Eur J Appl Physiol (2007) 99:387–391
DOI 10.1007/s00421-006-0358-7

ORIGINAL ARTICLE

Effect of cycling position on oxygen uptake and preferred cadence in trained cyclists during hill climbing at various power outputs

Chris Harnish · Deborah King · Tom Swensen

Accepted: 20 November 2006 / Published online: 13 December 2006

Abstract Numerous researchers have studied the physiological responses to seated and standing cycling, but actual field data are sparse. One open issue is the preferred cadence of trained cyclists while hill climbing. The purpose of this study, therefore, was to examine the affect of cycling position on economy and preferred cadence in trained cyclists while they climbed a moderate grade hill at various power outputs. Eight trained cyclists (25.8 ± 7.2 years, $\dot{V}O_{2\,max}$ 68.8 ± 5.0 ml kg^{-1} min^{-1}, peak power 407.6 ± 69.0 W) completed a seated and standing hill climb at approximately 50, 65 and 75% of peak power output (PPO) in the order shown, although cycling position was randomized, i.e., half the cyclists stood or remained seat on their first trial at each power output. Cyclists also performed a maximal trial unrestricted by position. Heart rate, power output, and cadence were measured continuously with a power tap; ventilation $\dot{V}$e, BF and cadence were significantly higher with seated climbing at all intensities; there were no other physiological differences between the climbing positions. These data support the premise that trained cyclists are equally economical using high or low cadences, but may face a limit to benefits gained with increasing cadence.

Keywords Cadence · Economy · Gradient · Lactate · Power

C. Harnish (✉)
Tradewind Sports, East Falmouth, MA 02536, USA
e-mail: tradewindsports@verizon.net

D. King · T. Swensen
Department of Exercise and Sport Sciences, Ithaca College, Ithaca, NY 14850, USA

Introduction

Unlike level ground cycling, where wind resistance is the major opposing force, uphill cycling requires a significant portion of power to overcome gravity. Level ground cycling is also largely restricted to the seated position, whereas a cyclist may stand or remain seated while climbing. Whether a cyclist climbs a hill seated or standing depends on many factors, including the gradient of the hill, available gearing, the length of the climb, the situation (e.g., leisurely ride vs a race, or an attack or sprint), and an individual's experience, body morphology, and preference. The issue is further complicated by contemporary anecdotal coaching opinions regarding elite cyclists that suggest that higher cadences, such as those greater than 80 rpm, which are more applicable to the seated position, maximize performance. It is not clear, however, which climbing position is most efficacious.

Numerous studies (Miller et al. 1988; Ryschon and Stray-Gundersen 1991; Swain and Wilcox 1992; Tanaka et al. 1996) have attempted to elucidate the physiological differences between seated and standing cycling. Differences in methodology, however, such as subject cohort, cadence, gradient, exercise intensity, and venue make data interpretation difficult. For example, Miller et al. (1988) found few cardiorespiratory differences between seated and standing positions. In contrast, later studies (Ryschon and Stray-Gundersen 1991; Tanaka et al. 1996) show that seated cycling is more economical than standing when cycling up a moderate grade at greater than 70% . The applicability of the aforementioned data to actual road riding is limited, as the data were generated during treadmill cycling, which differs significantly from riding in the field (Kenny et al. 1995); standing treadmill cycling, moreover, is difficult above 70 rpm (Ryschon and Stray-Gundersen 1991), which may have restricted the researchers' options.

The choice of climbing position while cycling is often determined by cadence, which is influenced by gear availability; inadequate gearing often necessitates standing. Racing observations and experience, combined with unpublished power data collected by C. Harnish suggest that many cyclists may under gear for steep climbs, forcing them to use a lower, less optimal cadence. Whereas there is little dispute that cyclists use higher cadences than untrained individuals (Marsh and Martin 1993, 1997, 1998, 2000), it is unclear what the relationship is between cadence and cycling position while cycling uphill when gearing is not limited, i.e., will cyclists adopt a high uphill cadence if they have the gears to do so. To our knowledge, no studies have examined the preferred climbing cadence over a variety of power outputs.

