ORIGINAL ARTICLE

Relation between preferred and optimal cadences during two hours of cycling in triathletes

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Objectives: To determine whether the integrated electromyographic signal of two lower limb muscles indicates preferred cadence during a two hour cycling task.

Methods: Eight male triathletes performed right isometric maximum voluntary contraction (MVC) knee extension and plantar flexion before (P1) and after (P2) a two hour laboratory cycle at 65% of maximal aerobic power. Freely chosen cadence (FCC) was also determined, also at 65% of maximal aerobic power, from five randomised three minute sessions at 50, 65, 80, 95, and 110 rpm. The integrated electromyographic signal of the vastus lateralis and gastrocnemius lateralis muscles was recorded during MVC and the cycle task.

Results: The FCC decreased significantly ($p<0.01$) from P1 (87.4 rpm) to P2 (68.6 rpm), towards the energetically optimal cadence. The latter did not vary significantly during the cycle task. MVC of the vastus lateralis and gastrocnemius lateralis decreased significantly ($p<0.01$) between P1 and P2 (by 13.5% and 9.6% respectively). The results indicate that muscle activation at constant power was not minimised at specific cadences. Only the gastrocnemius lateralis muscle was affected by a two hour cycling task (especially at 95 and 110 rpm), whereas vastus lateralis remained stable.

Conclusion: The decrease in FCC observed at the end of the cycle task may be due to changes in the 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 self selected values in running,[3] this has not been shown in either cycling[4] or the cycling leg of a cycle to run event.[5] An obvious difference exists between the most economical cycling cadence (defined as that eliciting the minimum $\dot{V}O_2$ at a given power output) and the higher cadence commonly used in the field by both competitive cyclists[4,6] and triathletes.[7–9]

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 in the range 40–70 rpm[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 rpm. In this context, Brisswalter *et al*[7] showed that, at the end of 30 minutes of exercise at 80% of Pmax, triathletes choose a cadence close to the energetically optimum cadence (EOC).

Whereas some research groups have investigated EOC,[4,6] others have focused on biomechanically optimum cadence—that is, that at which neuromuscular recruitment (as determined by electromyographic (EMG) signal measurements) is lowest during submaximal exercise.[14,15] The biomechanically optimum cadence normally occurs at about 90 rpm. It is determined by surface EMG, the relation of which to muscle fatigue has been extensively researched.[16,17] This evolved to integrated EMG (iEMG) which has been widely accepted as a means of assessing muscle fatigue.[18] Previous studies have suggested that optimal pedalling cadence is closely related to peripheral muscle fatigue.[19] Moreover, the cadence at which minimal neuromuscular fatigue occurs is not associated with the cadence at which minimal $\dot{V}O_2$ is recorded, but is coincident with FCC.[15,20] However, no data are available on the influence of exercise duration (>1 hour 30 minutes) on cycling efficiency at different cadences (including FCC) and its association with neuromuscular fatigue.

The aims of this study therefore were to:

(1) examine the changes in energy cost of cycling at different cycling cadences during a cycle task of two hours duration

(2) determine whether the iEMG of two specific lower limb muscles can be used as an indicator of a triathlete's preferred cadence during a two hour 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 pedalling cadence.

METHODS

Subjects

Eight male triathletes gave their written informed consent to participate in this study. The study was approved by the local ethics committee of the Saint-Germain (France). The basic physical and physiological characteristics of the subjects were as follows (values are mean (SD)): age 26.1 (4) years; height 182.5 (4.8) m; mass 73.9 (4.8) kg; $\dot{V}O_{2}$MAX 66.3 (9.2) ml/kg/min; maximal aerobic power (MAP) 378 (34) W; 65% of MAP 246 (22) W; maximum heart rate 192.9 (6.0) beats/min. The data indicate that the subjects can be classified as well trained triathletes.[21,22]

Determination of $\dot{V}O_{2}$MAX

After a 48 hour restriction on strenuous physical activity, each of the eight subjects performed a continuous, incre-

