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Abstract

The purpose of this study was to examine the relationship between strength capacity and preferred and optimal cadence in well trained cyclists. Eighteen cyclists participated in this study. Each subject completed three sessions. The initial session was to evaluate the maximal isokinetic voluntary contraction level of lower limb. The second session was an incremental test to exhaustion. During the third session subjects performed a constant cycling exercise (20min) conducted at five randomly cadences (50, 70, 90, 110 rpm) and at the preferred cadence (FCC) at the power reached at ventilatory threshold. Cardiorespiratory and EMG values were recorded. A metabolic optimum (EOC) was observed at 63.5 ± 7.8 rpm different from preferred cadence (FCC, 90.6 ± 9.1 rpm). No difference was found between FCC and the neuromuscular optimal cadence (NOC, 93.5 ± 4). Significant relationships were found between EOC, NOC and strength capacities (r = – 0.75 and – 0. 63), whereas FCC was only related with V˙ O2max (r = 0.59). The main finding of this study was that during submaximal cycling energetically optimal cadence or neuromuscular optimum in trained cyclists was significantly related with strength capacity and whereas preferred cadence seems to be related with endurance training status of cyclists. Key words : cyclists ; freely chosen cadence ; strength capacity ; energetical optimum ; neuromuscular optimum

Introduction

During road cycling, performance is limited by numerous physiological or biomechanical factors. Among it has been suggested that performance during submaximal cycling is related to the capacity of the subject to sustain maximal locomotion speed with low metabolic energy expenditure during the whole race [1,17]. Within this framework, the more economical athlete should theoretically be able to move faster, or conserve energy for the later stage of an event better, than a less economical athlete. This capacity is assessed by the measurement of the energy cost of locomotion that also reflects the biomechanical demand associated with changes in movement pattern [1,6, 32]. Therefore, in order to minimize the energy cost of locomotion, the choice of a particular cadence in cycling or running is classically evoked by coaches and researchers [24]. For running or walking, the relation between movement frequencies and energy cost has been widely studied, often suggesting that the performer spontaneously adopts the pattern of locomotion leading to the lowest energy cost [3]. This does not appear to be the case for cycling. On the one hand the energetically optimal cadence ranges from 40 rpm to 80 rpm in trained or untrained cyclists [2,4,12,19] but, observations of cyclists often reveal a

significant difference between their preferred and most economical cadences [10]. The following functional assumptions have been made to explain this apparent conflict: changes in pedaling forces [26], neuromuscular activation [29], aerobic power or cycling experience [20]. Although these parameters could influence the relationship between energy cost and cadence, the lack of consistence of literature results highlights the difficulty in identifying precisely explain factors of the difference [1,19, 21]. In fact, optimization principles governing locomotion for cycling are probably as numerous as for other forms of locomotion, and it has been classically described in motor control studies that the adoption of a specific locomotor pattern could be seen as a function of (a) the task constraints and (b) the constraints of the performer [15]. Within this framework, Marsh and Martin [19] hypothesized that preferred cadence could be related to muscular properties of the lower extremity muscles. At each cadence a corresponding mean torque value is associated and therefore a specific force is applied on the pedals. This mean torque or force corresponds to a percentage of the maximum strength capacity that differs between subjects. Indeed, during cycling at the same cadence, the corresponding mean torque will correspond to a lower percentage of maximal force capacity for the stronger cyclists. To the best of our knowledge, no previous study has examined the relation between the choice of a particular cadence and the strength capacity of the cyclists. Therefore, the purpose of this study is to examine the relationship between strength capacity and preferred, most economical and optimal neuromuscular cadences.

Methods

Subjects

Eighteen trained and motivated male cyclists (age: 31.6 ± 5.2 years; mass: 71.4 ± 7.0 kg; height: 1.77 ± 0.06m) who currently took part in competition at national level served as subjects in this study. Each laboratory session was undertaken during the "pre-competition" (i.e. winter: January) period of the sport season. Before participating in this study, subjects were fully informed about the protocol, and informed consent was obtained prior to all testing. This study was approved by a local research ethics committee. Each subject completed three laboratory based testing sessions separated by at least 48 h rest period.

