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Stability of pedalling mechanics during a prolonged cycling exercise performed at different cadences

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Abstract

The aim of this study was to analyse the effect of pedalling rate on the pattern of mechanical torque application and on neuromuscular fatigue during prolonged cycling exercise. Eleven well-trained individuals performed three 1-h pedalling sessions, at 50 $\text{rev} \cdot \text{min}^{-1}$, 110 $\text{rev} \cdot \text{min}^{-1}$ and a freely chosen cadence, at an intensity corresponding to 65% of their maximal aerobic power. The mechanical torque applied on the right pedal was recorded for 30 s every 5 min while pedalling. Contractile and neural properties of the quadriceps and hamstring muscles were analysed before and immediately after each of the three pedalling sessions. The post-exercise reduction in knee extensors maximal voluntary contraction was significant ($P < 0.01$) irrespective of the cadence, but no difference was found between cadences. The use of a particular cadence did not lead to preferentially central or peripheral fatigue. An increase in cadence resulted in greater positive and negative work generated during pedalling. The mechanical pattern was not altered during the exercise, whatever the selected cadence. The present study demonstrates that despite the occurrence of neuromuscular fatigue, trained individuals maintained a stable pedalling pattern throughout an endurance cycling exercise for cadences ranging from 50 to 110 $\text{rev} \cdot \text{min}^{-1}$.

Keywords: *Activation, electromyography, fatigue, mechanical pattern, negative work, pedalling rate*

Introduction

The term "mechanical pattern" is used in the present study to refer to the pattern of application of the mechanical torque during the whole crank cycle. Previous studies have shown that negative torque generated by the rear leg during the pedal upstroke of the crank cycle increases with increased pedalling rate (Neptune & Herzog, 1999; Patterson & Moreno, 1990; Sanderson, Hennig, & Black, 2000). Thus cyclists apply a force on the rear pedal that is opposite to the movement. This force increases with cadence and, therefore, needs to be overcome by the front leg. To our knowledge, only one previous study has examined modifications of the mechanical pattern during prolonged cycling exercise (Sanderson & Black, 2003). The authors found greater negative impulse during the final minute, compared with the first minute, of exercise performed at 80% maximal aerobic power output until exhaustion. Hence, a significant increase in positive impulse occurred during the final minute of the exercise to compensate for this increased negative impulse, and to produce the required net power output. However, since exercise was performed until exhaustion in Sanderson and Black's (2003) study, it is possible that this increase in negative impulse resulted from an unsmooth pedalling pattern, due to the fatigued state of the participants. Unfortunately, these authors did not relate the changes in the mechanical pattern to any modifications in the neuromuscular properties of the knee extensor and flexor muscles (i.e. fatigue). Moreover, it is possible that the evolution of this negative force (i.e. mechanical pattern) throughout prolonged pedalling could depend on the selected cadence. This was not been tested by Sanderson and Black (2003), who used a single cadence (90 $\text{rev} \cdot \text{min}^{-1}$).

Several studies have noted that neuromuscular fatigue occurs during prolonged endurance exercises, such as cycling, cross-country skiing and running (Millet & Lepers, 2004). A reduction in maximal force-generating capacity of the knee extensor muscles during endurance cycling has been reported by some authors (Bentley, Zhou, & Davie, 1998; Lepers, Hausswirth, Maffiuletti, Brisswalter, & van Hoecke, 2000; Lepers, Maffiuletti,

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Rochette, Brugniaux, & Millet, 2002; Lepers, Millet, & Maffiuletti, 2001; Millet, Millet, Lattier, Maffiuletti, & Candau, 2003). Maximal voluntary contraction (MVC) was found to fall by 12% following 30 min of cycling at 80% of maximal oxygen uptake (Bentley, Smith, Davie, & Zhou, 2000; Lepers *et al.*, 2001), or after 2 h cycling at 65% of maximal aerobic power output (Lepers *et al.*, 2000). This reduction in force production capacity following cycling exercise was due both to a decrease in central activation and peripheral failure. Central fatigue implies a decrease in neural drive, which reduces the ability of the central nervous system to fully activate the muscles, whereas peripheral fatigue includes mechanisms that intervene after the neuromuscular junction, such as excitation – contraction coupling (Gandevia, 2001; Kent-Braun, 1997).

