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# Cycling efficiency and time to exhaustion are reduced after acute passive stretching administration

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**The aim of this study was to assess the effects of acute passive stretching on cycling efficiency during an exercise of heavy intensity. After maximum aerobic power ($\dot{V}O_{2max}$) assessment, nine active males ($24 \pm 5$ years; stature $1.71 \pm 0.09$ m; body mass $69 \pm 7$ kg; mean $\pm$ standard deviation) performed tests at 85% of $\dot{V}O_{2max}$ ($\dot{W}_{85}$) until exhaustion, with and without pre-exercise stretching. During the tests, we determined the gas exchange, metabolic and cardiorespiratory parameters. With stretching, no differences in $\dot{V}O_{2max}$ occurred ($3.64 \pm 0.14$ vs $3.66 \pm 0.07$ L/min for stretching and control, respectively). During $\dot{W}_{85}$, pre-exercise stretching (i) decreased time to exhaustion ($t_{lim}$) by 26% ($P<0.05$); (ii) increased average $\dot{V}O_2$ by 4% ($3.24 \pm 0.07$ and $3.12 \pm 0.07$ L/min in stretching and control, respectively; $P<0.05$); and (iii) reduced net mechanical efficiency ($e_{net}$) by 4% ($0.185 \pm 0.006$ and $0.193 \pm 0.006$ in stretching and control, respectively; $P<0.05$). Although acute passive stretching did not have an effect on $\dot{V}O_{2max}$, $t_{lim}$ and $e_{net}$ during heavy constant load exercise were significantly affected. These results are suggestive of an impairment in cycling efficiency due to changes in muscle neural activation and viscoelastic characteristics induced by stretching.**

Stretching is commonly considered as an important component of warmup and training programs, performed to increase muscle flexibility, to reduce the incidence of injuries and to ameliorate maximum performance (Taylor et al., 1990). Many studies, though, reported that stretching can temporarily compromise maximum force-generating capacity (Fowles et al., 2000; Nelson et al., 2005; Cè et al., 2008), maximal jump performance (Wallmann et al., 2005) and running speed (Nelson et al., 2005), even though some investigations showed contradictory results (Alpkaya & Koceja, 2007).

Alteration in the muscle–tendon unit characteristics and reduction in the central drive command are considered as the primary mechanisms causing the limitation in maximum force and power output induced by stretching (Fowles et al., 2000; Evetovich et al., 2003; Cè et al., 2008). Indeed, mechanical modifications, such as a decrease in muscle–tendon unit stiffness (Magnusson et al., 1996; Kubo et al., 2001), and neuromuscular changes, such as an increased muscle spindle activation threshold and a decreased spinal reflex excitability (Guissard et al., 1988; Chalmers, 2004), have been reported after acute stretching administration. These observations are also supported by electromyographic (EMG) studies, in which stretching-induced force deficit was accompanied by a decrease in motor unit recruitment (Fowles et al., 2000; Cramer et al., 2007). Given their larger size and higher activation threshold (Freund, 1983), type II motor units are prevailingly affected by stretching administration (Godges et al., 1989; Hayes & Walker, 2007), as suggested also by the reduction in maximum force due to this maneuver.

While stretching effects on anaerobic exercise have been studied extensively under several experimental conditions (Fowles et al., 2000; Evetovich et al., 2003; Cè et al., 2008), the mechanical and neurological effects of stretching on aerobic performance have been investigated poorly so far. Craib et al. (1996) reported an inverse correlation between the cost of running and flexibility, suggesting that a reduced flexibility may enhance running economy by increasing the storage and return of elastic energy and minimizing the need for muscle-stabilizing activity. Given that acute passive stretching increases muscle flexibility by decreasing muscle–tendon unit stiffness (Magnusson et al., 1996; Kubo et al., 2001), aerobic performance could be compromised by this maneuver. Moreover, a stretching-induced reduction in neural drive to the working muscles (Guissard

et al., 1988; Avela et al., 1999a; Behm et al., 2001) could be responsible for changes in motor unit activation strategies during aerobic tasks, leading to an altered exercise efficiency.

While Godges et al. (1989) reported an improvement in running economy immediately after passive stretching, other studies found no effects (Hayes & Walker, 2007; Allison et al., 2008). Hayes and Walker (2007) explained the lack of changes by the fact that exercise economy was assessed during running at an intensity below the so-called lactate threshold, the intensity at which peak vertical ground reaction forces are approximately 20% of the maximal peak force during a vertical jump (Hickson et al., 1988). With such low forces, type II motor units, affected more by stretching, are recruited only to a low extent during each running step. For the same reason, Allison et al. (2008) found that static stretching did not influence running economy at 70% of $\dot{V}O_2$ peak, despite significant changes in neuromuscular activation. They concluded that, when running at 70% of $\dot{V}O_2$ peak, muscle activation and force generation are clearly far below that required for maximal strength tasks. Besides the relatively low effort involved, both studies investigated the acute effects of stretching during tests of a relatively short duration (10 min), which could have not allowed the effects of the maneuver to become evident.

In these investigations, exercise economy was determined during running exercises. To our knowledge, no studies in the literature have assessed the stretching effects on cycling performance. Contrary to running, it has been reported that during a heavy-intensity cycle exercise at a constant workload (85% $\dot{V}O_{2max}$), the peak tension developed with each pedal thrust amounts to about 60% of the maximal isometric force that can be exerted on the pedals, thus requiring a significant recruitment of type II fibers (Sale, 1987). For this reason, stretching-induced reduction in aerobic performance could be preferentially retrieved during cycling than during running exercises and might only be observed during tasks requiring high-intensity efforts, with a large involvement of type II motor units.

Therefore, the aim of the present study was to determine the effects of acute stretching administration on exercise efficiency (an index of exercise economy) during a high-intensity, aerobic cycle task performed until exhaustion. Our hypothesis was that stretching, by altering the muscle–tendon unit characteristics and the central neural drive, would significantly impair cycle efficiency and exercise performance. For this purpose, nine participants completed cycle exercises at 85% $\dot{V}O_{2max}$ ($\dot{W}_{85}$) until exhaustion, with and without previous stretching administration.