Experimental procedures

Maximal isokinetic voluntary contraction
The initial session was to evaluate the maximal isokinetic voluntary contraction level (MVCi) of lower extremity limb from a squat movement conducted on a specific ergometer (Ariel Dynamics Inc., type Ariel Computerized Exercise System [ACES] "multifunction exercise", Trabuco Canyon, CA, USA) validated by Grooten et al. [11]. Before each session, the ergometer was calibrated according to manufacturer specifications. The range of motion was standardized so that the movement started from zero position with a trunk/thigh angle of 908 and finished with an extended lower limb (knee angle = 1808). All subjects were familiarized with this ergometer and have made a warm-up of two set of ten repetitions at a velocity of 65 cm• s–1 before the squat evaluation. Each subject performed three sets of two repetitions of maximal isokinetic squat at two different velocities (16 and 8 cm• s–1). A short rest time was imposed between each repetition (30 sec) and each set (5 min). The subjects were instructed to push the bar "as fast as possible", and they were encouraged to perform at their maximal capacity. The maximal peak force values (Fmax) were obtained either for isokinetic velocities of 16 or 8 cm• s–1. Since body mass (BM) values are different between subjects and thus could affect force capacities, Fmax

was also expressed according to body mass values (Fmax/BM). For all subjects, the right leg was their dominant leg.

Incremental cycling exercise

Subjects were then asked to perform an incremental cycling session on an electromagnetically braked ergocycle (Lode, type Excalibur, Gröningen, The Nederland) at the self-selected cadence. The handlebars and racing seat are fully adjustable both vertically and horizontally to reproduce conditions known to subjects from their own bicycles. Moreover, this ergometer was equipped with individual racing pedals and toes clips allowing subject to wear their own cycling shoes. The ergometer allowed subjects to maintain the power output constant independent of the selected cadence, by automatically adjusting torque to angular velocity. The test began with a warm-up of 100W lasting 6 min, after which the power output was increased by 30W each minute until the subjects were exhausted. The criteria used for the determination of maximal oxygen uptake ($\dot{V}O_2max$) were a plateau inVO2max despite an increase in work rate and a respiratory exchange ratio (RER) above 1.1 or a heart rate (i.e. HR) over 90% of the predicted maximal HR [13]. The four highest consecutive VO2 values were summed in the last stage to determine $\dot{V}O_2max$. In addition, the ventilatory threshold (VT) was determined by using the criteria of an increase VE/VO2 with non-concomitant increase of VE/VCO2 [31] (VE, expiratory flow). Visual evaluation to determine VT was carried out independently by three experienced investigators.

Constant cycling exercise

Before starting the third session, subjects were placed in a seated position and were securely strapped into the test chair to perform an isometric knee extension and flexion using an isometric ergometer (Type: Schnell Trainingsgesäte GmbH, Peutenhausen, Deutschland). The studied limb was the right leg. Subjects sat with a 908 knee angle (08 as full leg extension), with the ankle attached to the ergometer arm. The knee axis was aligned with the dynamometer axis. Surface electromyographic signal (EMG) was recorded on vastus lateralis (VL) during the knee extensors maximal voluntary contraction (MVC, N), and on biceps femoris (BF) during the knee flexors MVC. Subjects performed two maximal isometric contraction of short duration (2–3 s) of the knee flexor and extensor muscles. A 60 s period of rest was imposed between each contraction. The maximal force values in knee extension and flexion movement were measured using a strength sensor and the best performance consecutive to the two trials was selected as the MVC. Maximal integrated EMG values were calculated for VL and BF muscles during MVC (period of 500ms), and were used to normalize the neuromuscular activity recorded during cycling according to Hunter et al. [14].