However, differences in mechanical pattern (i.e. muscle recruitment; Neptune & Herzog, 1999; Sarre, Lepers, Maffiuletti, Millet, & Martin, 2003), while pedalling at different cadences, might induce differences in neuromuscular fatigue. To the best of our knowledge, only one study has investigated the influence of pedalling rate upon neuromuscular fatigue following prolonged cycling. Lepers *et al.* (2001) demonstrated that the use of different cadences (ranging from 69 ± 3 to 103 ± 5 $\text{rev} \cdot \text{min}^{-1}$) during 30 min cycling exercise performed at 80% of maximal aerobic power output did not result in any difference in strength loss or neuromuscular alterations of the knee extensor muscles, despite a trend for lower cadences to induce greater central drive failure than higher cadences. Lepers *et al.* (2001) hypothesized that the range of tested cadences, extending the freely chosen cadence by $\pm$ 20%, was too narrow, and the exercise duration too short, to induce significant differences in post-exercise neuromuscular fatigue. Moreover, this study did not link the decrease in force production capacity to the mechanical pattern utilized during pedalling.

The first aim of the present study was to determine whether using extreme cadences, such as 50 and 110 $\text{rev} \cdot \text{min}^{-1}$, characterized by different mechanical patterns, would lead to differences in neuromuscular fatigue during 1-h endurance cycling. Based on previous studies (Lepers *et al.*, 2000, 2001) and pilot testing, maintaining 65% of maximal aerobic power output for 1 h was used to represent a very intense effort when performed at extreme cadences such as 110 $\text{rev} \cdot \text{min}^{-1}$. A second aim of the study was to test the hypothesis that modifications of the mechanical pattern during prolonged pedalling exercise is dependent on the selected cadence.

Methods

This study complies with the current French laws on human experimentation, and was approved by the local ethic committee.

Participants

Eleven well-trained males volunteered to take part in the present experiment (age 27.8 ± 5.6 years, body mass 71.1 ± 7.8 kg; mean $\pm$ *s*). All of them had regularly taken part in cycling or triathlon competitions in the previous 4 years. All participants signed an informed consent form.

Preliminary session

One week before the experiment, all participants performed a maximal test to assess their individual maximal aerobic power. Briefly, the initial power output of 100 W was increased by 25 W every 2 min until the participant could no longer sustain the required power output. The cadence was freely selected by the participant. Maximal aerobic power output was assumed to be the highest power output completed by the participants (381 ± 43 W).

Neuromuscular fatigue test procedure

The method used for fatigue testing is similar to that described by Lepers *et al.* (2002). The participants were seated on an isokinetic dynamometer (Biodex, Shirley, NY), with the trunk secured to the back by straps, at a 90° angle. The studied limb was the right leg. The ankle was attached to the ergometer arm. All tests were performed at a knee angle of 90°. The neuromuscular properties of the quadriceps muscle were examined by stimulating the femoral nerve using a cathode ball electrode positioned on the femoral triangle. The anode was a 5×10 cm electrode pasted on the gluteus maximus muscle. The transcutaneous electrical stimulus was a rectangular pulse delivered by a digitimer stimulator (DS7, Hertfordshire, UK). The intensity used corresponded to that after which twitch amplitude no longer increased.

The neuromuscular tests were performed before and after each pedalling session. A single stimulation (twitch) was electrically evoked. It was followed by a quadriceps isometric MVC during which a double pulse stimulation was superimposed. A double pulse immediately followed (1 s) the MVC, and was therefore potentiated, due to residual Ca^{2+} in the sarcoplasmic reticulum. The potentiated double pulse was found to provide a more accurate estimation of central activation (Gandevia, 2001). A knee flexion isometric MVC was also performed in each test session. The participants performed two trials of each MVC before and after the pedalling session. The trials were separated by 30 s recovery. The best performance was recorded in all cases. The duration of the MVCs was 4 s.

The M-wave of the vastus lateralis, rectus femoris and vastus medialis was recorded during the electrically evoked single twitch stimulation. The amplitude of the associated mechanical response was noted. Maximal isometric extension torque and associated root mean square (RMS) of vastus lateralis, rectus femoris and vastus medialis muscle activity were analysed during a quadriceps MVC. The torque value corresponding to the superimposed (during the MVC plateau) and potentiated (1 s after MVC) double pulses were also recorded. Potentiated double pulse was chosen since potentiated stimulations have been shown to be a better index of muscle fatigue than unpotentiated ones (Kufel, Pineda, & Mador, 2002).

