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Research article

Effects of Cadence on Aerobic Capacity Following a Prolonged, Varied Intensity Cycling Trial

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Abstract
We determined if high cadences, during a prolonged cycling protocol with varying intensities (similar to race situations) decrease performance compared to cycling at a lower, more energetically optimal, cadence. Eight healthy, competitive male road cyclists (35 ± 2 yr) cycled for 180 min at either 80 or 100 rpm (randomized) with varying intensities of power outputs corresponding to 50, 65 and 80% of VO_2max. At the end of this cycling period, participants completed a ramped exercise test to exhaustion at their preferred cadence (90 ± 7 rpm). There were no cadence differences in blood glucose, respiratory exchange ratio or rate of perceived exertion. Heart Rate, VO_2 and blood lactate were higher at 100 rpm vs. 80 rpm. The total energy cost while cycling during the 65% and 80% VO_2max intervals at 100 rpm (15.2 ± 2.7 and 19.1 ± 2.5 kcal·min^{-1}, respectively) were higher than at 80 rpm (14.3 ± 2.7 and 18.3± 2.2 kcal·min^{-1}, respectively) ($p < 0.05$). Gross efficiency was higher at 80 rpm vs. 100 rpm during both the 65% (22.8 ± 1.0 vs. 21.3 ± 4.5%) and the 80% (23.1 vs. 22.1 ± 0.9%) exercise intensities ($P< 0.05$). Maximal power during the performance test (362 ± 38 watts) was greater at 80 rpm than 100 rpm (327 ± 27 watts) ($p < 0.05$). Findings suggest that in conditions simulating those seen during prolonged competitive cycling, higher cadences (i.e., 100 vs. 80 rpm) are less efficient, resulting in greater energy expenditure and reduced peak power output during maximal performance.

Key words: Power output, energy expenditure, varied intensity, cycling efficiency, lactate, oxygen consumption.

Introduction

During training and competition, competitive cyclists tend to select cadences that are higher (>90 rpm) than cadences (50-80 rpm) that optimize efficiency, economy and ratings of perceived exertion (Ferguson et al., 2001; Foss and Hallen, 2005; Gaesser and Brooks, 1975; Hansen et al., 2002; Lucia et al, 2001b; 2004; Marsh and Martin, 1993; 1997; Marsh et al., 2000; Moseley et al., 2004; Nickleberry and Brooks, 1996; Nielsen et al., 2004). Moreover, during submaximal cycling, trained cyclists tend to select cadences that are higher than those that are energetically optimal, resulting in an excess energy expenditure of approximately 5% (Hansen et al., 2006). While many factors can affect which cycling cadence is most energetically optimal (including exercise duration and intensity, fitness level and muscle fiber recruitment patterns) (Lucia et al., 2001a; 2001b; Marsh and Martin, 1997; Vercruyssen et al., 2001, 2010; Whitty et al., 2009), it has been hypothesized that freely-chosen high cadences represent an innate compromise between stresses on the cardiovascular system and those on contracting skeletal muscle (Lucia et al., 2004). However, in addition to greater energy expenditure, higher cadences also increase oxygen demand, which requires greater oxygen delivery and thus greater cardiac output (Moore et al., 2008).

These potential negative impacts of choosing a higher cadence may be even more evident during long competitive road races, where ~70% of the race consists of sub-maximal cycling at 60-70% of maximal oxygen consumption (VO_2max) (Broker, 2003; Lucia et al, 1999). Although previous studies have shown that a reduction in freely chosen cadence towards a more energetically optimal cadence (~80 rpm) occurs during prolonged periods of cycling in the laboratory (i.e., 2 h) (Argentin et al., 2006; Lepers et al., 2000; Vercruyssen et al., 2001), little is known about effects of cadence on performance in these conditions. Interestingly, most studies that have examined effects of cadence on performance utilized constant-power tests that do not accurately simulate an actual cycling race where there are multiple changes in intensity due to changes in terrain, environmental factors and race strategies. Thus, data from these studies may not translate directly to competitive cycling road races. Based on these observations, we tested the hypothesis that the use of high cadences during a prolonged cycling protocol with varying intensities (a protocol that more closely simulates competition) would decrease performance compared to cycling at a lower, more energetically optimal, cadence.