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Abbreviations: EOC, energetically optimal cadence; EMG, electromyography; FCC, freely chosen cadence; iEMG, integrated electromyography; MAP, maximal aerobic power; MVC, maximal voluntary contraction; RMS, root mean square; $\dot{V}O_2$, oxygen uptake

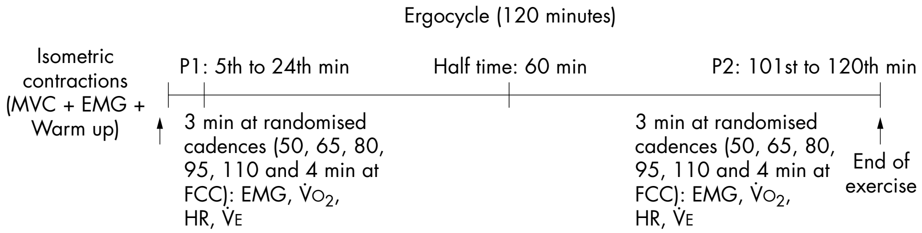

Figure 1 Protocol of experiment applied during period 1 and period 2 of a two hour cycling task. FCC, freely chosen cadence; EMG, surface electromyography signal; $\dot{V}O_2$, oxygen uptake; HR, heart rate; $\dot{V}E$, pulmonary ventilation.

mental cycling test on an electromagnetically braked ergocycle (Type Excalibur; Lode, Groningen, The Netherlands). The test began with a warm up at 150 W for 10 minutes, after which the power output was increased by 25 W every two minutes until volitional exhaustion. During this incremental exercise, $\dot{V}O_2$, minute ventilation ($\dot{V}E$), and respiratory exchange ratio were continuously measured every 15 seconds using a telemetric gas analysis system (Cosmed K4RQ, Rome, Italy). The criteria used for the determination of $\dot{V}O_{2MAX}$ were as in a previous publication.[23].

Exercise and constant power output

The level of 65% of MAP was chosen on the basis of previous work in this laboratory which showed it to correspond to the highest power output that can be maintained for about two hours. The test consisted of sustaining 65% of MAP for two hours (fig 1). Data were collected between the 5th and 24th minute (period 1: P1) and between the 101st and 120th minute (period 2: P2) of the cycling task. Five sessions of three minutes at pedalling rates of 50, 65, 80, 95, 110 rpm, and one session of four minutes at FCC, 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 about the value of FCC was given to the subjects. Pedalling cadence was continuously recorded and heart rate was monitored using the Cosmed K4RQ.

EMG activity was recorded during the second to the third minute of each three minute cadence test segment (50, 65, 80, 95, 110) and during the last minute of cycling at the FCC, during P1 and P2. The iEMG values were considered to be measurements of muscle activity. For two muscles (vastus lateralis and gastrocnemius lateralis), normalized iEMG values were expressed as a percentage of $iEMG_{max}$ obtained during maximal voluntary contraction (MVC). The MVC was recorded between the end of the warm up of 10 minutes at 33% of MAP and before the start of the two hour cycling task.

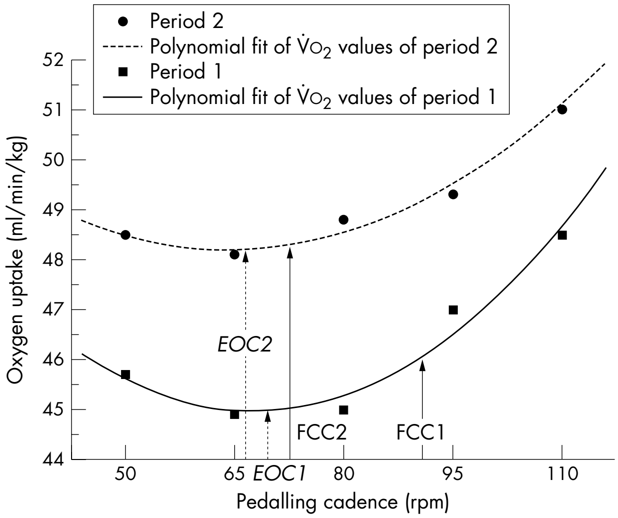

Figure 2 Polynomial regressions calculated from oxygen uptake values recorded during period 1 and period 2 of a two hour cycling task. All values are plotted from each cadence except the freely chosen cadence. Period 1, Start of the two hour cycling task; period 2, end of the two hour cycling task; FCC1, 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.