Central activation during knee extensors MVC was calculated using the following equation:

$$\mathrm{A}(\%) = (1 - (\text{superimposed double pulse}/\text{potentiated double pulse})) \times 100$$

The RMS/M-wave ratios of the vastus lateralis, rectus femoris and vastus medialis muscles were obtained by dividing the RMS measured during the knee extensors MVC by the RMS of the M-wave corresponding to the single twitch. A reduction in the RMS, without a reduction in the M-wave (i.e. RMS/M-wave ratio), could be interpreted as reduced central activation (Gandevia, 2001).

Electromyography

The electromyographic (EMG) activity of the vastus lateralis, rectus femoris and vastus medialis muscles was recorded using silver-chloride circular surface electrodes (Control Graphique Medical, Brie-Comte-Robert, France) attached to the right leg. Low impedance (< 5 kΩ) between the electrodes and skin was obtained by light abrasion of the skin, and oil and dirt were removed with an alcohol swab. The 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 apophysis of the left wrist. The EMG 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) and digitized on-line (sampling frequency 5000 Hz). All EMG signals were quantified using the RMS.

Pedalling session

The experiments were conducted on an electromagnetically braked cycle ergometer (Excalibur, LODE, Groningen, The Netherlands). This cycle ergometer is specially constructed to automatically adjust the resistance to keep the power output constant irrespective of the cadence selected. The participants used their own racing shoes and pedals, and adjusted the seat and handlebars to mimic the position set on their own bicycles. The exercise duration was set to 1 h, and the intensity corresponded to 65% of individual maximal aerobic power output, which reflects approximately the mean intensity during road cycling races (Padilla *et al.*, 2001). The cadences tested were 50 $\text{rev} \cdot \text{min}^{-1}$, 110 $\text{rev} \cdot \text{min}^{-1}$ and a freely chosen cadence. Visual feedback of the cadence was provided only during the sessions performed at 50 and 110 $\text{rev} \cdot \text{min}^{-1}$. The participants were asked to either precisely keep the required cadence or pedal naturally as if on their own bicycle.

Torque measurements

Mechanical torque during pedalling was measured by means of strain gauges mounted in the crank arms of the cycle ergometer. Recordings were taken for 30 s every 5 min during the pedalling sessions, and then plotted against crank angle. The crank angle value was provided by the cycle ergometer. When the right crank arm was at bottom-dead centre, the crank angle was 0°. The mechanical pattern was defined as the repartition of mechanical torque over the complete pedalling cycle. Positive and negative work was calculated by integrating respectively the positive and negative parts of the torque versus crank angle curve (Figure 1). The mechanical pattern was assessed by analysing the mean peak torque angle, and positive and negative work over 30 s.

Experimental procedure

To assess the influence of cadence manipulations on neuromuscular fatigue, a sequence of neuromuscular tests was performed before and immediately after each pedalling session. A standardized warm-up was performed before the experimental protocol, which consisted of 10 min pedalling at 33% of maximal aerobic power output, at a freely chosen cadence and without any cadence feedback. Then, the experimental protocol began, which consisted of a sequence of neuromuscular tests followed by the 1-h pedalling session performed at a given cadence, immediately followed by another sequence of tests. To prevent interference of recovery effects on fatigue