## Materials and methods

### Participants

Nine physically active males [age $24 \pm 5$ years; stature $1.71 \pm 0.09$ m; body mass $69 \pm 7$ kg; mean $\pm$ standard deviation (SD)] volunteered to participate in the study. They were all involved in recreational activities two to three times per week. At the time of the study, none of them had pathologies of the upper or the lower limbs. After a full explanation of the experimental design and procedures, each participant gave written informed consent before engaging in the experiments. The study was approved by the local Ethics Committee, in accordance with the principles of the 1964 Declaration of Helsinki.

### Experimental design

After an initial visit for familiarization purposes, during which each participant became used to high-intensity cycling while wearing the expired air-collecting face mask, they reported to the laboratory eight times. They have been highly motivated to reach their performance limit. Participants, however, were blind to the experimental hypothesis and the expected outcomes of the study. They were recommended to abstain from any form of heavy exercise in the previous 2 days, with the last meal at least 3 h before. On the days of the tests, they were asked to avoid caffeine or any other similar beverages. For each participant, tests were performed at the same time of the day in a climate-controlled laboratory (constant temperature of $20 \pm 1$ °C and relative humidity of $50 \pm 5\%$). On different days, two maximum square-wave incremental tests were performed, with and without pre-exercise stretching, in a randomized order, to determine $\dot{V}O_{2max}$. Then, six tests (three with and three without pre-exercise stretching, in a randomized order), at a constant workload of 85% of the minimum power requested to elicit $\dot{V}O_{2max}$ ($\dot{W}_{85}$), were carried out. Cycle ergometric tests were separated by at least 48 h. Participants' flexibility and maximum voluntary contraction (MVC) of the knee extensor muscles were assessed before and after stretching administration.

### Experimental procedures and measurements

MVC of the knee extensor muscles was determined isometrically at a knee joint angle of 90° and was defined as the highest value of three trials, each lasting 3 s. Among the trials, 5 min of recovery were allowed to the subject. During muscle contraction, the EMG signal was recorded from the *vastus lateralis* muscle. EMG was amplified (gain of 1000; mod. ASE16, LiSin, Turin, Italy; input impedance: 60 MΩ; common-mode rejection ratio >90 dB), filtered (bandwidth of 10–500 Hz) and stored on a personal computer after A/D conversion (mod. UM150, Biopac System, Goleta, California, USA) at a sampling rate of 2048 Hz. The skin area under the electrodes was shaved, gently abraded with fine sand paper and carefully cleaned with ethyl alcohol and conductive gel, to achieve an inter-electrode impedance below 2000 Ω. A map with some skin identification aspects (moles, angiomas and scars) and the position of the EMG probe was drawn on a transparency, to allow repeated measurements from the same area of the muscle throughout all tests. The force output generated by the knee-extensor muscles was recorded using a calibrated load cell (mod. SM-2000 N, Interface, Crowthorne, UK), operating linearly between 0 and 2000 N. The force signal was filtered (bandwidth 2–64 Hz) and stored on a personal computer after A/D conversion (mod. UM150, Biopac System) with a sampling frequency of 2048 Hz.



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Cycle tests were performed on a mechanically braked, electronically controlled cycle ergometer (mod. 839E, Monark, Vansbro, Sweden). Immediately before the first test, anthropometric measurements were collected and the positioning of the subject on the cycle ergometer (saddle height, handlebars angle of inclination and feet placement on pedals) was standardized to maintain a similar position in all cycle tests. The pedal rate was set at 100 revolutions per minute (r.p.m.) to achieve a considerable recruitment of type II fibers (Sargeant, 1994). Visual feedback of the pedal rate was provided to the participants in order to maintain a constant cadence of $100 \pm 3$ r.p.m.

After 5 min of rest for baseline measurements, the incremental test to determine $\dot{V}O_{2max}$ started with the same two workloads (50 and 100 W) for all subjects. The following workloads were administered according to the individual cardiorespiratory response, in order to reach the maximum working capacity within three more workloads. Each workload lasted 5 min to achieve a steady-state condition. Between one workload and the following, 5 min of rest was allowed. Verbal encouragement was given to participants during all the trials. Tests were considered terminated when pedal cadence could not be maintained at $100 \pm 3$ r.p.m. for more than 10 s.

At rest and during exercise, expiratory ventilation ($\dot{V}E$), $O_2$ uptake ($\dot{V}O_2$), $CO_2$ production ($\dot{V}CO_2$), respiratory exchange ratio (RER) and other gas exchange parameters were measured breath by breath by a metabolimeter (mod. Quark $b^2$, Cosmed, Rome, Italy). The system was calibrated before each test with gas mixtures of known concentrations (16% $O_2$, 5% $CO_2$, balance $N_2$). Heart rate (fH) was continuously monitored by electrocardiography (mod. Delta VIS, Remco Italia Cardioline, Vignate, Italy). At rest and at the end of each workload (at minutes 1, 3, and 5), arterialized blood samples from the ear lobe were taken and blood lactate concentration ($[La^-]$) was determined using a spectrophotometric system (Lactate Pro LT-1710, Arkray, Kyoto, Japan).

The individual $\dot{V}O_{2max}$ was established from the plateau attained by the relationship between $\dot{V}O_2$ and mechanical power. When the plateau was not evident, the following criteria for establishing $\dot{V}O_{2max}$ were used: (i) the lack of increase in fH between two successive loads ($\Delta fH < 5$ beats/min), (ii) RER values higher than 1.1 and (iii) $[La^-]$ higher than 10 mM. If the stated criteria were not fulfilled, we asked the subject to repeat the trial on a different day. The minimum power required at which $\dot{V}O_2$ was equal to $\dot{V}O_{2max}$ was defined as $\dot{W}_{max}$. Thus, $\dot{W}_{max}$ was considered as the power necessary to elicit $\dot{V}O_{2max}$. The average $\dot{V}O_2$ for each workload was calculated during the last minute of each step.