Subsequently, subjects performed a constant cycling exercise (20min) conducted at five randomly assigned cadences (4 min at 50, 70, 90, 110 rpm and the preferred cadence [FCC]) for a power output corresponding to the work rate reached at VT (222.6 ± 25.9W). A bicycle computer with a cadence monitor provided feedback to subjects so that the cadence could be maintained within ± 1 rpm of the target cadence during the duration of test. For the FCC trial, the cadence monitor was covered and the subject was asked to cycle at a cadence considered as the most comfortable during an extended period of time (> 1 h). The cadence was continuously monitored during the overall cycling exercise. Moreover, pulmonary gas exchanges were measured using a portable telemetric gas exchange system (Cosmed K4RQ ®, Rome, Italia) and the EMG activity was recorded on the right VL and BF muscles during the overall cycling bout. The Cosmed K4RQ ® was calibrated prior to each experimental session according to external temperature and humidity. Cardiorespiratory and EMG data were recorded during the fourth minute at each imposed cadence (50, 70, 90 and 110 rpm) and at FCC. It was assumed that a steady state was achieved when four consecutive 30 s $\dot{V}O_2$ readings were within ± 1

ml•min–1 •kg–1 of each other. All subjects were able to reach this criterion after 2–3min of cycling.

Measurement of EMG signal
The muscles activities of VL and BF muscles of the right leg, selected for their high contribution to the propulsive cycling task [28], were monitored with surface EMG. The subjects were prepared for placement of EMG electrodes by shaving the skin of each electrode site, cleaning it carefully with alcohol swab and lightly abrading it to maintain a low inter-electrode resistance of < 1000 W. Pairs of Ag/AgCl pre-gelled surface electrodes (Medicotest, type Blue Sensor, Q-00-S, Copenhagen, Denmark) of 40mm diameter with a center to center distance of 25mm were applied along the fibers over the bellies of the two muscles for EMG data acquisition. The electrodes were secured with chirurgical tape and cloth wrap to minimize disruption during the movement. A ground electrode was placed on a bony site over the right anterior superior spine of the iliac crest.
EMG signals were pre-amplified closed to detection site (Common Mode Rejection Ratio, CMRR = 100 dB; Z input = 10 G¢W; gain = 600, bandwidth frequency = from 6 Hz to 1600Hz). Prior to acquisition, a third order, zero lag Butterworth antialiasing filter at 500Hz was applied. EMG data were collected from each muscle during 40 consecutive crank cycles during the last minutes of each cadence. Data were digitized through an acquisition board (DT 9800-series, Data Translation, Marlboro, VT, USA) and stored on a computer to be analyzed using custom-written addon software (Origin 6.1®, OriginLab, Northampton, MA, USA). The EMG data were sampled at 1000 Hz, normalized (normalized EMG) to muscle maximal EMG obtained during MVC test for each individual muscle and analyzed on all 40 consecutive crank cycles.

Statistical analyses
All data were expressed as mean ± standard deviation (SD). Based on previous studies, the relationships between VO2 and pedaling cadence [2,4,19–21] but also between the sum of normalized VL and BF integrated electromyogram signal (iEMG) and pedaling cadence [22,23] for each subject were fitted using a polynomial regression with a quadratic model. The minimum point of the U-shape represented the theoretical energetically optimal cadence (EOC) and the theoretical neuromuscular optimal cadence (NOC). Relationship between dependant variables and differences between cycling cadence optima were analyzed using both Parametric and non Parametric correlation tests. The 0.05 level of significance was used for all statistical procedures.

Results

Table 1 shows the mean values in MVCi, VO2max, the maximal aerobic power (Pmax) and the power output at VT concerning the experimental group.
A quadratic relationship was observed between VO2 and cadence with the identification of the EOC at 63.5 ± 7.8 rpm significantly different from FCC (90.6 ± 9.1 rpm). No significant difference was found between FCC and NOC (93.5 ± 4.0 rpm) (Fig. 1). Relationships between dependant variables are presented Table 2. Significant negative relationships were found between EOC and strength capacities (respectively for Fmax, Fmax/BM and the maximal velocity (Vmax), r = – 0.75; – 0.67 and – 0.73). Furthermore, a significant relationship was found between NOC, EOC and Fmax (respectively r = 0.69 and – 0.63), whereas FCC was only significantly related with VO2max and BM (respectively r = 0.59 and 0.56).
A previously evocated, a significant relationship was found between resultant force applied on the pedal and Fmax but only for 50 rpm (respectively for 50, 70, 90, 110 rpm, r = 0.46[S], 0.28[NS], 0.11[NS], 0.08[NS]).