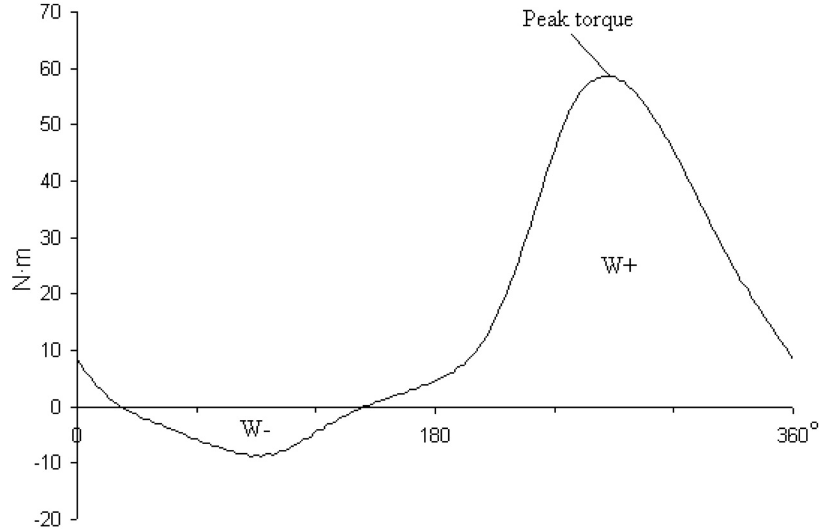

Figure 1. Typical torque recordings during one pedalling cycle for the right leg (0° = right pedal at bottom-dead centre). The mechanical pattern was assessed by examining peak torque angle, and by calculating positive (W +) and negative (W-) work, which corresponded to the integration value of positive and negative torque versus angle, respectively.

testing after pedalling, the participants were quickly transferred from the cycle ergometer to the isokinetic dynamometer. The second sequence of testing ended 5 min after the pedalling exercise. Each participant had to perform three times, in random order, the complete procedure, in order to cycle at the three cadences (50 rev · min^{-1}, 110 rev · min^{-1} and freely chosen cadence). At least 1 week separated the three conditions.

Statistical analysis

Statistical significance was set at $P < 0.05$. All data in the tables are expressed as the mean $\pm$ standard deviation, but as the mean $\pm$ standard error of the mean in the figures. Student's *t*-test was used to examine differences between pre- and post-exercise values. A one-way analysis of variance was conducted to examine the influence of cadence on the post-exercise decrease of neuromuscular parameters (electrically evoked stimulations, MVC), and cadence effects on the mechanical pattern (positive and negative work, peak torque angle). Repeated-measures analyses of variance were conducted to examine the effect of time on the mechanical pattern. Newman-Keuls *post-hoc* procedures were used when statistical differences were significant.

Results

The mean pedalling rate during the 1-h cycling exercise at the freely chosen cadence was 87.9 ± 11.0 rev · min^{-1}, which did not change significantly during exercise.

Neuromuscular fatigue

Maximal voluntary contraction of the knee extensor muscles was significantly decreased after 1 h of cycling ($P < 0.01$) for all three cadences tested (Table I).

There was no effect of cadence on maximal isometric torque loss, despite a trend ($P = 0.15$) for knee extensors MVC to decrease to a larger extent after pedalling at 110 rev · min^{-1} (-11.1 ± 11.5% at 50 rev · min^{-1}, -13.9 ± 12.1% at the freely chosen cadence, -17.7 ± 7.4% at 110 rev · min^{-1}). The decrease in MVC of the knee flexor muscles was significant at 50 rev · min^{-1} ($P < 0.01$) and 110 rev · min^{-1} ($P < 0.05$), but not at the freely chosen cadence. Nevertheless, no cadence effect was found on MVC losses of the knee flexors.

Central activation decreased significantly ($P < 0.01$) after exercise, irrespective of the cadence, but no significant effect of cadence on central activation was observed (see Figure 2). The decrease in the RMS/M-wave ratio was significant ($P < 0.05$) for the vastus lateralis and rectus femoris muscles after 1 h of exercise performed at 110 rev · min^{-1} (Figure 2). No effect of cadence on the reduction in the RMS/M-wave ratio was noted for any of the three muscles tested.

Table II shows the changes in neuromuscular properties of the quadriceps muscle after 1 h of cycling exercise at the three cadences tested. Electrically evoked torque (twitch and doublet) was found to fall significantly after exercise, for each cadence. The RMS of M-waves of the vastus lateralis and vastus medialis muscles decreased significantly after 1 h pedalling at 50 rev · min^{-1} and at the freely