From the maximum incremental test, the $\dot{W}_{85}$ was then calculated. During all the $\dot{W}_{85}$ tests, participants were asked to maintain a constant pedal rate of $100 \pm 3$ r.p.m. The test terminated when the imposed cadence could not be maintained for more than 10 s. Verbal encouragement was given to the subjects to continue until exhaustion. $[La^-]$ was measured at rest, during exercise (every 3 min) and at minutes 1, 3 and 5 of recovery. Cardiorespiratory and metabolic variables were recorded breath by breath during the entire test.

### Data analysis

During the MVC test, only the central 2-s intervals of contraction were analyzed to avoid the interference of transient phenomena. From the EMG signal, the root mean square (RMS) was calculated. During the $\dot{W}_{85}$ tests, the cardiorespiratory and metabolic variables were averaged at the third minute and the last minute of exercise. These variables were also averaged from minute 3 over the entire $\dot{W}_{85}$ exercise duration, for both the control and the stretching condition. The net mechanical efficiency of cycling ($e_{net}$), as an index of exercise economy, was calculated from the ratio of work performed (watts) to the rate of $\dot{V}O_2$ above rest, according to the following equation:

$$e_{net} = \frac{\text{Watts}}{\dot{V}O_{2ex} - \dot{V}O_{2rest}}$$

where $\dot{V}O_{2ex}$ is the $\dot{V}O_2$ during exercise and $\dot{V}O_{2rest}$ is the $\dot{V}O_2$ determined at rest while sitting on the cycle ergometer.

Finally, the cardiorespiratory and metabolic variables were plotted as a function of exercise duration, expressed as a percentage of the total exercise time ($t_{TOT}$).

### Stretching protocol

The pre-exercise stretching routine consisted of different elongations of the muscle groups of the lower limbs mainly involved during cycling: knee extensors and flexors, plantar flexors of the ankle and hip extensors. Each muscle group was stretched to the point of discomfort. Five series of stretching were applied to the muscle groups of both limbs. During each series, the stretched position was maintained for 45 s, with 15 s of rest in between. Each stretching session lasted approximately 30 min. Before and after stretching, the flexibility of the participants was evaluated with a sit-and-reach test.

### Statistical analysis

Statistical analysis was performed using a statistical software package (SigmaStat for Windows, v 3.11, Systat Software Inc., Richmond, VA, USA). To check the normal distribution of the sampling, a Kolgomorov–Smirnov test was applied. A sample size of nine participants was selected to ensure a statistical power higher than 0.70. Paired Student's *t*-test was applied to identify differences between the control and the stretching condition in the force and the EMG parameters during MVC determination and in the cardiorespiratory and metabolic variables during the $\dot{V}O_{2max}$ test. To assess significant differences in the cardiorespiratory and metabolic variables during the $\dot{W}_{85}$ tests, a two-way (condition and time) analysis of variance (ANOVA) for repeated measurements was performed. When necessary, a *post hoc* Holm–Sidak test was utilized. Finally, to test the reliability of the results of the three trials within the same experimental condition, an intraclass correlation test with a two-way mixed average measure was applied. Unless otherwise stated, the values are expressed as means ± standard error. The level of significance was set at $P < 0.05$.

## Results

### Sit-and-reach test

A significant difference ($+3.5 \pm 0.5$ cm; $P < 0.05$) in the sit-and-reach measurements between the pre- and the post-stretching conditions was found, providing evidence that stretching significantly increased the flexibility of the posterior muscular chain. The sit-and-reach test did not reveal any significant difference when performed before and after a resting period equal to the duration of the stretching maneuvers.



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### MVC

Before stretching, the MVC was 619 ± 20 N. Stretching maneuvers decreased the MVC significantly by 8% (572 ± 32 N; $P<0.05$). The significant difference in the MVC was accompanied by a reduction of 33% in the EMG RMS (from 0.114 ± 0.008 to 0.094 ± 0.001 mV before and after stretching, respectively; $P<0.05$).

### $\dot{V}O_{2max}$ tests

The mean values of cardiorespiratory and metabolic variables at $\dot{V}O_{2max}$ are given in Table 1. No statistical differences were found between the two experimental conditions for any of the investigated parameters.

### $\dot{W}_{85}$ tests

The average workload during the $\dot{W}_{85}$ tests was 194 ± 10 and 198 ± 9 W for the stretching and the control conditions, respectively ($P>0.05$). The exercise intensity was considered in the heavy-intensity domain, as [$La^-$] increased significantly above the 4 mM threshold in the first minutes of each test, then increasing throughout the rest of the exercise. The $\dot{V}O_2$ time course of a representative participant during $\dot{W}_{85}$ tests, with and without stretching, is given in Fig. 1. A reliability test lead to α values of 0.909 and 0.957 for the control and the stretching condition, respectively. Moreover, two-way ANOVA for repeated measurements did not show any significant differences among the trials within the same condition. Thus, the differences between the control and the stretching conditions could be reasonably ascribed to stretching itself. For each participant, the trials preceded by stretching were always shorter than the control trials. Exercise performance during the $\dot{W}_{85}$ tests was significantly affected by stretching. Indeed, as shown in Fig. 2, the time to exhaustion ($t_{lim}$) was significantly shorter by 26% when the exercise was preceded by stretching (1377 ± 183 vs 1872 ± 334 s with and without stretching, respectively; $P<0.05$).

Table 1. Cardiorespiratory and metabolic variables at $\dot{V}O_{2max}$

| | Control | Stretching |
|---|---|---|
| Power (W) | 233 ± 9 | 231 ± 10 |
| $\dot{V}O_2$ (mL/min) | 3656 ± 74 | 3635 ± 141 |
| $\dot{V}CO_2$ (mL/min) | 4104 ± 99 | 4034 ± 192 |
| RER | 1.13 ± 0.02 | 1.11 ± 0.02 |
| $\dot{V}E$ (L/min) | 162 ± 6 | 152 ± 9 |
| VT (liter) | 2.63 ± 0.11 | 2.62 ± 0.16 |
| fR (breaths/min) | 63 ± 3 | 59 ± 3 |
| fH (beats/min) | 192 ± 2 | 187 ± 3 |
| [$La^-$] (mM) | 12.8 ± 0.5 | 11.7 ± 0.5 |

$\dot{V}O_2$, oxygen uptake (STPD); $\dot{V}CO_2$,$CO_2$ production (STPD); RER, respiratory exchange ratio; $\dot{V}E$ expiratory ventilation (BTPS); VT, tidal volume; fR, respiratory rate; fH, heart rate; [$La^-$], blood lactate concentration.