Table 1 Characteristics of subjects

Subjects (N = 18)	VO2max (ml •min–1 •kg–1)	Pmax (W)	VT (W)	Vmax (m• s–1)	Fmax (N)	Fmax/BM (N•kg–1)	BM (kg)
Mean	65.3	402.8	222.6	0.264	1717.1	19.0	73.0
SD	7.1	32.2	25.9	0.027	284.6	3.1	6.7

VO2max: maximal oxygen uptake; Pmax: maximal aerobic power; VT: ventilatory threshold; Vmax: maximal velocity; Fmax: maximal peak force; BM: body mass

Table 2 Relationship between strength capacity, physiological optima and preferred cadence

	EOC (rpm)	VO2max (ml •min–1 •kg–1)	Pmax (W)	VT (W)	Vmax (m• s–1)	NOC (rpm)	Fmax (N)	Fmax/BM (N•kg–1)	FCC (rpm)
EOC									
VO2max	0.02								
Pmax	− 0.44	0.40							
VT	− 0.47	0.55*	0.51*						
Vmax	− 0.73*	0.19	0.46	0.22					
NOC	0.69*	0.10	− 0.35	− 0.28	− 0.46				
Fmax	− 0.75*	− 0.05	0.50*	0.16	0.83*	− 0.63*			
Fmax/BM	− 0.67*	0.31	0.35	0.26	0.88*	− 0.46	0.84*		
FCC	− 0.16	0.54*	0.15	− 0.23	0.28	− 0.15	0.37	0.03	
BM	- 0.25	− 0.59*	0.29	− 0.15	0.05	− 0.40	0.44	− 0.11	0.56*

EOC: energetically optimal cadence; V̇O2max: maximal oxygen uptake; Pmax: maximal aerobic power; VT: ventilatory threshold; Vmax: maximal velocity; NOC: neuromuscular optimal cadence; Fmax: maximal peak force; BM: body mass; FCC: preferred cadence. * when a statistical relationship was found between dependant variables, $p < 0.05$

Discussion

Based on the hypothesis of Marsh and Martin [19], the objective of the current study was to examine the relationship between strength capacity and cadences corresponding to physiological optima or FCC. The main finding of this study was that energetically optimal cadence (EOC) at submaximal power in trained cyclists was significantly related with strength capacity and NOC whereas FCC was only correlated with Pmax.

According to previous literature, our cyclists have naturally selected a cadence (range: 77–114 rpm) significantly higher than the EOC (range: 51–73 rpm) but not significantly different from NOC (range: 84–99 rpm) (l" Fig. 1). Furthermore, no significant relationship was found between