Methods

Participants

Eight healthy, competitive male road cyclists (35 ± 2 yrs) were studied. Participants had been competing in their sport for > two yrs and trained 10–15 h·week^{-1} (mean = 13±1 h). Research was conducted in accordance with the Helsinki Declaration, and was approved by the University of California Institutional Review Board. Informed written consent was obtained from each participant.

Procedures

Participants were asked to rest and follow the same hydration and eating patterns 24 h prior to all testing. Similar fluid and energy intake (600 ml·h^{-1} of fluids and 40 g·h^{-1} of carbohydrate) were maintained during all tests (ACSM Position Stand, 2009). Experiments were conducted on 3 separate days, at least 48 h apart. During visit 1, exercise

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capacity (VO_2max) was assessed. During visits 2 and 3, participants cycled for three h at either 80 or 100 rpm with varying intensities at 50, 65 and 80% of VO_2max, simulating a cycling road race (Lucia et al., 1999; Palmer et al., 1994).

Protocols

Visit 1: Participants arrived at the laboratory 3 h after eating. Body mass, height and body compositions were measured (Jackson and Pollock, 1978). After 15 min of warm-up, each subject completed, at his preferred cadence (101 ± 11 rpm), a graded exercise test to exhaustion on his own bike, which was fitted with a power measuring device (Graber Products, Madison, WI, USA) and mounted to a compu-trainer (Racermate Inc., Seattle, WA, USA), which allows for a fixed power output to be maintained despite changes in cadence by adjusting resistance levels. The exercise test began at an intensity of 100 watts (W) and increased by 40 W every 3 min. During exercise, measurements of heart rate (HR) (Polar Heart Rate Monitor, Woodbury, NY, USA) and oxygen consumption, VO_2, ventilation (VE) and carbon dioxide production (VCO_2) (ParvoMedics Metabolic Cart, Sandy, UT, USA) were made continuously. The metabolic cart pneumotachometer and gas analyzers were calibrated pretest and verified post-test using a 3 L syringe (Hans Rudolf Inc. Kansas City, MO, USA) at varying flow rates and a calibration gas mixture of 4% CO_2 and 16% O_2.

Rating of perceived exertion (RPE) was assessed using a 10 point scale (Noble et al, 1983) and assessed every 3 min. Ventilatory threshold (Vt) was determined using the criteria of an increase in the ventilatory equivalent for oxygen ($VE \cdot VO_2^{-1}$) without an increase in the ventilatory equivalent for carbon dioxide ($VE \cdot VCO_2^{-1}$) (Lucia et al., 2001b).