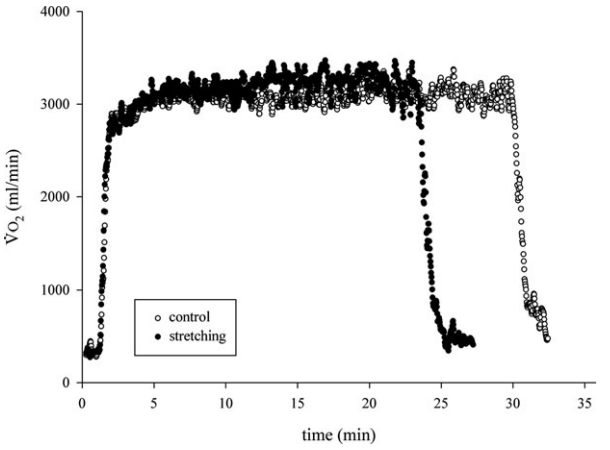


*Fig. 1.* Time course of $\dot{V}O_2$ in a representative subject during the $\dot{W}_{85}$ tests, with and without pre-exercise stretching. In all the subjects, the trial preceded stretching (closed circles) was significantly shorter (−26%) than the control trial (open circles).

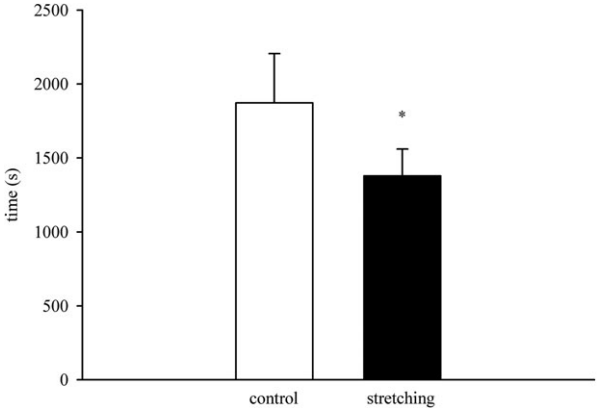


*Fig. 2.* Average time to exhaustion for the $\dot{W}_{85}$ tests with (black column) and without (white column) pre-exercise stretching. *$P<0.05$ stretching vs control.

Table 2 shows the average values of the cardiorespiratory and metabolic variables at minute 3, during the last minute of exercise as well as the mean of the variables. For all parameters except for $\dot{V}CO_2$, the difference between minute 3 and the last minute of exercise was significant for both experimental conditions.

At minute 3, stretching showed a significant effect only on $\dot{V}E$ (+5.7%). At the end of exercise, $\dot{V}O_2$ (+3.7%), tidal volume (VT; +8.4%) and respiratory rate (fR; −9.0%) were significantly affected by stretching. Compared with the control condition, the mean values of the considered variables for the entire exercise duration during the stretching protocol were significantly different for $\dot{V}O_2$ (+4.3%), $\dot{V}CO_2$ (+4.6%) and $\dot{V}E$ (+5.9%).

Stretching affected $e_{net}$ markedly, which decreased significantly throughout the exercise in both experi-



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Table 2. Cardiorespiratory and metabolic variables during the $\dot{W}_{85}$ test

| | Control | | | Stretching | | |
|---|---|---|---|---|---|---|
| | Minute 3 | Last minute | Average | Minute 3 | Last minute | Average |
| $\dot{V}O_2$ (mL/min) | 2931 ± 83 | 3175 ± 99$^{\#}$ | 3122 ± 68 | 2985 ± 98 | 3298 ± 90$^{\#,\star}$ | 3244 ± 70$^{\star}$ |
| $\dot{V}CO_2$ (mL/min) | 3123 ± 78 | 3016 ± 106 | 3043 ± 77 | 3219 ± 84 | 3100 ± 114 | 3176 ± 87$^{\star}$ |
| RER | 1.07 ± 0.01 | 0.95 ± 0.01$^{\#}$ | 0.98 ± 0.01 | 1.08 ± 0.02 | 0.94 ± 0.02$^{\#}$ | 0.98 ± 0.02 |
| $\dot{V}E$ (L/min) | 83 ± 3 | 119 ± 6$^{\#}$ | 101 ± 3 | 88 ± 2$^{\star}$ | 120 ± 6$^{\#}$ | 106 ± 3$^{\star}$ |
| VT (liter) | 2.46 ± 0.17 | 1.97 ± 0.12$^{\#}$ | 2.24 ± 0.14 | 2.51 ± 0.16 | 2.15 ± 0.09$^{\#,\star}$ | 2.31 ± 0.10 |
| fR (breaths/min) | 34.7 ± 1.7 | 62.3 ± 4.6$^{\#}$ | 46.7 ± 2.8 | 36.7 ± 2.7 | 56.7 ± 2.5$^{\#,\star}$ | 47.2 ± 1.8 |
| fH (beats/min) | 155 ± 5 | 176 ± 5$^{\#}$ | 168 ± 5 | 157 ± 6 | 175 ± 5$^{\#}$ | 169 ± 5 |
| [La$^-$] (mM) | 4.8 ± 0.3 | 8.4 ± 0.8$^{\#}$ | 7.5 ± 0.5 | 5.3 ± 0.7 | 8.8 ± 1.5$^{\#}$ | 7.8 ± 1.0 |
| $e_{net}$ | 0.207 ± 0.007 | 0.190 ± 0.007$^{\#}$ | 0.193 ± 0.006 | 0.203 ± 0.008 | 0.182 ± 0.007$^{\#,\star}$ | 0.185 ± 0.006$^{\star}$ |

$^{\star}P<0.05$ stretching vs control.

$^{\#}P<0.05$ last minute vs minute 3.

$\dot{V}O_2$, oxygen uptake (STPD); $\dot{V}CO_2$, $CO_2$ production (STPD); RER, respiratory exchange ratio; $\dot{V}E$, expiratory ventilation at body temperature and pressure, saturated; VT, tidal volume; fR, respiratory rate; fH, heart rate; [La$^-$], blood lactate concentration; $e_{net}$, net mechanical efficiency.

