# Alterations in Running Economy and Mechanics After Maximal Cycling in Triathletes: Influence of Performance Level

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**The effects of the triathlon performance level on the metabolic and mechanical alterations in running after an exhaustive cycling exercise were studied. Eight elite and 18 middle-level triathletes completed two 7 min runs on a treadmill at a velocity corresponding to that sustained during a triathlon before and after maximal cycling exercise. Energy cost of running was quantified during the last minute of each run from the net oxygen uptake. External mechanical cost was quantified during the last minute of each run from displacements of the centre of mass using a kinematic arm. The effect of cycling on the running energy cost differed when comparing the elite (from $4.01 \pm 0.46$ to $3.86 \pm 0.34\,J \times kg^{-1} \times m^{-1}$) and the middle-level triathletes (from $3.67 \pm 0.37$ to $3.76 \pm 0.39\,J \times kg^{-1} \times m^{-1}$) ($P < 0.01$). The effect of cycling on the respiratory muscle $O_2$ was more important ($P < 0.05$) for the middle-level (from $120.1 \pm 27.2$ to $166.4 \pm 47.8\,ml \times min^{-1}$) than for elite triathletes (from $124.5 \pm 24.5$ to $143.7 \pm 28.9\,ml \times min^{-1}$). A tendency to a decrease of the mechanical cost and of the vertical displacement of the centre of mass during the braking phase was observed for the elite triathletes, suggesting a better leg stiffness regulation than for their less successful counterparts.**

**Key words: Triathlon, mechanical cost, energy cost, cycle-run transition, leg stiffness.**

## Introduction

The ability to sustain high metabolic power for long periods of time has been presented as a deciding factor of performance in triathlons [32]. As a result, it is well documented that high maximal oxygen uptake ($\dot{V}O_2max$) and fractional utilisation of $\dot{V}O_2max$ are required for success in this sport [17,36]. Also, it has been suggested that the ability to link the three disciplines is an important parameter of the performance [23]. Furthermore, as stated by di Prampero et al. [18], the speed achieved in competition relies not only on the rate of energy expenditure, but also on the energy cost of the considered locomotion. Regarding the activities that compose triathlon, it is thus not surprising that energy cost was related to the level of performance in swimming [33], cycling [13] and running [14]. Dengel et al. [17] have also shown that the energy cost of the three activities measured in separate testing sessions were correlated to the respective performance in swimming, cycling and running during a real triathlon. However, to the best of our knowledge, no study has examined the relationship between the level of performance and the energy cost of running after exhaustive cycling exercise.

The effect of fatigue on the energy cost of running ($C_R$) after prolonged exercise is a controversial issue [30,38]. When fatigue conditions are generated by cycling (i.e. specific fatigue for triathletes), an increase in $C_R$ has also been observed for on-ground [20,21] and treadmill [16,22,26] running. However, it is not known whether the ability to minimise the increase in running $C_R$ under a fatigued state is a determining factor for triathlon performance. Examination of this issue has recently become more important with modifications of triathlon rules to allow drafting during the cycling component, which makes running more important in the overall performance. The increase of the respiratory muscle $O_2$ demand has been identified as a partial cause of the increase of $C_R$ [8,23,34]. Another cause of the modifications of $C_R$ in fatigue state could be related to mechanical alterations [8]. Among mechanical parameters, the primary factor is the external mechanical work done per unit of distance ($C_M$, or mechanical cost). The relationship between $C_R$ and $C_M$ has been previously reported in non-fatigue state and loaded running [5]. The second factor is the leg stiffness regulation. It has been shown that $C_R$ is correlated to the leg stiffness of the lower limbs [14], suggesting a potential role of this factor especially in fatigue state. The stretch reflex implicated in the stiffness regulation seems altered in such conditions [31]. Thus, the purpose of the present study was to test the hypothesis that elite triathletes have less of an increase in running $C_R$ following a maximal cycling exercise, associated to a lower rise in oxygen consumption of the respiratory muscles and lower alterations in running mechanics, than their less successful counterparts.