Therefore the purposes of this study were to examine the affect of cycling position on economy during hill climbing at various power outputs and to determine the preferred cadence of trained cyclists at various power outputs and cycling positions while climbing a moderate grade hill.

Methods

Eight highly trained cyclists (seven males, one female) 25.8 ± 7.2 years of age, 68.5 ± 8.7 kg, 7.3 ± 3.9 years of training, 68.8 ± 5.0 ml kg^{-1} min^{-1}, and peak power of 407.6 ± 69.0 W served as subjects; three subjects were elite caliber, while one female was a former US national road medalist. Prior to participation, each signed an informed consent that was approved by the human subjects committee at Ithaca college; all experimental procedures in this study conformed to the american college of sports medicine's policy regarding the use of human subjects. Each subject performed two test sessions; the first session was held in the laboratory, while the second was held at an outdoor venue.

Laboratory testing

The initial testing session took place in the laboratory where each subject's $\dot{V}O_{2\,max}$ and mechanical power (W) that were maintained for at least one minute of testing.

Prior to, and 5 min after the max test, three 25 µl blood samples were drawn from the subject's fingertip, which was sterilized with an alcohol swap. Blood lactate was assessed from these blood samples using a YSI 1500 Sport Tester (Yellow Springs, OH; CV = 5.3%); pre- and post-trial blood lactate were reported as the mean of the three samples. Throughout all testing the lab temperature was kept between 19 and 22°C and subjects were cooled with a powerful fan.

Field testing

Within one week of completing lab testing, subjects performed a series of hill climb trials on a nearby 1.9 km climb with an average gradient of 5%. All subjects were equipped with the same gear cluster, which included a 25 cog that produced a minimum gear size of 3.33 meters per pedal revolution. The mild gradient and large gear selection allowed subject's to choose a preferred cadence.

After a 25 min low intensity warm up, subjects completed two series of hill climbs, one seated and one standing, at the following three intensities: LOW, MEDIUM and HIGH, which corresponded to approximately 50, 65 and 75% of their PPO, respectively; power output was maintained with the aid of a power tap. Each climb was separated by 15 min of active recovery, allowing time to ride down the hill and to spin easily prior to the next trial, which were completed in a progressive manner, beginning with the lowest intensity; hand position was not controlled. To minimize the effects of fatigue, the two cycling positions were randomized using a standard coin toss. In short, four subjects completed the first trial at each power output in the standing position, whereas the other four subjects started in the seated position. Once all positional trials were completed, subjects performed a final maximal trial where they rode as fast as possible, unrestricted by position. Subjects started with a standing sprint and then recorded positional changes using a standard stopwatch lap counter. Heart rate, power output, and cadence were measured continuously using the power tap during each trial, while breathing frequency (BF) and $\dot{V}e$ (seated was lower) and breathing frequency (seated was lower). Table 2 presents selected data for the final maximal trial, which was completed at approximately 93% of PPO.

Discussion

Previous studies (Ryschon and Stray-Gundersen 1991; Tanaka et al. 1996) suggested that standing climbing elicited a higher oxygen consumption and/or HR than seated climbing. These studies, however, were limited by their use of a treadmill, which may have precluded