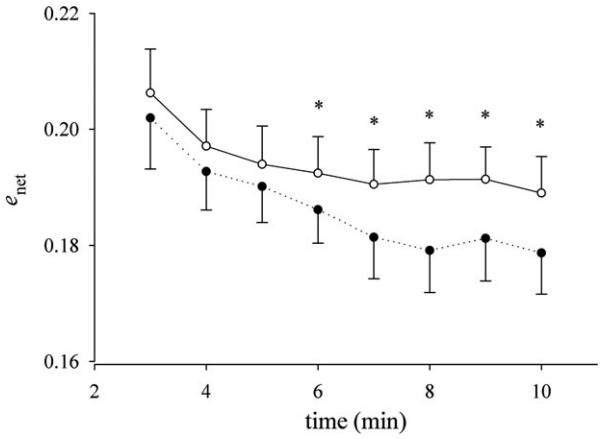


*Fig. 3.* Time course of $e_{net}$ from minute 3 to minute 10 of the $\dot{W}_{85}$ exercise with (closed circles) and without (open circles) pre-exercise stretching. $^{\star}P<0.05$ stretching vs control.

mental conditions ($P<0.05$), but to a higher extent after stretching. Differences in $e_{net}$ between the two experimental conditions became statistically significant after the fifth minute of exercise, as shown in Fig. 3. Moreover, during the last minute of exercise, $e_{net}$ was significantly lower in stretching than in control by 4.1% ($P<0.05$). As basal $\dot{V}O_2$ immediately before the tests was similar in both experimental conditions, it can be reasonably assumed that stretching had an effect on exercise efficiency and not on basal metabolism.

The exercise duration of the $\dot{W}_{85}$ tests was normalized for time to exhaustion ($t_{TOT}$). The values of the cardiorespiratory and metabolic parameters were averaged and represented in 5% time intervals. Figure 4 illustrates the time course of the main parameters in the two experimental conditions. $\dot{V}O_2$ was significantly higher while $e_{net}$ was significantly lower during stretching than in control ($P<0.05$).

## Discussion

The main and novel finding of the present investigation was that stretching administration decreased the net mechanical efficiency ($e_{net}$) during a heavy-intensity cycle exercise. Indeed, when pedaling at 85% of $\dot{V}O_{2max}$ ($\dot{W}_{85}$) after stretching administration, the average $\dot{V}O_2$ was significantly higher (+4%) than that in the control condition, despite the same mechanical work, leading to a significant reduction in $e_{net}$ (−4%) and in time to exhaustion (−26%).

The effectiveness of stretching maneuvers was verified by the changes in flexibility assessed during the sit-and-reach test. During knee extension isometric tests, stretching decreased EMG RMS and MVC, suggesting that muscle activation and force production were significantly impaired. These results agree with previous studies, showing an increase in the joint range of motion after stretching (Godges et al., 1989, 1993), a decrease in muscle electrical activation (Fowles et al., 2000; Kay & Blazevich, 2009) and a reduction in maximal strength and power output (Fowles et al., 2000; Kay & Blazevich, 2009).

Stretching did not have any significant impact on $\dot{V}O_{2max}$. To our knowledge, this is the first study showing the effect of acute passive stretching on maximum aerobic power; thus, no comparison with previous reports can be made. The peripheral effects of stretching involve changes at the muscle–tendon unit, such as a decrease in stiffness and a reduction in maximum force-generating capacity (Magnusson et al., 1996; Fowles et al., 2000; Kubo et al., 2001). At the muscle level, stretching seems to affect mainly type II motor units (Hayes & Walker, 2007), while during an aerobic exercise of a short duration, the source of energy is mainly provided by the aerobic pathway. Moreover, the stretching effects on tendons and muscles might not become evident in efforts of a short duration, such as the square-wave 5-min ex-



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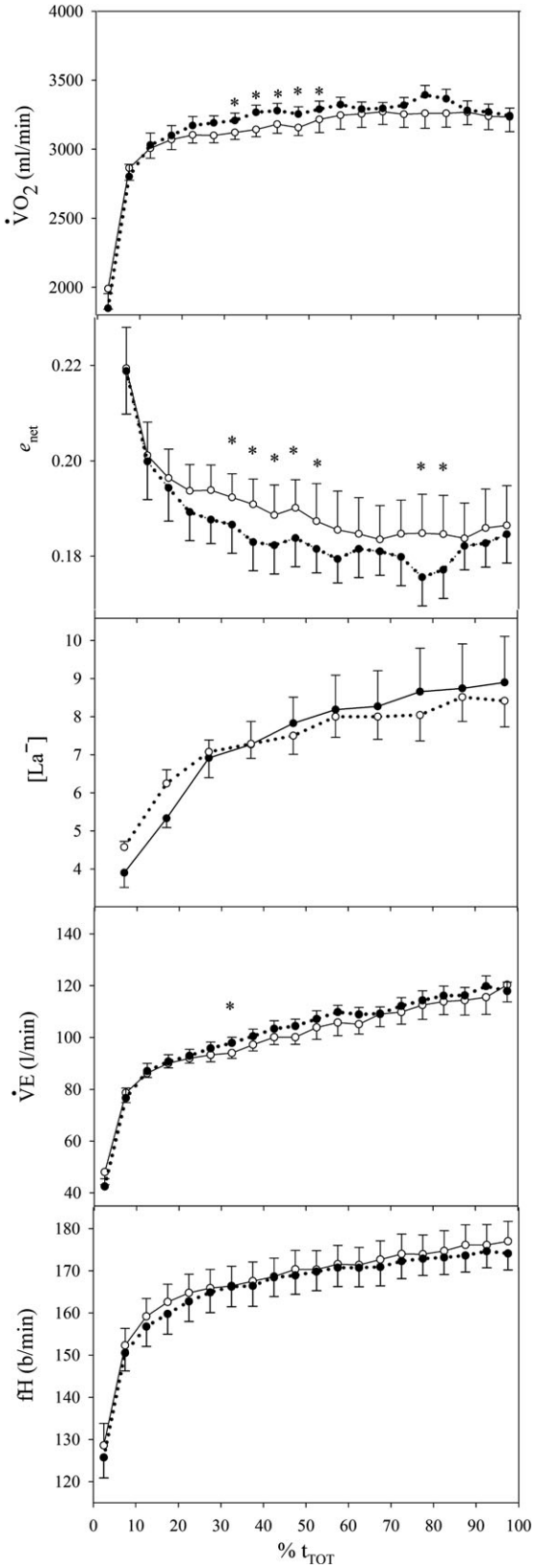
ercises of the $\dot{V}O_{2max}$ protocol. To further support this explanation, $e_{net}$ becomes significantly lower in stretching compared with control only after the fifth minute of exercise, as shown in Fig. 3.




