Journal of Science & Cycling
Breakthroughs in Cycling & Triathlon Sciences

OPEN ACCESS

Original article

Pedaling cadence does not affect aerobic performance during an incremental maximal test among male and female adult cyclists

Stacey Brickson, Kristin Haraldsdottir, Drew Richards, Isak Bowron, Andrew Watson
Department of Orthopedics and Rehabilitation at the University of Wisconsin School of Medicine and Public Health, University of Wisconsin – Madison, Madison, WI

* Correspondence: Kristin Haraldsdottir, Kristin.haraldsdottir@wisc.edu

Received: 26 May 2022; Accepted: 19 September 2022; Published: 31 December 2022

Abstract: The purpose of the study was to evaluate the effect of pedaling at the energetically optimal cadence (EOC) on aerobic capacity and cycling efficiency in experienced male and female adult cyclists. Twenty-four experienced cyclists underwent a progressive, maximal metabolic exercise test on a cycling ergometer pedaling at their freely chosen cadence (FCC). EOC was determined by maintaining an output of 65% of peak power during seven consecutive 3-minute stages of cadences between 50 rpm to 110 rpm in 10 rpm increments in a randomized order. Cyclists were then randomized to either an FCC or EOC group and performed a second maximal exercise test. Oxygen consumption (VO_{2max}), time to exhaustion (T_{max}), ventilatory threshold (VO_{2VT}) and time to ventilatory threshold (T_{VT}) were compared between the FCC and EOC groups. Submaximal average oxygen consumption was significantly higher during FCC (85±11 rpm) than EOC (60±8 rpm; 38.2±6.64 ml/kg/min v. 35±7.7 ml/kg/min, $p<0.001$). There were no significant interactions between group and order of maximal exercise tests with respect to VO_{2max} ($\beta=1.59$, $p=0.38$), T_{max} ($\beta=0.31$, $p=0.55$), VO_{2VT} ($\beta=0.05$, $p=0.98$) or T_{VT} ($\beta=0.18$, $p=0.82$). FCC was significantly lower among female cyclists compared to male cyclists. We conclude that cycling at EOC at submaximal workloads demands less oxygen consumption than FCC, but does not significantly improve VO_{2max}, and that there may be sex-specific differences with regards to FCC among experienced adult cyclists.

Keywords: cycling, aerobic capacity, cycling cadence, optimal cadence, performance

1. Introduction

Cycling performance is largely dependent on aerobic capacity and metabolic efficiency (Horowitz, Sidossis, & Coyle, 1994; Jobson, Nevill, George, Jeukendrup, & Passfield, 2008; Passfield & Doust, 2000). Metabolic efficiency in cycling can be defined as gross efficiency, or the ratio of mechanical work to the total metabolic energy consumed to do the work (Ettema & Loras, 2009; Lucia, Hoyos, Perez, Santalla, & Chicharro, 2002). Many factors are known to affect metabolic efficiency, including muscle fiber type composition (Coyle, Sidossis, Horowitz, & Beltz, 1992; Horowitz et al., 1994), external work rate (Lucia et al., 2002), muscle capillary density (Coyle et al., 1991), peak power, and pedaling technique (Chavarren & Calbet, 1999; Leirdal & Ettema, 2011a, 2011b; Londeree, Moffitt-Gerstenberger, Padfield, & Lottmann, 1997; McDaniel, Durstine, Hand, & Martin, 2002). While physiological factors affecting performance have been widely studied, the impact of pedal cadence on aerobic capacity and performance are less well defined (Horowitz et al., 1994; Jobson et al., 2008; Nickleberry & Brooks, 1996; Passfield & Doust, 2000).

