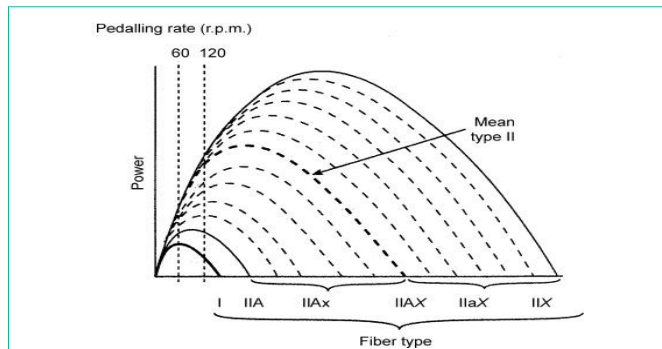
Figure 4: Peak power production as a function of cadence in fibres expressing only type I or continuum of type II myosin isoform expression. (Sargeant, 2007).

Figure 5: Rate of heat production during low intensity exercise with (□) and without (□) occlusion and high intensity exercise (r) (Krustrup et al, 2003).

Combining data from studies measuring the maximum shortening velocity of slow and fast twitch muscle [16], a continuum of the effects of myosin isoform expression was produced to demonstrate the consequences of different muscle fibre composition on the power velocity relationship [15] (Figure 4). Using this model and the data from [14] it seems plausible to suggest that the cadence required to produce a sustained power output (i.e. that observed in elite cyclists) should be around 100rpm but does this correspond to the freely chosen cadence adopted by these athletes?

Observed pedal cadence in cyclists

A range of studies report that the cadence adopted by experienced elite level cyclists is somewhere between 60 and 100 rpm, which is a function of the type of event and the topography of the course [1,2,5,17]. In contrast, [18] recommended that a cadence of 40-60 rpm should be adopted during the standard experimental assessment of aerobic capacity because the lower pedal cadence was hypothesised to be the most efficient. Nonetheless during the measurement of maximum power production, such as the Wingate test [19], individuals are instructed to pedal as fast as possible and the peak cadence observed under these conditions can be as great as 160 rpm [20], and with an average pedal cadence of ~140rpm during 30sec of all-out sprinting. The relationship of pedal cadence and maximum power output was investigated by [21] who also manipulated the length of the crank from 120 to 220 mm. Their overall conclusion was that a shorter crank length resulted in an optimal pedal cadence of ~135rpm for peak power production that was higher than the longest crank (110rpm). Interestingly, the optimal pedal cadence was higher (~2.5m.s^{-1}) for the longest crank than that of the shortest crank (~1.75m.s^{-1}). The most commonly adopted crank length (175mm) produced a curvilinear relationship between pedal cadence and power output with a cadence between 130 and 140 rpm producing a peak power output of 1200W. The self-selected pedal cadence employed by well-trained cyclists varies between 70 and 90 rpm for those participating in road cycling events [5] and higher during track cycling with a recorded value of 100rpm during the completion of the world 1hr record [2]. During mass start events the lowest reported cadences are reported to occur when there was a substantial proportion of the stage committed to climbing [5], while at the same time the highest average power output was generated. The effect of differences in pedal cadence, as a function of the terrain, was examined by [22] with a focus on interrelationship between torque
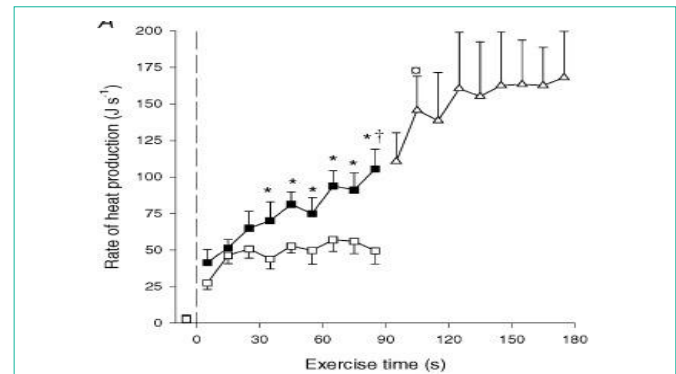
production and crank angle while maintaining the same power output. The authors determined that the higher the cadence the lower the torque production and, in addition, the phase at which the peak torque was applied occurred at a later stage of the cyclical phase. In comparing the same cadence when cycling either uphill or on a level surface the authors reported a small but insignificant difference (P<0.06) in torque production at a crank angle of 45°. However, [22] also observed that the torque produced when cycling uphill with a cadence of 60rpm was always higher than that for level cycling and a cadence of 100rpm. Taken collectively it would appear that the reason for selecting a lower cadence is to produce more force, and this may be appropriate for hill climbing where the speed of ascent is lower and the athlete is working against gravity. It does not, however, explain the higher cadences adopted on flat stages or during track events and suggests that other factors such as energy turnover may have a role in determining pedal cadence other than simply power production.

