Neuromuscular function during prolonged pedalling exercise at different cadences

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Abstract

Aim: The purpose of the present work was to assess the strategies set by the central nervous system in order to provide the power output required throughout a prolonged (1-h) pedalling exercise performed at different cadences (50 rpm, 110 rpm and the freely chosen cadence).

Methods: Neuromuscular (NM) activity of vastus lateralis, rectus femoris, biceps femoris and gastrocnemius lateralis muscles was studied quantitatively [root-mean square (RMS) and mean power frequency (MPF)] and qualitatively (timing of onset and offset of muscle bursts during crank cycle). **Results:** The present results showed that increased cadence resulted in earlier muscle activation in crank cycle. The influence of cadence on RMS and MPF depended on the considered muscle and its functional role during pedalling. Timing of onset and offset of muscle bursts was not altered by fatigue throughout the prolonged exercise. In contrast, RMS and MPF of some muscles was found to increase during prolonged exercise.

Conclusion: In summary, the present study revealed that tonic aspects of the NM activity (RMS, MPF) are altered during prolonged pedalling exercise, while phasic aspects are remained unchanged. These results suggest that the strategies set by the central nervous system in order to provide the power output required by the exercise are held constant throughout the exercise, but that quantitative aspects of the central drive are increased in order to adapt to the progressive occurrence of the NM fatigue.

Keywords cycling, electromyogram, endurance, muscle, oxygen uptake.

Neuromuscular (NM) activity of the muscles involved in pedalling movement can be considered as reflecting the central strategies set in order to provide the power output required by the exercise. NM activity can be assessed quantitatively [temporal and frequential aspects, respectively, assessed by calculating root-mean square (RMS) and mean power frequency (MPF)] or qualitatively (timing of onset and offset of muscle bursts during crank cycle).

The level of NM activity, indicating muscle recruitment level, has been first studied in cycling in order to try to explain the consistent choice of high pedalling rates used by trained cyclists while riding on a flat road (around 90 rpm, Lucia *et al.* 2001). Several studies (Coast & Welch 1985, Coast *et al.* 1986, Marsh &

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Martin 1998, Lucia *et al.* 2001) have shown that minimization of oxygen uptake could not be considered as determinant in the choice of the cadence. Some authors have therefore proposed the hypothesis that the freely chosen cadence (FCC) could minimize the NM activity during pedalling (Marsh & Martin 1995, Takaishi *et al.* 1998, MacIntosh *et al.* 2000). However, there is no strong evidence that FCC induces lower NM activity in all recruited muscles. Sarre *et al.* (2003) have demonstrated that the influence of cadence on the level of NM activity depends on the considered muscle and its functional role. The results obtained by these previous studies seem to widely depend on the experimental protocol (power output, range of cadences, training level of subjects, etc.). It has also been suggested that the changes in muscle activation with fatigue could lead the choice of the cadence. Takaishi *et al.* (1994, 1996) have demonstrated that a cadence of 90 rpm induced a smaller increase in electromyographic (EMG) activity of vastus lateralis (VL) muscle during a short-duration (15-min) pedalling exercise. According to these authors, cyclists spontaneously adopt high pedalling rates in order to minimize NM fatigue during prolonged cycling exercises. However, the single VL muscle analysed in these studies may limit the possible interpretations. The statement that riding at FCC gives some NM advantage during prolonged cycling exercise should therefore be considered cautiously.

Spectral analysis has also been used to characterize NM activity during pedalling. MPF reflects the action potential velocity in motor units (Hagg 1992), which could be modified by many concurrent effects. MPF has been found to be decreased by NM fatigue, or increased by muscle heating. These results imply that changes in MPF should be interpreted carefully. Considering that the action potential velocity is higher in fast motor units, increase in MPF has been suggested to be related to an enhanced recruitment of fast motor units. Borrani et al. (2001) have demonstrated a rise in MPF during a prolonged pedalling exercise. These authors have hypothesized that increased MPF may be due to the progressive recruitment of fast motor units, in order to compensate for progressive fatigue of already recruited muscle fibres.