The choice of cycling cadence by cyclists can be influenced by work rate, intracortical inputs, experience and fitness (Hansen & Smith, 2009). The effect of cadence on metabolic efficiency has been an area of considerable investigation and debate (Chavarren & Calbet, 1999; Coyle et al., 1992; Horowitz et al., 1994; Sidossis, Horowitz, & Coyle, 1992) and was reviewed by Ettema and Loras (Ettema & Loras, 2009). Briefly, the contribution of cycling cadence to efficiency is thought to be relatively low compared to work rate (Ettema & Loras, 2009), and while lower cycling cadence has been found to correspond to lower oxygen consumption, pedaling rate does not correlate to heart rate (Chavarren & Calbet, 1999), where the other investigations report a negative curvilinear relationship between cadence and metabolic efficiency at submaximal cycling efforts (Mitchell et al., 2019; Takaishi, Yasuda, Ono, & Moritani, 1996). This relationship, however, may only apply to lower power outputs, where cadence may not have a deleterious effect on metabolic efficiency at near maximal power outputs (Foss & Hallen, 2004), and little is known about the effect of energetically optimal cadence at maximal efforts on endurance and aerobic capacity. Time to exhaustion (Tmax), determined as the duration of time to volitional exhaustion during a maximal aerobic capacity test, has been used as a surrogate for cycling endurance (Haraldsdottir, Brickson, Sanfilippo, Dunn, & Watson, 2018), and was used in the present study as a more sensitive measure of maximal exhaustion than maximal power (Pmax).

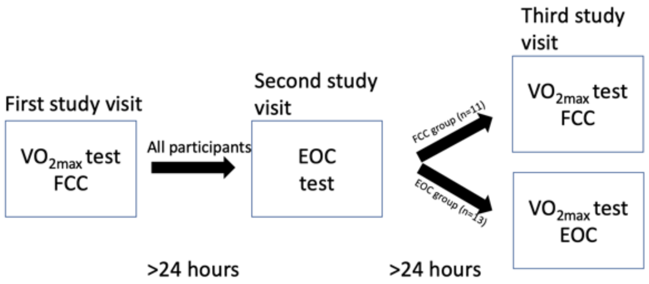
This presents a cycling paradox whereby the selection of cadence between 90 and 100 rpm, the often preferred cadence range by cyclists, is well above energetically optimal cadence found between 60 and 70 rpm (Boning, Gonen, & Maassen, 1984; Marsh & Martin, 1997; Sidossis et al., 1992). Self- selection of higher cadence has been attributed to reduced neuromuscular fatigue (Takaishi, Yamamoto, Ono, Ito, & Moritani, 1998; Takaishi et al., 1996), optimization of muscle activation (Neptune & Hull, 1999), lower active muscle blood flow (Mitchell et al., 2019), minimization of the sum of hip and knee net forces (Redfield & Hull, 1986), and reduced rate of perceived exertion (Boning et al., 1984; Sidossis et al., 1992). Although several studies have evaluated the effect of cycling cadence on gross efficiency to cycling performance (Horowitz et al., 1994; Jobson et al., 2008; Nickleberry & Brooks, 1996), to our knowledge, no prior research has evaluated the influence of cadence modulation on aerobic capacity and cycling performance, as determined by Tmax, during a maximal incremental test. Therefore, the purpose of this study was to compare cycling at FCC and EOC during progressive maximal exercise on aerobic capacity and Tmax in experienced road cyclists.

2. Materials and Methods

All procedures performed in this study were approved by the Institutional Review Board at the University of Wisconsin-Madison, and they were in accordance with the ethical standards of the 1964 Helsinki Declaration. Twenty five experienced adult road cyclists were recruited from local cycling and triathlon clubs and provided written informed consent. Inclusion criteria for the study was defined as participants having at least 5 years of cycling experience (16.8±11.8 years) and 5000 miles of training on a road bike with a clipless pedal system. Cyclists with clinically significant cardiac or pulmonary disease or musculoskeletal injuries that precluded a maximal cycling effort were excluded. One subject did not undergo randomization and did not complete the final maximal exercise testing, so this individual was removed from the study.

Subjects were randomized into control (FCC; n=11) or EOC (n=13) groups and completed a series of three study visits within a 3-week period, with at least 24 hours of rest in between consecutive visits (figure 1).

Figure 1. Study design schematic



EOC = energetically optimal cadence; FCC=freely chosen cadence; VO_{2max} = maximal aerobic capacity

Subjects were asked to refrain from intense exercise 24 hours prior to all testing. At the initial study visit, participants completed a detailed questionnaire regarding cycling experience and injury history. Height was measured with a stadiometer to the nearest 0.25 cm and body mass was measured with a calibrated balance beam scale to the nearest 0.1 kg.