Visit 2: After a recovery period of at least 48 h, and 3 h after eating, participants performed the first experimental protocol, which began with a 10–15 min warm-up. A 190 min continuous, varied intensity cycling test was then conducted at a constant cadence of either 80 or 100 rpm (randomized) at power outputs corresponding to 50%, 65% and 80% of each subject's predetermined VO_2max from the maximal exercise test performed during visit one. These power outputs were maintained for both varied intensity trials and were not adjusted for changes in VO_2. Initially, participants exercised at a power that elicited 65% of VO_2max for 30 min. Subsequently, 4 identical, 40 min varied intensity cycling bouts were performed consisting of 12 min at 80% of VO_2max, 8 min at 65% of VO_2max, 10 min at 50% of VO_2max and 10 min at 65% of VO_2max. Respiratory gases (O_2, CO_2) were collected during the 12 min at 80% of VO_2max and 8 min at 65% of VO_2max for each of the 4 cycling bouts, and averaged across the whole trial. From an earlobe blood sample, blood lactate (Lactate Pro, Arkray, Inc, Kyoto, Japan) and glucose (glucose analyzer, Accu-Check, Roche, Mannheim, Germany) were determined during each 40 min cycling bout to correspond with the 65 and 80% VO_2max intensities. Metabolic power (Pmet) was calculated by multiplying VO_2 with the oxygen equivalent: Pmet (W) = $VO_2 \times [(4{,}940 \times RER + 16{,}040)/60]$ according to Garby and Astrup (1987), under the assumption that respiratory exchange ratio (RER) is equal to the respiratory quotient (RQ) at sub-maximal intensities. The measured mechanical power output divided by the calculated Pmet defined gross efficiency (GE). Energy expenditure (EE) for the 80 min spent at 65 and 80% VO_2max for each cadence was determined at the same time points where VO_2 was measured. EE was calculated using the equation: EE ($kcal \times L \cdot min^{-1}$) = VO_2 ($L \cdot in^{-1}$) x (5 $kcal \times LVO_2^{-1}$) (Swain, 2000). At the end of the 3 h cycling period, participants completed a ramped exercise test to exhaustion at their preferred cadence. Only HR was measured during this test. The ramped exercise test started at an intensity of 65% of VO_2max and was increased by 25 $W \cdot min^{-1}$ until the subject could no longer maintain a cadence of 60 rpm. The power output for the last full min during the exercise test was used as the index of performance.

Visit 3: During this visit, the previous 3 h exercise protocol was repeated with the exception that the other cadence was used. The cadence used during the subsequent ramped exercise test (100 rpm) was the same as that used during Visit 2. A rest period of at least 48 h was provided between visits 2 and 3.

Statistical analysis

Descriptive statistics were used to compare physical characteristics of the participants and are reported as means ± standard deviation (S.D.). This study employed a within-subject repeated measures design comparing the effects of cadence on blood lactate, blood glucose, HR, RPE, RER, VO_2, CO, EE, GE and peak power attained during the performance test. Statistical significance was determined by a two-way (cadence, intensity) repeated measures analysis of variance (ANOVA) using a Fisher's post-hoc analysis (StatView 5.0.1, SAS Institute Inc., Cary, NC). Statistical significance was accepted at $p \leq 0.05$.

Results

Subject anthropometric data is presented in Table 1. Table 2 shows the results from the 190 min bouts of varied exercise intensity. Power outputs during the 65% VO_2max cycling bouts were below the power at ventilatory threshold as measured during the maximal exercise test on visit 1, while power outputs during the 80% VO_2max were right at the power at ventilatory threshold.

Table 1. Characteristics of participants. Data are means (±SD).

Variable	
Age (yr)	33.6 (6.8)
Height (m)	1.80 (.04)
Body mass (kg)	73.1 (4.3)
Body fat (%)	8.3 (2.4)
VO_2 max	
$l \cdot min^{-1}$	4.7 (0.6)
$ml \cdot kg^{-1} \cdot min^{-1}$	64.0 (4.3)
Peak power (watts)	370.0 (41.4)
Watts at V_t	295.0 (49.9)

VO_2 max (maximal oxygen uptake), V_t (ventilatory threshold)

Effects of Power Output: During the 190 min exercise trials, regardless of cadence, lactate, RER, heart rate, VO_2, RPE and energy expenditure were greater at the

Table 2. Effects of cycling cadence and intensity on power, blood glucose and lactate, respiratory exchange ratio (RER), heart rate, oxygen uptake (VO_2), rating of perceived exertion (RPE), energy expenditure and gross efficiency. Data are means (± SD).

