Effect of Supra-Lactate Threshold Training on the Relationship between Mechanical Stride Descriptors and Aerobic Energy Cost in Trained Runners

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Abstract

The aim of this study was to determine the effect of endurance training on the relationship between mechanical stride descriptors (stride rate and stride rate variability) and the aerobic energy cost that would be decreased by training in an all-out supra-lactate threshold run.

Six long distance runners (175 ± 6 cm; 72 ± 9 kg; 27 ± 4 years) performed two identical track tests before and after 8 weeks of supra-lactate threshold training: an incremental test and a constant load test at 50% of the velocity difference between the lactate threshold and VO₂max (vΔ50). During the constant load test, aerobic energy cost (EC), stride rate (SR) and stride rate variability (SRV) were measured. The constant load tests were carried out before and after training at the same absolute intensity, in order to compare stride mechanical descriptors.

Our results show that after eight weeks of intermittent running at vΔ50, the velocity associated with VO₂max (v VO₂max) increases (p = 0.03) due to the decrease of running economy (RE, p = 0.02), and not due to an increase in VO₂max (p = 0.5). EC remained unchanged with training (p > 0.1), but SRV was significantly reduced (p < 0.03). No relationship was observed before and after training between the stride rate variability and the aerobic energetic cost (rs < 0.5; p > 0.05).

This study indicates that because of the initial level of the runners, endurance training has not induced an increased VO₂max, but a decrease of the SRV. Further studies have to be conducted with more subjects in order to elucidate the mechanisms underlying this decrease in SRV which is observed with training.

Keywords: Oxygen kinetics, training, running, stride rate variability.

Introduction

Numerous authors have shown that mechanical parameters such as stride frequency and stride rate variability are related to the oxygen cost (Högberg, 1952ab; Cavanagh & Williams, 1982; Candau et al., 1998). These authors have suggested that runners naturally choose the most economical stride rate and they have demonstrated significant relationships between this rate and the oxygen consumption during supra-lactate threshold constant-load exercise. Moreover, an increase in stride rate variability (SRV) has been reported during fatigue. It has been suggested that since a large variability is not favourable for maintaining an optimal step frequency, the increase in step rate variability observed during fatigue could partly explain the increase in aerobic energy cost (EC) observed at the end of the exercise (Candau et al., 1998). Therefore step rate variability could be related to the aerobic energy cost during supra-lactate threshold constant load exercise. However, no study has investigated the possible modifications of this SRV with training and its relationships with the kinetics of oxygen uptake or EC.

Figure 1 illustrates a typical increase of the oxygen kinetics. For moderate constant-load cycle exercise (i.e., below lactate threshold) it has been shown that endurance training influences the kinetics of oxygen uptake. Moreover, several studies have reported that following an endurance training
program, the slope of the fast component is increased (Hickson et al., 1978; Hagberg et al., 1980; Yoshida et al., 1992; Phillips et al., 1995). Several studies have evaluated the effects of training above the lactate threshold on the VO2 slow component (defined in these studies as the increase in VO2 between 3 and 6 min of exercise; Casaburi et al., 1987; Womack et al., 1995) and they have shown that this type of training reduces the VO2 slow component for the same absolute power output. A recent study has shown that 6 weeks of endurance training results in a significant reduction in the amplitude of the VO2 slow component for the same absolute treadmill running speed (Jones & Carter, 2000). Although the reductions in blood lactate, ventilation, heart rate and plasma catecholamine levels accompanying endurance training, could partly explain the reduction in the aerobic energy cost of a supra-lactate exercise after training (Jones & Carter, 2000). However, other factors, such as mechanical stride descriptors, could be related to the modification in the kinetics of oxygen uptake or EC to endurance training. Indeed, most running endurance training sessions do not focus on mechanics. To improve performance of runners, it would be very interesting to integrate some running mechanics training into a classical training session. Few studies have focused on the effect of endurance training on stride mechanical parameters that may easily be verified by the trainer.

Therefore, this work was designed to study the effect of supra threshold training on the relationship between mechanical stride descriptors and the kinetics of oxygen uptake or the aerobic energy cost in an exhaustive supra-lactate threshold constant speed run. We made the hypothesis that training could induce a reduction of SRV that would be linked to a reduction in the aerobic energy cost at the end of a supra-threshold all-out run (C_end).

To test this hypothesis, good endurance runners performed an all-out severe run at the same absolute intensity (in order to compare mechanical parameters) before and after eight weeks of supra-threshold training.