On the first and third study visits, eligible participants underwent a progressive, maximal exercise test after being familiarized with the exercise testing equipment, described previously (Watson, Brickson, Brooks, & Dunn, 2017) and briefly below. An electronically braked cycle ergometer (Velotron, Racermate, Seattle, WA) was adjusted to each participant's preference for bike dimensions and fit with the clipless pedal system of the subject's choosing. Before testing, the metabolic cart system (Cosmed, Chicago, IL) was calibrated with known oxygen and carbon dioxide concentrations.

During the second study visit to determine EOC, participants warmed up on the electronically braked cycle ergometer for 3 minutes at FCC at a workload corresponding to 55% PP from the first maximal exercise (figure 1). Participants then performed a prolonged cycling effort (PCE) of 10 minutes at 65% PP at FCC. Participants then maintained an output of 65% PP during the EOC determination, which consisted of 7 consecutive 3-minute stages of cadences 50, 60, 70, 80, 90, 100 and 110 rpm in a randomized order. This was followed by a 3-minute cool down at FCC at 40% PP. The total cycling time was 37 min (Figure 2). A participant's EOC was determined as the wattage requiring the lowest average oxygen consumption.

Figure 2. Energetically optimal cadence determination protocol.

	Time (min)	Intensity (% PP)	Cadence (rpm)
Warm up	3	55	FCC
Prolonged cycling effort	10	65	FCC
Energetically optimal cadence determination	21	65	3-minutes at each of 7 cadences between 50-110rpm in random order
Cool down	3	4	FCC

EOC= energetically optimal cadence; FCC= freely chosen cadence.

During the first maximal test, participants were asked to pedal at their FCC, and in the second VO_{2max} test (third study visit), participants were asked to pedal at either FCC again or EOC (as determined by the EOC visit outlined below) based on their randomized group assignment. In each maximal exercise test, participants cycled at 155 W for 3 minutes, and wattage increased by 35 W at 3-minute intervals to the point of volitional exhaustion, defined as the point when the participant could no longer maintain cycling cadence despite strong verbal encouragement, at which time to volitional exhaustion was recorded (T_{max}). Oxygen consumption (VO_2), carbon dioxide (VCO_2) and respiratory exchange ratio (RER; VCO_2/VO_2) were recorded and calculated in a continuous, breath-by breath manner during the test and expressed as a 30-second rolling average. VO_{2max} was defined as the highest rolling VO_2 value during the test and recorded. Heart rate (HR) was continuously recorded using a chest strap (Garmin, Olathe, KS). Ventilatory threshold (VT) was determined as the point at which an upward deflection was noted in the slope of minute ventilation over time, and time to VT (T_{VT}), oxygen consumption (VO_{2VT}) and heart rate (HR_{VT}) at VT were recorded. VO_{2max} and VT were expressed absolutely (L/min) and relative to body mass (ml/kg/min). Peak power (PP) was defined as the last completed stage in Watts plus the fraction of time spent (seconds completed divided by 180) in the final partially completed stage multiplied by 35 W. The test was considered maximal if the participant achieved 2 of the following 3 objective criteria: heart rate > 90% predicted maximal HR (208 - 0.7 x age), RER> 1.0, or plateau in oxygen consumption, defined as a change of < 2.0 ml/kg/min of oxygen consumption during the final 30 seconds of the test.

Variables were evaluated for normality using histogram analysis and descriptive statistics. Baseline variables were compared between FCC and EOC groups using Wilcoxon Rank Sum and Chi-Square tests, with adjustment for multiple comparisons using the method previously described by Holm (Holm, 1979). Cadence and oxygen consumption were compared between PCE and EOC using paired Wilcoxon tests. To evaluate the effect of FCC/EOC assignment on exercise variables, separate mixed effects linear regressions were developed to predict each outcome variable, including the interaction of session (maximal test 1, maximal test 2) and cadence (EOC, FCC) as a fixed effect and each individual as a random effect. EOC and FCC were compared between genders using Wilcoxon Rank Sum tests. Cohen's d was calculated to determine effect sizes (Cohen, 1988). Significance was determined a priori at 0.05 and all tests were 2-tailed. All statistical analyses were conducted in R ("R" 2013).

