Effects of different pedalling techniques on muscle fatigue and mechanical efficiency during prolonged cycling

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The present study aimed to test the influence of the pedalling technique on the occurrence of muscular fatigue and on the energetic demand during prolonged constant-load cycling exercise. Subjects performed two prolonged (45 min) cycling sessions at constant intensity (75% of maximal aerobic power). In a random order, participants cycled either with their preferred technique (PT) during one session or were helped by a visual force-feedback to modify their pedalling pattern during the other one (FB). Index of pedalling effectiveness was significantly ($P<0.05$) improved during FB (41.4/5.5%) compared with PT (36.6/4.1%). Prolonged cycling induced a significant reduction of maximal power output, which was greater after PT (−15±9%) than after FB (−7±12%). During steady-state FB, vastus lateralis muscle activity was significantly ($P<0.05$) reduced, whereas biceps femoris muscles activities increased compared with PT. Gross efficiency (GE) did not significantly differ between the two sessions, except during the first 15 min of exercise (FB: 19.0±1.9% vs PT: 20.2±1.9%). Although changes in muscular coordination pattern with feedback did not seem to influence GE, it could be mainly responsible for the reduction of muscle fatigue after prolonged cycling.

Cycling performance results from the interaction of environmental, mechanical and performer constraints. To improve cycling performance, engineers have mainly devoted their efforts to the development of more efficient bicycles, that is, engines permitting to minimize counteractive external forces (e.g., aerodynamic drag). On the other hand, the issue of how to reduce performer’s constraints has been less frequently addressed in the literature. In this respect, it is currently admitted that, among the important performer’s variables, a key factor that may reduce counterproductive forces is the mechanical pattern adopted during cycling (Sanderson et al., 2000). The term “mechanical pattern” usually refers to how the mechanical torque is applied during full crank cycle (Sarre et al., 2005).

For instance, previous studies have demonstrated that the adoption of a “pulling” pedalling pattern, which consisted in actively pulling on the pedal during upstroke phase, significantly improved mechanical effectiveness, thereby resulting in a reduction of negative torque during upstroke phase (Korff et al., 2007; Mornieux et al., 2008). However, results also showed that the “pulling pattern” significantly altered muscular efficiency (i.e., gross efficiency [GE]) during steady-state cycling efforts (Korff et al., 2007; Mornieux et al., 2008). A possible reason is that alterations of GE resulted from the modifications of muscle coordination accompanying the adoption of the pattern corresponding to the pulling technique. Indeed, assuming that the increase in mechanical work during the upstroke phase was achieved by an increase in flexor muscles activation (Mornieux et al., 2008), when adopting the “pulling” pattern, extensor muscles might be more efficient in producing power than flexor muscles (Korff et al., 2007). In contrast, Takaishi et al. (1998) showed that, contrary to non-cyclists, the pedalling technique adopted by trained cyclists led to a reduction of negative torque during the upstroke phase, which in turn could contribute to reduce energetic cost. It was hypothesized that a significant diminution of muscular strains during downstroke phase reduced the level of extensor muscle activation that could contribute to limit metabolic demand and probably neuromuscular fatigue (Nordlund et al., 2004).