	80 RPM		100 RPM	
	65% VO_2 max	80% VO_2 max	65% VO_2 max	80% VO_2 max
Power (W)	223 (42)	292 (34)	223 (42)	292 (34)
Glucose ($mmol·L^{-1}$)	5.4 (.5)	5.3 (.6)	5.4 (.4)	5.3 (.4)
Lactate ($mmol·L^{-1}$)	1.2 (03)	2.6 (.7) *	1.5 (.5)	3.2 (1.4) *†
RER	.88 (.03)	.94 (.01) *	.88 (.02)	.96 (.02) *
Heart rate (bpm)	135 (11)	158 (10) *	140 (12) †	163 (11) *†
VO_2 ($L·min^{-1}$)	2.86 (0.53)	3.67 (0.44) *	3.05 (0.54) †	3.82 (0.50) *†
RPE (0-10 scale)	3.8 (1.5)	6.5 (1.0) *	3.9 (1.5)	6.8 (1.2) *
Energy expenditure ($kcal·min^{-1}$)	14.3 (2.7)	18.3 (2.2) *	15.2 (2.7) †	19.1 (2.5) *†
Gross efficiency (%)	22.8 (1.0)	23.1 (0.7)	21.3 (4.5) †	22.1 (0.9) *†

* $p < 0.05$ vs. 65% VO_2 max, † $p < 0.05$ vs. 80 RPM, (n = 8)

higher power output (292 ± watts watts/80% VO_2 max) compared to the lower power output (223 ± 42 watts/65% VO_2 max) (Table 2). Gross efficiency was increased at the higher power output (i.e., 292±34 watts/80% VO_2max vs. 223 ± 4 2 watts/65% VO_2max) but only at 100 rpm (Table 2). There were no differences in glucose between conditions (Table 2).

Effects of Cadence: During the 190 min exercise period at the higher power output, lactate concentrations were 18.8% greater at the 100 rpm cadence than those seen at the 80 rpm cadence (Table 2). Regardless of power output, heart rate (3-4%), VO2 (4%), and EE (4-6%) were higher at 100 vs. 80 rpm (Table 2). However, at both the low and high exercise intensities, gross efficiencies were 4-7% less at 100 vs. 80 rpm (Table 1.). Glucose concentrations, RER and RPE were not altered by cadence (Table 2).

Changes in Efficiency over Time: Examination of the drift in efficiency over the duration of one trial revealed a similar decrease from the start to the finish during both exercise intensities and cadences (-0.9 vs. -0.6% for the 80 and 100 rpm trials at 65% VO_2max and -0.5 vs. -0.6% for the 80 and 100 rpm trials at 80% VO_2max).

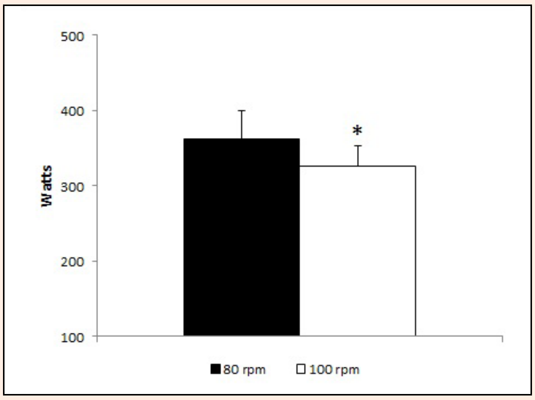

Figure 1. Effects of cycling cadence during prolonged submaximal exercise on subsequent maximal power during exercise to exhaustion.

Effects of Cadence on Peak Power Test: Peak power achieved during the ramped performance test following the 190 min varied-intensity exercise bout at 80 rpm was 9.7% greater than that seen after a similar bout at 100 rpm (Figure 1). Preferred cadence during these tests was lower than that used during their initial maximal test (101 ± 11 rpm). The preferred cadences following the endurance trial were 88 ± 7 and 93 ± 7 rpm following the 80 and 100 rpm trials, respectively. These cadences were not statistically different between trials.

Discussion

The results of this study confirm our hypothesis that during prolonged cycling at varying sub-maximal intensities and power outputs, higher cadences (100 rpm) reduce maximal power output during a subsequent performance test compared to a lower more energetically economical cadence (80 rpm). When a fixed cadence was used throughout this test, final maximal performance was ~35 W lower for the 100 vs. 80 rpm condition.

