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Prior muscular exercises affects cycling pattern

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ABSTRACT



The aim of this study was to investigate the effect of concentric or eccentric fatiguing exercise on cycling pattern. Eleven well trained cyclists completed three sessions of cycling (control cycling test (CTRL), cycling following concentric (CC) or eccentric (ECC) knee contractions) at a mean power of 276.8 ± 26.6 Watts. Concentric and eccentric knee contractions were performed at a load corresponding to 80% of one repetition maximum with both legs. Before and after CTRL, CC or ECC knee contractions and after cycling, a maximal voluntary contraction (MVC) test was performed. Cardiorespiratory, mechanical and electromyographic activity (EMG) of the rectus femoris, vastus lateralis and biceps femoris muscles were recorded during cycling. A significant decrease in MVC values was observed after CC and ECC exercises and after the cycling. ECC exercise induced a significant decrease in EMG root mean square during MVC and a decrease in pedal rate during cycling. EMG values of the three muscles were significantly higher during cycling exercise following CC exercise when compared to CTRL. The main finding of this study was that a prior ECC exercise induces a greater neuromuscular fatigue than a CC exercise, and changes in cycling pattern.

INTRODUCTION



Muscle fatigue was defined as an exercise-induced reduction in maximal voluntary muscle force [9]. During the last decade, many investigators have observed the effect of muscle fatigue on locomotor tasks and more particularly during cycling [2, 7, 19, 24, 28]. Within this framework, it is well documented that muscle fatigue appearance is associated with changes in locomotor pattern. For example, Lepers et al. [19] have observed the effects of a prolonged exercise (2h cycling exercise) on neuromuscular properties of the quadriceps muscle and the freely-chosen cadence (FCC). Their results have shown a decrease of FCC during cycling associated with a loss of maximal muscular quadriceps torque during isokinetic test ranging from 12 to 13% immediately after the cycling exercise. To describe the effect of muscle fatigue on locomotor pattern modifications, many studies have

investigated the effect of a prior exercise on a subsequent locomotor task [12, 26]. In the literature, this effect was mainly observed using two different prior exercises: cycling or running. On the one hand, studies have reported that cycling before running leads to a significant modification of the running pattern, when compared with an isolated run [12]. Furthermore, the characteristics of the cycling exercise, such as a cadence changes or drafting is associated with a particular locomotor adaptation without any effect on metabolic efficiency [36]. On the other hand, when the previous exercise was a running bout, results showed an increase in electromyography activity (EMG) and a decrease in running efficiency during the subsequent run associated with a particular re-organization of the running pattern [13]. These investigators have related these effects to a modification of the locomotor pattern due to structural damage induced by the previous run and a modification of the pattern of motor unit recruitment. The main difference between these investigations was the locomotor mode involved during prior exercises. Indeed, cycling is characterized by longer phase of concentric (CC) muscular contraction, whereas running involves successive phases of eccentric (ECC)-concentric muscular actions [3]. Thus, it could be expected that different muscle contraction (ECC and CC) induced distinct changes in the locomotor pattern. To our knowledge, only one study has examined the effect of an ECC fatiguing exercise on a subsequent cycling exercise [26]. These investigators have observed the effect of an eccentric squatting exercise on the efficiency of muscle contraction. They have showed that ECC exercise does not reduce cycling efficiency (from $17.1 \pm 0.3 \%$ to $16.0 \pm 0.4 \%$, NS) although an intense delayed soreness and loss of muscle strength (-15%) was observed. In the scientific literature, the effects of type of contractions on muscle fatigue are well documented. Within these frameworks, it has been classically reported in experimental studies focusing on ECC contractions effects on muscle function, that ECC exercise induces delayed-onset muscle soreness, muscle fibre disruption, and functional impairment, as shown by the concomitant decrease in maximal voluntary contraction (MVC) [30]. However, results on the effect of ECC exercise compared to CC exercise on muscle function remains contradictory. For example, Komi and Viitasalo [16] and more recently Lavender and Nosaka [18] showed that eccentric maximal repeated contractions caused a greater reduction in muscle tension than the corresponding concentric exercise. These authors reported that the decrease in MVC was greater after repeated ECC contractions, suggesting greater muscle fatigue than after CC contractions. In contrast, previous researches [17, 34] have compared the magnitude of force decline between ECC and CC muscle actions. They reported a greater loss of force production

after isokinetic CC contractions due to greater metabolic and neural demands than after ECC contractions. This result suggests that one part of the muscle fatigue could be ascribed to neuromuscular fatigue. These differences could be, in part, explained by different methodological procedures, but the effect of muscle contraction on muscle function remains unclear. As consequence, it could be speculated that the effect of muscle fatigue on locomotor pattern could be different after CC or ECC contractions. The purpose of the present study was therefore to investigate the effect of concentric or eccentric fatiguing exercise on cycling pattern.