Energetics and pedal cadence: efficiency effects

Energy turnover increases during exercise as a function of power output, such that the higher the power requirement the greater energy turnover [23] (Figure 5). Were able to demonstrate that as the external power output, during knee extensor exercise, increased from 29W (SD 1W) to 65W (SD 5W), so too did the energy turnover from an average of 134J.s^{-1} to 224J.s^{-1}. At submaximal workloads the relationship between energy production and power output is linear, however at higher workloads, whereby there is a significant contribution to overall energy turnover from anaerobic metabolism, the relationship deviates from a linear relationship to a higher energy turnover per unit of power production [24]. The relationship between power and energy turnover under these laboratory constraints is different from that observed during cycling. In addition, the internal energy cost i.e. the energy required to move the limb could play an important role in determining cadence as a function of the required power output [25]. Measured the external workload and calculated the internal and total power requirements of single leg knee extension exercise at different movement frequencies of 60 and 100 rpm. They observed that the internal power output was about 18W at the lower frequency of contraction and that this almost doubled at the higher frequency (33W). At the higher movement frequency the effect of increasing the external load from 0 W to 50 W resulted in a decrease in internal power generation by about 10W. The overall effect of increasing movement frequency was at the expense of a higher oxygen
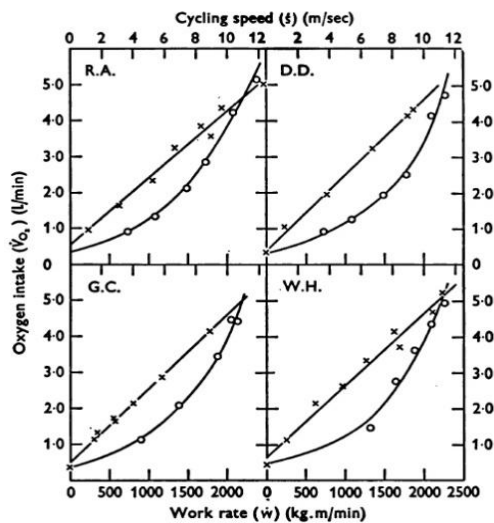
Figure 6: The relationship between oxygen cost and work rate (x) and oxygen cost and cycling speed (o). Pugh (1974).

uptake of about 0.3l/min^{-1} but this effect was reduced to 0.1l/min^{-1} when the total power was matched at the two contraction frequencies. The higher oxygen cost and hence energy turnover associated with a higher pedaling rate still appear to confound the adopted practice of elite cyclists.