Table 1 Selected data comparing seated versus standing hill climbing in cyclists

Mean (SD)	LOW		MEDIUM		HIGH	
	Seated	Standing	Seated	Standing	Seated	Standing
% PPO	49.4 (2.6)	49.4 (2.6)	64.4 (3.3)	64.6 (3.5)	74.3 (3.9)	74.3 (4.0)
Cadence (RPM)	**74.6 (6.0)**	**57.0 (6.8)**	**81.1 (5.9)**	**61.6 (7.2)**	**82.4 (6.8)**	**65.8 (7.3)**
$\dot{V}O_{2\,max}$ (L min^{-1})	2.7 (0.5)	2.7 (0.6)	3.3 (0.6)	3.3 (0.6)	3.7 (0.7)	3.6 (0.6)
$\dot{V}e$ (L min^{-1})	**71.3 (11.4)**	**76.3 (13.1)**	**95.0 (17.7)**	**100.3 (18.6)**	**121.2 (26.8)**	**124.1 (23.8)**
BF (b min^{-1})	**31.3 (2.9)**	**34.5 (1.9)**	**37.4 (2.8)**	**40.5 (2.6)**	**43.7 (4.2)**	**47.5 (4.6)**
TV (L min^{-1})	2.3 (0.4)	2.2 (0.4)	2.5 (0.4)	2.5 (0.5)	2.8 (0.5)	2.6 (0.4)
Economy (W L^{-1} min^{-1})	74.5 (3.9)	76.9 (9.6)	79.5 (3.2)	80.9 (6.3)	82.7 (4.6)	84.8 (6.7)
Net efficiency[a]	24.2 (1.7)	25.1 (3.7)	25.2 (1.4)	25.7 (2.2)	26.0 (1.7)	26.7 (2.3)
HR (bpm)	150.8 (7.9)	153.4 (11.9)	165.8 (7.3)	168.5 (10.4)	174.6 (7.9)	175.5 (9.1)
Hla (mM)	1.7 (0.6)	1.9 (0.5)	2.7 (0.5)	3.1 (1.0)	5.1 (1.6)	5.6 (1.2)
RPE	9.3 (1.5)	9.9 (1.2)	12.8 (1.0)	12.7 (1.0)	15.3 (0.8)	15.1 (0.8)

Values given in bold denote a significant ($P < 0.05$) difference between seated and standing position at the designated power output

[a] Net efficiency values are presented as a percentage and assume $R = 0.96$, the energy equivalent of O_2 is 20.9 kJ and resting $\dot{V}O_{2\,max} = 300$ ml min^{-1}

cyclists from choosing their preferred cadence, thereby unwittingly increasing oxygen consumption in the standing position. In short, the physiological responses of treadmill cycling are significantly different from those of actual road riding (Kenny et al. 1995). Balance maintenance while climbing steep treadmill grades, like those used in many earlier studies, is a major problem in early climbing studies (Ryschon and Stray-Gundersen 1991), and likely unduly influenced preferred cadence regardless of gearing. Thus, the primary purpose of our study was to examine the affect of cycling position on economy during actual hill climbing in the field at various power outputs.

Table 2 Mean data for cyclists during a final maximal uphill trial. Cycling position was not imposed, though subjects provided an approximate record of positional changes. All physiologic and mechanical (i.e. power and cadence) were significantly higher than HIGH (75% PPO) trials

	Mean (SD)
Power (W)	377.1 (58.2)
% PPO	92.8 (3.5)
Cadence (RPM)	77.6 (7.1)
$\dot{V}O_{2\,max}$ (L min^{-1})	3.7 (0.7)
$\dot{V}e$ (L min^{-1})	136.4 (58.7)
BF (b min^{-1})	60.2 (7.5)
Economy (W L^{-1} min^{-1})	99.4 (6.2)
Net efficiency[a]	31.2 (2.3)
HR (bpm)	183.7 (9.3)
HLa (mM)	12.2 (2.1)
RPE	18.9 (0.6)
% Seated climbing	65.9 (17.4)
% Standing climbing	34.1 (17.4)

[a] Net efficiency values are presented as a percentage and assume $R = 0.96$, the energy equivalent of O_2 is 20.9 kJ and resting $\dot{V}O_{2\,max} = 300$ ml min^{-1}

Our data showed no differences in economy, $\dot{V}O_{2\,max}$, HR, RPE or blood lactate between the two positions at any of the intensities used in the study. In contrast to $\dot{V}O_{2\,max}$, however, standing climbing elicited both a higher breathing frequency and ventilatory rate, lending support to data from Millet et al. (2002). We surmise that riders utilize a rhythmic breathing pattern in coordination with their standing climbing technique. Mechanically speaking, the riders timed their breathing with the shifting of the bicycle as they climbed, which was unnecessary from the seated position. This breathing entrainment may have limited tidal volume slightly, albeit insignificantly. As shown in Table 1, the tidal volume difference was greatest, approximately 7%, during the high power output trial. Alternatively, perhaps the standing position, which requires the use of the arms to support the upper body, limits the rider's chest capacity, thereby somewhat lowering tidal volume. The relevance to performance of this TV difference remains unclear.