METHOD



Subjects

Eleven well trained male cyclists (age: 33.5 ± 7.2 yrs; height: 175.2 ± 5.6 cm; weight: 69.1 ± 7.1 kg) participated in this study. They had been competing at the national level for at least 5 years. The participants were all familiarized with laboratory testing. They were fully informed of the procedures of the experiment and gave written informed consent prior testing. The project was approved by a local ethic committee for the protection of individuals.

Overview

Each athlete completed four testing sessions in the morning separated by a rest period of at least 72h (Fig. 1). Before the test, subjects were asked to get up three hours before starting the test, to take a light breakfast 2 hours before exercise and a light dinner the day before. Moreover subjects were asked to abstain from intensive training 24h before each experimental session.

During the first visit, subject performed a leg dominance test following by an incremental test of maximal oxygen uptake ($\dot{V}O_{2max}$) determination. On their second visit the subjects underwent a 10 min control cycling test (CTRL) and were evaluated for their knee extension one repetition maximum (1RM). On their third and fourth visit, all subjects performed, in a random order, a prior bout of either an eccentric (ECC) or concentric (CC) knee contractions with both legs followed by 10 min of cycling.

Determination of leg dominance and $\dot{V}O_{2max}$

On their first visit to the laboratory the cyclists underwent two tests. The first test aimed to determine their leg dominance, in which the 11 participants were classified by kicking dominance according to the method describe by Daly and Cavanagh [6]. The second test was an incremental cycling test at a self-selected cadence on an electromagnetically braked ergocycle (Excalibur sport, Lode, Gröningen, The Nederland). The handlebars and racing seat are fully adjustable both vertically and horizontally to reproduce conditions known from the subjects' own bicycles. Moreover, this ergometer is equipped with individual racing pedals and toes clips allowing subject to wear their own cycling shoes. The ergometer allows subjects to maintain the power output constant independent of the selected cadence, by automatically adjusting torque to angular velocity. No feedback was given to the subjects concerning their pedal rate during the entire ride. The test began with a warm-up of 100 W lasting 6 min, after which the power output was increased by 30 W each minute until the subjects were exhausted. Minute ventilation (\dot{V}_E), oxygen uptake (\dot{V}_{O_2}) and, carbon dioxide production (\dot{V}_{CO_2}) were recorded using the Cosmed K4b² telemetric system (Rome, Italy) validated by MacLaughlin et al. [22]. The criteria used for the determination of $\dot{V}_{O_{2max}}$ were a plateau in \dot{V}_{O_2} despite an increase in workrate and a respiratory exchange ratio (RER) above 1.1 or a heart rate (HR) over 90% of the predicted maximal HR [15]. From breath by breath data, the four highest consecutive \dot{V}_{O_2} values were averaged in the last stage to determine $\dot{V}_{O_{2max}}$. In addition, the first ventilatory threshold (VT₁) was determined by using the criteria of an increase \dot{V}_E/\dot{V}_{O_2} with non-concomitant increase of \dot{V}_E/\dot{V}_{CO_2} [18] and the second ventilatory threshold (VT₂) was determined by using the criteria of a concomitant increase of \dot{V}_E/\dot{V}_{O_2} and \dot{V}_E/\dot{V}_{CO_2} [37].

Control exercise and 1RM knee evaluation

The 10 min control cycling test (CTRL) was performed on the electromagnetically braked ergocycle. For this test, a load designed to elicit a power output corresponding to:

$$P_{\text{exercise}} = (\text{Power output corresponding to VT}_1 \text{ (PVT}_1\text{)} + \text{Power output corresponding to the VT}_2 \text{ (PVT}_2\text{)}) / 2.$$

Immediately before (CTRL_{Pre}) and after (CTRL Post cycling) the control cycling test, subjects were placed in a seated position and were securely strapped into the test chair to perform a maximal voluntary isometric knee extension and flexion of their dominant leg using an isometric dynamometer (Type: Schnell Trainingsgeräte GmbH, Peutenhausen, Deutschland). Subjects sat with a 90° knee angle (0° as full leg extension), with the ankle attached to the ergometer arm. The knee axis was aligned with the ergometer axis. EMG

was recorded on vastus lateralis (VL) and rectus femoris (RF) muscles during the knee extensors MVC and on biceps femoris (BF) during the knee flexors MVC. Subjects performed two MVC 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 strain gauge (Type: TME F501TC, Toulon, France) and the best performance consecutive to the two trials was selected as the MVC. Root mean square (RMS_{MVC}) and maximal integrated EMG values were calculated for VL, RF and BF muscles during MVC (period of 500 ms).

One hour after the end of the previous test, subjects were evaluated for their 1RM during inertial knee extension exercise on a leg ergometer (Type: Schnell Trainingsgeräte GmbH, Peutenhausen, Deutschland) using method described by Bishop et al. [4]. Following ten submaximal warm-up contractions, each subject's 1RM was determined by gradually increasing the resistance until the subject could only achieve full knee extension once (1RM) and not twice. This was recorded as the subject's 1RM.