**Methods**

**Subjects**

Six well-trained runners (175 ± 6 cm, 72 ± 9 kg, 27 ± 4 years) gave their consent in accordance with the guidelines of the University of Lille, to participate in the 8 weeks supra-threshold training program and to the test session. All subjects were highly motivated and familiar with symptoms of fatigue during heavy exhaustive running exercise.

**Experimental procedure**

Pre-training tests comprised:

*An incremental test (3-min stages) to exhaustion.* This test was performed on track in order to determine the maximal oxygen consumption (VO2max). This parameters was defined as the highest 30 s VO2 value attained during the test. The velocity associated with VO2max (v VO2max) was defined as the
At the time of all tests, pulmonary gas exchange measurements were carried using a breath by breath portable gas analyser (Cosmed K4b2, Roma, Italy, Hausswirth et al., 1997; McLaughlin et al., 1999). Before each test, O2 and CO2 analysers were calibrated using ambient air and sample gas references. The flowmeter was calibrated with a 3-l syringe (Quinton instruments, Seattle, USA). The O2 analyser is an infrared analyser with precision of 0.05 to 0.1% and a time analyse of about 100 ms. The O2 analyser is a paramagnetic system with a time analyse of 150 ms and a precision of 0.003%.

The fingertip capillary blood samples were collected into a capillary tube and were analysed for blood lactate concentration using a Doctor Lange (GmbH, Berlin, Germany).

Data analysis

The breath by breath oxygen uptake data of the constant load test were reduced to 5 s averages. These data were smoothed to reduce the noise so as to enhance the underlying characteristics and were then fitted to a double exponential model (Barstow & Mole, 1991), using an iterative non-linear regression on Sigma Plot software (SPSS, Chicago, IL, USA). The oxygen uptake kinetic parameters were obtained using a double exponential model where the first component accounted for the VO2 fast component and the second component accounted for the VO2 slow component. The VO2 initial component (phase 1), resulting from a sudden change in the venous blood return in combination with a small change in the mixed venous gas tension (Phillips et al., 1995), does not have to be fitted because breath by breath data had been reduced to 5 s averages and there were not enough points to determine the phase 1. Moreover, Whipp & Ozyener (1998) have suggested previously that the phase 1-phase 2 transition can be directly determined from the beginning of the decrease in the respiratory exchange ratio. This is often not precise enough because of the ‘noise’ in the data on a single transition. The oxygen uptake kinetics were described as a function of time using the following equation:

\[
\dot{V}O_2(t) = y_0 + A_1 \times (1 - e^{-(t-TD_1/\tau_1)}) \times U_1 + A_2 \times (1 - e^{-(t-TD_2/\tau_2)}) \times U_2
\]

(1)

Where, ‘\(y_0\)’ is the basal oxygen consumption, ‘\(A_1, A_2\)’ are the fast and slow component (exponential terms) of oxygen consumption, ‘\(\tau_1, \tau_2\)’ are the time constants of these exponential terms. ‘TD1, TD2’ (in seconds), indicate the times at which the first and second amplitude of VO2 begin.

\(U_1 = 0\) for \(t < TD1\) and \(U_1 = 1\) for \(t \geq TD1\)

\(U_2 = 0\) for \(t < TD2\) and \(U_2 = 1\) for \(t \geq TD2\)

Equation 1 by replacing time (t) allows one to obtain the value of \(\dot{V}O_2(t)\) 3 min after the beginning of the exercise, and 1 min before exhaustion. These values were divided by the running speed (expressed in m.min\(^{-1}\)) and the weight of the

An all-out test at vΔ50 until exhaustion. Runners followed a pacing cyclist travelling at the required velocity. The cyclist received audio cues via a walkman, the cue rhythm determining the speed needed to cover 20 m. Visual marks were set at 20 m intervals along the track (inside the first lane). During this test session, runners were filmed by a video camera (Hitachi) at 25 Hz. Twenty steps were analysed 3 min after the beginning (non-fatigued state) of the test and twenty more steps 1 min before exhaustion (fatigued state). Velocity of locomotion was controlled by photo-cells (Brower timing systems, USA, Utah, Salt Lake City) placed at the extremities of the camera area (30 m).