While oxygen consumption did not differ between positions, economy was shown to increase in both positions as power increased. These findings corroborate other data that show efficiency, or in our case economy, as power output increases irrespective of cadence (Chavarren and Calbet 1999; Coast and Welch 1985; Foss and Hallen 2004; Kuipers et al. 1985; Nielsen et al. 2004; Samozino et al. 2006). Collectively, the data show that the added muscle mass used during standing climbing increases oxygen use, which, along with the diminishing differences in $\dot{V}O_2$ between low and high cadence while power output increases, offsets the higher economy typically seen at lower cadences.

A secondary purpose of this study was to determine the preferred cadence of trained cyclists at various power outputs and cycling positions while hill climbing. Like climbing, cadence has been studied frequently (Chavarren and Calbet 1999; Coast and Welch 1985; Foss and Hallen 2004; Hagberg et al. 1981; Kohler and Boutellier 2005; Kuipers et al. 1985; Lepers et al. 2000, 2001; Lucia et al. 2001, 2004; MacIntosh et al. 2000; Marsh and Martin 1993, 1997, 1998, 2000; Miller et al. 1988; Millet et al. 2002; Nielsen et al. 2004; Samozino et al. 2006; Swain and Wilcox 1992; Takaishi et al. 1998; Vercruyssen et al. 2001; Watson and Swensen 2006), often in an effort to determine why trained individuals, whether runners or cyclists, choose higher cadences than those that minimize either oxygen consumption or RPE (Marsh and Martin 1993). It has been suggested that individuals choose higher cadences to minimize neuromuscular stress (MacIntosh et al. 2000; Takaishi et al. 1998) at the expense of energy use. However, Vercruyssen et al. (2001) showed that preferred cadence decreases with duration, possibly due to neuromuscular fatigue (Lepers et al. 2000). More recently, Kohler and Boutellier (2005) asserted that the optimal cadence lies between the most powerful and efficient cadences and that event duration and intensity are the dominant determining factors for cadence choice. They argue that trained cyclists tend toward higher cadences when power output is most important, particularly during events lasting under 5 min, but ultimately increasing duration forces the cadence optimum down. Data from Lucia et al. (2004) support this assertion, as do data from Watson and Swensen (2006), from which one can infer that the trained cyclists in their study used a cadence that maximized power output during an 8 km TT.

While this study is not the first to examine uphill cycling in the field (Millet et al. 2002), we believe it is the first to allow well-trained cyclists to use their preferred cadence and gearing during climbing at various power outputs. Our data show that cadence was higher for seated than standing climbing, and, more significantly, increased as power output did during seated climbing, ultimately reaching a 'ceiling' of approximately 82 rpm.

Collectively, our data show that the trained cyclists preferred a relatively high cadence of 80 rpm during seated climbing on a moderate grade at power outputs greater than 65% of PPO. These data contrast sharply with data from Millet et al. (2002), who found that cyclists used a cadence of about 60 rpm while climbing. Our data do, however, support those of Lucia et al. (2001), who reported that professional cyclists in a major stage race who were required to perform maximally to sustain their high over all position in the general classification used a climbing cadence of about 80 rpm. In contrast, racers who were not general classification contenders used a lower cadence of 71 rpm at about 73% of PPO. This non-contender cadence is somewhat higher than the one reported by Millet et al. (2002), but lower than our subjects' cadence regardless of cycling position. It is difficult to reconcile the Millet data with ours, collected on a climb of similar distance and grade. Their subjects also had a similar PPO of about 390 W. There was, however, no mention of the gearing available to their riders. Gear availability may have affected cadence choice.

A cyclist's gear options often determine his or her cadence; our experience has been that even on relatively shallow gradient climbs, sufficient gearing is necessary to allow riders a full choice of cadence. In the present study, we equipped each subject with a range of climbing gears, which appeared to be more than adequate for them. Irrespective of gear availability, cadence is still lower with sustained climbing compared to other aspects of road racing (Lucia et al. 2004). Kohler (Personal communication, 2006) postulates that the lower cadence seen during uphill cycling, or even into a strong headwind, is related to differences in angular velocity of the pedal stroke during its low power phase, which decreases faster during climbing than with level ground cycling. This drop in pedal angular velocity with a corresponding increase in force while climbing does not seem to unduly affect efficiency (Mongoni and di Prampero 2003), and may ultimately lower cadence. Perhaps this change in cycling mechanics is related to the cadence 'ceiling' seen in uphill cycling.