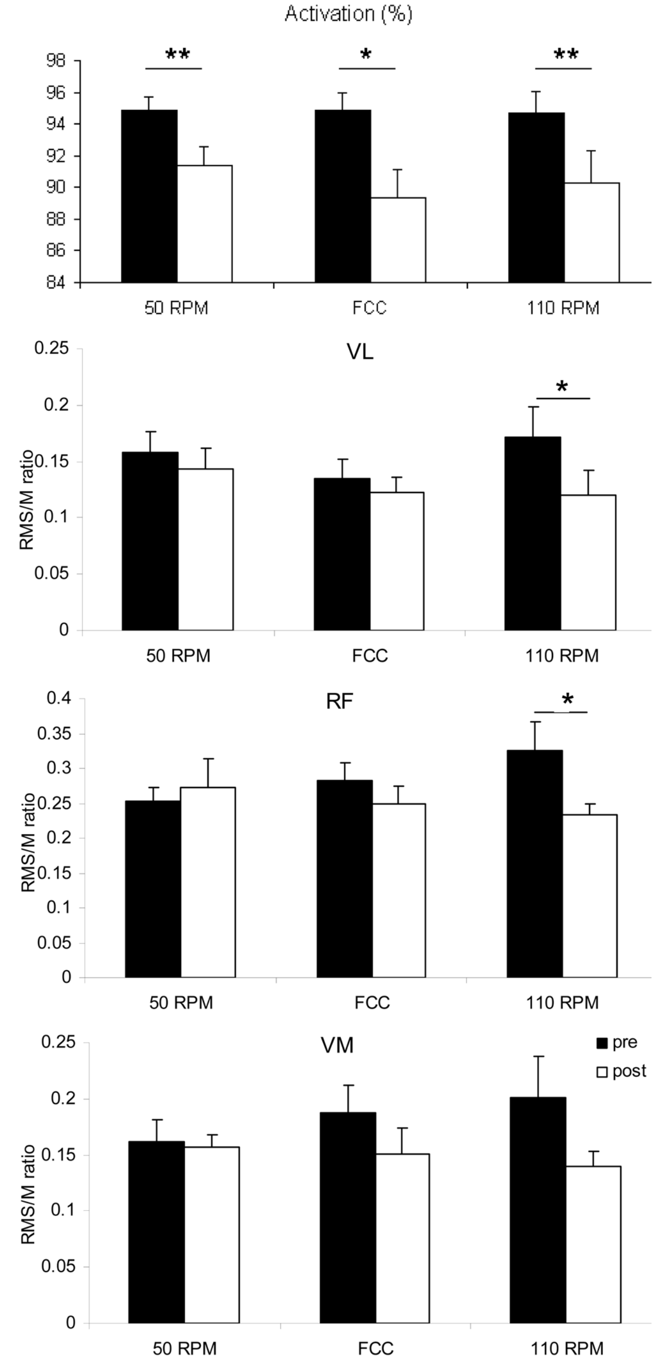

Figure 2. Central activation and RMS/M-wave ratios of the vastus lateralis (VL), rectus femoris (RF) and vastus medialis (VM) muscles. Central activation significantly decreased after exercise for each cadence tested. A significant decrease ($P < 0.05$) in the RMS/M-wave ratio of the vastus lateralis and rectus femoris muscles was also noted after exercise performed at 110 rev $\cdot$ min^{-1}. There was no effect of cadence effect on any of these parameters. FCC = freely chosen cadence. Significant post-exercise decrease: * $P < 0.05$, ** $P < 0.01$.

chosen cadence. No effect of cadence on the decrease in the RMS of M-waves was observed for any muscle or electrically evoked torque.

Mechanical pattern

Cadence was found to exert a significant effect ($P < 0.01$) on positive work, negative work and peak torque angle (Figure 3). Both positive and negative work increased significantly when shifting from 50 rev $\cdot$ min^{-1} to the freely chosen cadence, and from the freely chosen cadence to 110 rev $\cdot$ min^{-1}. The peak torque angle was found to shift earlier in the crank cycle as cadence increased. *Post-hoc* tests revealed that values of positive work, negative work and peak torque angle were different from each other across cadences. No significant effect of time on positive work, negative work or peak torque angle was observed. Indeed, repeated-measures analyses of variance conducted on positive work, negative work and peak torque angle revealed that these parameters did not change significantly throughout exercise.