The subjects completed an eight week endurance training program which was composed of two interval-training sessions and three continuous sessions per week. The interval-training involves repeated short to long bouts of rather high intensity exercise (equal or superior to maximal lactate steady-state velocity) interspersed with recovery periods (light exercise or rest). During the interval-training sessions, the duration of the severe and moderate runs was respectively set at 50% and 25% of the running time until exhaustion at the pre-training vΔ50, giving a work/rate duration ratio of 2/1 (Renoux et al., 1999; Billat et al., 2000). The interval-training sessions were run at the pre-training vΔ50 for the severe runs and at 50% of the pre-training vVO2max for the moderate runs. The subjects performed either n minus 1 or n minus 2 intervals during the interval-training sessions, where n was the maximal number of intervals that could be run by a subject. This parameter was recorded during the first and the eighth interval-training sessions. The training volume at this intensity was increased during the eight weeks of training. For example, subjects who were able to run 4.1 ± 0.7 intervals during the first session, were then able to run 5.3 ± 0.7 intervals during the eighth session. The continuous (recovery) sessions were run for one hour at 60–70% of the pre-training vVO2max.

Post-training tests comprised:

An incremental test and a run at vΔ50. Performed at the same absolute velocity as in the pre training test in order to compare stride mechanical parameters. All the tests and training sessions were performed on a synthetic track, at the same time of day for a given subject.

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Supra-threshold Training Decreases Stride Rate Variability

Subjects were trained for 8 weeks, consisting of 3 days per week of interval training at 90% of lactate threshold intensity. Training had significantly decreased the stride rate variability (SRV; \( p = 0.03 \)) and at the end of the exercise (EC\(_{\text{end}}\)) expressed in m\(\text{l}O_2\cdot\text{m}^{-1}\cdot\text{kg}^{-1}\).

Cine films were analysed using a video tape recorder with a double framework which allows one to obtain 50 frames per s and thus to decrease the error of measurement to approximately 3%. Therefore, by counting the number of images for a stride and the number of strides over a calibrated area (30 meters), it was easy to obtain the step rate (SR) by a simple calculation (equation 2). By this procedure, calculation of the average SR and the coefficient of variation of SR (SRV), called stride rate variability, were made 3 min after the beginning of the test (non fatigued state), and 1 min before exhaustion (fatigue state). Velocity was calculated by dividing the distance (30 m) by the time taken to cover this distance. Step length (SL) was deduced from the equation 3:

\[
SR(\text{Hz}) = \frac{1}{\text{images for one step } \times 0.02} 
\]

\[
SL = \frac{\text{Velocity (m.s}^{-1})}{SR(\text{Hz})} 
\]

0.02 express in s, is the time between two successive pictures.

Statistical analysis

Statistical analysis was performed using the Wilcoxon paired comparisons test. The correlation between bioenergetic and mechanical characteristics were determined using the Spearman correlation coefficient. All of these analyses were carried out using Statview 4.5 (Berkeley, CA), and the level of statistical significance was set at \( p = 0.05 \).

Results

Effects of training on the aerobic parameter and performance (i.e., running time until exhaustion)

Table 1 shows that the endurance training program significantly improved \( \dot{V}O_2\text{max} \) (\( p = 0.03 \)), \( v\Delta50 \) (\( p = 0.02 \)), RE (\( p = 0.02 \)). However, \( \dot{V}O_2\text{max} \) did not change significantly (\( p = 0.5 \)) after training. Average time until exhaustion was not significantly increased by endurance training (\( p = 0.2 \)).

Table 2 shows that only \( \tau_1 \) was decreased significantly after training (\( p = 0.03 \)). The \( \dot{V}O_2 \) slow component was not significantly modified (\( p = 0.3 \)). Similarly aerobic energy cost at the beginning and at the end of exercise were not decreased (\( p > 0.1 \)).

Effects of training on aerobic energy cost, stride rate and stride rate variability

As shown in Table 3, stride rate variability had decreased significantly after training, both for the fatigued (SRV\(_{\text{F}}\); \( p = 0.03 \)) and the non fatigued state (SRV\(_{\text{NF}}\); \( p = 0.03 \)). Endurance training had significantly enhanced the stability of the stride rate during an exhaustive run at \( v\Delta50 \). However, we did not notice any significant difference between step rate before and after training for the non fatigued (SRV\(_{\text{F}}\)), or the fatigued state (SRV\(_{\text{F}}\)) (respectively \( p = 0.2 \); \( p = 0.5 \)). It is interesting to note that after training the stride rate variability did not show any further increase with exhaustion.