Watson and Swensen (2006) argue that a cadence ceiling on flat land is based on a subject's fitness level as higher cadences did not increase racing velocity in their subject cohort; instead, higher cadences decreased performance. Indeed, a cadence of 82 rpm appeared to maximize performance in the 8 km test. Their assertion is tentatively supported by data showing that higher cadences of about 100 rpm are more economical than 60 rpm in professional cyclists (Lucia et al. 2004), whose subjects had a PPO of about 500 W compared to the 390 W PPO for subjects in Watson and Swensen (2006). Moreover, Lucia et al. (2004) showed that pedaling at 100 rpm is less physiological taxing than a cadence of 80 rpm. In contrast, 100 rpm was more taxing than 80 rpm for the less talented or fit subjects in Watson and Swensen (2006). Perhaps fitness level also contributes to the cadence ceiling seen with climbing. Whether or not this ceiling can be raised through training so that climbing cadences approach those to that of flatland cycling is unclear.

In conclusion, we found that $\dot{V}e$ and BF were significantly higher during standing climbing at all intensities; there were no other physiological differences between the cycling positions despite the significantly higher cadence exhibited during seated climbing at all intensities. These data, taken in conjunction with the literature, support the premise that trained cyclists are, at the very least, no less economical using high cadences than they are lower cadences, but may ultimately face an upper limit to any benefits gained with increasing cadence.

Acknowledgments We wish to thank Chad Butts, Kelly Brady and Janet Wigglesworth, Ph.D. for their help with this study. We would also like to thank Dr. Pietro di Prampero for his help in preparing our efficiency data.

References

Bertucci W, Duc S, Villerius V, Pernin JN, Grappe F (2005) Validity and reliability of the powertap mobile cycling powermeter when compared with the SRM device. Int J Sports Med 26(10):868–873

Borg G (1957) Simple rating methods for estimation of perceived exertion. In: Borg G (ed) Physical work and effort. Pergamon Press, New York, pp 39–46

Brooks GA, Fahey TD, White TP, Baldwin KM (2000) Cardiovascular dynamics during exercise. In: Exercise physiology: human bioenergetics and its applications. 3rd edn. Mountain View, Mayfield Press, pp 329–330

Chavarren J, Calbet JAL (1999) Cycling efficiency and pedaling frequency in road cyclists. Eur J Appl Physiol 80:555–563

Coast R, Welch HG (1985) Linear increase in optimal pedal rate with increased power output. Eur J Appl Physiol 53:339–342

Coyle EF, Sidossiss LS, Horowitz JF, Beltz JD (1992) Cycling efficiency is related to the percentage of Type I muscles fibers. Med Sci Sports Exerc 24(7):782–788

Foss O, Hallen J (2004) The most economical cadence increases with increasing workload. Eur J Appl Physiol 92:443–451

Hagberg JM, Mullin JP, Giese MD, Spitznagel E (1981) Effect of pedaling rate on submaximal exercise responses of competitive cyclists. J Appl Physiol 51(2):447–451

Harnish CR, Swensen TC, Pate RR (2001) Methods for estimating the maximal lactate steady state in trained cyclists. Med Sci Sports Exerc 33(6):1052–1055

Kenny GP, Reardon FD, Marion A, Thoden JS (1995) A comparative analysis of physiological responses at submaximal workloads during different laboratory simulations of field cycling. Eur J Appl Physiol Occup Physiol 71(5):409–415

Kohler G, Boutellier U (2005) The generalized force-velocity relationship explains why the preferred pedaling rate of cyclists exceeds the most efficient one. Eur J Appl Physiol 94(1–2):188–195