Muscle tests

Right isometric knee extensions were performed on a Biodex isokinetic dynamometer (Biodex Medical Systems, Shirley, NY, USA). The subjects were tested in a sitting position that

Table 1 Changes in oxygen uptake ($\dot{V}O_2$; ml/min/kg), minute ventilation ($\dot{V}E$; litres/min), and heart rate (HR; beats/min) for the five imposed pedalling cadences (50, 65, 80, 90, 110 rpm) and the freely chosen cadence (FCC: P1 = 87.4 rpm and P2 = 68.6 rpm)

	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)
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)
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)
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)**

Values are mean (SD).
Period 1 (P1), start of the two hour cycling task; period 2 (P2), end of the two hour cycling task.
*$p<0.05$, **$p<0.01$ compared with the P1 values.

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 so 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]

Muscle electrical activity (EMG) and surface potential action on the vastus lateralis and gastrocnemius lateralis muscles were recorded with two pairs of silver chloride surface electrodes fixed to the right leg. The electrodes were coated with electrode gel and fixed lengthwise over the motor points with an interelectrode distance of 16 mm. The reference electrode was fixed to the right wrist. Myoelectric signals were amplified with a bandwidth frequency ranging from 1.5 to 500 Hz (common mode rejection ratio, 90 dB; Z input, 100 MΩ; gain, 1000). Torque and EMG signals were digitised online (sampling frequency 1000 Hz) using a digital computer (IPC 486).

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 (vastus lateralis, gastrocnemius lateralis), normalised RMS amplitude data were expressed as a percentage of the RMS value obtained during the maximal isometric contraction conducted before the two hour cycling exercise. During isometric actions, the RMS was calculated over a period of one second after the torque had reached a plateau.

Statistical analysis

All data were expressed as mean (SD). A two way analysis of variance for repeated measures was used to analyse the effect of duration and cycling cadence by using $\dot{V}O_2$, $\dot{V}E$, respiratory exchange ratio, heart rate, and iEMG as dependent variables. The Newman-Keuls post hoc test was used to determine differences between all pedalling cadences and durations during the two hour exercise. The accepted level of significance was set at $p<0.05$ for all tests using Statistica 5.1 for Windows.

RESULTS

Physiological variables

Maximal tests

The average data obtained during the maximal incremental cycle test are presented above.

Submaximal tests

Analysis of variance revealed a significant effect of exercise duration ($p<0.01$) on ventilatory and heart rate variables. A significant ($p<0.05$) increase in $\dot{V}O_2$ was found between P1 and P2 for all of the cadences tested apart from 110 rpm. A significant ($p<0.01$) increase was also found between P1 and P2 in $\dot{V}E$ and heart rate at each pedalling cadence (table 1). A significant ($p<0.05$) effect of exercise duration was observed on $\Delta\dot{V}O_2$ ($\dot{V}O_{2(P2)} - \dot{V}O_{2(P1)}$) during the two hour cycling task at each cadence. No significant difference in $\dot{V}O_2$ was exhibited at 110 rpm ($p>0.05$). $\dot{V}E$ and heart rate were significantly different between P1 and P2 at each cadence ($p<0.01$; table 1).The results of the analysis of variance revealed no significant effect of cadence at each time point on physiological variables.