To date, several studies have demonstrated significant muscle fatigue following prolonged (>30 min) exercise that could limit cycling performance (e.g., Booth et al., 1997; Bentley et al., 2000; Lepers et al., 2000, 2002). Among others exercise variables, neuromuscular fatigue appears to be particularly...
influenced by the intensity of muscular work (for review, see Enoka & Stuart, 1992). Yet, Mornieux et al. (2008) have shown that, when adopting the pulling technique in cycling, the increase of flexor muscle activity allowed a reduction of negative torque during upstroke phase, and therefore limited maximal torque applied by leg extensor muscles during downstroke phase. In addition, Neptune and Herzog (2000) reported that negative torque during the upstroke phase corresponded to 25% of the propulsive torque produced by extensor muscles, when cycling at 90 rpm. Surprisingly, however, Mornieux et al. (2008) reported that the increase of leg flexors muscle (i.e., biceps femoris [BF], rectus femoris [RF] and gastrocnemius medialis [GM]) activity during upstroke phase did not significantly affect the activity of extensor muscles during downstroke phase. However, because they averaged the electromyographic (EMG) activity over a full crank revolution, accurate information about the maximal muscle EMG activity throughout different crank cycle phases (i.e., downstroke vs upstroke) was lacking. Moreover, a change in mechanical pattern could also result in significant modifications of muscle coordination strategies. For example, Hasson et al. (2008) reported that the improvement of one-leg pedalling effectiveness was accompanied by a reduction of the ankle-joint torque production, and by an increase of hip-joint torque production. However, muscles that span the ankle, knee and hip could have different metabolic properties and morphological characteristics, which could lead to differential joint-specific muscle resistance to fatigue (Allen et al., 2008). For example, Martin and Brown (2009) showed that during fatiguing cycling exercise, the ankle-joint torque production was reduced to a greater extent than both knee-joint and hip-joint torque production.

Although the modification of pedalling technique seemed to have an impact on the occurrence of muscular fatigue during prolonged exercise, to our knowledge, this issue has rarely been directly investigated in the literature. The present study thus aimed to test the influence of pedalling technique on muscular fatigue and on muscular efficiency during prolonged constant-load cycling exercise. According to the above reviewed literature, we hypothesized that adopting the pulling technique to improve mechanical effectiveness could (i) limit the occurrence of muscular fatigue by reducing muscle activation level during leg extension and (ii) affect GE during cycling, in particular, by modifying muscular coordination.

Methods and procedures
Participants
Nine male subjects (age: 28 [mean] ± 8 (SD) years, weight: 69 ± 5 kg, height: 175 ± 5 cm) volunteered to participate in this study after they were informed in detail about the nature of the experiment and possible risks. Written informed consent was given by each subject and the study was conducted according to the Declaration of Helsinki. A local ethics committee for the protection of individuals gave approval concerning the project before its initiation. The subjects had regularly trained in cycling or triathlons. The subjects were asked to avoid high-intensity or exhaustive exercise during 48 h before the laboratory trials.

Experimental protocol
Participants had to perform two cycling sessions. Both sessions were separated by 1 week and were performed in a randomized order. Experimental protocol (Fig. 1) was strictly identical for both sessions, except for the adopted pedalling technique.

Subjects were asked to perform a 45 min cycling exercise at 75% (208 ± 33 W) of the estimated MAP, and at a fixed pedalling rate (75 rev/min), in order to induce significant muscle fatigue (Bentley et al., 2000; Theurel & Lepers, 2008). During one condition, participants were asked to use their preferred technique (PT), whereas during the second condition, subjects were helped with a visual feedback to modify their pedalling technique (FB) (Mornieux et al., 2008). During FB condition, cyclists were asked to keep the tangential force positive during the upstroke phase, which inevitably forced subjects to pull up the pedal during this phase.

During each session, in addition to fatiguing cycling exercise, participants performed two cycling tests in order (i) to estimate their maximal oxygen uptake (VO₂) and (ii) to evaluate their maximal power output (Pmax): at the beginning, after 10 min at rest to determine their resting heart rate (HRrest), subjects performed the Astrand test (1954), which consists in pedalling at a constant power output (150 W) during 6 min. The HR measured at the end of test was reported onto the Astrand–Ryhming nomogram in order to estimate the theoretical maximal oxygen uptake (VO₂max). The maximal aerobic power (MAP) was estimated according to the Storer (1990) algorithm

\[
\text{MAP} = [\text{VO}_{2\text{max}} - (6.35 \times \text{mass}) + (10.49 \times \text{age})] - 519.3)/10.51
\]