During $\dot{W}_{85}$, stretching-induced changes in $t_{lim}$ and $\dot{V}O_2$ suggest a reduction in exercise efficiency. Exercise efficiency expresses the oxygen cost needed to perform a trial at a given submaximal intensity or velocity (Bassett & Howley, 2000). The ratio ($e_{net}$) between power output and the net exercise cost decreased significantly with stretching. A higher energy expenditure with the same power output is suggestive of a less efficient system.

Very few studies have assessed the stretching effects on running economy. Godges et al. (1989) reported a significant improvement in running economy at 40%, 60% and 80% of $\dot{V}O_{2max}$ immediately after one session (40 min) of sustained passive stretching, which was applied at the end ranges of hip extension and flexion. On the contrary, Hayes and Walker (2007) did not find acute effects of active stretching on running economy. They explained the lack of effects because: (i) the exercise intensity was relatively low, with minor recruitment of type II fibers; (ii) running economy was assessed after a period of submaximal running, which has been shown to reverse the reductions in neuromuscular performance caused by static stretching (Rosenbaum & Hennig, 1995); and (iii) the increase in muscle temperature could have reduced viscous resistances and masked the effects of stretching. Also, Allison et al. (2008) examined the acute effects of active stretching on exercise economy at 70% $\dot{V}O_{2max}$, sustained for 10 min. The cardiorespiratory and metabolic response to exercise was unaffected by the maneuver, despite significant changes in the sit-and-reach range of motion (+2.7%), isometric strength (−5.6%) and countermovement jump height (−5.5%). They concluded that global stretching of the lower limbs, regardless of significant changes in neuromuscular function, had no influence on running economy, as muscle activation and force production were clearly far below that required for maximal strength and power tasks.

Our results are somehow contradictory to these previous reports. Apart from some differences in stretching administration (passive vs active), these discrepancies might be attributable to different testing modalities and/or exercise durations. Indeed, while previous studies utilized running tests, the present study is the first investigation aimed at assessing stretching effects on exercise efficiency uti-

*Fig. 4*. Time course of cardiorespiratory and metabolic variables, normalized for the total exercise time ($t_{TOT}$), during the $\dot{W}_{85}$ tests with (closed circles) and without (open circles) pre-exercise stretching. $\dot{V}O_2$, oxygen uptake; $e_{net}$, net mechanical efficiency; [La$^-$], blood lactate concentration; $\dot{V}E$, expiratory ventilation at body temperature and pressure, saturated; fH, heart rate. *$P<0.05$ stretching vs control.



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lizing cycle exercise. During cycle exercise at a constant workload of heavy intensity (85% $\dot{V}O_{2max}$), the peak tension that can be developed with each pedal thrust amounts to about 60% of the maximal force that can be exerted on the pedals (Sale, 1987). This implies an asynchronous activation of motor units with a significant recruitment of type II fibers (Gollnick et al., 1974). Conversely, when running at a speed corresponding to relative working intensities similar to that reported above for cycling, the peak vertical force is $\sim$20% of the maximal peak force exerted during the vertical jump (Hickson et al., 1988). This would involve a low, even negligible recruitment of type II fibers during each running step. Thus, stretching-induced reduction in exercise economy could be preferentially retrieved during cycling with respect to running exercises.

Moreover, the present testing protocol required a constant load task of heavy intensity up to exhaustion, with an overall exercise duration markedly longer than that adopted in the above-mentioned studies. It might be argued that during this kind of exhaustive effort, stretching effects could become more evident later (after 10 min), i.e., when the slow component markedly increases its amplitude due to the massive recruitment of less efficient type II fibers (Gaesser & Poole, 1996). When exercising at heavy or very heavy submaximal levels (higher than the so-called lactate or ventilatory threshold), $\dot{V}O_2$ does not reach a metabolic steady state, but continues increasing with time even though the workload is constant (Gaesser & Poole, 1996). Despite some controversial findings (Scheuermann et al., 2001), EMG studies (Mateika & Duffin, 1994) and analysis of glycogen and creatine phosphate content from muscle biopsies (Krustrup et al., 2004) showed that the most likely mediator for the $\dot{V}O_2$ slow component is the increased recruitment of the less efficient type II motor units. Thus, a mechanistic link between the energetic of contraction of type II fibers and the $\dot{V}O_2$ slow component has been suggested (Gaesser & Poole, 1996; Krustrup et al., 2004). In our study, the occurrence of a slow component has been demonstrated under both experimental conditions, whereby $\dot{V}O_2$ increased significantly from minute 3 to the end of exercise. The magnitude of the slow component, though, was significantly larger in stretching than in control.

A difference between the two experimental conditions in the muscle fiber recruitment pattern, which follows the level of relative force expression, could explain the findings of the present study. With stretching, the contribution of the less efficient type II motor units in maintaining the heavy-intensity constant workload could have been changed. The 8% decline in MVC, indeed, suggests that the subjects, during the $\dot{W}_{85}$ task preceded by stretching, exerted a higher relative force on the pedals to maintain the same constant workload as in the control condition. In other words, after stretching, given the lower MVC, the same absolute force during each pedal thrust amounts to a percentage of the maximal force higher than 60% (as during control condition) reported by Sale (1987). With the present experimental design, we are not able to quantify the increase in the relative intensity applied to pedals after stretching. However, we can reasonably assume that after stretching, the relative force exerted on the pedals during each single thrust was higher than that in control. This could have led to a situation in which the $\dot{W}_{85}$ exercise started already with a higher level of type II motor unit involvement, thus leading to an earlier occurrence of muscle fatigue and a consequent reduction in time to exhaustion.