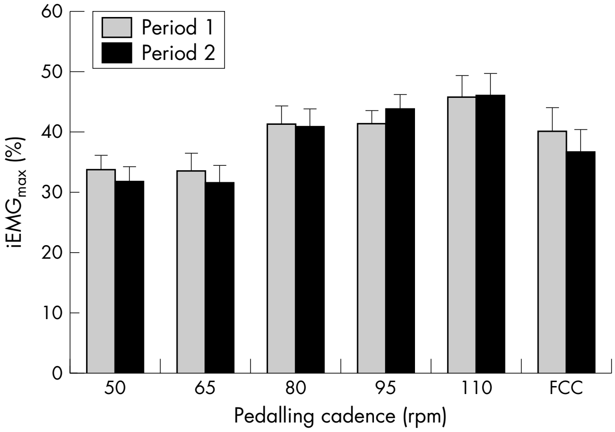

Figure 3 Percentage of integrated electromyographic (iEMG) values (normalised from maximal EMG) recorded during period 1 (start) and period 2 (end) of the two hour cycling task for the activation of the vastus lateralis muscle. All EMG data were averaged at each cadence (50, 56, 80, 95, 110) including the freely chosen cadence (FCC).

Determination of EOC

A quadratic trend (fig 2) for the description of the relation between $\dot{V}O_2$ and pedalling cadence 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 EOC (the lower point of the curve) was identified at 67.1 (4.8) rpm for EOC calculated during P1 (EOC1) and at 65.8 (4.2) rpm for EOC calculated during P2 (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) *v* 87.4 (6.7) rpm, $p<0.01$), but not between EOC2 and FCC2 (65.8 (4.2) *v* 68.6 (7.1) rpm).

Muscular strength, isometric contraction, and EMG activity

Before P1 (after the warm up), isometric MVC of the vastus lateralis (isoMVC$_{VL}$; obtained in knee extension) and the gastrocnemius lateralis (isoMVC$_{GL}$; obtained in plantar flexion) were 303 (37) N.m and 198 (21) N.m respectively (table 2). After P2 (after the two hour cycling task), the values were significantly different from P1 values (262 (48) N.m (−13.5%; $p<0.01$) for isoMVC$_{VL}$, and 179

Table 2 Changes in isometric maximal voluntary contraction for the vastus lateralis (isoMVC$_{VL}$) and the gastrocnemius lateralis (isoMVC$_{GL}$) muscles before and after the two hour cycling exercise. Isometric electromyographic data (isoEMG) are expressed in percentage of the root mean square value (%RMS) for both muscles

	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

*$p<0.05$, **$p<0.01$ compared with the before values.

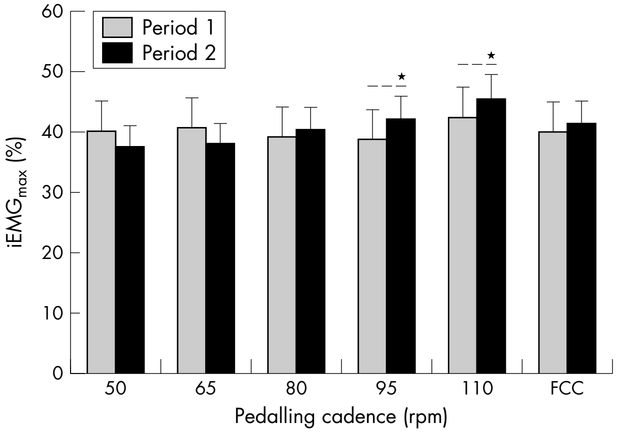

Figure 4 Percentage of integrated electromyographic (iEMG) values (normalised from maximal EMG) recorded during period 1 (start) and period 2 (end) of two hour cycling task for the activation of the gastrocnemius lateralis muscle. All EMG data were averaged at each cadence (50, 56, 80, 95, 110) including the freely chosen cadence (FCC). *Significantly different from the group of period 1, $p<0.05$.

(24) N.m (−9.6%; $p<0.05$) for $isoMVC_{GL}$). As indicated in table 2, no significant difference was found in $isoEMG_{VL}$ before P1 and after P2; the loss of 8.3% was not statistically significant. The decrease of 14.1% in $isoEMG_{GL}$ before period 1 and after period 2 was significant ($p<0.01$).