3. Results

There were no significant differences in anthropometric measurements, cycling experience (Table 1) and baseline exercise capacity variables (Table 2) between the FCC and EOC groups. There was no significant interaction between maximal test session and group assignment (Table 3).

Table 1. Participant characteristics

	FCC Group (n=11)	EOC Group (n=13)	p	Cohen's d
Gender (male)	6 (55%)	8 (62%)	0.70	-
Age (years)	45.7±13.4	41.7±12	0.35	0.31
Height (cm)	176.8±10.8	176.0±8.0	0.73	0.08
Weight (kg)	71.9±8.4	74.5±10.5	0.24	0.27
Experience (years)	13.9±10.5	19.2±13.8	0.40	0.43

Table 2. Comparison of baseline exercise capacity variables

	FCC Group (n=11)	EOC Group (n=13)	p	Cohen's d
VO_{2max} (ml/kg/min)	47.7± 7.2	53.7±10.8	0.16	0.65
VO_{2max} (L/min)	3.5± 0.8	4.0± 0.8	0.14	0.63
T_{max} (min)	12.1± 5.2	15.7± 4.9	0.09	0.71
HR_{max} (bpm)	173± 11	177± 9	0.43	0.40
PP (W)	292± 60	327± 56	0.12	0.60
RER_{max}	1.12±0.07	1.08±0.04	0.12	0.70
VO_{2VT} (ml/kg/min)	44.3± 5.9	48.6±10.8	0.20	0.49
T_{VT} (min)	12.1± 4.8	12.2±4.8	0.11	0.02
HR_{VT} (bpm)	163±12	166±10	0.43	0.27

VO_{2max}, maximal oxygen consumption; T_{max}, time to exhaustion; P_{max}, maximal power; HR_{max}, maximal heart rate; bpm, beats per minute; PP, peak power; RER_{max}, maximal respiratory equivalent ratio; VT, ventilatory threshold ;VO_{2vt}, oxygen consumption at VT; T_{VT}, elapsed time at VT; HR_{VT}, heart rate at VT.

The average FCC for all participants, as determined during the PCE, was significantly higher than EOC (85±11 v. 60±8 rpm, p<0.001). Average VO_2 relative to body mass was significantly higher during PCE than each participant's EOC (38.2±6.64 ml/kg/min v. 35.0±7.7 ml/kg/min, p<0.001). VO_2 at 65% PP was lower during FCC compared to cadences between 50 and 70rpm, and significantly lower than during cadences of 100 and 110 (Figure 3).

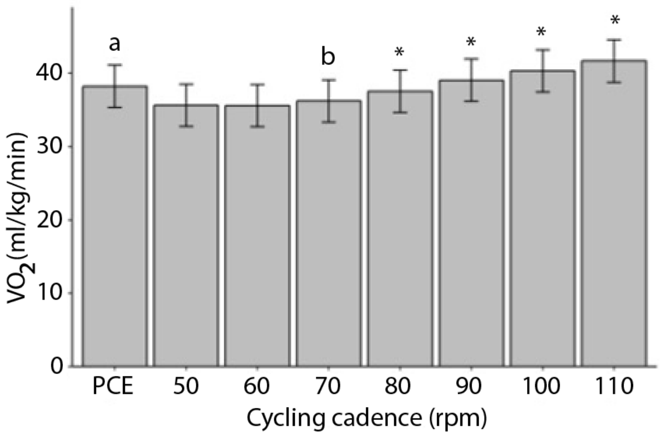
The EOC for all cyclists fell between 50 and 70rpm and is shown separately for males and females in Table 4. Oxygen consumption relative to body mass at any cadence 80 rpm or greater was significantly higher than at 50, 60, or 70 rpm. During the PCE, male cyclists demonstrated a higher FCC compared to female cyclists, though EOC was not significantly between genders (Table 4).

