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# The relationship between preferred and optimal cadences during 2-h cycling in triathletes

**Abbreviated title: Preferred and optimal cycling cadences**

SEBASTIEN ARGENTIN[1], CHRISTOPHE HAUSSWIRTH[1], THIERRY BERNARD[2], FRANCOIS BIEUZEN[2] , JEAN-MICHEL LEVEQUE[1], ANTOINE COUTURIER[1], ROMUALD LEPERS[3]

[1]Laboratoire de Biomécanique et de Physiologie, Institut National du Sport et de l'Education Physique, 75012 Paris (France)

[2]EA 3162, Université de Toulon-Var, BP 132, 83957 LA GARDE (France)

[3]INSERM/ERIT-M 0207 Motricité-Plasticité UFR STAPS, Université de Bourgogne BP 27877, 21078 Dijon. Cedex (France)

Corresponding author:

Dr. Christophe HAUSSWIRTH, Ph.D.,
Laboratoire de Biomécanique et de Physiologie,
Institut National du Sport et de l'Education Physique (INSEP),
11 Avenue du Tremblay 75012 Paris, FRANCE

Fax : +33 1 41 74 45 35
Email: christophe.hausswirth@wanadoo.fr

# The relationship between preferred and optimal cadences during 2-h cycling in triathletes

**Abbreviated title**: Preferred and optimal cycling cadences

**Key words**: oxygen uptake, cadence, muscular torque, EMG

## What is already known on this topic ?

**1-** Various authors have reported contradictory results concerning the evolution of the energetically optimal cadence (EOC) during prolonged cycling exercises. Thus, some authors [7] demonstrated a significant increase in EOC over 30-min of laboratory cycling but others [9] have shown a quasi-stability in EOC over 60-min of cycling on a track.

**2-** The cadence at which minimal neuromuscular fatigue occurs is not associated with the cadence at which the minimal oxygen uptake is recorded, but is coincident with freely chosen cadence [15, 20].

## What this study adds ?

**1-** Our results show a stability of EOC (67 to 65 rev.min$^{-1}$) over the 2-h period and demonstrated a significant shift in the freely chosen cadence (FCC) (87 to 68 rev.min$^{-1}$, $P<0.01$) towards the EOC (65 rev.min$^{-1}$) at the end of a 2-h cycling exercise conducted in laboratory.

**2-** We confirmed a stability of EMG activity for the vastus lateralis muscle over a 2-h cycle task at 65 % MAP. This indicated that the firing rate of motor units of VL muscle was not affected by this exercise in well-trained triathletes.

**Abstract**

**Objectives:** This study aimed to determine whether the integrated electromyographic (iEMG) signal of two lower limb muscles might indicate preferred cadence during a 2-hour cycling task.

**Methods:** Eight male triathletes underwent right maximal isometric (MVC) knee extension and plantar flexion before (P1) and after (P2) a 2-h laboratory cycle (CT) at 65 % of maximal aerobic power (MAP). Freely chosen cadence (FCC) was also determined, also at 65 % of MAP, via five randomised 3-minute sessions at 50, 65, 80, 95, and110 $rev.min^{-1}$. The iEMG of the vastus lateralis (VL) and gastrocnemius lateralis (GL) muscles was recorded during MVC and CT.

**Results:** The FCC decreased ($P<0.01$) from P1 (87.4 $rev.min^{-1}$) to P2 (68.6 $rev.min^{-1}$), towards the energetically optimal cadence (EOC). This EOC did not vary significantly over CT. The MVC of VL and GL decreased ($P<0.01$) between P1 and P2 (by 13.5% and 9.6%, respectively). Our results indicated that muscle activation at constant power was not minimised at specific cadences. Only Gastrocnemius Lateralis muscle was affected by a 2-h cycling task (especially at 95 and 110 $rev.min^{-1}$) whilst VL muscle was stable.

**Conclusion:** The decrease in FCC observed at the end of CT may be due to changes in muscle fibre recruitment pattern with increasing exercise duration and cadence.