Dynamic contractions and EMG activity

Figure 3 shows the lack of significant effect of both exercise duration and cadence on the percentage of integrated EMG for the vastus lateralis muscle calculated from data obtained during the two hour cycling exercise ($p>0.05$). Figure 4 shows that the percentage of iEMG for the gastrocnemius lateralis muscle calculated from data obtained during the two hour cycling exercise differed between 95 rpm (+9.2%; $p<0.05$) and 110 rpm (+9.3%; $p<0.05$).

DISCUSSION

These results show that a two hour cycling task performed under laboratory conditions by well trained triathletes induced changes in physiological, biomechanical (pedalling cadence, static strengths), and muscular (dynamic and isometric contractions, EMG activity) variables. We observed a significant increase in $\dot{V}O_2$ for FCC from the start to the end of the two hour cycling task. EOC remained stable throughout the exercise task. The study hypothesis that minimal EMG activity for each muscle would be observed at a unique pedalling cadence while the power output remained constant was not confirmed.

Effects of exercise duration on physiological variables at different cycling cadences

The two hour cycling task elicited an increase in $\dot{V}O_2$, 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 (+9%, $p<0.05$). $\dot{V}O_2$, $\dot{V}E$, and heart rate were significantly higher during P2 than during P1 ($p<0.01$; table 1). Many studies on triathletes have investigated the effect of cycling duration on FCC.[7–9] Brisswalter *et al*[7] showed a $\dot{V}O_2$ discrepancy between FCC and EOC from three to six minutes of cycling at 80% of MAP, which 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 rpm and EOC1 calculated at 67 rpm ($p<0.01$). 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 being delivered in the non-fatigued state in this study. Brisswalter *et al*[7] showed a significant ($p<0.01$) increase in EOC (from 70 to 86 rpm) over 30 minutes of laboratory cycling, but Vercruyssen *et al*[9] showed quasi-stability of EOC (from 65–80 to 78 rpm) over 60 minutes of cycling on a track. Our results confirm those of Vercruyssen *et al*[9] showing stability of EOC (67 to 65 rpm) over the two hour period. Moreover we showed a significant shift in FCC (87 to 68 rpm, $p<0.01$) towards the EOC (65 rpm) at the end of the two hour cycling task in the laboratory. This may be partly explained by the training volume and cycling expertise of the study subjects. Indeed, Lucia *et al*[26] showed that elite cyclists training 500 km a week were able to maintain a mean pedalling cadence above 90 rpm for several hours a day. In contrast, we showed a shift of FCC towards EOC for triathletes riding 180 km a week. 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 shown to affect the force-velocity properties of the lower limb musculature.[27] Caiozzo *et al*[27] showed that, in untrained subjects, training of the knee extensor muscles at 4 rad/s induced an improvement in the shift of the force-velocity curve across all test velocities (from 0 to 5 rad/s). This increase was greater at higher velocities (from 2 to 4 rad/s). In contrast with 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.[23] In well trained triathletes, the EOC may coincide with the FCC during exercise lasting from 30 minutes to two hours. Cadence choice may also influence metabolic cost through fibre-type recruitment pattern and consequently the extent of neuromuscular fatigue exhibited by the working muscles.

What is already known on this topic

- Results on the evolution of the energetically optimal cadence (EOC) during prolonged cycling have been contradictory: a significant increase in EOC over 30 minutes of laboratory cycling was shown in one study and a quasi-stability in EOC over 60 minutes of cycling on a track in another
- 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

What this study adds

- These results show a stable EOC (67 to 65 rpm) over two hours of cycling in the laboratory and a significant shift in the freely chosen cadence (87 to 68 rpm, $p<0.01$) towards the EOC (65 rpm) at the end
- We confirmed a stability of electromyographic activity for the vastus lateralis muscle over a two hour cycle task at 65% maximal aerobic power, indicating that the firing rate of the motor units of this muscle is not affected by such exercise in well trained triathletes