Previous research has revealed a discrepancy between cadences believed to be energetically effective, and those being used by competitive cyclists. This discrepancy may be due to differences in the exercise protocols used in laboratory studies (Booker, 2003; Gaesser and Brooks, 1975; Hansen et al., 2002) and the actual intensities, modes and durations of exercise used by competitive cyclists during training and competitions (Gaesser and Brooks, 1975; Hansen et al., 2002; Lucia et al., 1999). These laboratory investigations of cadence effects were typically conducted using short bouts of exercise (6-30 min) at constant external power outputs. The competitive cycling model we used revealed that when a preferred (i.e. higher) cadence is used during prolonged exercise (consisting of repetitive high intensity efforts, interspersed with low intensity exercise) the energy cost is greater than when a more energetically-optimal cadence (i.e., 80 rpm) is employed.

As expected (Ferguson et al., 2001; Nielsen et al., 2004), VO_2 was slightly but significantly higher at 100 rpm than at 80 rpm for both the 65% and 80% VO_2max exercise intensities. During prolonged cycling exercise, there is evidence that the most economical cadence (i.e., that which evokes the lowest metabolic cost [VO_2]) is relatively stable (Argentin et al., 2006; Vercruyssen et al., 2001). This "optimal" cadence minimizes the amount of muscle activation for a given power output and increases as power output is elevated (Coast and Welch 1985; MacIntosh et al, 2000); effects that may be linked to the force-velocity relationships of the contracting muscles (Coast and Welch 1985; MacIntosh et al., 2000). However, the higher oxygen uptakes observed while pedaling at 100 rpm suggests that this cadence also causes greater muscle activation and energy turnover. Higher pedal frequencies necessitate higher oxygen uptakes at a given power output due to elevations in internal work associated with concomitant increases in repetitive leg movement (Coast and Welch, 1985; Gasser and Brooks, 1975). Since the majority of the cycling time during our two protocols (i.e., 73% of the total time) was spent at or below the lower exercise intensity (65% VO_2max), the total energy cost of completing the protocols at 100 rpm was ~5-6% greater than during the respective 80 rpm protocols (Table 2.), which also may have contributed to the concomitant lower power output at the end of this protocol

Substrate utilization appears to have been similar at both cadences because plasma glucose levels were not different from baseline values, and no cadence-specific effects on RER were found. However, we did see higher lactate levels during the more intense exercise bouts (100 vs. 80 rpm), but these effects were relatively small. While all exercise intensities were below the ventilatory threshold, the higher intensities were conducted at power outputs close to this threshold. It is not clear what factors contributed to the higher O_2 uptake and blood lactate levels seen during the higher cadence (100 rpm) and workload (80% VO_2max). Previous studies have reported that elevations in cycling cadence can increase the recruitment of muscles that work during the recovery phase of pedaling (Dantas et al, 2009) and decrease tissue oxygenation (Jacobs et al, 2013). Thus, cadence-induced alterations in the recruitment and oxygenation of active muscle may be contributing factors (Hansen and Sjogaard, 2007).

We found that gross efficiency was within the range reported by previous investigators (15-25%) (Marsh et al, 2000; Ettema and Lorås, 2009). Similar to previous reports, we also found that efficiency decreased over time in response to prolonged cycling (Passfield and Doust, 2000). The magnitude of this decrease was not dependent on exercise intensity or cadence. On the other hand, efficiency at the end of the prolonged cycling period was lower during both exercise intensities at our higher cadence (100 rpm). This negative effect of cadence on gross efficiency has been found in other investigations (Ettema and Lorås, 2009) and it has been suggested that factors other than work rate are involved (e.g., force-velocity properties and activation-relaxation dynamics) (Ettema and Lorås, 2009).