Some investigations have used energy cost of locomotion as a reflection of the mechanical requirements of modifications in movement pattern.[1] [2] Although oxygen uptake ($\dot{V}O_2$) has been shown to be lowest at cadences that approach the self-selected values in running [3], this has not been shown to be the case in either cycling [4] or within the cycling leg of a cycle-to-run event.[5] An obvious discrepancy exists between most economical cycling cadence (defined as that eliciting the minimum oxygen uptake at a given power output) and the higher cadence that is commonly used in the field by both competitive cyclists [4] [6] and by triathletes.[7][8][9]

Those studies that have manipulated cadence during cycling at constant power outputs have obtained similar results. The most energetically economical cadence has been shown to fall within the range of 40-70 rev.min$^{-1}$ [10] [11] but to increase with increasing power output. The freely chosen cadence (FCC) of experienced cyclists [12] and well-trained triathletes [13] approximates 85-95 rev.min$^{-1}$. In this context, Brisswalter et al [7] showed at the end of 30 minutes exercise at 80% of Pmax, triathletes choose a cadence close to the energetically optimal cadence.

Whilst some research groups have investigated EOC [4] [6] , other authors have focused on biomechanically optimum cadence (BOC) i.e. that at which neuromuscular recruitment [as determined by electromyographic signal measurements] is lowest during submaximal exercise.[14][15] The BOC normally occurs at approximately 90 rev.min$^{-1}$. It is determined by surface electromyography (sEMG)- the relationship of which with muscle fatigue has been extensively researched.[16] [17]. Thus, the evolution of integrated EMG (iEMG) has been widely accepted as a means of assessing muscle fatigue.[18] Previous studies have suggested optimal pedaling cadence to be closely

related to peripheral muscle fatigue.[19] Moreover, the cadence at which minimal neuromuscular fatigue occurs is not associated with the cadence at which the minimal oxygen uptake is recorded, but is coincident with freely chosen cadence.[15] [20] However, no data are available concerning the influence of the exercise duration (>1h30) on cycling efficiency at different cadences (including the freely-chosen cadence), and its association with neuromuscular fatigue.

The aims of the present study, therefore, were to:

1. Examine the changes in energy cost of cycling exercise at different cycling cadences during a cycle task of 2h duration,
2. Determine whether the iEMG of two specific lower limb muscles may be used as an indicator of a triathlete's preferred cadence during a 2h cycling task. It was hypothesised that, during cycling at a constant power output, the minimal EMG activity for each muscle would be observed at a unique pedaling cadence.

## Methods

### *Subjects*

Eight male triathletes gave their written informed consent to participate in this study. The study was approved by the local Ethical Committee of the Saint-Germain (France). Description of the subjects are presented in Table 1. The data indicated that the subjects for this study could be classified as 'well-trained' triathletes.[21][22]

### *Determination of* $\dot{V}O_{2max}$ *evaluation*

After a 48-hour restriction upon strenuous physical activity, each of the 8 subjects performed a continuous, incremental cycling test on an electromagnetically braked ergocycle (Type Excalibur, Lode, Groningen, The Nederlands). The test began with a warm-up at 150 watts for 10 minutes, after which the power output was increased by 25 watts every 2 minutes until volitional exhaustion. During this incremental exercise, oxygen uptake ($\dot{V}O_2$), minute ventilation ($\dot{V}E$), and respiratory exchange ratio (RER) were continuously measured every 15 seconds using a telemetric gas analysis system (Cosmed $K4_{RQ}$®, Rome, Italy). The criteria used for the determination of $\dot{V}O_{2max}$ were cited by previous authors.[23].

*Exercise and constant power output*

Said level of 65% of MAP was chosen on the basis of previous work in this laboratory showing it to correspond to the highest power output that may be maintained for approximately 2 hours. The test consisted of sustaining 65% of MAP for 2 hours (see Figure 1). Data were collected between the 5$^{th}$ and 24$^{th}$ minute (period 1: P1) and between the 101$^{st}$ and 120$^{th}$ minute of the cycling task (period 2: P2). Five sessions of 3 minutes at pedaling rates of 50, 65, 80, 95, 110 rev.min$^{-1}$; and one session of 4 minutes at a freely chosen cadence, were performed in random order during P1 and P2. Only respiratory data collected between the last minute and a half of each period were included in each analysis. After P1 and before P2, the triathletes pedalled at their FCC. No feedback respecting the value of FCC was given to the subjects. Pedaling cadence was continuously recorded and heart rate was monitored using the Cosmed $K4_{RQ}$.