Secondly, a complementary warm-up period (6 min at 50% of MAP) was carried out by each subject before the evaluation of Pmax. To determine Pmax, subjects pedalled against a fixed resistance at their maximal frequency during 5 s. Subjects were asked to remain seated throughout the exercise. Three trials, separated by a 2 min recovery period, were performed for each subject at three different resistance levels. The peak of power output reached over the three trials was considered as Pmax, and the corresponding resistance was considered as the optimal resistance (Reff) for following maximal tests: Pmax was tested before steady-state cycling (Pre) and every 15 min (T1, T2 and T3) during fatiguing exercise (see Fig. 1). Pmax tests were performed in the same condition (i.e., without feedback) for both sessions (FB vs PT).

During the entire experimentation, cycling tests were performed on a cycle ergometer, composed of a mountain bike fixed onto a magnetic resistance home trainer system (Crono Mag, Elite, Fontaniva, Italy). Ergometer seat height was adjusted and recorded to match participant’s position during both sessions. Subjects wore cycling shoes that locked onto the pedal interface.
Feedback

A continuous visual feedback of the tangential pedal force was depicted on a video-projected image, positioned in front of the cyclist (Powertech soft, O-tec, Bensheim, Germany). The feedback representation was a circle, which was oriented with the top dead center being at the top. This arrangement made it relatively easy for the subject to recognize the downstroke and upstroke phases. The circle was scaled according to a theoretical unloaded crank revolution, which allowed subjects to know whether they were applying a positive tangential force. In order to fully understand the FB condition, all participants tested it during the warm-up period. It is worth noticing that this task was easily and quickly understood by all cyclists.

Data recording

**Pedal Forces**

Both right and left cranks of the cycle ergometer were equipped with the pedal forces measurement system. This device, where the pedal is screwed on, is based on two orthogonal sensor systems, both tangential and radial pedal force components were measured with an error of < 1% and 2%, respectively. The accuracy and the validity of the Powertech system have been described in the literature (Stapelfeldt et al., 2007). A magnetic switch was used as position signal for the left pedal top dead center. The crank length was 0.18 m. The force signal was acquired with a sampling frequency of 2 kHz and processed with a multichannel analogue–digital converter. Pedal force signal was recorded over a 3 s duration period during each P_{\text{max}} test and over a 5 s duration period at the 2nd and 13th min of each 15 min period (T_1, T_2, T_3) of cycling exercise (Fig. 1).

**EMG data**

EMG signals from superficial muscles of the right lower limb were recorded using pre-amplified bi-polar surface EMG (Delsys, Trigno Wireless, Boston, Massachusetts, USA). Surface electrodes were positioned lengthwise over the middle of the BF, RF, vastus lateralis (VL), GM, soleus (Sol) and tibialis anterior (TA) muscle belly with an interelectrode (center-to-center) distance of 20 mm and placed according to SENIAM’s recommendations. Low resistance between the two electrodes (< 5 kΩ) was obtained by abrading and cleaning the skin using alcohol. EMG signal was acquired with a sampling frequency of 2 kHz and processed with a multichannel analogue–digital converter. EMG signal was recorded on a 3 s period during each P_{\text{max}} test and on a 5 s period at the 2nd and 13th min of each 15 min period (T_1, T_2, T_3) of cycling exercise (Fig. 1).

Energetic parameters

Oxygen uptake (\(\dot{V}O_2\)) and respiratory exchange ratio (RER) were monitored breath to breath at rest and during the entire experimental session, using a gas exchange analyzer (K4B2, Cosmed, Rome, Italy) and stored on a personal computer. The gas analyzer was calibrated using gases of known concentrations before each session. Heart rate was also continuously recorded throughout experimental sessions by means of a heart rate monitor system.