Discussion

The aim of the present study was to assess the effects of pedalling rate on both neuromuscular fatigue and the mechanical pattern during prolonged cycling exercise. The results showed that: (1) 1 h of cycling exercise significantly altered the neuromuscular properties of the quadriceps muscle, irrespective of the cadence, with no statistically significant differences between the cadences; and (2) the mechanical pattern was significantly influenced by cadence, but was not altered during the prolonged exercise.

In line with previous studies (Bentley *et al.*, 2000; Lepers *et al.*, 2000, 2001), the present results showed a decrease in maximal isometric torque-generating capacity of the knee extensor muscles after 1 h of cycling exercise. The freely chosen cadence and the two standardized cadences (50 and 110 $rev \cdot min^{-1}$, corresponding to the extreme cadence generally used by trained cyclists) induced similar reductions in maximal isometric torque generated by the knee extensors. The present results are in line with those obtained by Lepers *et al.* (2001), who found no cadence effect after 30 min cycling exercise performed at cadences ranging from 69 to 103 $rev \cdot min^{-1}$.

Despite the absence of a cadence effect, there was interestingly a trend ($P = 0.15$) towards a greater decrease in the knee extensors MVC as cadence increased. This observation suggests that the knee extensor muscles were slightly more fatigued at the end of the exercise performed at 110 $rev \cdot min^{-1}$ compared with exercise at the freely chosen cadence and 50 $rev \cdot min^{-1}$. Opposite results would be expected, since muscular tensions are higher at low cadences, which may be supposed to induce greater neuromuscular fatigue.

The significant decrease in the RMS/M-wave ratio of the vastus lateralis and rectus femoris muscles observed after pedalling at 110 $rev \cdot min^{-1}$ could be related to the greater decrease in MVC after pedalling at this cadence. Indeed, decreases in central drive to these muscles, evidenced by a reduced RMS/M-wave ratio, may result in lower isometric torque. No effect of cadence was observed on either central activation or the peripheral index of fatigue (twitch, double pulse and M-wave), suggesting that pedalling at different cadences during 1-h endurance cycling bouts does not result in any

Table I. Pre- and post-exercise torques produced during the maximal voluntary contractions (MVC) of the knee extensor and knee flexor muscles, at 50 $rev \cdot min^{-1}$, 110 $rev \cdot min^{-1}$ and the freely chosen cadence (mean $\pm$ *s*)

	Knee extensors MVC ($N \cdot m$)	Knee flexors MVC ($N \cdot m$)
50 $rev \cdot min^{-1}$		
Pre-exercise	242.2 ± 47.2	87.4 ± 23.8
Post-exercise	216.6 ± 54.5	80.5 ± 22.0
Loss (%)	11.1 ± 11.4**	7.7 ± 8.6**
Freely chosen cadence		
Pre-exercise	239.4 ± 33.1	83.8 ± 25.3
Post-exercise	207.1 ± 44.2	81.5 ± 26.1
Loss (%)	13.9 ± 12.1**	2.0 ± 14.1
100 $rev \cdot min^{-1}$		
Pre-exercise	241.8 ± 30.6	84.1 ± 22.2
Post-exercise	198.3 ± 25.7	81.0 ± 24.2
Loss (%)	17.7 ± 7.4**	4.3 ± 6.7*

* Significant difference between pre- and post-exercise ($P < 0.05$).
** Significant difference between pre- and post-exercise ($P < 0.01$).

Table II. Pre- and post-exercise values of the neuromuscular properties of the quadriceps muscle: peak twitch torque, potentiated double pulse torque, and the RMS of M-waves (RMS_M) of the vastus lateralis, rectus femoris and vastus medialis muscles

	Peak twitch torque ($N \cdot m$)	Potentiated double pulse torque ($N \cdot m$)	RMS_M of vasutus lateralis (V)	RMS_M of rectus femoris (V)	RMS_M of vastus lateralis (V)
50 $rev \cdot min^{-1}$					
Pre exercise	39.96 ± 7.95	93.44 ± 12.08	3.56 ± 1.21	3.14 ± 1.45	4.17 ± 1.07
Post exercise	35.36 ± 6.55	80.22 ± 16.13	3.26 ± 1.27	2.85 ± 1.83	3.46 ± 1.12
P-value	< 0.01	< 0.01	< 0.01	N.S.	< 0.05
Freely chosen cadence					
Pre exercise	40.90 ± 7.87	99.00 ± 14.07	4.15 ± 0.99	3.44 ± 1.58	4.37 ± 1.81
Post exercise	32.90 ± 6.78	80.60 ± 13.62	3.81 ± 0.77	3.38 ± 1.83	4.06 ± 1.28
P-value	< 0.01	< 0.01	< 0.05	N.S.	< 0.05
100 $rev \cdot min^{-1}$					
Pre exercise	40.18 ± 5.84	90.34 ± 15.99	4.55 ± 1.56	3.23 ± 1.27	4.16 ± 1.79
Post exercise	33.72 ± 8.79	79.83 ± 11.97	4.60 ± 1.29	3.21 ± 1.26	3.49 ± 1.20
P-value	< 0.01	< 0.05	N.S.	N.S.	N.S.