Eccentric and Concentric exercises

On their third and fourth visit to the laboratory the cyclists underwent 2 submaximal randomized sessions. All subjects performed a prior bout of ECC or CC knee contractions with both legs subsequently followed by 10 min of cycling on the electromagnetically braked ergocycle at intensity equal to that of the control test. Sessions were separated by at least 72h. In both knee contraction exercises, eight sets of eight muscle actions with 3 min rest between sets were performed at a load corresponding to 80% of 1RM [10]. Ranges of motion for CC knee extensions and ECC knee flexions were from 110° to 0° and from 0° to 110°, respectively. Immediately before (CC_{Pre} and ECC_{Pre}) and after (CC_{Post} and ECC_{Post}) the CC or ECC knee contractions and after cycling following CC and ECC exercises, subjects performed two MVC of short duration (2 – 3 s) of the knee flexor and extensor muscles. Exactly like during the CTRL session, EMG was recorded, measured and analysed on vastus lateralis (VL), rectus femoris (RF) and on biceps femoris (BF) muscles.

Data collection and processing

The muscles activities of VL, RF, BF muscles of the dominant leg, selected for their high contribution to the propulsive cycling task [31], 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 wipe and lightly abrading it to maintain a

low inter-electrode resistance of $<1000 \Omega$. Pairs of Ag/AgCl pre-gelled surface electrodes (Medicotest, type Blue Sensor, Q-00-S, Copenhagen, Denmark) of 40 mm diameter with a center to center distance of 25 mm were applied along the fibres over the bellies of the three muscles for EMG data acquisition according to the SENIAM – European Guidelines for Surface Electromyography recommendations [14]. The electrodes were secured with surgical 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 = $10 \text{ G}\Omega$; gain = 600, bandwidth frequency = from 6 Hz to 1600 Hz). Prior to acquisition, a third order, zero lag Butterworth antialiasing filter at 500 Hz was applied. EMG data were collected from each muscle, digitized through an acquisition board (DT 9800-series, Data Translation, Marlboro, VT, USA) and stored on a computer to be analyzed using custom-written add-on software (Origin 6.1[®], OriginLab, Northampton, MA, USA). The EMG data were sampled at 1000 Hz and besides integrated. According to Hauswirth et al. [13], we normalized all integrated EMG value expressed with regard to the burst duration (integrated EMG/burst duration): these values were considered as the measurement of muscle activity. These values were named “ $\theta_i\text{EMG}$ ”. The criteria for the onset and the offset values were based on a minimum threshold of 3 standard deviations from the resting baseline and a minimum burst duration of 50 ms according to the study of Neptune et al. [27]. Upon reaching the determined threshold, the muscle was considered active, and the muscle “burst” duration was defined as the duration between the onset and offset values. The end of the second muscle burst was considered as muscle deactivation when the subject exhibited a double-burst pattern according to the study of Sarre and Lepers [33].

Torque measurement

During cycling, power output is continuously calculated as shown in Equation (1):

$$\text{Power (W)} = \text{Torque (Nm)} \times \text{Angular Velocity (rad.s}^{-1}\text{)} \quad (1)$$

The torque generated at the crank axle is measured by strain gauges developed and bonded on to the crank arm by the ergocycle's manufacturer. Pedal rate and torque data were stored every revolution and every 2° per recorded revolution and recorded by the power control unit. The Lode ergometer was calibrated prior to each trial. From these data, several parameters were calculated for each pedal revolution:

- The maximal (peak) value of the resultant torque exerted during the downstroke of the dominant leg (PTD, in Nm) and during the downstroke of the nondominant leg (PTND, in Nm).
- The arm crank angle corresponding to PTD (AD, in degrees) and PTND (AND, in degrees). Crank angle was reference to 0° at top dead center (TDC) of the right crank arm and to 180° at the TDC of the leg crank arm (thus the right leg downstroke was from 0° to 180° and the left downstroke was from 180° to 360°). Then, the crank angle for the left leg downstroke was expressed relative to the TDC of the left crank arm (i.e., 180° was subtracted to the value obtained).

The following variables: PTD, PTND, AD, AND, ζ_E , ζ_{O_2} , Θ_{iEMG} of BF, VL and RF were computed during the last 30 s of the ninth minutes (i.e. time corresponding to a steady state for all variables) of each cycling trials (CTRL, cycling following ECC and CC exercises).

Statistical analysis

All variables were expressed as mean and standard deviation ($M \pm SD$). Difference in biomechanical, physiological and EMG parameters between sessions (CTRL, CC exercise followed by a cycling test and ECC exercise followed by a cycling test) were analyzed using a two-way analysis of variance ANOVA 2R [session x period]. Tukey *post hoc* test was used to determine any differences among the exercise and time. The level of confidence was set at $p < 0.05$.