In a recent study, a group of cyclists underwent a 5 km time trial (cadence of the cycle ergometer voluntarily chosen), with or without lumbar epidural local anesthesia (Amann et al., 2008). Besides the blockade of the somatosensory feedback, anesthesia reduced the net excitatory current in the peripheral motor neurons, leading, according to the size principle, to a failure to reach the activation threshold of large (type II) motor units. Therefore, less type II fibers could be recruited and the overall number of available motor units was reduced. As a consequence, with the anesthetic, the MVC was significantly reduced by 22% and an increase in the time trial duration occurred. The 5 km time trial was performed with the same force applied perpendicular to the crank arms, but with a lower pedal frequency and, in turn, with a reduced power output. The authors suggested that a compensation for the reduction of available type II fibers due to anesthetic administration was possible with respect to pedal force by increasing type I motor unit recruitment and by the fact that each available motor unit performed more work. Also, stretching has been shown to affect motoneuron activation by pre- and post-synaptic mechanisms (Kohn et al., 1997; Avela et al., 1999a, b; Behm et al., 2001), causing the partial inhibition of large (type II) motor units (Guissard et al., 2001). In our study, with stretching, we observed findings partly compatible with Amann's study, i.e., a reduction in the time to exhaustion and an increased energy expenditure for the same power output. To maintain the required power output and pedal rate constant, the subjects of the present investigation were possibly also forced to recruit, together with type I fibers, the available type II fibers, with a prevailingly oxidative metabolism, from the beginning of $\dot{W}_{85}$. An early activation of the available type II fibers, which were recruited to a greater extent due to the increase in the relative force per



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pedal thrust, contributed to the lower $e_{net}$ and to the reduced $t_{lim}$.

Finally, it is generally accepted that passive stretching changes the visco-elastic properties of the muscle–tendon unit by decreasing its stiffness (Kubo et al., 2001; Morse et al., 2008; Ryan et al., 2008). The decrease in stiffness is the result of several mechanisms, involving the contractile (changes in cross-bridge status) and the connective (endomysium, perimysium, aponeurosis and tendons) elements (Rowe, 1981; Proske et al., 1993; Kubo et al., 2001). A relatively stiffer muscle–tendon unit reportedly has a greater capacity for force production owing to improved force/velocity and length/tension relationships and to a better initial transmission of force (Wilson et al., 1992). In cycle exercise, the time available to generate force depends on the cadence. When pedaling at a cadence of 80 r.p.m. or above, the time-to-peak force is less than 250 ms (Watsford et al., 2010). Thus, a decrease in muscle–tendon unit stiffness would imply a longer rate of force development and, in turn, a lower force applied to the pedals for each thrust. As a consequence, in our study, muscles were possibly required to exert a higher force output after stretching compared with the control, to maintain the cadence at the same rpm, because of the increased time of tension transfer to the bone.

## Perspectives

Previous studies investigated the acute effects of stretching administration on exercise economy utilizing running test models. They found positive or no effects of this maneuver on exercise performance. The present study showed that a preceding stretching routine significantly decreased exercise efficiency and time to exhaustion during a heavy-intensity, constant load cycle exercise at 85% of $\dot{V}O_{2max}$ ($\dot{W}_{85}$). These results are compatible with stretching-induced alterations of the motor unit recruitment pattern and utilization, and with changes in muscle–tendon unit mechanical and viscoelastic characteristics, leading to a less efficient system. From a practical point of view, these findings suggest that care must be taken in administering stretching immediately before an endurance task, especially when cycle exercise is involved. Indeed, stretching can affect not only maximum strength but also heavy-intensity aerobic exercise. Further studies are needed to clarify whether different stretching modalities could improve joint flexibility without impairing aerobic performance.

**Key words:** $VO_{2\ max}$, slow component, exercise duration, economy, oxygen cost.

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## References

Allison SJ, Bailey DM, Folland JP. Prolonged static stretching does not influence running economy despite changes in neuromuscular function. J Sports Sci 2008: 26: 1489–1495.

Alpkaya U, Koceja D. The effects of acute static stretching on reaction time and force. J Sports Med Phys Fitness 2007: 47: 147–150.

Amann M, Proctor LT, Sebranek JJ, Eldridge MW, Pegelow DF, Dempsey JA. Somatosensory feedback from the limbs exerts inhibitory influences on central neural drive during whole body endurance exercise. J Appl Physiol 2008: 105: 1714–1724.

Avela J, Kyrolainen H, Komi PV. Altered reflex sensitivity after repeated and prolonged passive muscle stretching. J Appl Physiol 1999a: 86: 1283–1291.

Avela J, Kyrolainen H, Komi PV, Rama D. Reduced reflex sensitivity persists several days after long-lasting stretch-shortening cycle exercise. J Appl Physiol 1999b: 86: 1292–1300.

Bassett DR Jr., Howley ET. Limiting factors for maximum oxygen uptake and determinants of endurance performance. Med Sci Sports Exerc 2000: 32: 70–84.

Behm DG, Button DC, Butt JC. Factors affecting force loss with prolonged stretching. Can J Appl Physiol 2001: 26: 261–272.

Cè E, Paracchino E, Esposito F. Electrical and mechanical response of skeletal muscle to electrical stimulation after acute passive stretching in humans: a combined electromyographic and mechanomyographic approach. J Sports Sci 2008: 26(14): 1567–1577.

Chalmers G. Re-examination of the possible role of Golgi tendon organ and muscle spindle reflexes in proprioceptive neuromuscular facilitation muscle stretching. Sports Biomech 2004: 3: 159–183.

Craib MW, Mitchell VA, Fields KB, Cooper TR, Hopewell R, Morgan DW. The association between flexibility and running economy in sub-elite male distance runners. Med Sci Sports Exerc 1996: 28: 737–743.