Data analysis

**Pedal forces and power output**

Right-side pedal forces were analyzed over 3 s during P_{\text{max}} and 5 s during constant-load cycling, respectively. The force signals were filtered with a cut-off frequency of 15 Hz. Positive and negative peak force (PF+ and PF−, respectively) were recorded for each crank revolution and for both tangential (effective force: \(F_E\)) and radial (ineffective force: \(F_I\)) forces, were averaged during each analysis period (i.e., 3 s during P_{\text{max}} and 5 s during steady-state cycling). Maximal power output during P_{\text{max}} tests was computed as the product of \(F_E\), crank length (0.18 m) and angular velocity (θ)

\[
P = F_E \times 0.18 \times \theta
\]  \[2\]
Pedalling effectiveness (IE) was calculated as the ratio between the $F_t$-time integral and the $F_{tot}$ ($=|F_e|/|F_l|$) time integral during the full revolution

$$IE(\%) = 100 \times \frac{\int_0^{2\pi} F_t(\theta) d\theta}{\int_0^{2\pi} F_{tot}(\theta) d\theta}$$  \[3\]

EMG data

All data post-processing was performed in MATLAB (Version 7, MathWorks Inc., Natick, Massachusetts, USA). EMG was filtered using a fourth-order band-pass Butterworth filter with low and high frequencies of 10 and 500 Hz, respectively. Root mean square EMG (EMG$_{rms}$) was calculated for each muscle over each analysis period. The calculations were made over three completed consecutive crank cycles during constant-load cycling, and over six consecutive crank cycles for cycling sprints (i.e., $P_{max}$ tests). EMG$_{rms}$ were also interpolated at 10° increments of crank angle relative to top dead center (0°). The interpolated EMG$_{rms}$ were scaled to the maximum EMG$_{rms}$ value occurring for each muscle during first $P_{max}$.

GE

$\text{VO}_2$ and RER were averaged every 30 s. GE was calculated during each 15 min period of cycling exercise (i.e., $T_1$, $T_2$ and $T_3$), by the following equation:

$$\text{GE}(\%) = 100 \times \left[ P/(\text{VO}_2 \times \text{EqO}_2) \right]$$  \[4\]

where $P$ is the mechanical power output developed during steady state, $\text{VO}_2$ is the averaged oxygen consumption at steady state (L/s), $\text{EqO}_2$ is the energetic equivalent for $O_2$, which is calculated by the following equation (Jéquier et al., 1987):

$$\text{EqO}_2 (\text{kJ/L}^{-1}) = 4.686 + 1.096(\text{RER} - 0.705)$$  \[5\]

To obtain a valid determination of muscular efficiency, the oxygen consumption was measured at steady state and under strict aerobic conditions ($P$ corresponded to 75% of MAP and the RER did not exceed 0.85). HR was averaged during each 15 min period of steady state cycling exercise.

Statistics

Ordinary statistical methods, including means and standard deviations, were calculated for each parameter. Separate two-factors (pedalling condition $\times$ time) ANOVAs with repeated measures on time were performed to compare dependent variables (GE, $\text{VO}_2$, HR, EMG$_{rms}$, IEP, peak forces, $P_{max}$) associated with rest (only for $P_{max}$) and with each of the three periods (i.e., $T_1$, $T_2$ and $T_3$) of steady-state cycling. A separate two factors (pedalling technique $\times$ crank angle) ANOVA was performed to compare EMG$_{rms}$ associated with downstroke ($0^{\circ}$–$180^{\circ}$) and upstroke ($180^{\circ}$–$360^{\circ}$) phases. Post hoc analyses (HSD Tukey) were used to test differences among pairs of means, when appropriate. A level of $P<0.05$ was used to identify statistical significance. The statistical analyses were performed by using Statistica software for Windows (Statsoft, version 6.1, Statistica, Tulsa, Oklahoma, USA).