either EOC or NOC and FCC. These results support, on the one hand, the fact that minimization of aerobic demand is not a critical determinant of self-selected cadence during a cycling exercise of ~ 200W in trained subjects [2,19,21, 29, 30]. In fact, during cycling a systematic difference is observed between EOC (50–60 rpm) and the self-selected cadence (80–90 rpm) reported either in trained cyclists and runners [19] or highly trained triathletes [30]. However, it seems that training and practicing level of the subjects affect the EOC. Indeed, the EOC (~ 80 rpm) of experimented [7, 8] and professional road cyclists [18] was higher than the EOC found on Marsh and Martin's subjects [19]. On the other hand, complementary studies have tried to analyze the FCC using criteria other than the minimization of energy expenditure, such as an optimization of the force applied to the cranks, a minimization of the lower extremity net joint moments [21, 23] or iEMG of the muscles [29]. In our study neuromuscular optimal values (93.5 ± 4.0 rpm) could be compared with previous results of the literature. For example, Takaishi et al. [29] noted a quadratic relationship with a reduced EMG activity (VL) at 80 and 90 rpm. However in our study no significant relationship was observed between NOC and FCC (r = – 0.15, NS). This result could be linked for one part to the difficulty raised in the literature to obtain consistent results on NOC determination. In this context, Neptune et al. [22] showed that gluteus maximus and soleus muscles had significant quadratic trends with minimum values at 90 rpm whereas hamstring and vastus medialis muscles systematically increased muscle activity as pedaling cadence increased. Furthermore, Marsh andMartin [15] indicated a reduced EMG activity (VL, rectus femoris, soleus and gastrocnemius) at cadences ranging from 50 to 65 rpm for a power output of 200W. These contradictory results obtained on various muscles and across different cadences make difficult the explanation of the FCC exclusively from the iEMG-based measures in trained cyclists. In this study the only significant relationship was found between FCC and $\dot{V}$ O2max values (r = 0.54). This result could be compared with previous results by Marsh and Martin [21] indicating that trained cyclists and runners of equal aerobic fitness level spontaneously adopt a similar cadence during cycling exercises conducted at a power output of 200W. These authors concluded that the reduction of aerobic demand and cycling experience are not key determinants of self-selected cadence in trained subjects but could be linked to endurance training status. Force velocity (F-V) properties of the lower extremity were often suggested to explain the choice of a particular cadence [16,19] muscles. Also, Marsh andMartin [19] hypothesized that the similar preferred cadences of trained cyclists and runners compared to less trained subjects are due to similarities in the F-V properties of the lower extremity muscles developed during endurance training (i.e. high repetitions or relatively fast joint angular velocities). Therefore, changes in the mechanical properties of muscle induced by the training characteristics may coincide with changes in FCC. Our results do not directly validate the hypothesis by Marsh and Martin [19] since no significant relationship was found between strength capacities and FCC. It must be noted that, in this investigation, the use of an isokinetic dynamometer did allow to assess only indirectly the F-V properties in vivo from a set of squat movements since the direct comparison with the F-V curves obtained in vitro has not been clearly established [25]. Therefore further studies conducted at different power outputs are necessary in attempt to validate the hypothesis regarding the influence of muscular properties on the self-selected cadence.

On the opposite, one interesting result of this study is the significant negative relationship between EOC and strength capacities (Fig. 2). During moderate exercise, several factors could explain the change in energy cost with increasing cadence. On the one hand, the rise in the ventilation cost and/or the increase in internal work for repetitive limb movements have been classically hypothesized to explain the increase in energy cost [5,9]. Francescato et al. [9] indicated that the fraction of overall VO2 due to internal work for a subject cycling at 100W and 60 rpm was about 0.2 whereas this fraction was around 0.6 at 100 rpm. In addition, Coast et al. [5] indicated that the cost of ventilation estimated from the increase in the work of breathing (i.e. variations in VE) could explain at least 30% of theVO2 rise. Therefore for moderate cadence we

could expect a rise in energy cost of locomotion with the increase in cadence. On the other hand, one of the factors often used to explain changes in energy cost of locomotion and pedal cadence manipulation is modification in muscle fiber recruitment [2,27]. Within this framework, Woledge [33] has suggested that the shift from type I to type II fibers (which have a lower muscle efficiency than type I fibers) could be linked to a decrease in thermodynamic muscle efficiency leading to an increase in energy cost. Thus, in our study one hypothesis could relate the relationship between strength capacities and EOC with muscle fibers recruitment. It is well established that a reduction in forces application on the cranks, minimum values of the average individual muscle activation, occur at a cadence of 90 rpm during a submaximal steady-state cycling [23]. Therefore in stronger cyclists force applied on the pedals at low cadence corresponds to a lower percentage of the maximum strength capacity allowing them to recruit more type I fiber more economically; on the opposite, weaker cyclists need to increase pedal rate to decrease the force applied on the pedals. Thus in stronger cyclists at submaximal intensities we can hypothesize that an increase in energy cost with pedal cadence is mainly related to the increase in internal work or ventilation whereas in weaker cyclists the relationship between cadence and energy cost results from both optimal force applied on the pedals and internal or ventilation work. This result gives indirect evidence to the fact that the relationship between cadence and energy cost is specific to the task constraints and the constraints of the performer. Further studies using different cycling intensities are necessary to validate this hypothesis