RESULTS



During the maximal cycling test, the mean value of $\zeta_{O_{2max}}$ and maximal aerobic power were respectively: $65.3 \pm 2.3 \text{ ml.min}^{-1}.\text{kg}^{-1}$ and $401.9 \pm 36.1 \text{ W}$. During the evaluation of the 1RM, the mean force value was $908.4 \pm 179.4 \text{ N}$. The cycling exercises and the ECC or CC knee contractions were respectively performed at a mean power of $276.8 \pm 26.6 \text{ W}$ and a mean force of $726.9 \pm 136.8 \text{ N}$.

Figures 2 and 3 show MVC and RMS_{MVC} values during CTRL and cycling sessions. No significant difference on MVC and RMS_{MVC} values were observed between CTRL_{Pre}, CC_{Pre} and ECC_{Pre} tests ($p > 0.05$). All MVC values recorded during the maximal voluntary isometric knee extension test were significantly lower after CC and ECC exercises ($p < 0.05$) without any difference between conditions (CC_{Post}: -18.3% and ECC_{Post}: -15.5%) whereas only the ECC exercise induced a significantly decrease of RMS_{MVC} of VL and BF. No difference was

observed on MVC or RMS_{MVC} after cycling following CC and ECC exercises when compared to the values measured immediately after these exercises.

During cycling following the ECC exercise, pedal rate was lower than during CTRL trial (respectively 80.1 ± 7.6 rpm vs. 90.2 ± 10.7 rpm) and an increase of the resultant peak torques (PTD and PTND) was observed whereas no significant difference was recorded during cycling following the CC exercise (Table 1). Moreover, during cycling following the ECC exercise, ζO_2 values were significantly lower than during the CTRL trial ($p < 0.05$).

Integrated EMG signal expressed with regard to burst duration ($\Theta iEMG$) was presented on figure 4. Significant differences were shown between CTRL and cycling following CC exercise for RF, VL, BF muscles. $\Theta iEMG$ values of these muscles were significantly higher during cycling following CC exercise than during CTRL trial. On contrary, no difference of $\Theta iEMG$ was observed between cycling following the ECC exercise and CTRL trial

During cycling following the ECC exercise, ζO_2 was lower than during CTRL trial but no difference was observed between trials on ζE .

No difference was observed between trials on the biomechanical parameters recorded from ergometer, the asymmetry of the legs (i.e. dominant vs. nondominant side).

Table 1 – Mean values of physiological and biomechanical parameters recorded during the control cycling exercise (CTRL) and during cycling following CC and ECC exercises.

| | CTRL | Cycling following CC exercise | Cycling following ECC exercise |
|---|------------------|----------------------------------|-----------------------------------|
| ζO_2 (ml.min ⁻¹ .kg ⁻¹) | 57.3 ± 4.4 | 55.6 ± 6.5 | 52.9 ± 7.3^a |
| ζE (l.min ⁻¹) | 107.0 ± 10.2 | 107.5 ± 9.5 | 105.9 ± 14.3 |
| Pedal Rate (rpm) | 90.2 ± 10.7 | 87.5 ± 10.2 | 80.1 ± 7.6^a |
| PTD (Nm) | 59.2 ± 6.5 | 61.6 ± 11.0 | 69.7 ± 11.3^a |
| PTND (Nm) | 56.5 ± 7.9 | 59.3 ± 7.7 | 66.5 ± 8.4^a |
| AD (degrees) | 86.5 ± 9.2 | 88.9 ± 6.0 | 86.7 ± 7.9 |
| AND (degrees) | 83.1 ± 13.0 | 84.7 ± 10.1 | 82.2 ± 13.2 |

$\dot{V}O_2$, oxygen uptake; \dot{V}_E , minute ventilation; PTD, maximal peak torque of the dominant leg; PTND, maximal peak torque of the nondominant leg; AD, arm crank angle corresponding to PTD; AND arm crank angle corresponding to PTND.

Significantly different, $p < 0.05$: ^a from CTRL trial; No significant difference between dominant and nondominant legs.

Table 2 – Summary of sessions, time, and interaction effects for each dependent variable as obtained from ANOVA repeated measures.

| Dependent variable | Sessions | | Time | | Sessions x Time | |
|---------------------------------------|----------|----------|---------|----------|-----------------|----------|
| | F(2,30) | <i>P</i> | F(2,60) | <i>P</i> | F(4,60) | <i>P</i> |
| MVC | 2.60 | NS | 31.53 | * | 2.76 | † |
| RMS _{MVC} - Biceps Femoris | 0.79 | NS | 21.81 | * | 7.32 | * |
| RMS _{MVC} - Rectus Femoris | 0.32 | NS | 0.84 | NS | 0.08 | NS |
| RMS _{MVC} - Vastus Lateralis | 1.10 | NS | 3.44 | † | 2.52 | NS |

NS: Statistically nonsignificant, $P \geq 0.05$

*, $P < 0.01$

†, $0.01 \leq P < 0.05$

Figure 1 – Graphic representation of the experimental protocol. CTRL, Control cycling exercise; $\dot{V}O_{2max}$, maximal oxygen uptake test; CC, concentric knee contractions; ECC, eccentric knee contractions; MVC, maximal voluntary contraction; 1RM, one repetition maximum; R, rest.