Surprisingly, no study seems to have investigated the influence of pedalling rate on MPF. Nonetheless, Ahlquist *et al.* (1992) have demonstrated that the pattern of recruitment of fast and slow muscle fibres was altered by cadence. This study has shown that fast twitch fibres were more recruited as cadence decreased, for a constant level of power output. It should therefore be expected that MPF would increase as cadence decreases. Moreover, the influence of pedalling rate on the changes in MPF during prolonged cycling exercise should be addressed.

Finally, NM activity has been qualitatively investigated. Some researchers have focused on NM pattern (Suzuki *et al.* 1982, Neptune *et al.* 1997, Raasch & Zajac 1999, Baum & Li 2003), which could be defined as the pattern of onset and offset of the EMG bursts of the involved musculature during pedalling cycle. These studies have consistently demonstrated that EMG bursts occurred progressively earlier during crank cycle as pedalling rate increased. This mechanism seems to allow peak pedal force to occur at about 90° of crank angle (crank arm at an horizontal position) whatever the cadence, despite the electromechanical delay (EMD). The EMD corresponds to the time lag between the onset of EMG activity and the beginning of force production. Neptune *et al.* (1997) have estimated this EMD to be close to 100 ms. This latency corresponds to 1/10th of crank cycle at 60 rpm, but to 1/5th of crank cycle at 120 rpm. Assuming a constant onset of EMG activity, pedal force may therefore occur too late in crank cycle as cadence increases.

Surprisingly, to the best of our knowledge, no study has explored the evolution of the NM pattern during endurance cycling in regard to the NM fatigue caused by such a prolonged exercise. Paasuke *et al.* (1999) have demonstrated that EMD was increased by NM fatigue. As NM fatigue has been found to occur during prolonged cycling exercise (Bentley *et al.* 1998, Lepers *et al.* 2000, 2002, Mercer *et al.* 1998), pattern of onset and offset of muscles bursts might also be influenced by NM fatigue. Moreover, two recent studies from our laboratory have suggested that NM fatigue could depend on cadence (Lepers *et al.* 2001, Sarre *et al.* 2005). It might therefore be expected that alterations of NM pattern during a prolonged cycling exercise depend on the selected cadence.

The goal of the present work was to study the NM activity during a 1-h cycling exercise performed at three different cadences, in order to investigate the NM strategies set by the central nervous system to control pedalling movement. It was hypothesized that: (1) the onset and offset of muscles bursts are altered during prolonged cycling exercise, as a consequence of NM fatigue, and these alterations depend on cadence, (2) MPF will decrease with cadence increase, and (3) the alterations of the MPF throughout prolonged exercise depend on the selected cadence.

Materials and methods

Subjects

Eleven well-trained subjects volunteered to participate in the present study (27.8 \pm 5.6 years, 71.1 \pm 7.8 kg). All of them had at least 4 years of competitive cycling or triathlon experience. Each participant signed a written consent form before starting the experimentation, which was approved by the local ethics committee.

The whole experimentation was conducted on an electromagnetically braked cycloergometer (Excalibur; Lode, Groningen, The Netherlands), which automatically adapts resistance to pedalling rate in order to keep constant the external power output.

Preliminary session

One week before the experimentation, all subjects performed a maximal incremental test on the ergocycle to determine their individual maximal power output (P_{max}) . The power output was increased by 25 W every

2 min from the first power output level (100 W). The test ended when the subject could no longer sustain the required power output. The P_{max} was defined as the last power output level completed. The mean P_{max} value for the subjects in the present study was 382 ± 43 W.

Experimental protocol

A standardized warm-up was performed before the protocol, and consisted of 10 min pedalling at 33% of the $P_{\rm max}$, at an FCC and without any cadence feedback. Afterwards, maximal isometric voluntary contractions (MVC) were performed. Then, subjects had to perform in a random order one of the three pedalling sessions corresponding to three cadences: 50 rpm, FCC and 110 rpm. The sessions were separated by at least 1 week.