Table 3. Comparison of exercise capacity variables between the two maximal exercise tests.

	FCC Group (n=11)			EOC Group (n=13)				
	Test #1 (FCC)	Test #2 (FCC)	Cohen's d order effect	Test #1 (FCC)	Test #2 (EOC)	Cohen's d group effect	Interaction Estimate	p
VO_{2max} (ml/kg/min)	47.7± 7.2	48.2± 8.5	0.06	53.7±10.8	52.6±9.3	0.11	1.59	0.38
VO_{2max} (L/min)	3.5±0.8	3.5±0.9	0.01	4.0±0.8	3.9±0.7	0.13	0.09	0.49
T_{max} (min)	12.1±5.2	12.5±5.7	0.07	15.7±4.9	16.4±5.0	0.14	-0.31	0.55
HR_{max} (bpm)	173±11	174±10	0.10	177±9	176±8	0.12	0.62	0.82
PP (W)	292±60	289±71	0.05	327±56	330±55	0.05	-5.87	0.50
RER_{max}	1.12±0.07	1.13±0.07	0.14	1.08±0.04	1.09±0.07	0.18	0.00	0.92
VO_{2VT} (ml/kg/min)	44.3± 5.9	43.3±6.9	0.16	48.6±10.8	53.4±8.9	0.49	-0.05	0.98
T_{VT} (min)	9.2±4.3	9.8±5.4	0.12	12.2±4.8	12.6±4.4	0.09	0.18	0.82
HR_{VT} (bpm)	163±12	163±12	0.0	166±10	163±11	0.29	2.45	0.43

VO_{2max}, maximal oxygen consumption; T_{max}, time to exhaustion; P_{max}, maximal power; HR_{max}, maximal heart rate; bpm, beats per minute; PP, peak power; RER_{max}, maximal respiratory equivalent ratio; VT, ventilatory threshold ;VO_{2vt}, oxygen consumption at VT; T_{VT}, elapsed time at VT; HR_{VT}, heart rate at VT.

Figure 3. Average oxygen consumption (ml/kg/min) at different cycling cadences at fixed 65% Peak Power.



Mean and 95% confidence limits for average oxygen consumption (ml/kg/min) at different cadences (rpm). [a]: p<0.05 versus 50, 60, 70, 100, 110 rpm; [b]: p<0.05 versus 80, 90, 100, 110 rpm; [*]p<0.05 versus all other rpm; PCE: prolonged cycling effort at freely chosen cadence

Table 4. Freely chosen and energetically optimal cadences with comparisons between genders.

	Overall (n=24)	Female (n=10)	Male (n= 14)	p
FCC (rpm)	85±11	80±9	89±10	0.04
EOC (rpm)	60±8	57±8	61±7	0.19

FCC, freely chosen cadence; rpm, revolutions per minute; EOC, energetically optimal cadence.

4. Discussion

The main purpose of this study was to evaluate aerobic capacity and time to exhaustion in cyclists pedaling at EOC compared to FCC. We found no differences in aerobic and endurance performance duration incremental maximal tests performed at FCC and EOC among experienced cyclists. This result was surprising, given that we also found that the cyclists pedaled at a cadence significantly higher than their EOC during a submaximal exercise test when allowed to freely choose their cadence at 65% of peak power. This is consistent with previous research, which has shown that highly trained cyclists prefer to cycle at cadences consistently higher than EOC, over 90 rpm (Carnevale & Gaesser, 1991; Mitchell et al., 2019).

Previous literature has highlighted that submaximal physiological variables, including cycling economy, can significantly contribute to a cyclist's endurance performance (Phillips & Hopkins, 2020). Our findings support the understanding that the metabolic cost of submaximal steady state cycling is lower at prescribed cadences between 50-70 rpm than at higher cadences, including FCC. Our findings are consistent with well established patterns in previous literature (Chavarren & Calbet, 1999; Hansen & Smith, 2009; Stebbins, Moore, & Casazza, 2014), where an increase in metabolic demand is observed as cycling cadence is increased (Shastri et al., 2019). However, there is little evidence in the literature exploring the influence of cycling cadence (EOC versus FCC) and maximal cycling efforts. Cycling at wattages close to peak power at FCC has been associated with lower cortical inhibition and higher cortical facilitation (Sidhu & Lauber, 2020), suggesting a trade-off between metabolic efficiency and neurophysiological cost. Interestingly, a previous study found that cycling at 100 rpm compared to 80 rpm elicited a higher heart rate, higher energy expenditure and lower energetic efficiency, though the rate of perceived exertion was no different between the two cadences (Stebbins et al., 2014). Further investigation is warranted to evaluate the relationship between perceived exertion, intracortical inhibition, and energetic cost. Biomechanical factors impacting muscular fatigue may also be subconsciously factored by the cyclist, and should be considered for future study.