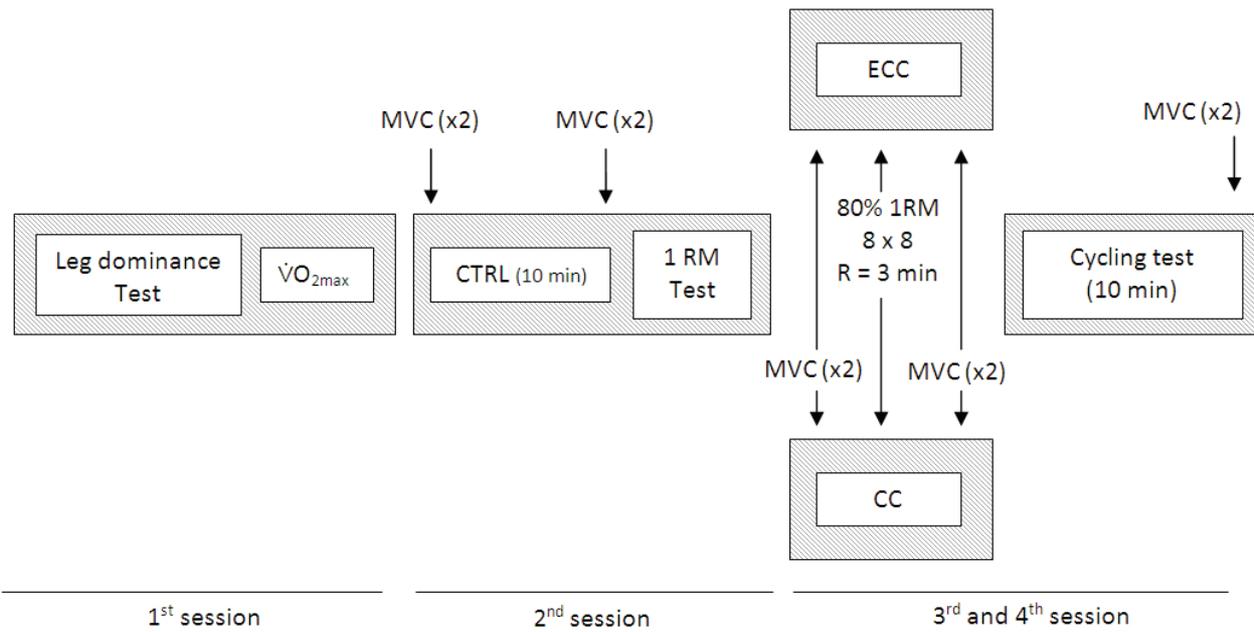
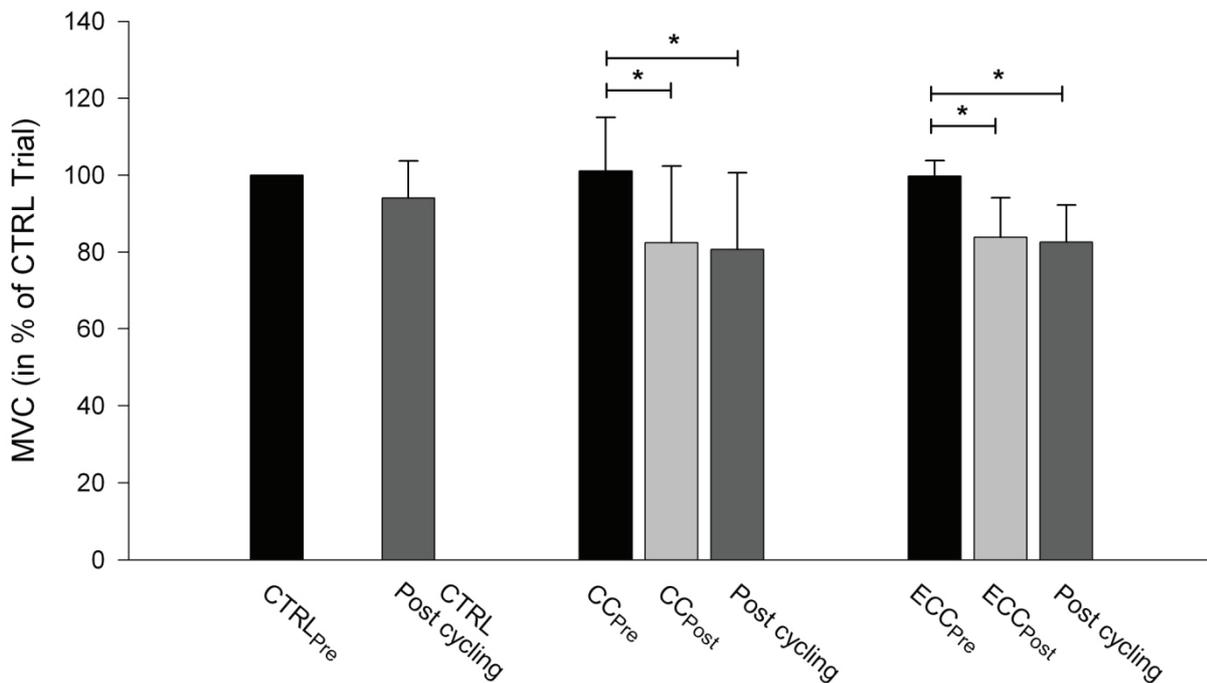