Effects of exercise duration on muscular strength and fatigue

Classically, power is the product of force and velocity. Thus, if pedalling 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 fibres,[28] but the decreased force production may allow greater reliance on slow twitch fibres.[29] To explain changes in $\dot{V}O_2$ with exercise duration in association with manipulation of pedalling cadence, Woledge[30] evoked the change in recruitment from type I to type II fibres during prolonged exercise. This may lead to a decrease in thermodynamic muscle efficiency and consequently an increase in metabolic cost. In relation to the results of the present study, one hypothesis relates the increase in $\dot{V}O_2$ at each cadence (from 50 to 110 rpm) from P1 to P2 to the additional recruitment of type II muscle fibres. The latter have a lower muscle efficiency than type I fibres.[30] However, the hypothesis that minimal EMG activity for each muscle could be observed at a unique pedalling cadence for constant power output was not confirmed by the present study. Indeed, activation of neither the vastus lateralis nor gastrocnemius lateralis muscles was related to manipulation of pedalling cadence. In accordance with the results obtained by Marsh and Martin,[31] no quadratic relation was found for the EMG of gastrocnemius lateralis muscle with changes in cadence. Moreover, no relation was found between cadence and iEMG of the vastus lateralis. Furthermore, the duration of the cycling task did not affect iEMG in the subjects. This indicates that the firing rate of the motor units of vastus lateralis muscle was not affected by this exercise in well trained triathletes. Therefore it could be speculated that it should be directly replaced by activation of the rectus femoris muscle—synergic with the vastus lateralis muscle—as fatigue occurred. The decrease in MVC after the two hour cycling task (−13.5%) was similar to values in the literature for isometric leg extension[8] obtained after two hours cycling at FCC in well trained cyclists and triathletes (−13%), and after 85 minutes of cycling at a fixed cadence in non-expert cyclists (−34%).[35] This occurrence of muscle fatigue, characterised by a decrease in MVC, was not supported by a significant difference in %RMS during the MVC (−8.3%, NS). The shift of MVC towards low torques after two hours of cycling suggests that the muscular fatigue is not linked to acute fatigue of the vastus lateralis muscle. Indeed, it remained stable in terms of activation. This result contradicts those obtained in triathletes during the running section of a triathlon (2 hours 15 minutes duration) and a prolonged run (2 hours 15 minutes duration).[36] From these results, the changes in recruitment pattern of the vastus lateralis muscle appear to depend on the type of exercise performed, which depends on the modality of muscle contraction induced by the exercise itself. The magnitude of strength loss appears to depend on the type of muscular demand during the prolonged exercise, with greater reductions being recorded after running, a type of physical exercise known to induce severe muscle damage.[37] As for the vastus lateralis, MVC recorded in plantar flexion induced a significant decrease in MVC after the two hour cycling task (−9.6%). However, this reduction induced a significant decrease in %RMS EMG (−14.1%). This supports the hypothesis of significant muscle fatigue after long duration cycling exercise, and may partially explain the 9.6% loss of MVC during plantar flexion. This means that the triathletes in this study had more pronounced local fatigue in the gastrocnemius lateralis than in the vastus lateralis.

In conclusion, we showed a significant decrease in FCC towards the EOC after a two hour cycling task. This EOC showed no significant variation from the start to the end of the task. No quadratic or linear relation was found between metabolic cost of cycling and EMG activity of two muscles. We have presented evidence that muscle activation at constant power output is not minimised at a unique cadence and that only the gastrocnemius lateralis muscle is affected (particularly so at cadences of 95 and 110 rpm) by a two hour cycling task.

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COMMENTARY

This paper presents an interesting scientific analysis of the cycling event of the triathlon. Some research on this topic has been published, but the factors that determine the relation between freely chosen cadence and physiological optima—that is, from electromyographic and metabolic variables—have never been examined for a cycling task exceeding one and a half hours. This paper provides information on factors that may explain the decrease in freely chosen cadence with exercise duration, especially in trained triathletes. The methods have been well chosen to examine this research topic and conform with the scientific literature.

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