Neither EC\(_{\text{beg}}\) nor EC\(_{\text{end}}\) were correlated with SRV\(_{\text{NF}}\), SRV\(_{\text{F}}\), SRV\(_{\text{NF}}\) or SRV\(_{\text{F}}\) before or after training (Table 4).

Only two parameters, the slope of the \( \dot{V}O_2 \) fast component and the stride rate variability measured during the constant load intensity test were significantly modified by training. However, the decrease in SRV\(_{\text{NF}}\), was not correlated with the decrease in \( \tau_1 \) (\( r_s = 0.5 \); \( p = 0.2 \)).

Discussion

These data show that a supra lactate endurance training had significantly improved the running economy, \( v\Delta50 \) and \( \dot{V}O_2\text{max} \). However, in contrast to our hypothesis during constant load exercise the aerobic energy cost was not related to SRV, nor was decreased by training. Only \( \tau_1 \) and...
the stride rate variability were reduced, but no relationship was observed between the changes in SRV and τp.

Table 3. Training effects on the stride rate (SR) and the stride rate variability (SRV) in non fatigued (NF) and fatigued (F) subjects.

<table>
<thead>
<tr>
<th>Mechanical parameters</th>
<th>Before training</th>
<th>After training</th>
</tr>
</thead>
<tbody>
<tr>
<td>SRNF (hz)</td>
<td>2.88 ± 0.15</td>
<td>2.91 ± 0.12</td>
</tr>
<tr>
<td>SRF (hz)</td>
<td>2.93 ± 0.17</td>
<td>2.94 ± 0.14</td>
</tr>
<tr>
<td>SRVNF (%)</td>
<td>3.80 ± 0.83</td>
<td>2.87 ± 0.41</td>
</tr>
<tr>
<td>SRF (%)</td>
<td>4.49 ± 1.13</td>
<td>2.82 ± 0.46*</td>
</tr>
</tbody>
</table>

* Significantly improved from pre-training (p ≤ 0.05).

Table 4. Correlation between aerobic energetic cost (EC), stride rate (SR) and stride rate variability (SRV) in non fatigued (NF) and fatigued (F) subjects.

<table>
<thead>
<tr>
<th></th>
<th>Before training</th>
<th>After training</th>
</tr>
</thead>
<tbody>
<tr>
<td>ECbegin vs SRNF</td>
<td>rs = -0.20</td>
<td>p = 0.6</td>
</tr>
<tr>
<td>ECend vs SRF</td>
<td>rs = -0.10</td>
<td>p = 0.7</td>
</tr>
<tr>
<td>ECbegin vs SRF</td>
<td>rs = 0.30</td>
<td>p = 0.5</td>
</tr>
<tr>
<td>ECend vs SRVNF</td>
<td>rs = -0.06</td>
<td>p = 0.9</td>
</tr>
<tr>
<td>ECend vs SRF</td>
<td>rs = -0.01</td>
<td>p = 0.9</td>
</tr>
</tbody>
</table>

The absolute intensity of the all-out post training test is lower than before training, thus, the amplitude of the slow component would have been reduced (Billat, 2000). However, the training did not have any effect on the VO2 slow component. This can be in relation to the fact that the training program did not induce any increase of VO2max as it was the case in previous studies performed in novice subjects (Casaburi et al., 1987; Womack et al., 1995). The stability of the slow component after training has induced a stability of the aerobic energy cost (EC) (Jones & Carter, 2000). Thus, for the same absolute speed runners do not decrease their energy consumption after training. But, if the impact of training on VO2max had been higher than in the present work, we don’t know what would have been the effect on the amplitude of the VO2 slow component or EC.