Figure 2 – Mean values of maximal voluntary contraction (MVC) recorded during the maximal voluntary isometric knee extension test before (CTRL_{Pre}) and after (CTRL Post cycling) the control exercise, before (CC_{Pre} and ECC_{Pre}) and after (CC_{Post} and ECC_{Post}) the CC or ECC knee contractions and after cycling following ECC and CC exercises (Post

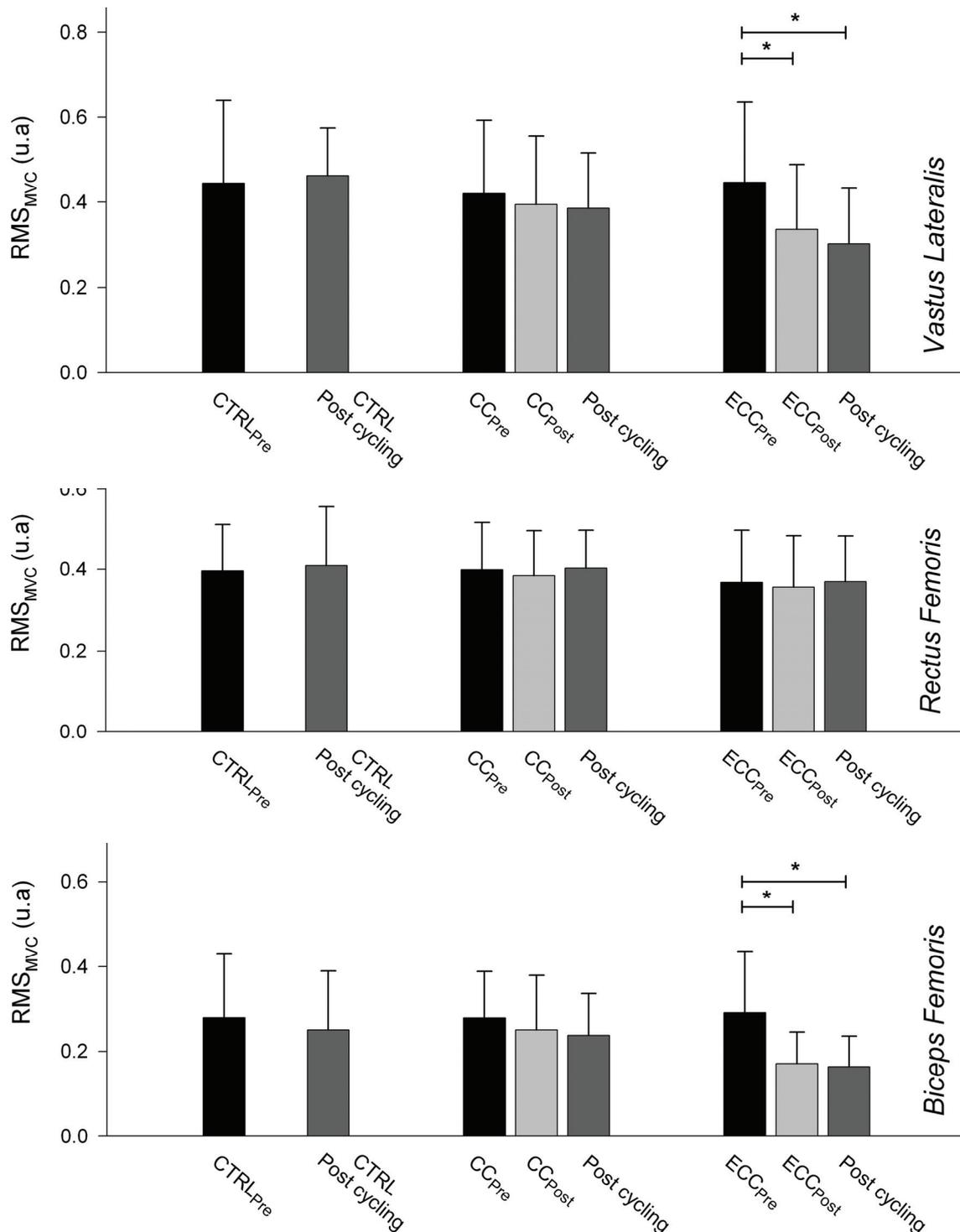


cycling) (expressed in % of CTRL trial).