Results

Pedalling pattern

Mean power output during steady-state cycling, corresponding to 75% of the MAP, was 208 ± 33 W. The index of force effectiveness did not significantly change throughout the steady-state cycling, whatever exercise condition. IE was significantly ($P<0.05$) greater during cycling exercise with feedback (41.4 ± 5.5%), than during PT session (36.6 ± 4.1%). Effective and ineffective pedal forces plots are presented in Fig. 2a and b. Both negative and positive peaks of $F_e$ were significantly ($P<0.05$) lower during FB session (246 ± 43 and −45 ± 15 N, respectively) than during PT session (265 ± 33 and −55 ± 12 N, respectively). Similarly, both negative and positive peaks of $F_l$ were significantly ($P<0.05$) lower during FB session (250 ± 48 and −50 ± 25 N, respectively) than during PT session (283 ± 52 and −78 ± 24 N, respectively).

During steady-state cycling, statistical analyses did not report significant time effect on muscular activity for all studied muscles, whatever the pedalling condition. Statistical analyses showed a trend ($P=0.07$) for RF muscle activity to decrease during downstroke phase with feedback, compared with PT condition. In contrast, both BF and RF muscles activity significantly ($P<0.05$) increased during the upstroke phase, when cycling with feedback. During FB session, VL muscle activity significantly ($P<0.05$) decreased during downstroke phase, in comparison with PT session (Fig. 3). GM, TA and Sol muscle activity patterns were similar for both conditions.

Fig. 2. Mean effective (a) and ineffective (b) force traces during full crank cycle for both cycling sessions: feedback (FB) vs preferred technique (PT). Statistical analyses compared peak force for effective ($F_e$) and ineffective ($F_l$) components among both conditions; *$P<0.05$, PT > FB.
**Muscular fatigue**

Before exercise, maximal power output was similar for both sessions and reached, on average, 944 ± 187 W. During FB session, $P_{\text{max}}$ significantly decreased after 30 min ($T_2, P < 0.05$) and 45 min ($T_3, P < 0.05$) in comparison with initial values (Fig. 4). During PT session, $P_{\text{max}}$ also significantly decreased after 15 min ($T_1, P < 0.001$), 30 min ($T_2, P < 0.001$) and 45 min ($T_3, P < 0.001$) in comparison with initial values. At the end of cycling exercise ($T_3$), the reduction of $P_{\text{max}}$ was significantly greater for PT condition (−15 ± 9%) than for FB condition (−7 ± 12%) (Fig. 4).

During $P_{\text{max}}$ exercise, the VL muscle activity decreased throughout both PT and FB cycling exercise. During the last cycling sprint, the reduction of EMG$_{\text{rms}}$ for VL muscle was significantly ($P < 0.05$) greater with PT (≈ −17% of RMS$_{\text{max}}$), than with feedback (≈ −10% RMS$_{\text{max}}$). RF muscle activity during $P_{\text{max}}$ significantly ($P < 0.05$) decreased throughout PT, (≈ −20%, at the end of exercise), but did not change during exercise with feedback. During the last $P_{\text{max}}$, RF muscle activity was significantly ($P < 0.05$) lower for PT session (77 ± 15% of pre-value) than for FB session (90 ± 14% of pre-value). BF and GM muscles activity were significantly ($P < 0.05$) reduced from the second $P_{\text{max}}$ (after 15 min of exercise, $T_1$) in a similar extent, whatever the pedalling condition. At the end of exercise BF muscle activity corresponded to 77 ± 15% of pre-values, and RF muscle activity to 80 ± 15% of pre-values. TA and Sol muscles activity during $P_{\text{max}}$ did not significantly change during both cycling conditions.

**GE**

During the first 15 min of cycling exercise ($T_1$), GE was significantly ($P < 0.05$) lower with the pull-up technique (i.e., FB session) in comparison with the
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During the last 30 min of cycling exercise ($T_1$ and $T_2$), GE did not significantly differ between both sessions (FB: 19.7 ± 2.0 vs PT: 19.7 ± 1.8).

Averaged HR did not significantly change between the two pedalling techniques (148 ± 17 bpm and 150 ± 13 bpm, respectively). Whatever the pedalling technique, HR significantly ($P < 0.05$) increased during $T_3$ (151 ± 17 bpm) in comparison with $T_1$ (146 ± 14 bpm).