Maximal voluntary contraction

Maximal voluntary contraction of the knee flexor and knee extensor muscles were performed on an isokinetic dynamometer (Biodex, Shirley, NY, UA), between warmup and pedalling session, on each experimental session. The studied limb was the right leg. Subjects sat with a 90° knee angle $(0^{\circ}$ as full leg extension), with the ankle attached to the ergometer arm. The knee axis was aligned with the dynamometer axis. EMG was recorded on VL and rectus femoris (RF) muscles during the knee extensor MVC, and on biceps femoris (BF) during the knee flexor MVC. Electrodes and wires were secured with adhesive tape in order to prevent movement artefacts. To allow the recording of EMG signal of the BF muscle, a board was placed underneath the subject, with a cavity so as to avoid any compression of the surface electrodes and wires. Maximal RMS values of VL, RF and BF muscles obtained during the MVCs were used to normalize the NM activity recorded during cycling.

Pedalling session

The exercise duration was 60 min, at a power output corresponding to 65% of the P_{max} . This duration was chosen because it corresponds to the duration of many cycling events such as time trial cycling or bike course of short distance triathlon (40 km). Tested cadences were 50 rpm, FCC and 110 rpm; 50 and 110 rpm represent extreme values of the range of pedalling rates commonly used by trained cyclists. Subjects used their own racing shoes and pedals, and adjusted the seat and handlebar so as to be close to the position set on their bicycle. When the subjects cycled at either 50 or 110 rpm, a visual cadence feedback was given, whereas it was not at FCC. Subjects were asked to either precisely keep the desired cadence, or pedal naturally as if they were riding their own bicycle. The riders freely

selected their cadence during the entire session performed at FCC, and were not asked to keep it stable. Subjects were allowed to drink water *ad libitum* during the exercise.

EMG recording

EMG signals of VL, RF, gastrocnemius lateralis (GL) and BF muscles were recorded for 30 s periods every 5 min during the whole exercise duration. EMG activity was recorded with silver-chloride circular surface electrodes (Control Graphique Medical, Brie-Comte-Robert, France) fixed on the right leg. Electrodes were positioned preliminarily to MVC. Low impedance (<5 k Ω) between the electrodes was obtained by light abrasion of the skin, and oil and dirt were removed with an alcohol swab. Electrodes were coated with electrolytic gel and fixed lengthwise over the middle of the muscular belly, with an inter-electrode distance of 20 mm. The reference electrode was secured over the styloid process of the left wrist. EMG signals were amplified with a bandwidth frequency ranging from 1.5 to 500 Hz (common mode rejection ratio, CMRR = 90 dB, Z input = 100 M Ω , gain = 1000) and digitized on-line (sampling frequency 5000 Hz). In order to prevent movement artefact, wires between the electrodes and the computer were secured to the skin with adhesive tape. EMG signals were quantified using RMS method, and normalized to muscle maximal RMS during MVC, except for GL muscle for which no MVC was performed. EMG bursts of each muscle, recorded synchronously with crank position during each 30 s period, were plotted vs. crank angle in order to obtain the average onset and offset of muscles bursts in pedalling cycle. NM pattern was defined as the pattern of activation and deactivation of each muscle during crank cycle, and was characterized by both onset and offset angles, which were expressed in fractions of the crank cycle (0 corresponding to the right pedal at the bottom-dead center, and 1 as full crank cycle). The end of the second muscle burst was considered as muscle deactivation angle when the subject exhibited a double-burst pattern. This mainly occurred for RF muscle at the highest cadence (110 rpm). The MPF of the EMG signal of each muscle was calculated using MATLAB software package. Pedalling cycles were isolated and analysed individually in order the EMG spectrum not to be influenced by cadence. For each muscle, MPF was determined for each crank cycle. MPF values were then averaged.

Gas exchange analysis

 O_2 uptake was measured during 30 s every 5 min, synchronously with EMG activity, by means of a

Vacumed (Ventura, CA, USA) system including a volume meter (no. 17150) and O_2 and CO_2 analysers (nos. 17518 and 17515).