No significant difference between CTRL, CC_{Pre} and ECC_{Pre} values ($p > 0.05$).

*, Significantly different from the pre-values.

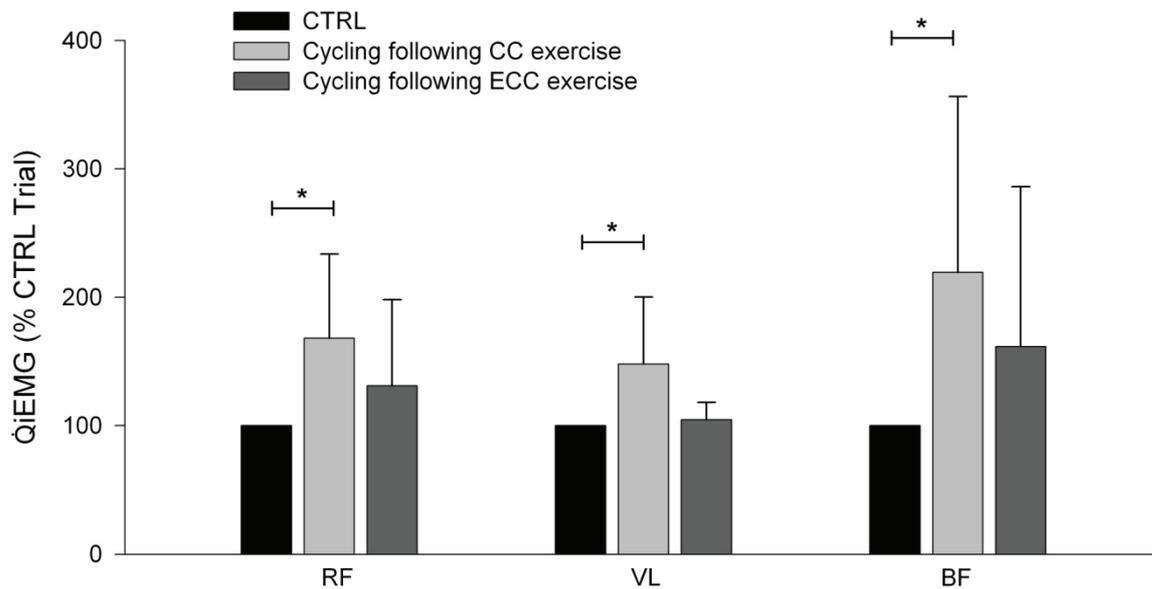
Figure 3 – Mean values of EMG root mean square during the maximal voluntary contraction (RMS_{MVC}) of Vastus Lateralis (VL), Rectus Femoris (RF) and Biceps Femoris (BF) muscles recorded during the MVC tests: before ($CTRL_{Pre}$) and after ($CTRL_{Post}$) the control exercise, before (CC_{Pre} and ECC_{Pre}) and after (CC_{Post} and ECC_{Post}) the CC or ECC knee contractions and after cycling following ECC and CC exercises (Post cycling).



VL, BF and RF: No significant difference between CTRL, CC_{Pre} and ECC_{Pre} values ($p > 0.05$).

*, Significantly different from the pre-values.

Figure 4 – Mean values of integrated EMG expressed with regard to the burst duration (Θ iEMG) of rectus femoris (RF), vastus lateralis (VL), biceps femoris (BF) muscles recorded during the control cycling exercise (CTRL) and cycling following ECC and CC exercises



(expressed in % of CTRL trial).

Significantly different, $p < 0.05$: * from CTRL trial

DISCUSSION



The present study aimed to analyse the effect of two different muscular fatiguing exercises on mechanical and electromyographic activity during cycling.

Main findings were 1) MVC values decreased after CC and ECC but, only ECC exercise induced a significant decrease of RMS_{MVC} ; 2) MVC and RMS_{MVC} values were not different between the end of CC or ECC exercises and the end of the cycling exercises following the ECC and CC knee contractions 3) Pedal rate was lower only during cycling following the ECC exercise when compared with CTRL exercise 4) Θ iEMG was increased only during cycling following the CC exercise.