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## Methods

### *Subjects*

Twenty-six triathletes provided a written informed consent to participate in this study after the procedures and possible risks and benefits of participation were explained. Selected characteristics of the subjects are outlined in Table **1**. The triathletes were separated into two groups in accordance with level of performance. The elite triathletes were members of the French national team (3 ranked in the World top-12 and the others in the World top-50) and the middle-level triathletes were regional to national level competitors.

**Table 1** Selected characteristics of the subjects (mean ± SD)

| Characteristic | Elite ( = 8) | | Middle-level (n = 18) | |
|---|---|---|---|---|
| | Males (n = 1) | Females (n = 7) | Males (n = 14) | Females (n = 4) |
| Age (yr) | 31 | 29 ± 3 | 23 ± 3 | 18 ± 1 |
| Height (cm) | 181.0 | 168.0 ± 5.5 | 178.3 ± 6.5 | 168.0 ± 4.1 |
| Mass (kg) | 72.5 | 62.5 ± 5.6 | 70.2 ± 5.9 | 58.2 ± 3.9 |
| $\dot{V}O_2$max (ml × kg$^{-1}$ × min$^{-1}$) | 74.3 | 58.0 ± 4.7 | 70.5 ± 4.9 | 59.1 ± 1.3 |
| DT (yr) | 8 | 9 ± 4 | 6 ± 2 | 5 ± 1 |

$\dot{V}O_2$max = maximal oxygen uptake, DT = duration of training for triathlon.

### *Protocol*

Each subject performed a test including two 7 min runs on a treadmill (PowerJog E30, Sport Engineering Limited, Birmingham, England) before and after a maximal cycle exercise on an electronically-braked ergometer (Orion, S.T.E, Toulouse, France) allowing a freely chosen pedalling frequency (Fig. **1**). The 7 min duration for the runs was chosen in order to avoid, at the end of the second running bout, the effect of excess post exercise oxygen consumption due to the maximal cycling exercise. All subjects were familiar with being assessed at least twice a year on a treadmill. Immediately before the test, each subject warmed-up at work rates corresponding to approximately 60% of $\dot{V}O_2$max for 10 min on the ergometer and 7 min on the treadmill. The first 7 min run was performed at a speed corresponding to the average velocity ($V_{run}$) sustained during the 10 km running portion of a short-distance triathlon (1.5 km swim – 40 km cycle – 10 km run) (Table **2**). Immediately after the first run, the subjects performed a progressive test to exhaustion (70 W step increments in power output every 3 min starting from 70 W until 280 W, then 35 W step increments every 2 min) in which maximal aerobic power output (MAP in W × kg$^{-1}$) was determined. Once MAP was determined, the power output was immediately dropped to 80% of MAP and cycling was continued until the subject indicated he or she was unable to maintain this work rate. The subjects then ran at $V_{run}$ for another 7 min. In order to simulate real competition conditions, the two transitions (run to cycle ergometer and cycle ergometer to run) never exceeded 1 min.

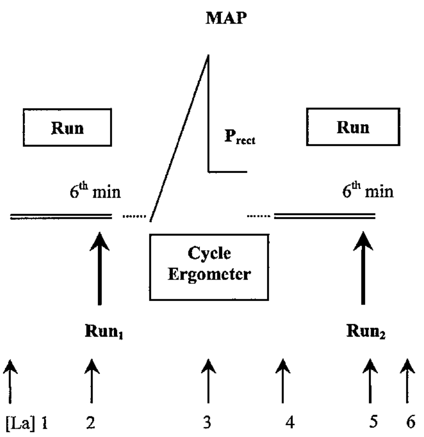


**Fig. 1** Graphic representation of the experimental protocol, MAP = maximal aerobic power, $P_{rect}$ = constant rectangular power, [La] = lactate measurement.