**Discussion**

The purpose of the present study was to examine the influence of pedalling technique on the energetic demand and on the occurrence of muscular fatigue during prolonged cycling exercise. Modifications of pedalling technique toward a “pulling pattern” were guided by a force-feedback, allowing the subjects to change the direction of forces applied on the pedals. The use of force-feedback during cycling reduced the negative and positive peak torques during crank cycle. The changes in mechanical pattern only increased the energetic cost at the beginning of exercise and reduced muscular fatigue.

**Mechanical pattern**

Our results confirmed the influence of force-feedback on pedalling pattern during a steady-state exercise (Mornieux et al., 2008) as well as on forces applied to the pedals (Sanderson & Black, 1990). Indeed, during the preferred pedalling technique condition (i.e., without feed-back), negative torque during the upstroke phase corresponded to 21% of the positive torque produced during the downstroke phase. In contrast, with an on-line feedback, both negative peak torque during upstroke phase and positive peak torque during downstroke phase significantly decreased. These findings are consistent with those reported by Mornieux et al. (2008) but the present study adds to the existing data by extending them to prolonged cycling exercise (45 min). In both conditions (i.e., with and without feedback), no significant effect of time was observed on pedalling force traces, suggesting that subjects were able to quickly (<2 min) modify their pedalling technique thanks to the feedback, and that the adopted mechanical pattern remained stable throughout prolonged exercise, despite the occurrence of neuromuscular fatigue. These findings are consistent with previous works (Sarre et al., 2005) that have also reported a relative stability of the mechanical pattern during comparable fatiguing protocol (1 h, 65% of MAP).

**Muscular fatigue**

The results of the present experiment also showed a significant reduction of maximal power output after 15 min of exercise, whatever the adopted pedalling technique. However, at the end of exercise, a decrease in $P_{\text{max}}$ was lower in the feedback condition than without feedback. The reduction of maximal power output during intense effort such a sprint has been frequently used to demonstrate the occurrence of muscular fatigue during cycling exercise (Fritzsche et al., 2000; Kay et al., 2001; St. Clair Gibson et al., 2001). In the present study (45 min at 75% of MAP), the reduction of maximal power output reached approximately 15% at the end of exercise with the spontaneously adopted pattern. This result was consistent with a previous study by Fritzsche et al. (2000), which reported that the maximal power output developed during a cycling sprint (4 s) decreased 15% after 2 h of cycling at 62% of MAP. Kay et al. (2001) have also shown that the reduction of maximal power output developed during prolonged sprint (1 min) reached 13% after 50 min cycling exercise, performed at 75% of MAP. In our study, after cycling exercise with feedback, the reduction of $P_{\text{max}}$ was significantly lower (≈ 7%) compared with
the session with the PT, suggesting that pulling action could limit neuromuscular fatigue following prolonged exercise. Neuromuscular alteration fatigue responsible of the reduction of maximal power production in cycling can be evidenced by a reduction of EMG signal during maximal voluntary exercises (Lepers et al., 2000, 2002). For example, Kay et al. (2001) have demonstrated that the reduction of maximal power output was paralleled by a reduction of EMG activity of RF muscle. In the present study, the reduction of maximal power output was accompanied by a reduction of the majority of studied muscles (VL, RF, BF, and GM) from the first 15 min of exercise, whatever the pedalling condition. Nevertheless, at the end of exercise, the reduction of both RF and VL EMG activity was lower during feedback condition, than with PT. These findings suggested that fatigue of RF and VL muscles was reduced in the feedback condition.