EMG activity was recorded during the second to the third minute of each 3-minute cadence test segment (50, 65, 80, 95, 110) and during the last minute of cycling at the

FCC, during P1 and P2. All integrated EMG ($_{i}$EMG) values were considered as the measurement of muscle activity. For both muscles (VL, GL), normalized $_{i}$EMG values were expressed as a percentage of the $_{i}EMG_{max}$ value obtained during MVC. The MVC was recorded between the end of the warm-up of ten minutes at 33% of MAP and before the start of the 2-h cycling task.

*Muscle tests*

Right isometric knee extensions were performed on a Biodex isokinetic dynamometer (Biodex Shirley Corporation, NY, USA). The subjects were tested in a sitting position that met hip and knee angle specifications of 100° and 80° , respectively.

Right isometric plantar flexions were performed using a seat-calf isometric ergometer (Schnell, Petenhaussen, Germany). The subjects were placed in a sitting position with their superior limbs secured across their chest such as to prevent upper body movement. Hip, knee and ankle angle were all 90°. The position that was adopted was such as to elicit the maximal force in accordance with the normal sitting posture adopted by cyclists.[24]

Recording of muscle electrical activity (EMG) and surface potential action on the vastus lateralis (VL) and gastrocnemius lateralis (GL) muscles was achieved by means of two pairs of silver-chloride surface electrodes affixed to the right leg. Electrodes were coated with electrode gel and fixed lengthwise over the motor points with an inter-electrode distance of 16 mm. The reference electrode was affixed to the right wrist. Myoelectric signals were amplified with a bandwidth frequency ranging from 1.5 to 500 Hz (Common Mode Rejection Ratio, CMRR=90dB; Z input = 100 MΩ; gain = 1000).

Torque and EMG signals were digitised on-line (sampling frequency 1000 Hz) using a digital computer (IPC 486).

Maximal voluntary contraction (MVC) values during isometric tests were determined from the highest values of the two trials. During isometric contractions, EMG signals were quantified using the Root Mean Square (RMS). For both muscles (VL, GL), normalized RMS amplitude data were expressed as a percentage of the RMS value obtained during the maximal isometric contraction conducted prior to the 2-h cycling exercise. During isometric actions, the RMS was calculated over a period of 1 second after the torque had reached a plateau.

*Statistical Analysis*

All data were expressed as mean ± standard deviation (SD). A two-way ANOVA for repeated measures was used to analyse the effect of period time and the cycling cadence by using $\dot{V}O_2$, $\dot{V}_E$, RER, HR, $_i$EMG as dependant variables. Newman-Keuls *post-hoc* test was used to determine differences among all pedaling cadences and periods during the 2-h exercise. The accepted level of significance was set at $P<0.05$ for all tests using Statistica 5.1 for Windows.

**Results**

*Physiological parameters*

*Maximal tests*. The average data obtained during the maximal incremental cycle test are presented in Table 1

*Submaximal tests.* ANOVA revealed a significant effect of exercise duration ($P<0.01$) upon ventilatory and heart rate parameters. A significant increase in $\dot{V}O_2$ ($P<0.05$) was

found to occur between P1 and P2 for all of the tested cadences apart from 110 rev.min$^{-1}$. A significant increase was also found between P1 and P2 in $\dot{V}_E$ and HR ($P$<0.01) at each pedaling cadence (see Table 2). A significant effect of exercise duration was observed on $\Delta\dot{V}O_2$ during the 2-h cycling ($\dot{V}O_{2(P2)}$ - $\dot{V}O_{2(P1)}$, P<0.05) at each cadence. No significant difference in $\Delta\dot{V}O_2$ was exhibited at 110 rev.min$^{-1}$ ($P$>0.05). Minute ventilation and heart rate values were significantly different between P1 and P2 at each cadence ($P$<0.01; in Table 2).The results of the ANOVA revealed no significant effect of cadence at each time point on physiological parameters.

*The energetically optimal cadence determination.* A quadratic trend (*cf.* Figure 2) for the description of the $\dot{V}O_2$ – pedaling cadence relationship was found in all subjects, and the mean value regression coefficient was r = 0.89 (in P1, $P$<0.01) and r = 0.82 (in P2, $P$<0.01). The mathematical determination [25] of the mean energetically optimal cadence (EOC) – the lower point of the curve – was identified at 67.1 ± 4.8 (rev.min$^{-1}$) for EOC calculated during P1 (i.e. EOC1), and at 65.8 ± 4.2 (rev.min$^{-1}$) for EOC calculated during P2 *(i.e.* EOC2). No difference was observed between EOC1 and EOC2 ($P$>0.05). A significant difference was recorded between EOC1 and FCC1 (67.1 ± 4.8 *vs.* 87.4 ± 6.7 rev.min$^{-1}$, $P$<0.01), but not between EOC2 and FCC2 (65.8 ± 4.2 *vs.* 68.6 ± 7.1 rev.min$^{-1}$).