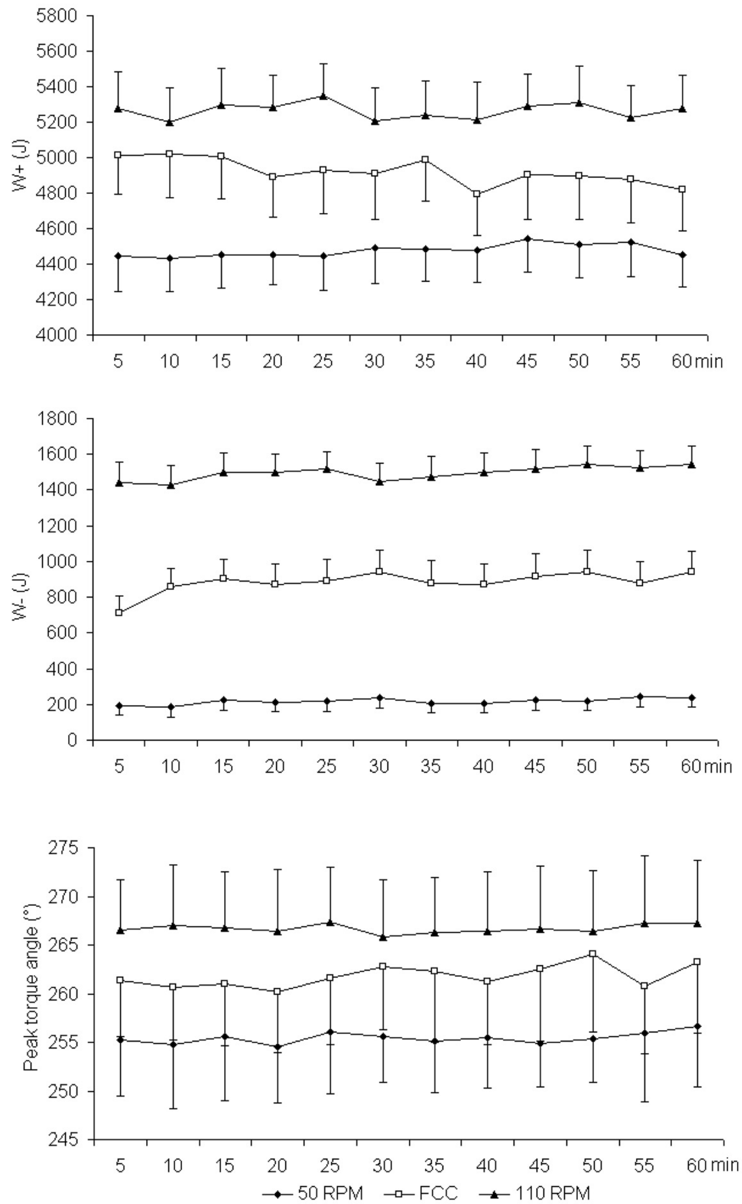

Figure 3. Positive work (W+) and negative work (W-) calculated over 30 s, and mean peak torque angle, during cycling exercise performed at the three different cadences (50 rev · min^{-1}, 110 rev · min^{-1} and the freely chosen cadence [FCC]). A significant effect of cadence on these three parameters was observed. Positive and negative work increased with cadence. Increased cadence also resulted in the later occurrence of peak torque in the crank cycle. There was no effect of time on any of these three parameters.

preferential central or peripheral fatigue. Taken together, these results suggest that neuromuscular fatigue is not significantly influenced by cadence during endurance cycling exercise of 30 – 60 min duration. This needs to be verified at higher power outputs, or longer exercise durations, that lead participants to become fatigued. Nevertheless, it should be mentioned that all participants perceived the 1-h cycling exercise performed at 110 rev · min^{-1} as a very intense effort, which could not have been sustained for much longer.