Statistical analysis

The data are reported as mean \pm SD in text and mean \pm SEM in figures. Repeated measures ANOVAS were used to analyse cadence \times time effects on RMS, onset and offset of EMG bursts, and MPF. Newman-Keuls *post-hoc* procedure was used when statistical differences were significant. Level of statistical significance was set at 0.05.

Results

Freely chosen cadence equalled to 87.9 ± 11 rpm, and did not significantly change during the 1-h cycling exercise. The amplitude of the fluctuations of the FCC, quantified with the coefficient of variation (CV = SD/mean) was 12.5%.

Levels of EMG activity of all tested muscles were significantly (P < 0.01) influenced by cadence (Fig. 1). RMS of VL muscle was significantly higher at 110 rpm compared with 50 rpm (P < 0.05) and FCC (P < 0.01). RMS of RF muscle was significantly higher at 50 rpm (P < 0.01), compared with FCC and 110 rpm. RMS values of GL muscle at each cadence were all significantly different from each others (P < 0.01), with RMS at 110 rpm greater than at FCC, and RMS at FCC greater than at 50 rpm. RMS value of BF muscle at 110 rpm was significantly higher compared with 50 rpm (P < 0.01). No difference was found between RMS at FCC and 110 rpm on BF muscle.

Significant (P < 0.01) time effects were found on EMG activity. RMS of VL and RF muscles was found to increase during the exercise performed at 110 rpm. In contrast, NM activity of BF muscle decreased during the exercise session realized at 50 rpm.

Significant (P < 0.05) cadence × time effect was found on the MPF of the EMG signal of VL muscle (Fig. 2). *Post-hoc* analysis revealed that the MPF value measured at FCC at the beginning of the exercise (5th minute) was significantly lower than each of the other values. A significant global time effect was found on the MPF of BF muscle (P < 0.01), with values at the 60th minute being significantly higher than at the 5th minute.

Activation and deactivation patterns were influenced (P < 0.01) by cadence for VL, RF and BF muscles (Fig. 3). Increase in cadence induced significantly lower values of activation and deactivation angles in crank cycle for VL and BF muscles, and of activation angle for RF muscle. No cadence effect was found on activation and deactivation angles of GL muscle.



Figure 1 Influence of cadence on the level of neuromuscular activity of vastus lateralis (VL), rectus femoris (RF), gastrocnemius lateralis (GL) and biceps femoris (BF) muscles at the beginning (5th minute) and the end (60th minute) of the prolonged cycling exercise. *Significant (P < 0.05) difference between the two cadences, **significant (P < 0.01) difference between the two cadences, \$significant (P < 0.05) time effect.

No time effect was found on the activation and deactivation patterns of any muscle during the 1-h exercise.

 O_2 uptake was significantly higher (P < 0.01) at 110 rpm than at 50 rpm and FCC (Fig. 4). A significant increase was found on oxygen uptake during the exercise performed at 50 rpm (P < 0.01) and at FCC (P < 0.05).





Figure 2 Influence of cadence on EMG MPF of vastus lateralis (VL), rectus femoris (RF), gastrocnemius lateralis (GL) and biceps femoris (BF) muscles at the beginning (5th minute) and the end (60th minute) of the prolonged cycling exercise. MPF of EMG signal of VL muscle was significantly (P < 0.05) minimized at the beginning of the exercise performed at the FCC. A significant (P < 0.01) global time effect was found on the MPF of the EMG signal of BF muscle.

Discussion

The aim of this study was to assess the influence of pedalling rate on the NM activity during a prolonged

Figure 3 NM pattern of vastus lateralis (VL), rectus femoris (RF), gastrocnemius lateralis (GL) and biceps femoris (BF) muscles during the 1-h pedalling exercise. All muscles but GL started and stopped earlier in crank cycle as cadence increased. The neuromuscular pattern remained unchanged throughout the prolonged exercise.

cycling exercise. Present results showed that NM parameters were differentially altered by cadence during a 1-h cycling exercise performed at 65% of P_{max} .