*Muscular strength, isometric contraction and EMG activity.* Before P1 (*i.e.* after the warm-up), isoMVC$_{VL}$ (obtained in knee extension) and isoMVC$_{GL}$ (obtained in plantar flexion) values were 303 ± 37 N.m and 198 ± 21 N.m, respectively (see in Table 3). After P2 (i.e. after the 2-h cycling task), values were significantly different from P1

values (262 ± 48 N.m (-13.5%; P<0.01) for $isoMVC_{VL}$, and 179 ± 24 N.m (-9.6%; *P*<0.05) for $isoMVC_{GL}$). As indicated in Table 3, no significant difference was found in $isoEMG_{VL}$ between the values recorded before P1 and after P2; the loss of 8.3% was not statistically significant. The decrease of 14.1% of $isoEMG_{GL}$ before period 1 value and after period 2 value was significant (P<0.01).

*Dynamic contractions and electromyographic activity.* Figure 3 demonstrates the lack of significant effect of both exercise duration and cadence on the percentage of the integrated EMG for the vastus lateralis muscle calculated from data obtained during the 2-h cycling exercise (P>0.05). Figure 4 demonstrates that the percentage of the $_{i}$EMG for the gastrocnemius lateralis muscle calculated from data obtained during the 2-h cycling exercise differed between 95 $rev.min^{-1}$ (+9.2%; P<0.05) and 110 $rev.min^{-1}$ (+9.3%; P<0.05).

**Discussion**

Our results demonstrated that a 2-h cycling task performed under laboratory conditions in well-trained triathletes induced changes in physiological, biomechanical (pedaling cadence, static strengths) and muscular (dynamic and isometric contractions, EMG activity) parameters. We observed a significant increase in $\dot{V}O_2$ values for FCC from the start to the end of 2-h cycling. In addition, a stability of energetically optimal cadence (EOC) was observed throughout the exercise task. The study hypothesis that minimal EMG activity for each muscle would be observed at a unique pedaling cadence while the power output remained constant was not confirmed.

*Effects of exercise duration on physiological parameters at different cycling cadences.*

As regards FCC, the 2-h cycling task elicited an increase in oxygen uptake - which is an indicator of metabolic efficiency and cycling economy when power output is constant - from 66% of $\dot{V}O_{2max}$ (at FCC1) to 74% (at FCC2) of $\dot{V}O_{2max}$ (+9%, $P<0.05$) Oxygen uptake, minute ventilation and heart rate values were significantly higher during P2 than during P1 ($P<0.01$; Table 2). Many studies on triathletes have investigated the effect of cycling exercise duration on FCC.[7][8][9] Brisswalter et al. [7] showed an oxygen uptake discrepancy between FCC and EOC from 3 to 6 minutes of cycling at 80% of MAP that had been previously observed in short duration exercise. [4] [15] We confirmed this result at a power output of 65% of MAP, with a FCC1 recorded at 87 rev.min$^{-1}$ and EOC1 calculated at 67 rev.min$^{-1}$ ($P<0.01$). This large discrepancy between FCC1 and EOC1 compares favourably with other results obtained in triathletes [7] [9] and may be explained by the weakest power delivered in the non-fatigued state in our study. Brisswalter et al. [7] demonstrated a significant ($p<0.01$) increase in EOC (from 70 to 86 rev.min$^{-1}$) over 30-min of laboratory cycling but Vercruyssen et al. [9] have shown a quasi-stability in EOC (from 65-80 to 78 rev.min$^{-1}$) over 60-min of cycling on a track. Our results confirm with those of Vercruyssen et al. [9], showing a stability of EOC (67 to 65 rev.min$^{-1}$) over the 2-h period. Moreover we demonstrated a significant shift in FCC (87 to 68 rev.min$^{-1}$, $P<0.01$) towards the EOC (65 rev.min$^{-1}$) at the end of a 2-h cycling exercise conducted in laboratory. This may be partly explained by the training volume and cycling expertise of the study subjects. Indeed, Lucia et al. [26] demonstrated that elite cyclists training 500 km.wk$^{-1}$ were able to maintain a mean pedaling cadence above 90 rev.min$^{-1}$ for several hours each day. In