The first interesting observation is a similar decrease of the MVC after the two knee contractions exercises (CC_{Post} : -18.3% and ECC_{Post} : -15.5%). These results indicate a comparable mechanical effect of muscle fatigue after ECC and CC exercises. The reduction of force production after eccentric or concentric exercises was classically observed in the literature [11, 32]. For example, Lavender and Nosaka [30] reported a loss

of MVC after concentric and eccentric repeated actions respectively of 28.5 % and 63.1 %. Many reasons were evoked to explain this torque loss. After an eccentric exercise, strength decrease was mainly ascribed to excitation-contraction coupling impairment and ultrastructural damages, such as wavy Z-band, A-band disruptions and over-stretched sarcomeres [0, 24]. On the opposite, after concentric exercise, no ultrastructural damages was observed and peripheral fatigue was mainly due to depressed actin-myosin cross-bridge formation and could originate from a metabolic inhibition of the contractile process [23].

However, despite a similar decrease of MVC values after ECC and CC exercises, our results showed different decreases of RMS_{MVC} after CC and ECC exercises with a significant decrease in RMS_{MVC} values observed after ECC exercise. This result could indicate a greater neuromuscular fatigue after ECC exercise than after CC exercise. Among the different hypothesis proposed, the main hypothesis regarding a greater reduction of RMS_{MVC} after ECC exercise was an alteration of the neural input but also a decreased in excitability (alteration of the M-wave and isometric twitch) [19]. However, other factors could also explain the reduction of force production after an eccentric exercise, such as peripheral failure (for example, changes in organization of the sarcomeres structure, in excitation-contraction (E-C) coupling [24, 29]) [10]. This study was mainly descriptive and it was not possible to analyse factors affecting RMS_{MVC} decrease after different contraction type exercises. Further works are necessary to distinguish peripheral or central mechanism related to this effect [20].

The second interesting result of our study was that a decrease of the pedal rate was observed only during cycling following the ECC exercise. A decrease in pedal rate was classically observed in the literature after prolonged exercise [2, 19, 21, 24]. For example, Lepers et al. [19] and Argentin et al. [2] have respectively observed a decrease of pedal rate of 21 % and 22 % during the last 20 min of a 2h cycling test. Our results could be compared to these previous studies. In our study, this effect was observed only during cycling following the ECC exercise (-12.6 %) and was associated with a greater torque applied on the pedal (PTD: +13.2 % and PTND: +12.2 %). The main hypothesis classically proposed, relates this shift to factors affecting the relationship between the energetically optimal cadence (EOC) and the freely chosen cadence (FCC) [19, 35]. In these previous studies, authors showed that at the beginning of a short duration cycling exercise, subjects adopted a pedal rate corresponding to the minimum of the integrated EMG slope for VL muscle, called neuromuscular optimal cadence (NOC). On the opposite, after a

prolonged cycling exercise, they observed a decrease in pedal rate close to the EOC. From these results, these authors interpreted the decrease of pedal rate with muscle fatigue like an adaptation of the movement pattern to minimize the energy cost rather than the "neuromuscular cost". Our results were indirectly in agreement with this hypothesis since a significantly lower oxygen uptake (-8.3 %) was observed during cycling following the ECC exercise when compared with CTRL trial. The main factors proposed in the literature to explain this decrease of oxygen uptake at EOC when compared to NOC is the decrease in the ventilation cost and/or in internal work for repetitive limb movements [5, 8]. For example, Francescato et al. [8] indicated that the fraction of overall $\dot{V}O_2$ due to internal work for a subject cycling at 100 W and 60 rpm was about 0.2 whereas this fraction was around 0.6 at 100 rpm. However, in our study, decrease in the ventilation cost cannot explain the decrease of oxygen uptake at EOC because \dot{V}_{E} was not different between trials. Consequently, this previous observation can be only related to the increase in internal work.

The third result of our study showed an increase of Θ_i EMG of each tested muscle during cycling only after CC exercise. This result could be directly related to the type of prior exercise (CC vs. ECC) and indirectly to the pedal rate adopted by the cyclist. Indeed, MVC results showed that after the two prior exercises, a muscle fatigue appears but only ECC exercise induces a neuromuscular fatigue sufficient to reduce the RMS_{MVC} . As we described previously, this loss of muscular capacity after ECC exercise was generally due to an alteration of the neural input and constrains the cyclist to mechanical adaptations (i.e. decrease of pedal rate). On the opposite, after CC contractions, no significant cadence modification was observed despite a loss of maximal strength capacities. Therefore, cycling at 87.5 rpm seems to conduct to a greater recruitment of motor units (increase number and/or discharging rate) to maintain a high pedal rate close to the pedal rate adopted without prior fatigue (90.2 rpm).

On conclusion, despite a similar effect of CC and ECC on the force-generating capacity, prior ECC exercise induces a greater neuromuscular fatigue than CC exercise. This greater neuromuscular fatigue induces a decrease of the pedal rate toward a more economical cadence. In contrast, CC exercise does not induce any modification of the freely chosen cadence. In this condition, to maintain a high cadence, muscle activity increases. This increase can be explained by a greater recruitment in motor unit and/or a change in muscle activation strategy. It could be interesting to investigate the mechanisms underlying

these observations, using for example, the twitch interpolation technique to distinguish the role of peripheral or central fatigue.

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