Cramer JT, Beck TW, Housh TJ, Massey LL, Marek SM, Danglemeier S, Purkayastha S, Culbertson JY, Fitz KA, Egan AD. Acute effects of static stretching on characteristics of the isokinetic angle–torque relationship, surface electromyography, and mechanomyography. J Sports Sci 2007: 25: 687–698.

Evetovich TK, Nauman NJ, Conley DS, Todd JB. Effect of static stretching of the biceps brachii on torque,



16000838, 2012, 6, Downloaded from https://onlinelibrary.wiley.com/doi/10.1111/j.1600-0838.2011.01327.x by Macquarie University Library, Wiley Online Library on [17/09/2026]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

electromyography, and mechanomyography during concentric isokinetic muscle actions. J Strength Cond Res 2003: 17: 484–488.
Fowles JR, Sale DG, MacDougall JD. Reduced strength after passive stretch of the human plantarflexors. J Appl Physiol 2000: 89: 1179–1188.
Freund HJ. Motor unit and muscle activity in voluntary motor control. Physiol Rev 1983: 63: 387–436.
Gaesser GA, Poole DC. The slow component of oxygen uptake kinetics in humans. Exerc Sport Sci Rev 1996: 24: 35–71.
Godges JJ, Macrae H, Longdon C, Tinberg C, Macrae PG. The effects of two stretching procedures on hip range of motion and gait economy. J Orthop Sports Phys Ther 1989: 10: 350–357.
Godges JJ, MacRae PG, Engelke KA. Effects of exercise on hip range of motion, trunk muscle performance, and gait economy. Phys Ther 1993: 73: 468–477.
Gollnick PD, Piehl K, Saltin B. Selective glycogen depletion pattern in human muscle fibres after exercise of varying intensity and at varying pedalling rates. J Physiol (London) 1974: 241: 45–57.
Guissard N, Duchateau J, Hainaut K. Muscle stretching and motoneuron excitability. Eur J Appl Physiol Occup Physiol 1988: 58: 47–52.
Guissard N, Duchateau J, Hainaut K. Mechanisms of decreased motoneurone excitation during passive muscle stretching. Exp Brain Res 2001: 137: 163–169.
Hayes PR, Walker A. Pre-exercise stretching does not impact upon running economy. J Strength Cond Res 2007: 21: 1227–1232.
Hickson RC, Dvorak BA, Gorostiaga EM, Kurowski TT, Foster C. Potential for strength and endurance training to amplify endurance performance. J Appl Physiol 1988: 65: 2285–2290.
Kay AD, Blazevich AJ. Moderate-duration static stretch reduces active and passive plantar flexor moment but not Achilles tendon stiffness or active muscle length. J Appl Physiol 2009: 106: 1249–1256.
Kohn AF, Floeter MK, Hallett M. Presynaptic inhibition compared with homosynaptic depression as an explanation for soleus H-reflex depression in humans. Exp Brain Res 1997: 116: 375–380.
Krustrup P, Soderlund K, Mohr M, Bangsbo J. The slow component of oxygen uptake during intense, sub-maximal exercise in man is associated with additional fibre recruitment. Pflugers Arch 2004: 447: 855–866.
Kubo K, Kanehisa H, Kawakami Y, Fukunaga T. Influence of static stretching on viscoelastic properties of human tendon structures in vivo. J Appl Physiol 2001: 90: 520–527.
Magnusson SP, Simonsen EB, Dyhre-Poulsen P, Aagaard P, Mohr T, Kjaer M. Viscoelastic stress relaxation during static stretch in human skeletal muscle in the absence of EMG activity. Scand J Med Sci Sports 1996: 6: 323–328.
Mateika JH, Duffin J. The ventilation, lactate and electromyographic thresholds during incremental exercise tests in normoxia, hypoxia and hyperoxia. Eur J Appl Physiol Occup Physiol 1994: 69: 110–118.
Morse CI, Degens H, Seynnes OR, Maganaris CN, Jones DA. The acute effect of stretching on the passive stiffness of the human gastrocnemius muscle tendon unit. J Physiol (London) 2008: 586: 97–106.
Nelson AG, Driscoll NM, Landin DK, Young MA, Schexnayder IC. Acute effects of passive muscle stretching on sprint performance. J Sports Sci 2005: 23: 449–454.
Proske U, Morgan DL, Gregory JE. Thixotropy in skeletal muscle and in muscle spindles: a review. Prog Neurobiol 1993: 41: 705–721.
Rosenbaum D, Hennig EM. The influence of stretching and warm-up exercises on Achilles tendon reflex activity. J Sports Sci 1995: 13: 481–490.
Rowe RW. Morphology of perimysial and endomysial connective tissue in skeletal muscle. Tissue Cell 1981: 13: 681–690.
Ryan ED, Beck TW, Herda TJ, Hull HR, Hartman MJ, Costa PB, Defreitas JM, Stout JR, Cramer JT. The time course of musculotendinous stiffness responses following different durations of passive stretching. J Orthop Sports Phys Ther 2008: 38: 632–639.
Sale DG. Influence of exercise and training on motor unit activation. Exerc Sport Sci Rev 1987: 15: 95–151.
Sargeant AJ. Human power output and muscle fatigue. Int J Sports Med 1994: 15: 116–121.
Scheuermann BW, Hoelting BD, Noble ML, Barstow TJ. The slow component of O(2) uptake is not accompanied by changes in muscle EMG during repeated bouts of heavy exercise in humans. J Physiol (London) 2001: 531: 245–256.
Taylor DC, Dalton JD Jr., Seaber AV, Garrett WE Jr. Viscoelastic properties of muscle–tendon units. The biomechanical effects of stretching. Am J Sports Med 1990: 18: 300–309.
Wallmann HW, Mercer JA, McWhorter JW. Surface electromyographic assessment of the effect of static stretching of the gastrocnemius on vertical jump performance. J Strength Cond Res 2005: 19: 684–688.
Watsford M, Ditroilo M, Fernandez-Pena E, D'Amen G, Lucertini F. Muscle stiffness and rate of torque development during sprint cycling. Med Sci Sports Exerc 2010: 42: 1324–1332.
Wilson GJ, Elliott BC, Wood GA. Stretch shorten cycle performance enhancement through flexibility training. Med Sci Sports Exerc 1992: 24: 116–123.



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