contrast, we showed a shift of FCC towards EOC for triathletes riding 180 km.wk$^{-1}$. This may be governed by factors related to the cross-training effects of the running and swimming disciplines of the triathlon. Type of training has been demonstrated to affect the force-velocity properties of the lower limb musculature.[27] Caiozzo et al. [27] demonstrated that in non-trained subjects training of the knee extensor muscles at 4 rad.s$^{-1}$ induced an improvement in the shift of the force-velocity curve across all test velocities (from 0 to 5 rad.s$^{-1}$). This increase was better at higher velocities (from 2 to 4 rad.s$^{-1}$). In contrast to an their performance of an isolated cycle task, the triathlete may conserve some energy during the cycle section of a triathlon in anticipation of the succeeding run.[22] In well-trained triathletes the energetically optimal cadence might coincide with freely chosen cadence during exercise lasting from 30-min to 2-h. Cadence choice may also influence metabolic cost via fibre-type recruitment pattern, and consequently, the extent of neuromuscular fatigue exhibited by the working muscles.

*Effects of exercise duration on muscular strength and fatigue.*

Classically, power is the product of force and velocity. Thus, if pedaling cadence is altered, pedal force must be inversely altered to maintain a specific mechanical power output. The requirement for increased shortening velocity may elicit greater recruitment of fast-twitch fibers [28], but the decreased force production may allow for greater reliance on slow-twitch fibers.[29] To explain changes in oxygen uptake with exercise duration in association with pedaling cadence manipulation, Woledge [30] evoked the change in recruitment from Type I to Type II fibers during prolonged exercise. This might lead to a decrease in thermodynamic muscle efficiency and, consequently, an increase in metabolic cost. In relation to our study results, one hypothesis could relate

the increase in $\Delta \dot{V} O_2$ at each cadence (from 50 to 110 rev.min$^{-1}$) from P1 to P2 to an additional recruitment of Type II muscle fibers. The latter have a lower muscle efficiency than Type I fibers.[30] However, the hypothesis that minimal EMG activity for each muscle could be observed at a unique pedaling cadence for constant power output was not verified by our study. Indeed, both the VL and GL muscles activations were not related to pedaling cadence manipulation. In accordance with the results obtained by Marsh and Martin [31], no quadratic relation was found for the EMG of GL muscle with changes in cadence. Moreover, no relationship was found between cadence and $_{i}$EMG of the VL. Moreover, the duration of the cycling task duration did not affect iEMG in the subjects. This indicated that the firing rate of motor units of VL muscle was not affected by this exercise in well-trained triathletes. Therefore, it could be speculated that it action should be directly replaced by the activation of the Rectus Femoris muscle – synergic with the Vastus Lateralis muscle – as fatigue occured. Concerning the MVC values we obtained before and after the 2-h cycling exercise, results (-13.5%) were not far from the literature for isometric leg extension [8] obtained after 2-h cycling done at the FCC in well-trained cyclists and triathletes (-13 %), and after 85-min cycling done at a fixed cadence in non-expert cyclists (-34%; [32]). This occurrence of muscular fatigue, characterised by a decrease in MVC, was not supported by a significant difference of %RMS during the MVC (-8.3%, NS). The shift of the MVC towards low torques after 2-h cycling suggested that the muscular fatigue is not linked to an acute fatigue of the VL muscle. Indeed, it remained stable in terms of activation. This result contradicts those results obtained in triathetes during the run section of a triathlon (i.e. 2h15 duration) and a prolonged run (*i.e.* 2h15 duration; [33]). From these results, the changes of recruitment

pattern of the VL muscle should be dependent of the type of exercise done, meaning depending on the modality of muscle contraction induced by the exercise itself. The magnitude of strength loss appears to be dependent on the kind of muscular solicitations during the prolonged exercise with greater reductions being recorded after running, physical exercise known to induce severe muscular damage.[34] As for the VL, MVC recorded in plantar flexion induced a significant decrease in MVC between before and after the 2-h cycling (-9.6%). However, this reduction induced a significant decrease of %RMS-EMG (-14.1%); this result supported the hypothesis of a significant muscular fatigue obtained after long duration cycling exercise, and could partially explain the loss of 9.6% of MVC during plantar flexion. This means that triathletes of our study had obviously a more pronounced local fatigue in GL compared with VL muscle.