Most of the current studies have found that the training program did not modify mechanical stride parameters such as stride rate or stride length (Williams & Cavanagh, 1987; Bailey & Messier, 1991; Lake & Cavanagh, 1996; Franch et al., 1998). The present results have confirmed these studies showing that stride rate appears to be resistant to change due to endurance training. However, the effect of training on stride rate variability has never been studied and in the present study we have shown that SRVNF as SRF were significantly reduced after endurance training. Stride rate variability computed as the ratio between standard deviation of step rate and the average of 20 steps rate expresses the regularity of the step length. A variation in that step length will disturb the anteroposterior and vertical movements of the centre of mass (Cavagna et al., 1991). These additional movements of the mass centre involve in an increase of kinetics, and potential energy variation, which provoke an increase of mechanical work. So, the improvement of SRV with training could reduce these additional movements of mass centre and could involve in a decrease of mechanical cost. However, direct measurements of the effect of the training on kinetics and potential work of the centre of mass are necessary to confirm this hypothesis. Moreover, SRV was significantly affected by fatigue and have demonstrated consistent relationship with aerobic energy cost (Belli et al. 1995; Candau et al., 1998). These authors proposed that the increase in SRV at the end of an exercise is not favourable for maintaining an optimal step frequency and thus a low aerobic energy cost (Candau et al., 1998). Step rate has to be controlled very accurately to match the optimal step frequency in order to improve leg stiffness (Cavagna et al., 1991). If an energy elastic loss potential occurs (impute to a lawlessness of the rhythm of the step rate), it will induce an increase of work during push-of-phase and thus an increase of energy expenditure (Kram & Taylor, 1990; Komi, 2000). Thus, the fatigue process provokes a loss of elastic energy potential that is responsible for an increase in strength associated with an increase in the aerobic energy cost (Komi, 2000) and for a possible increase in SRV. The results of the present study point of view, this indicates that training sessions, after rest periods, should include specific exercises in order to improve RE.
Supra-threshold Training Decreases Stride Rate Variability

Fig. 2. Explanation of the effect of training on the relationship between oxygen consumption (VO$_2$), running economy (RE) and running speed during the incremental test

have only demonstrated that although exhaustion has provoked a slight increase of SRV before training (non significant), there was not relationship between SRV and EC before or after training (Table 4). Thus a direct relationship between aerobic energy cost and SRV must be taken with care, however the elastic energy loss that occurs with fatigue (Komi, 2000) could be associated effectively to an increase of SRV. Indeed, the training decreases significantly SRV in such a way that after training SRV remains unchanged even with exhaustion. Therefore, it can be hypothesised that training would reduce muscle damage induced by the fatigue process and would enhance leg stiffness and thus stride rate variability. Finally, this study has demonstrated that during the constant load exercise, only two parameters have been modified with training: the stride rate variability and the slope of the fast VO$_2$ component ($\tau_1$). The decrease in $\tau_1$ has already been observed by numerous authors (Hickson et al., 1978; Hagberg et al., 1980; Yoshida et al., 1992; Phillips et al. 1995). They have suggested in one hand that the heart rate time constant can be reduced by 49% and thus the heart rate as the kinetics of oxygen uptake increase more rapidly towards its steady-state at the trained state. On the other hand, the oxygen speed utilization by the active muscles can be improved at the onset of exercise (Yoshida et al., 1992; Phillips et al., 1995) with training and could also provide a good explanation of the decrease of $\tau_1$. The decrease in $\tau_1$ was not linked to the decrease in SRV. So, this observation may provide an argument to the hypothesis following which SRV would be bounded to passive muscles structures (i.e., elastic structures) more than that active muscles structures and aerobic energy cost. Indeed, if SRV and $\tau_1$ have been correlated, the decrease of SRV with training could be related to the improvement of the utilisation of the oxygen by muscle and thus aerobic energy cost.

Thus, the reduction of SRV with training is independent from the aerobic energy cost. But this reduction of SRV, if confirmed by other studies with more subjects, may be very interesting from a training point of view. Indeed, these mechanical parameters can be checked by the trainer and the runner. During interval training sessions some mechanical instructions concerning SRV could be added to classical method of training (Billat, 2001). For example, the trainer could give specific instructions about the cadence of the step rate. Using this method, neuromuscular control and leg stiffness could be improved more rapidly.

Nevertheless, the mechanisms responsible for such training adaptation have not been established, further studies focusing on the effect of training on the elastic properties of the muscle-tendon and muscle damage have to be conducted to elucidate the underlying mechanisms of the decrease which was been observed in of SRV with training.

In conclusion, this study has shown that training significantly improves running economy, $\nu$$\Delta$50, and $\nu$ VO$_{2\text{max}}$ but without any improvement in VO$_{2\text{max}}$ in our previously well trained runners. Stride rate variability was also improved and seems to be related to the storage and recoil of elastic energy. However, in contrast to our initial hypothesis no relationship was observed between the stride rate variability and aerobic energetic cost. The nature of the linkage between the aerobic energy cost at the end of the exercise and the mechanical stride parameters remains unclear, and further studies need to be conducted in order to document the change in neuro-
muscular activity during constant-load exercise before and after training.

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