**Table 2** Physiological characteristics sustained by the subjects (mean ± SD)

| Characteristics | Elite (n = 8) | | Middle-level (n = 18) | |
|---|---|---|---|---|
| | Males (n = 1) | Females (n = 7) | Males (n = 14) | Females (n = 4) |
| $V_{run}$ (km × h$^{-1}$) | 18.5 | 15.1 ± 0.6 | 17.6 ± 0.6 | 14.2 ± 0.2 |
| %$\dot{V}O_2$max (%) | 83.1 | 90.3 ± 9.7 | 84.2 ± 5.5 | 85.8 ± 4.8 |
| MAP (W × kg$^{-1}$) | 5.3 | 4.8 ± 0.4 | 4.9 ± 0.3 | 4.2 ± 0.2 |
| $P_{rect}$ (W × kg$^{-1}$) | 3.9 | 3.7 ± 0.3 | 3.9 ± 0.2 | 3.5 ± 0.1 |
| $T_{rect}$ (s) | 600 | 472 ± 257 | 352 ± 180 | 167 ± 62 |

$V_{run}$ = velocity sustained over two treadmill runs, %$\dot{V}O_2$max = average percentage of $\dot{V}O_2$max sustained over treadmill runs, MAP = maximal aerobic power, $P_{rect}$ = constant rectangular power and $T_{rect}$ = time sustained at $P_{rect}$ on cycle ergometer.

### *Physiological Measurements*

Gas exchange was monitored continuously throughout the protocol. Ventilation ($\dot{V}E$), $CO_2$ production ($\dot{V}CO_2$) and oxygen uptake ($\dot{V}O_2$) were recorded breath by breath and averaged every min with an automatic gas analyser (CPX analyser, Medical Graphics Corporation, Saint-Paul, MN). Calibration was completed before each test using certified commercial gas preparations. Heart rate was measured with a telemetry monitor (Polar Vantage XL, Polar Electro, Finland). Blood samples were obtained from the antecubital vein on six occasions as shown in Fig. **1** from which whole blood lactate concentration [La-] was measured with a lactate analyser (Microzym L, S.G.I., Toulouse, France). A rating of perceived exertion (RPE) using a 6–20 scale [4] was requested at the end of the first min and at the end of each run.

The energy cost was calculated during the last minute of each 7 min run from the $\dot{V}O_2$ above basal metabolic rate as follows:

$$C_R = (\dot{V}O_2 - 0.083) \times E_{02} \times V^{-1}$$

where $\dot{V}O_2$ is expressed in ml × kg$^{-1}$ × s$^{-1}$, 0.083 ml × kg$^{-1}$ × s$^{-1}$ is the y-intercept of the $\dot{V}O_2$-treadmill velocity relationship established by Medbø et al. [29] in young adults, and V is the mean velocity of the treadmill in m × s$^{-1}$.

The anaerobic energy supply evaluated as proposed by Di Prampero et al. [19] from the elevation of [La-], represented only a minor part of the overall energy. The anaerobic energy supply didn't modify the difference of $C_R$ between both groups. Thus, $C_R$ was determined only from the aerobic energy supply.

The work of breathing ($W_B$, in kg × m × min$^{-1}$) corresponding to minute ventilation ($\dot{V}E$ in l × min$^{-1}$) was estimated from the equation proposed by Coast et al. [11]:

$$W_B = 0.251 - 0.0382 \times \dot{V}E + 0.00176 \times \dot{V}E^2$$

Finally, the $\dot{V}O_2$ of the respiratory muscles ($\dot{V}RMO_2$ in ml × min$^{-1}$) was evaluated [11]:

$$\dot{V}RMO_2 = 34.9 + 7.45 \times W_B$$

*Mechanical measurements*

The mechanical variables were evaluated with a kinematic arm (KA). The KA consists of four light rigid bars linked by three joints. At each joint, an optical encoder measured the angle between the consecutive segments. It was then possible to compute the instantaneous displacement of the end of the KA (the moving end) relative to the fixed end (the reference end). The moving end of the KA was linked to the subject by means of a belt fastened around his/her waist while the reference end was fixed to the ceiling. In running conditions, the measurement errors with the KA are equivalent or lower than errors of tracking systems or to video analysis [2]. The displacement of the treadmill belt was measured with an extra optical encoder fixed on a wheel mounted on the treadmill belt with an accuracy of 0.1 mm. The velocity of the treadmill was obtained by a first order digital derivation of the displacement signal. As in previous studies [3], the contact between the foot and the treadmill belt was clearly determined by a sudden decrease in the treadmill velocity signal. This latter parameter was used to identify the step period as shown in Fig. **2**. Treadmill and KA encoder signals were collected during the last minute of each running bout ($Run_1$ and $Run_2$, see Fig. **1**). According to the recommendations of Belli et al. [3], the sampling duration and frequency were 16 s and 100 Hz, respectively (corresponding to 45 to 50 steps). A zero-phase lag fourth-order Butterworth low pass digital filter with a cut-off frequency of 10 Hz was applied to the KA data. Assuming that the waist movements were a reasonable approximation of centre of mass (CG) displacement [2], the position of the CG was computed as previously described [1].

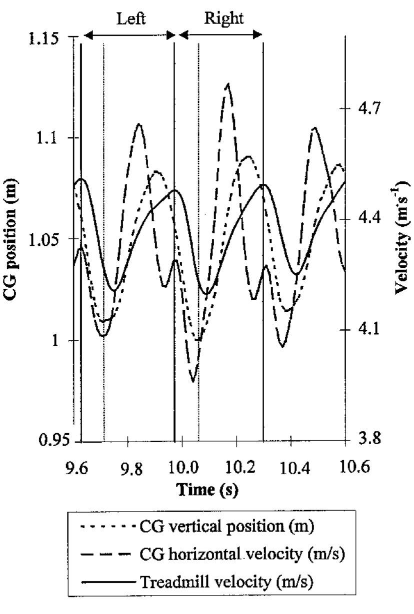


**Fig. 2** Example of the changes in CG vertical positions, CG horizontal velocity and treadmill velocity during running. Two steps are presented. The sudden decrease in treadmill velocity identified by the solid vertical solid lines indicates the beginning of the contact between the foot and the treadmill belt. The dashed vertical lines indicate the lowest vertical position of the CG.

According to previous studies of Cavagna et al. [9,10], the changes of positive potential energy ($W_{pot}$ in J) and positive kinetic energy ($W_{kin}$ in J) within each step were determined:

$$W_{pot} = BM \times g \times (H_{max} - H_{min})$$

$$W_{kin} = 0.5 \times BM \times (V_{max}^2 - V_{min}^2)$$

Where BM is the body mass (in kg), g is the gravitational acceleration (9.81 m × s$^{-2}$ ), $H_{max}$ and $H_{min}$ are the maximal and minimal heights of CG (in m), and $V_{max}$ and $V_{min}$ are the maximal and the minimal horizontal velocities of CG (in m × s$^{-1}$). In fast running the potential and kinetic energies do not interchange and the work due to lateral displacement is negligible [9], thus the external positive work ($W_{ext}$) was calculated as:

$$W_{ext} = W_{pot} + W_{kin}$$

Mechanical cost (in J × kg$^{-1}$ × m$^{-1}$) was determined as the ratio between $W_{ext}$ and the stride length (SL). Similarly, kinetic and potential costs ($C_{kin}$ and $C_{pot}$) were equal to $W_{kin}$ and $W_{pot}$ divided by SL. Average time of each step ($T_{step}$), step frequency ($SF = 1 \times T_{step}^{-1}$), stride length ($SL = V \times SF^{-1}$ ), average height of the CG ($H_{AVE}$) and vertical displacement of CG during the braking phase ($\Delta H_{STRIKE}$) were also determined.