A significant cadence effect was found on the level of NM activity of all tested muscles. Minimization of NM activity of VL muscle at FCC supports findings of



Figure 4 Oxygen uptake at the 5th (filled diamonds) and 60th (open diamonds) minutes of the pedalling sessions. O₂ uptake was significantly (P < 0.01) increased by cadence at the beginning of the exercise. $\dot{V}O_2$ drift during the exercise was significant when performed at 50 rpm (P < 0.01) and at FCC (P < 0.05).

previous works, such as Takaishi et al. (1998) and Vercruyssen et al. (2001). However, the statement that the minimization of the NM activity of this single muscle could constitute a criterion in the choice of the cadence may be considered cautiously. Indeed, this minimization could correspond to an adaptation in cyclists used to train in a given range of pedalling rates. RMS of GL and BF muscles increased with cadence, in accordance with previous results (Marsh & Martin 1995, Takaishi et al. 1998, MacIntosh et al. 2000). This rise in NM activity of GL muscle could be explained by its functional role during crank cycle. Indeed, GL muscle acts as a 'power transmitter' (Fregly & Zajac 1996). Sarre et al. (2005) have showed that increased cadence resulted in the necessity to produce more positive work with the front leg, for a given power output. Increased cadence therefore requires higher recruitment, i.e. NM activity, of GL muscle in order to transmit this greater amount of positive work to the crank arm. Increased NM activity of BF muscle with cadence is also in line with the result obtained by Takaishi et al. (1998), who suggested that the greater recruitment of the BF muscle is aimed at alleviating the rear leg in order to prevent the increase in negative force applied on the pedal during upstroke. Lastly, RMS of RF muscle was greater at 50 rpm, what confirms the hypothesis that this muscle is largely recruited as needed torque level increases (i.e. cadence decreases for a constant power output), probably in order to facilitate the top-dead centre transition (Neptune & Herzog 2000, Sarre et al. 2003) by propelling forward the pedal.

EMG activity of VL and RF muscles significantly increased only during the 1-h cycling exercise performed at 110 rpm. This finding is consistent with the results from Takaishi *et al.* (1996), who found an EMG

drift on VL muscle during a prolonged cycling exercise. An upward drift in NM activity may be attributed to the progressive recruitment of additional motor units, as NM fatigue occurs. The EMG drift found on VL and RF muscles in the present results might be related to the central fatigue concerning these two muscles, as evidenced by Sarre et al. (2005) after a prolonged cycling exercise performed at a high pedalling rate (110 rpm). Taken together, these results suggest that the central fatigue found at the end of the exercise for these muscles induces the necessity to increase NM activity in order to keep constant the power output. In contrast, RMS of BF muscle significantly downward drifted during the 1-h exercise performed at 50 rpm. This decreased NM activity might be attributed to a reduction in BF co-activation. As the exercise performed at a low cadence (50 rpm) induced a high level of muscle tensions, the decrease in BF co-activation may allow reducing muscular tensions in the knee extensor muscles. This could represent an acute adaptation aimed at preventing too high quadriceps muscle tension levels (Hautier et al. 2000). Finally, the present data pointed out that FCC did not minimize the RMS of the four tested muscles.

The MPF of the EMG signal of VL muscle was found to be significantly minimized at FCC at the beginning of the exercise. Assuming that decrease in MPF might be interpreted as an enhanced recruitment of slow motor units, the present results may confirm the hypothesis of Sargeant (1994), that the FCC corresponds to the cadence at which maximal recruitment of slow twitch fibres is expected. The authors postulated that utilizing a higher or a lower cadence may result in greater participation of fast motor units in power output generation. As this hypothesis does not seem to be suitable for the other tested muscles, FCC could not be considered as the cadence allowing preferential recruitment of slow motor units in all muscles involved in pedalling movement, as hypothesized by Sargeant (1994). Although increased MPF with cadence in GL and RF muscles was not significant, it might be hypothesized that the increased recruitment of these muscles, evidenced by concomitant rise in RMS, could mainly involve fast motor units.