The significant effect of cadence on both positive and negative work is consistent with previous studies (Neptune & Herzog, 1999; Patterson & Moreno, 1990; Sanderson *et al.*, 2000). *Post-hoc* tests revealed that the increase in pedalling rate resulted in significantly greater negative work (Patterson & Moreno, 1990; Sanderson *et al.*, 2000). This negative work is generated by the rear leg during the pedal upstroke. The increase in negative work with increasing cadence may be due to insufficient activation of the hip and knee flexor muscles (Neptune & Herzog, 1999). An increase in negative work may oblige the front leg to overcome this by producing more positive work, in order to maintain the required torque. Therefore, an increase in cadence for a constant power output results in additional positive work production by the front leg during each pedal down-stroke. The amount of additional positive work produced during a pedalling bout at high (110 rev $\cdot$ min^{-1}) compared with low (50 rev $\cdot$ min^{-1}) cadences might explain the slightly greater force loss after 1 h of cycling at 110 rev $\cdot$ min^{-1} observed in the present study.

It should be borne in mind that increasing cadence, for a constant power output, results in two distinct phenomena: first, a decrease in mean torque and, second, a rise in positive work that the participant has to provide (see Figure 3). This increase in positive work corresponds to the need to overcome negative work in order to provide the required power output. It could, therefore, be supposed that mechanical power provided by the front leg (i.e. the hip and knee extensor muscles) during the pedal down-stroke may increase with cadence, for a constant power output. This assumption may provide some insight regarding the total energy expended during pedalling at various cadences (Kautz & Neptune, 2002).

The absence of a time effect on both negative and positive work, and on peak torque angle, demonstrates that the mechanical pattern remained stable during the 1 h of cycling performed at 65% maximal aerobic power output, despite the occurrence of neuromuscular fatigue. The mean torque during submaximal pedalling, in the range of commonly used cadences, corresponds to approximately 20–25% of knee extensor muscles MVC (Gollnick, Piehl, & Saltin, 1974). The muscular system remains able to provide the torque required during the pedal down-stroke despite the alteration in force production capacity evidenced at the end of the exercise. Moreover, the absence of a time effect on negative work shows that negative force is not modified during prolonged cycling, suggesting that the control of pedalling movement remains unchanged during the exercise. The present results contrast with those recently reported by Sanderson and Black (2003), who showed that the mechanical pattern was altered during the final minute of an exhausting cycling bout performed at 80% maximal aerobic power output. This study evidenced an increase in negative force generated by the rear leg in the final minute of pedalling. This discrepancy might be explained by the high power output and exhausted state of the participants at the end of the exercise in the study of Sanderson and Black (2003). Indeed, it is possible that cyclists performing exhausting cycling bouts exhibit unsmooth pedalling at the end of the exercise. The lower intensity used in the present study could explain the absence of changes in mechanical pattern during the 1 h of exercise. It may be that changes in mechanical pattern only occur in an exhausted state. In this framework, it would be relevant to analyse the effects of a preliminary fatiguing exercise on the leg muscles, induced by evoked or voluntary contractions, on the mechanical pattern used during subsequent pedalling.

In conclusion, the mechanical pattern was found to remain stable throughout the 1 h of cycling exercise performed at 65% of maximal aerobic power output, irrespective of the cadence (from 50 to 110 rev $\cdot$ min^{-1}), despite the occurrence of neuromuscular fatigue at the end of exercise. This result suggests that the neuromuscular system manages to provide the torque required for pedalling, even in fatigued conditions. Changes in neural and contractile properties of the quadriceps muscle following exercise were independent of the cadence used. However, the present results revealed a trend for knee extensors MVC to decrease to a larger extent at the highest cadence (i.e. 110 rev $\cdot$ min^{-1}). Further studies are required to examine the interaction between fatigue, cadence and mechanical pattern for pedalling exercise performed for longer durations, or at higher intensities, or after a pre-fatiguing leg exercise.

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