*Statistical analysis*

The physiological and mechanical variables are presented as mean, standard deviation and mean change (%) from the first to the second run. Physiological and mechanical variables of the study were compared between groups and across $Run_1$ and $Run_2$ measurements with two-way analysis of variance (ANOVA) (1 between, 1 within). Comparisons between groups were made by examination of the group × time interaction. When F values were significant, individual comparisons were made with the Scheffe post-hoc test. Correlation analysis was used to assess the relationships of individual variations in $C_R$ with variations in the mechanical variables. For all statistical analyses, a P value of 0.05 was accepted as the level of statistical significance.

## Results

*Physiological variables*

Running velocity during the second run corresponded to 89.4 ± 8.8% and 84.5 ± 5.2% of $\dot{V}O_2$max for elite and middle-level triathletes, respectively (Table **2**) and this percentage was not significantly different between the two groups. Comparisons of the physiological responses are presented in Table **3**. Neither group showed a significant change in $C_R$ as a result of the cycling. Heart rate and $\dot{V}E$ were significantly increased by cycling for middle-level but not for elite triathletes. Additionally, $\dot{V}RMO_2$ increased significantly for the middle-level between the first and second runs (3.2 ± 0.3% and 4.2 ± 0.6% of $C_R$, respectively), but did not change significantly for elite triathletes (3.6 ± 0.6% and 4.3 ± 1.0% of $C_R$, respectively). Neither group showed a significant change in RPE from cycling.

**Table 3** Physiological variables at the end of the first ($Run_1$) and the second ($Run_2$) run (mean ± SD)

| Variables | Elite Run$_1$ | Elite Run$_2$ | Elite Change | Middle-level Run$_1$ | Middle-level Run$_2$ | Middle-level Change |
|---|---|---|---|---|---|---|
| [La-] (mmol × l$^{-1}$) | 2.61 ± 1.41 | 5.18 ± 2.61$^a$ | 98 ± 55 % | 1.82 ± 0.63 | 4.67 ± 1.49$^b$ | 157 ± 118 % |
| HR (bpm) | 162.6 ± 9.3 | 175.0 ± 5.2 | 7.6 ± 3.7 % | 174.8 ± 7.8 | 185.8 ± 8.2$^a$ | 6.3 ± 2.9 % |
| $\dot{V}$E (l × min$^{-1}$) | 92.4 ± 11.8 | 101.1 ± 11.9 | 9.3 ± 7.6 % | 90.0 ± 14.2 | 109.0 ± 19.2$^a$ | 21.1 ± 10.0 % |
| $\dot{V}RMO_2$ (ml × min$^{-1}$) | 124.5 ± 24.5 | 143.7 ± 28.9 | 16.5 ± 13.2 % | 120.1 ± 27.2 | 166.4 ± 47.8$^b$ | 37.7 ± 19.4 %* |
| $C_R$ (J × kg$^{-1}$ × m$^{-1}$) | 4.01 ± 0.46 | 3.86 ± 0.34 | – 3.7 ± 4.8 % | 3.67 ± 0.37 | 3.76 ± 0.39 | 2.3 ± 4.6 %** |
| RPE (points) | 10.2 ± 1.3 | 9.5 ± 2.3 | – 7.3 ± 27.0 % | 12.3 ± 2.5 | 13.9 ± 2.3 | 12.7 ± 25.1 % |

[La–] = blood lactate concentration; HR = heart rate, $\dot{V}$E = minute ventilation, $C_R$ = energy cost of running, $\dot{V}RMO_2$ = $\dot{V}O_2$ of respiratory muscles, RPE = rating of perceived exertion, $^a$ = P < 0.01, $^b$ = P < 0.001 for differences between the first and second runs, * = P < 0.05, ** = P < 0.01 for differences between groups in the effect of the cycling.