In conclusion, we showed a significant decrease of the freely chosen cadence after 2-h cycling, towards the energetically optimal cadence. This EOC reflected no significant variation from the start to the end of the long duration cycling exercise. No quadratic or linear relationship was found between metabolic cost of cycling and EMG activity of two muscles. We have presented evidence that muscle activation at a constant power output is not minimised at a unique cadence and that only the gastrocnemius lateralis muscle is affected (and particularly so at cadences of 95 and 110 rev.min$^{-1}$) by a 2-h cycling task

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**Table 1.** Physical and physiological characteristics of the subjects : $\dot{V}O_{2\ max}$, maximal oxygen uptake; MAP, maximal aerobic power; $HR_{max}$, maximal heart rate.

| Age (years) | Height (cm) | Mass (kg) | $\dot{V}O_{2\ max}$ ($mL.kg^{-1}.min^{-1}$) | MAP (Watts) | 65% of MAP (Watts) | $HR_{max}$ ($beats.min^{-1}$) |
|---|---|---|---|---|---|---|
| 26.1± 4 | 182.5 ± 4.8 | 73.9 ± 4.8 | 66.3 ± 9.2 | 378 ± 34 | 246 ± 22 | 192.9 ± 6.0 |

**Table 2.** Changes in oxygen uptake ($\dot{V}O_2$), minute ventilation ($\dot{V}E$), heart rate (HR) for the 5 imposed pedaling cadences (50, 65, 80, 90, 110 rev.min$^{-1}$) and the freely chosen cadence (FCC: P1=87.4 rev.min$^{-1}$ and P2=68.6 rev.min$^{-1}$). Values are means ± SD (standard deviation).

*Period 1* (P1): start; *Period 2* (P2): end the 2-h cycling.

| **Cadences (rev.min$^{-1}$)** | | **50** | **65** | **80** | **95** | **110** | **FCC** |
|---|---|---|---|---|---|---|---|
| $\dot{V}O_2$ | P1 | 45.7 ± 6.1 | 44.9 ± 5.2 | 45.0 ± 5.8 | 47.0 ± 7.7 | 48.5 ± 5.8 | 45.7 ± 6.2 |
| *(mL.min$^{-1}$.kg$^{-1}$)* | P2 | 48.8 ± 5.7 * | 48.1 ± 5.3 * | 48.8 ± 6.4 * | 49.3 ± 6.1 * | 51.0 ± 6.8 | 48.9 ± 5.5 * |
| $\dot{V}E$ | P1 | 75.4 ± 9.1 | 75.2 ± 6.4 | 77.0 ± 7.2 | 78.7 ± 10 | 86.6 ± 5.6 | 77.9 ± 8.7 |
| (L.*min$^{-1}$)* | P2 | 87.4 ± 8.4 ** | 87.9 ± 8.1 * | 89.2 ± 8.1 ** | 93.3 ± 7.2 ** | 101.1 ± 1.2 ** | 89.0 ± 7.3 ** |
| HR | P1 | 150.7 ± 12.6 | 149.2 ± 14.3 | 146.6 ± 12.1 | 151.4 ± 8.7 | 158.4 ± 10.7 | 151.1 ± 10.4 |
| *(beats.min$^{-1}$)* | P2 | 166.3 ± 12.4 ** | 168.7 ± 12.7 ** | 168.1 ± 10.8 ** | 169.4 ± 12.5 ** | 172.6 ± 10.7 ** | 168.6 ± 13.8 ** |

Significantly different from the "P1" values, * (P<0.05), ** (P<0.01)

**Table 3.** Changes in isometric maximal voluntary contraction (isoMVC) for the the vastus lateralis ($isoMVC_{VL}$) and the gastrocnemius lateralis ($isoMVC_{GL}$) muscles before and after the 2-h cycling exercise. Isometric electromyographic data (isoEMG) are expressed in percentage of the Root Mean Square value (%RMS) for the both muscles VL and GL.