While we hypothesized that lower oxygen consumption at EOC at submaximal intensities would translate into increased maximal aerobic capacity and performance metrics, we did not find a difference between maximum aerobic capacity and performance at EOC versus FCC. The finding that submaximal oxygen consumption was lower at EOC cadences suggests that fatigue during submaximal efforts compared to maximal efforts is likely not reflected in oxygen consumption. Because typical elite cycling competitions comprise of long-distance submaximal efforts, endurance performance, as measured in the current study by T_{max}, may not have been adequately captured. While, the workload of 65% of PP chosen in the current study to determine EOC is similar to the workload determined as the lactate threshold in elite cyclists (Bentley, McNaughton, Thompson, Vleck, & Batterham, 2001), we did not employ a true peak power test, and instead determined Peak Power as the maximal wattage attained during the VO_{2max} test in the first visit.

Interestingly, we found that while the average FCC in the current study was 85 rpm, which was higher than EOC on average, female FCC was significantly lower than that chosen by males (80±9 versus 89±10, p=0.04). We are not aware of other reports in the literature demonstrating differences in FCC by female versus male cyclists. In recent years, more research has been performed to explore female exercise physiology, and there are some differences of note that may support our finding of a lower FCC among female cyclists. Females often outperform males during submaximal exercise efforts, with a greater difference found at lower intensities (Hunter, 2014). Second, muscle fiber type composition in the rectus femoris has been found to have greater type-I fibers in females compared to males (Staron et al., 2000). It has also been demonstrated that females exhibit different central fatigue in response to maximal exercise compared to males, where males have greater relative fatigability related to deficits in motor output (Martin & Rattey, 2007). Finally, biomechanical factors may have affected the cycling efficiency, and thus cadence selection, for females versus males in the present study. It has been demonstrated that shorter cyclists are more efficient with shorter crank arms and higher pedaling rates (Hull & Gonzalez, 1988). Taken together, our finding that females chose a cycling cadence during FCC maximal exercise testing closer to their EOC is in line with previous research suggesting that females may have a more fatigue-resistant profile in endurance exercise, but caution should be taken in generalizing the results due to factors listed below.

The current investigation has some limitations to note. The participants in this study represent a relatively small group of experienced, recreational cyclists. While our sample size was initially based on other comparable studies in the literature identifying differences in our primary endpoints, the findings may not be generalizable to other populations due to differences in study design, gender of participants, and fitness level of participants. Additionally, while we did adjust seat height and handle bar height for participants of different heights, we did not adjust crank arm length for participants of different genders or leg lengths. As prior reports have demonstrated that cyclist height and crank arm length are related to metabolic cost of cycling (Hull & Gonzalez, 1988).

5. Practical Applications.

Freely chosen cadence among experienced adult cyclists is consistently higher than EOC determined in a lab, and is higher among males. No significant relationship was identified between pedaling at EOC and maximal aerobic capacity or performance, compared to FCC. Further research is warranted to identify the benefits of cycling at FCC that may offset the reduced metabolic efficiency during submaximal effort compared to EOC. Our findings suggest that cycling cadence among experienced cyclists is well matched to energy needs when freely chosen. They also suggest that factors beyond maximal aerobic capacity play a significant role in endurance performance, though this investigation did not explore these factors.

Funding: This research received no external funding.

Acknowledgments: The study team would like to thank the participants for their enthusiastic and generous participation in the study.

Conflicts of Interest: The authors declare no conflict of interest.

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