Kuipers H, Verstappen FTJ, Keizer HA, Guerten P (1985) Variability of aerobic performance in the laboratory and its physiologic correlates. Int J Sports Med 6:197–201

Lepers R, Hausswirth C, Maffiuletti N, Brisswalter J, van Hoecke J (2000) Evidence of neuromuscular fatigue after prolonged cycling exercise. Med Sci Sports Exerc 32(11):1880–1886

Lepers R, Millet GY, Maffiuletti NA, Hausswirth C, Brisswalter J (2001) Effect of pedalling rates on physiological response during endurance cycling. Eur J Appl Physiol 85(3–4):392–395

Lucia A, Hoyos J, Chicharro JL (2001) Preferred pedaling cadence in professional cycling. Med Sci Sports Exerc 33(8):1361–1366

Lucia A, San Juan AF, Montilla M, CaNete S, Santalla A, Earnest C, Perez M (2004) In professional road cyclists, low pedaling cadences are less efficient. Med Sci Sports Exerc 36(6):1048–1054

MacIntosh BR, Neptune RR, Horton JF (2000) Cadence, power, and muscle activation in cycle geometry. Med Sci Sports Exerc 32(7):1281–1287

Marsh AP, Martin PE (1993) The association between cycling experience and preferred and most economical cadences. Med Sci Sports Exerc 25(11):1269–1274

Marsh AP, Martin PE (1997) Effect of cycling experience, aerobic power, and power output on preferred and most economical cadences. Med Sci Sports Exerc 29(9):1225–1232

Marsh AP, Martin PE (1998) Perceived exertion and the preferred cycling cadence. Med Sci Sports Exerc 30(6):942–948

Marsh AP, Martin PE (2000) Effect of cadence, cycling experience, and aerobic power on delta efficiency during cycling. Med Sci Sports Exerc 32(9):1630–1634

Miller TA, Wells CL, Martin PE (1988) The effect of position and cadence on the cardiovascular response of up-hill cyclists. Med Sci Sports Exerc 20(2):S64

Millet GP, Tronche C, Fuster N, Candau R (2002) Level ground and uphill cycling efficiency in seated and standing positions. Med Sci Sports Exerc 34(10):1645–1652

Mognoni P, di Prampero PE (2003) Gear, inertial work and road slopes as determinants of biomechanics in cycling. Eur J Appl Physiol 90(3–4):372–376

Nielsen JS, Hansen EA, Sjogaard G (2004) Pedalling rate affects endurance performance during high-intensity cycling. Eur J Appl Physiol 92(1–2):114–120

Ryschon TW, Stray-Gundersen J (1991) The effect of body position on the energy cost of cycling. Med Sci Sports Exerc 23(8):949–953

Samozino P, Nicolas H, Frederique H (2006) Interactions between cadence and power output effects on mechanical efficiency during sub maximal cycling exercises. Eur J Appl Physiol 1:1–7

Signorile J, Holdern S, Coast JR (1990) The feasibility of the windload simulator as an alternative to on-road training. J Appl Sport Sci Res 4(1):5–8

Swain DP, Wilocox JP (1992) Effect of cadence on the economy of uphill cycling. Med Sci Sports Exerc 24(10):1123–1127

Swensen TC, Harnish CR, Beitman L, Keller BA (1999) Noninvasive estimation of the maximal lactate steady state in trained cyclists. Med Sci Sports Exerc 31(5):742–746

Takaishi T, Yamamoto T, Ono T, Ito T, Moritani T (1998) Neuromuscular, metabolic and kinetic adaptations for skilled pedaling performance in cyclists. Med Sci Sports Exerc 30(3):442–449

Tanaka H, Bassett DR Jr, Best SK, Baker KR (1996) Seated versus standing cycling in competitive road cyclists: uphill climbing and maximal oxygen uptake. Can J Appl Physiol 21(2):149–154

Vercruyssen F, Hausswirth C, Smith D, Brisswalter J (2001) Effect of exercise duration on optimal pedaling rate choice in triathletes. Can J Appl Physiol 26(1):44–54

Watson G, Swensen T (2006) Effects of altering pedal cadence on cycling time-trial performance. Int J Sports Med 27(4):296–300