| | $isoMVC_{VL}$ (N.m) | $IsoMVC_{GL}$ (N.m) | $IsoEMG_{VL}$ (%RMS) | $isoEMG_{GL}$ (%RMS) |
|---|---|---|---|---|
| Before | 303 ± 37 | 198 ± 21 | 100 | 100 |
| After | 262 ± 48** | 179 ± 24* | 91.7 ± 7.1 | 85.9 ± 7.9** |
| Difference(%) | 13.5 | 9.6 | 8.3 | 14.1 |

Significantly different from the "Before" values, * ($P<0.05$), ** ($P<0.01$)

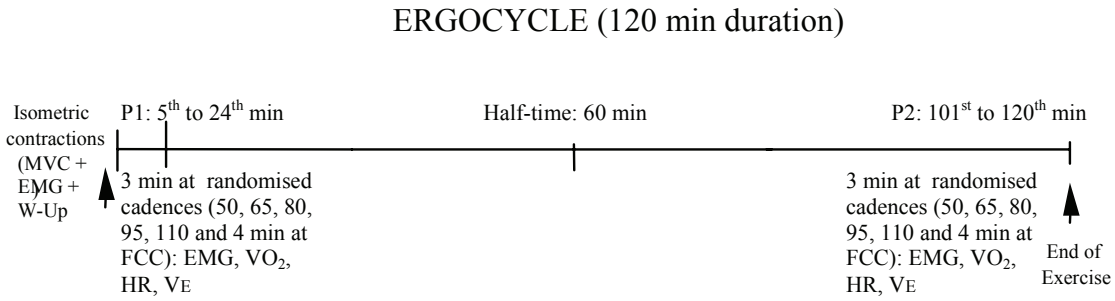



**Fig. 1.** Protocol of experiment applied during the period 1 and the period 2 of 2-h cycling. FCC: freely-chosen cadence; EMG, surface electromyography signal; $VO_2$, oxygen uptake, HR, heart rate; VE, pulmonary ventilation.

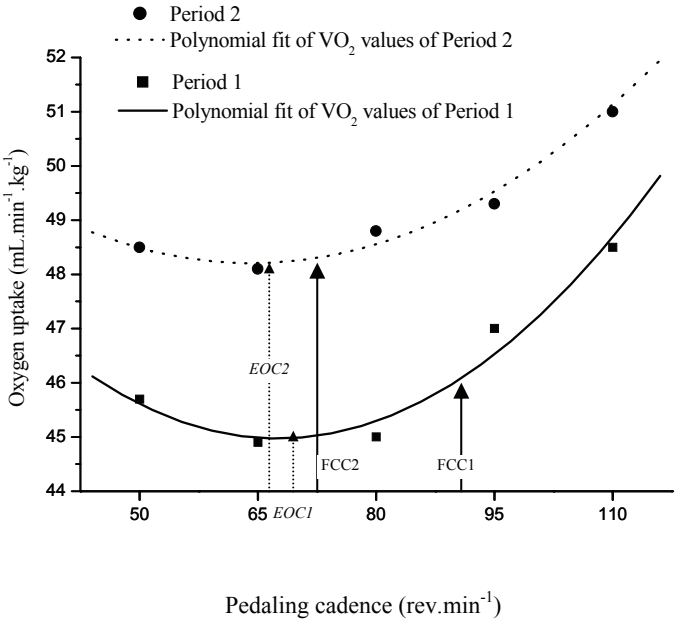



**Fig. 2.** Polynomial regressions calculated from oxygen uptake values recorded during the period 1 and the period 2 of 2-h cycling. All values are plotted from each cadence excepted the freely-chosen cadence.