MPF of BF muscle was significantly increased during prolonged exercise, which suggests that progressive derecruitment of this muscle during the prolonged exercise, demonstrated by decreased RMS, may preserve recruitment of fast motor units.

It should be kept in mind that MPF does not seem to be the most reliable way to determine action potential velocity, especially during dynamic contractions (Farina *et al.* 2004a). However, the present results may provide complementary results to that from Farina *et al.* (2004b), in particular relative to muscles other than vastii. Results relative to quantitative aspects of NM activity could provide elements to explain the influence of cadence and fatigue on physiological response to the exercise. Present results show that increased cadence induces a greater muscular recruitment. Ahlquist *et al.* (1992) have suggested that slow motor units are preferentially activated at high cadences. On the contrary, low cadences are supposed to induce a smaller muscles recruitment, but a preferential fast motor units activation, for a given power output. Hence, high cadences could induce greater NM and metabolic demand, but lower drifts, whereas low cadences would result in smaller response and higher drifts in NM activity and oxygen uptake.

Present results are consistent with this hypothesis, as oxygen uptake increases with cadence at the beginning of the exercise, whereas the $V'o_2$ drift becomes greater as cadence decreases.

The present results relative to NM activity and oxygen uptake are slightly different from those presented in a recent study (Lucia *et al.* 2004). These difference could be attributed to two main factors. First, the training level of the subjects. Lucia studied professional cyclists, i.e. riders who were able to generate higher wattages than the amateur cyclists who were involved in the present study. Moreover, the duration of the exercise was very different (6 vs. 60 min). Indeed, it could be summarized from the previous paragraphs that exercise duration is an important criterion in the cadence selection.

Our results dealing with NM pattern are consistent with those obtained by previous works (Neptune et al. 1997, Baum & Li 2003). Indeed, our data confirmed that EMG bursts occurred earlier in crank cycle as cadence increased, which may be aimed at allowing peak pedal force to occur approximately at the same crank angle whatever the cadence, despite the EMD. However, Sarre et al. (2004) demonstrated that mechanical torque occurred later in crank cycle as cadence increases. Taken together, these results therefore suggest that central nervous system may not adopt a strategy that would allow pedal force to occur exactly at the same crank angle whatever the cadence. It might be hypothesized that such a strategy may be too disadvantageous, perhaps by increasing coactivation between knee flexor and knee extensor muscles, what might be detrimental to energy cost.

The most original result of the present study was that activation and deactivation of EMG bursts of any muscle were not significantly altered during the pedalling session, suggesting that NM pattern is rigid throughout the exercise, whatever the selected cadence. NM strategies aimed at providing the required power output may therefore remain constant despite NM fatigue generated by this exercise (Sarre *et al.* 2005).

In conclusion, cadence was found to alter NM activity during a 1-h cycling exercise. The influence of cadence on RMS and MPF depends on the role of the considered muscle during pedalling cycle. Hence, as cadence differentially affects muscles EMG, NM activity could not be considered as a major criterion leading the choice of the cadence. NM pattern was not affected during prolonged exercise, in contrast with RMS and MPF. These results suggest that phasic aspects of NM activity are held invariant despite fatigue, while tonic aspects (RMS and MPF) are modified, what raises the hypothesis that central nervous system keeps constant the NM strategies set in order to provide the required power output, but only adapts quantitative aspects of the central drive in order to compensate the NM fatigue of involved muscles. Finally, NM activity allows explaining the physiological impact of exercise.

It could be hypothesized that the central nervous system selects strategies in respect to the role and specificity (mono-/biarticular) of each muscle, as a function of the current biomechanical conditions (fatigue, cadence). Further research is required to investigate the plasticity of the central strategies to altered biomechanics in various movements.

Conflict of interest

The authors state that there is no personal or financial conflict of interest in the present study.

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