Given that neuromuscular fatigue depends on the intensity of muscular contractions (Enoka & Stuart, 1992), one can hypothesize that the observed reduction of knee extensor muscle fatigue could be due to the decrease in muscular strains during downstroke phase (i.e., leg extension). Indeed, the present results showed that VL muscle activity was reduced during leg extension when using the feedback. These results contrasted with those observed in a previous study (Mornieux et al., 2008), which showed that modifying the upstroke phase (i.e., reduction of negative torque) did not result in a significant reduction of knee extensors work. Nevertheless, in the present study, modifications of muscular activity were consistent with the modifications of mechanical pattern observed in the feedback condition. Indeed, the pulling technique induced an increase in BF and RF muscles activation during upstroke phase, allowing a significant diminution of muscular work during knee extension of the opposite leg during downstroke phase. Considering that knee extensor muscles produce the main proportion of mechanical work during steady-state cycling (Ericson, 1988; Broker & Gregor, 1994, respectively), it could be suggested that the diminution of VL muscles strains during constant-load cycling with feedback mainly explained the lesser reduction of maximal power output compared with PT.

Mechanical efficiency

Recently, Korff et al. (2007) have evidenced that the increase of knee flexor muscles activity during pulling action could alter GE during steady-state cycling. These authors assumed that their results could be partly explained by the fact that flexor and extensor muscles could have different metabolic properties (e.g., mitochondrial and capillary density), as a result of long-term training adaptations. In addition, during cycling with feedback, controlling the direction of external force applied to the pedal may induced modifications of inter-muscular coordination (Van Ingen Schenau et al., 1992), which could also alter power production efficiency (Wakeling et al., 2010).

However, in the present study, while cycling with feedback resulted in significant modification of pedalling pattern, the effect on GE appeared to be quite limited. Indeed, change in pedalling technique altered GE mainly during the first bouts of exercise (15 min) and not during the last 30 min of cycling (from 15 to 45 min). The increase of oxygen consumption with feedback at the beginning of exercise was in accordance with previous works (Korff et al., 2007; Mornieux et al., 2008). For example, Korff et al., 2007 reported an alteration of GE with pulling technique over a 6 min period. Cannon et al. (2007) showed that modifying pedalling technique, by increasing ankle dorsiflexion into the pedal stroke, also decreased GE. In the present study, although mechanical pattern and muscle coordination were continuously modified throughout the feedback session, the GE was only altered at the beginning of exercise. One can conclude for these findings that, in previous studies, the short time allowed (<6 min) to adopt a different pedalling technique may have hidden the influence of pedalling technique on GE (Cannon et al., 2007; Korff et al., 2007; Mornieux et al., 2008).

Furthermore, Korff et al. (2007) hypothesized that the preferred pedalling technique was the most efficient, because it results from long-term training adaptations. Whatever the mechanical pattern of pedalling technique, it seems that the physiological and coordinative adaptations to training could mainly determine the energetic cost during cycling exercise. Consequently when comparing with PT, the effect of the modification of mechanical pattern on GE, by temporarily modifying pedalling technique with feedback, could be underestimated. Yet, in the present study, no significant influence of pedalling technique has been observed on averaged oxygen consumption during 45 min cycling exercise. To conclude on the relation between pedalling technique and cycling performance, it seems thus necessary to test the impact of IE on GE after a training period focusing on the reduction of negative force during upstroke.

Perspectives

The present experiment showed that the use of force-feedback during steady-state cycling led to a modification of pedalling technique that improved mechanical effectiveness. In addition, modifications
of pedalling technique induced significant change in muscular coordination, including a reduction of VL and RF muscles activities during leg extension. Reduction of muscular strains during leg extension presumably limited the occurrence of muscular fatigue after a prolonged cycling exercise. Considering its potential impact on cycling performance, these last results have practical implications and should be considered when creating coaching plans or training interventions. However, while mechanical effectiveness was improved by the use of feedback, the modifications of coordinative pattern did not significantly influence GE. To explain this result, it was hypothesized that flexor muscles could be less efficient that extensor muscles, due to long-term adaptation to training effect that could limit the interpretation of present findings. Future longitudinal studies will need to examine the effect of pedalling technique on GE after a specific training period with feedback.

**Key words:** EMG, oxygen uptake, pedal forces, muscle coordination.

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