Period 1: start of the 2-h cycling

Period 2: end of the 2-h cycling

FCC1: Freely-chosen cadence obtained during period 1

FCC2: Freely-chosen cadence obtained during period 2

EOC1: Energetically optimal cadence obtained during period 1

EOC2: Energetically optimal cadence obtained during period 2

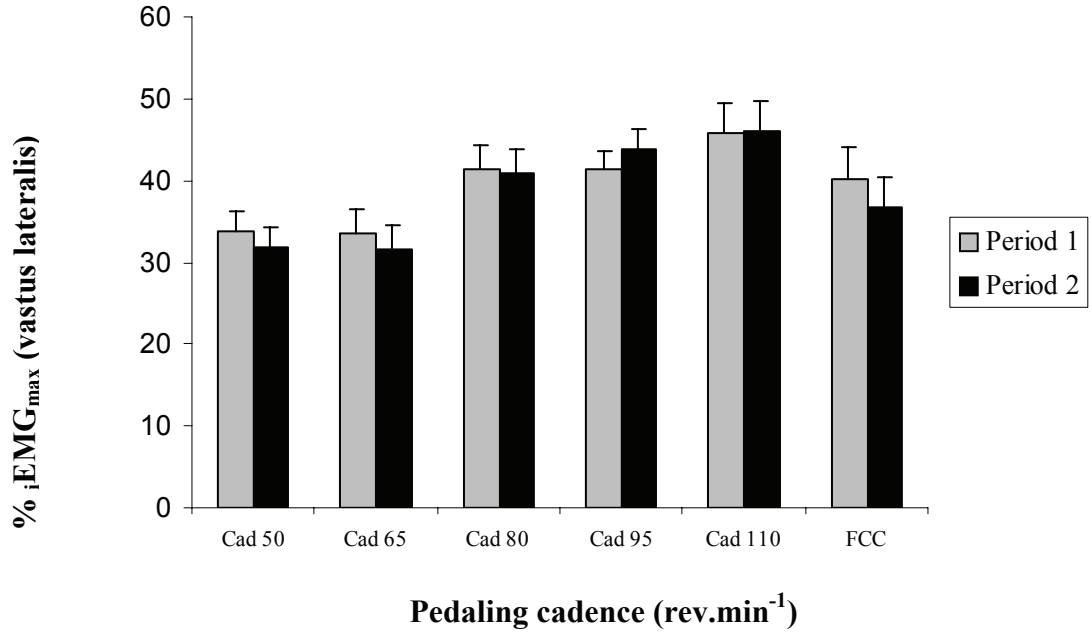



**Fig. 3.** Percentage of integrated EMG ($_{i}$EMG) values (normalised from the $EMG_{max}$) recorded during the period 1 (start) and the period 2 (end) of 2-h cycling for the activation of vastus lateralis muscle. All EMG data were averaged at each cadence (from 50 to 110) including the freely-chosen cadence (FCC).

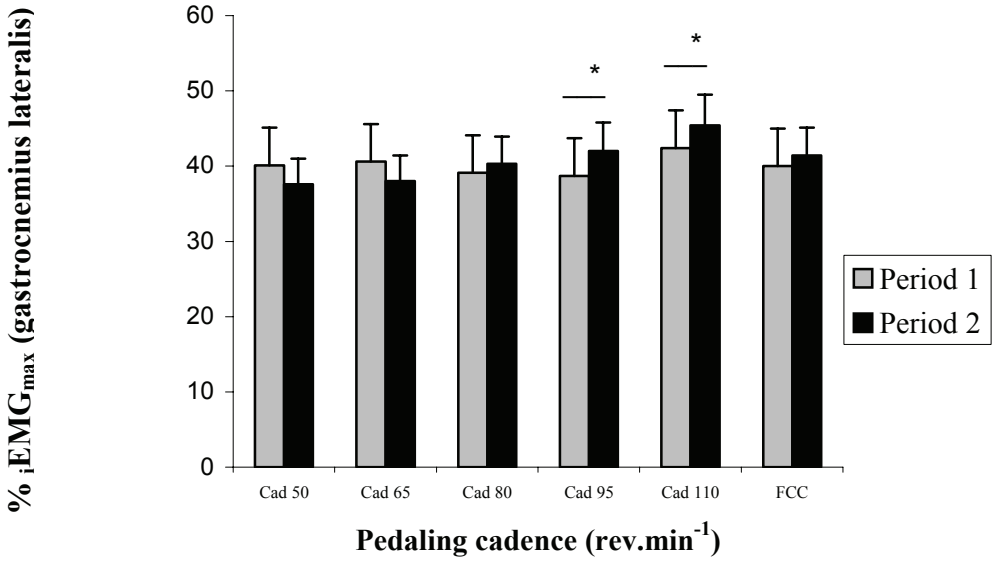



**Fig. 4.** Percentage of integrated EMG ($_{i}$EMG) values (normalised from the $EMG_{max}$) recorded during the period 1 (start) and the period 2 (end) of 2-h cycling for the activation of gastrocnemius lateralis muscle. All EMG data were meaned at each cadence (from 50 to 110) including the freely-chosen cadence (FCC).

* Significantly different from the group of period 1, $P<0.05$