Fig. 1   Physiological optima and preferred cadence in the experimental population.
EOC: energetically optimal cadence; NOC: neuromuscular optimal cadence; FCC: preferred cadence; VO2: oxygen uptake; iEMG: integrated EMG.
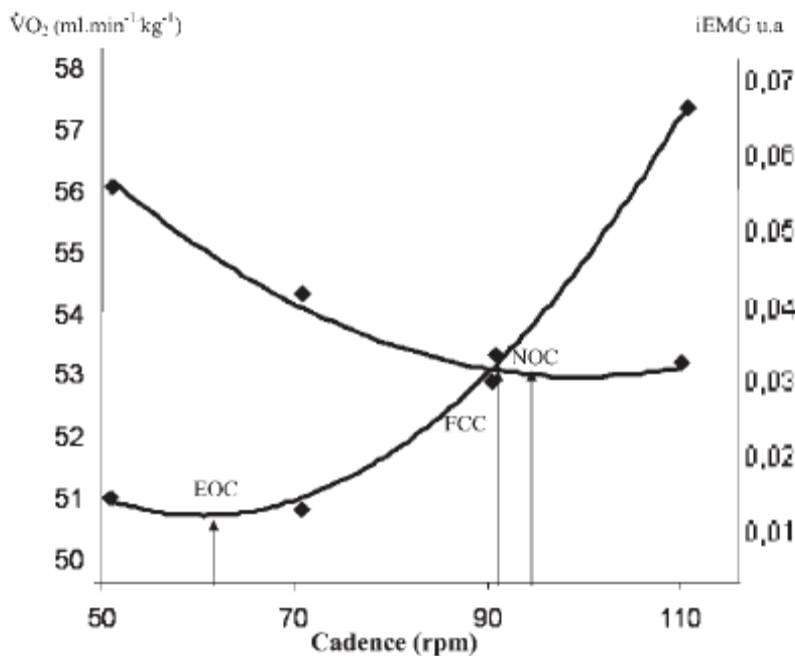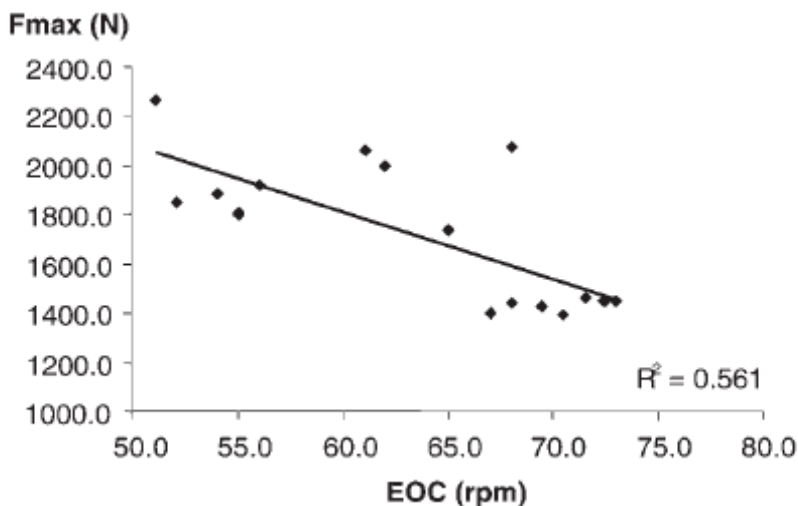
Fig. 2 Relationship between energetically optimal cadence and Fmax
Fmax: maximal peak force; EOC: energetically optimal cadence.

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