An increased time to exhaustion has been observed using a higher cadence (Nickleberry and Brooks, 1996). This outcome was not seen in our study and may be related to the fact that the same cadence was maintained throughout the varied intensity cycling protocol. On the other hand, we did observe a higher VO_2 when our participants pedaled at 100 rpm. Because VO_2 is directly related to the energy required to perform a given task (Powers and Howley, 2011), our results indicate that pedaling at 100 rpm requires more total body energy turnover than pedaling at 80 rpm. Given that gross efficiency was lower during the 100 rpm compared to 80 rpm cadence, and maximal power output during the ramped protocol to exhaustion was greater at the lower cadence, it appears that the use of a high cadence during low to moderate workloads is not economical and may compromise performance during prolonged cycling.

An increase in RPE was observed over the course of both protocols. Nonetheless, cadence did not appear to have a major effect on this variable. It has been shown that rhythmic repetitive movement is controlled to a greater extent by the central nervous system via central pattern generators than it is by sensory feedback (Delcomyn, 1980), which has led to the notion that central command may influence these pattern generators and, in turn, rhythmic movement of skeletal muscle (Smith and Denny, 1990). This contention is supported by the fact that freely chosen cadence is not altered by increases in the load on the cardiorespiratory system when mechanical load is held constant, suggesting that it represents an “innate voluntary motor rhythm” (Hansen and Ohnstad, 2008). Thus, when compared to a cadence of 80 rpm, an increase in central command may have occurred in response to the 100 rpm cadence in an effort to maintain power output in the face of an in increase in the level of muscle fatigue.

We found that the use of high cadences during prolonged low to moderate workloads reduced subsequent cycling performance in terms of maximal power output attained. These findings may be relevant for competitive cyclists who often participate in prolonged road competitions (e.g., >2-3 h), where ~70% of the race involves sub-maximal cycling requiring an exercise intensity similar to that of our lowest workload (i.e., 60-70% of VO_2max) (Broker, 2003; Hansen et al., 2006). Our results suggest that selection of a lower, more energetically economical cadence during these lower exercise intensities can result in greater overall performance. Supporting this contention are results from a study of laboratory simulated 8 kilometer time trials in amateur road cyclists where performance was reduced when a higher cadence was used (101 vs. 82 rpm) (Watson and Svensen, 2006). However, further research is necessary to confirm these findings during actual racing conditions.

Conclusion

When using our novel prolonged cycling protocol that simulated conditions that occur during competitive cycling (varied intensities and sub-maximal workloads), the selection of a higher freely chosen cadence (100 vs. 80 rpm) resulted in excess energy expenditure (~5-6 % greater) and an attenuation of subsequent maximal performance (i.e., reduced power output). In addition, gross efficiency was lower during both exercise intensities at our higher pedaling frequency. These results suggest that, in competitive cyclists, selection of a high cadence during prolonged, variable, low-moderate submaximal exercise intensities subsequently results in greater energy expenditure and reduced maximal power output when compared to a lower cadence. However, these findings must be viewed cautiously, as testing protocols did not allow conclusions to be drawn regarding effects of our prolonged exercise paradigm on subsequent sprint or time trial performance.

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Key points

- When competitive cyclists perform prolonged exercise that simulates racing conditions (i.e., variable, low-moderate submaximal cycling), a higher cadence results in excess energy expenditure and lower gross efficiency compared to a lower cadence at the same power output.
- Consequently, maximal power output is reduced during a subsequent exercise bout to exhaustion after using a higher cadence.
- Selection of a lower, more energetically optimal cadence during prolonged cycling exercise may allow competitive cyclists to enhance maximal performance later in a race.

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Degree

PhD

Research interests

Exercise physiology, neural control of the cardiovascular system, vascular biology, effects of nutritional supplements on skeletal muscle blood flow

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Jesse L. MOORE

Employment

Sport Director, California Giant/Specialized Cycling Team

Degree

MS

Research interest

Exercise physiology, cycling and human performance

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Gretchen A. CASAZZA

Employment

University of California, Davis, Department of Sports Medicine

Degree

PhD

Research interests

Metabolic adaptations to exercise, the effects of ovarian hormones on exercise performance and bone health, nutritional aspects of performance, injury prevention in young athletes.

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