In one of the earliest studies examining the oxygen cost of [4] demonstrated a linear relationship between work rate and oxygen cost during static cycling but an exponential relationship between cycling speed and oxygen cost (Figure 5). He observed that a cadence of 50rpm was most efficient at a low power output; an observation that provides evidence to support the proposal by [18] that when conducting assessments of aerobic power in recreationally active participants the adopted cadence should be around 60rpm. The effects of cadence on gross efficiency have been examined with the observation that in professional cyclists lower cadences (60rpm) are less efficient than higher cadences (100rpm) [26]. Some account of the required power output also plays a role in determining the most economical cadence i.e. in terms of the oxygen cost [7]. Recruited elite road cyclist and examined the effect of increasing workload in relation to the most economical cadence (60-120 rpm) across power outputs ranging between 0 and 350 W. They found that at 0W the most economical cadence was 60rpm and at a power output of 350W the most economical cadence was 80rpm [17]. Reported that the average cadence adopted by 10 well-trained cyclists varied between 95-102 rpm, where the values had been averaged over periods of 5-600s and competing in mass start road races. The power output generated during these respective time periods varied between 1000 and 350 W. One important feature of the observation by [17] was that despite similarities in power production between laboratory-based tests and measures taken on the road, the cadence adopted under laboratory conditions was always significantly higher than that observed during road races. One obvious difference between the two environments is that during the road races cyclists have to overcome the effects of wind resistance, which is the major retarding force at speeds greater than 13km/h [3]. Two further studies examining the role of cycling efficiency and cadence identified the issue of muscle

fibre type composition [14] and training history [14]. Identified the role that the higher proportion of type I muscle fibres was positively correlated to a greater efficiency across two exercise intensities with a pedal cadence of 80 rpm. They reported that the measured and calculated efficiency ranged between 18 and 26% and that the higher efficiency was observed when the % of type I fibres was greater than 70% of the total fibre population. The effects of 5 years of competition and training in elite cyclists and the relation to maximum oxygen consumption and delta efficiency was monitored by [10]. These authors reported that despite a relatively constant VO$_2$ max over this time period the delta efficiency increased from 23.6% to 27.0%. The use of delta efficiency as opposed to gross efficiency is based on the assumption that delta efficiency more closely represents a valid measure of muscle energetics to work completed [27]. The fibre type distribution could also be a consequence of training history [28], demonstrated that young sedentary males had a relatively lower type I isoform expression than endurance trained males and that those classified as highly trained had a greater number of hybrid isoform (co-expressing I and IIa) fibres than either sedentary or recreationally active males. The evidence from these studies suggests that, at power outputs that more closely represent those required to compete at an elite level, the adoption of higher cadences reduces the internal power to total power requirement and that a higher proportion of type I and II a fibres results in a greater efficiency. The average power output required to compete in multi-stage races is lower than the demands made in laboratory conditions (e.g. Sergeant, 2007) where the aim was to measure pedal cadence that would elicit peak power output and consequently a cadence of 80-100 rpm appears to be consistent with adopting the highest cycling efficiency.

All-out sprinting

The effects of varying cadence on the peak power output at VO$_2$ max was examined by [29-31] with the observation that at the lowest (40rpm) and highest (120rpm) cadence the power output was lower by ~60W than that observed at a cadence of 60 and 100 rpm. However, in the same study that also examined peak power output during 10s of all-out sprinting at the cadences between 40 and 120 rpm. The authors calculated the reserves in power generating capacity i.e. the power achieved to elicit VO$_2$ max and the maximum generated power with the conclusion that the higher the cadence the greater the reserves in power generating capacity. During sprint cycling the benefits of an increased cadence stem from the higher power generating reserve, this coupled with the better ATP return from high energy phosphate and glycolytic metabolism [23] demonstrate that a high velocity of contraction is better suited to sprinting than a lower cadence with a higher force production.

Conclusion

Cycling performance is a function of the maximum sustainable velocity, whether this is for 20s or for an hour, which is directly related to either maximum power production or the sustainable power output for that velocity. The cadence adopted by highly trained cyclists is somewhere between 85 and 100 rpm for events that last in excess of one hour. For the shorter events, where a higher power production is observed cyclists adopt a higher cadence between 120 and 150 rpm. The chosen cadence is multifactorial but includes an element of neuromuscular physiology, the reserve in power generating capacity,

topography of the road and the environmental conditions.

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