**Table 4** Mechanical variables at the end of the first ($Run_1$) and the second ($Run_2$) (mean ± SD)

| Variables | Elite Run$_1$ | Elite Run$_2$ | Elite Change | Middle-level Run$_1$ | Middle-level Run$_2$ | Middle-level Change |
|---|---|---|---|---|---|---|
| $H_{AVE}$ (m) | 1.03 ± 0.05 | 1.03 ± 0.04 | – 0.3 ± 6 % | 1.07 ± 0.05 | 1.07 ± 0.05 | – 0.2 ± 0.7 % |
| $\Delta H_{STRIKE}$ (cm) | 6.01 ± 1.87 | 5.76 ± 1.18 | – 4.2 ± 8.3 % | 4.96 ± 0.75 | 5.16 ± 0.77 | 4.0 ± 8.9 % |
| SF (Hz) | 3.04 ± 0.06 | 3.03 ± 0.07 | – 0.6 ± 1.3 % | 2.90 ± 0.12 | 2.89 ± 0.13 | – 0.6 ± 2.1 % |
| $C_{kin}$ (J × kg$^{-1}$ × m$^{-1}$) | 2.11 ± 0.40 | 2.00 ± 0.33 | – 5.3 ± 5.1 % | 1.97 ± 0.30 | 1.94 ± 0.27 | – 1.2 ± 23.3 % |
| $C_{pot}$ (J × kg$^{-1}$ × m$^{-1}$) | 0.51 ± 0.12 | 0.51 ± 0.08 | – 0.1 ± 7.3 % | 0.47 ± 0.06 | 0.49 ± 0.06 | 4.2 ± 4.8 % |
| $C_M$ (J × kg$^{-1}$ × m$^{-1}$) | 2.62 ± 0.49 | 2.51 ± 0.37 | – 4.3 ± 5.3 % | 2.44 ± 0.29 | 2.44 ± 0.25 | – 0.1 ± 4.3 % |

$H_{AVE}$ = average height of the centre of mass, $\Delta H_{STRIKE}$ = vertical displacement of the centre of mass during the braking phase, SF = step frequency, $C_{kin}$ = kinetic cost, $C_{pot}$ = potential cost, $C_M$ = mechanical cost. There were no changes between runs in either group.

The effect of cycling on $C_R$ differed between groups based upon a significant group × time interaction (P < 0.01). In other words, under the effect of cycling, $C_R$ decreased by 3.7 % for the elite and increased by 2.3 % for the middle-level triathletes; and this difference between groups was significant. Furthermore, the effect of cycling on $\dot{V}RMO_2$ differed between groups (P < 0.05), but the effect on [La-], heart rate, $\dot{V}$E and RPE was not different between groups (Table **3**).

### *Mechanical variables*

The effect of cycling on the mechanical variables at the end of each run did not differ significantly between groups (Table **4**). $C_M$ remained stable for both groups, despite a tendency of 4.3 ± 5.3 % decrease for the elite. Individual variations in $C_R$ between the two runs did not correlate with the variations in $C_M$.

## Discussion

The most important findings of the present study are that there was a significant difference between the elite and middle-level triathletes in the effect of a fatiguing cycling bout in the energy cost of running.

### *$C_R$ and $C_M$: comparison with the literature*

The present values of $C_R$ are similar to those reported in previous studies [7,19]. In the present study, there was no significant difference in $C_R$ between elite and middle-level triathletes. This finding is in line with the study of Krahenbuhl and Pangrazi [25], which reported no differences in $C_R$ related to level of training among athletes. It has also been demonstrated that trained athletes have a lower $C_R$ than non-trained individuals [6], but the influence of training on $C_R$ is thought to be small [24]. Since the number of years of training were comparable between middle-level and elite triathletes, the lack of difference in $C_R$ between the two groups seems reasonable. One could argue that the results have been affected by the fact that the elite group was composed of a majority of females, while the middle-level group was composed of a majority of males. In fact, when expressed per kg of body mass, $C_R$ has been shown to be slightly higher in females than in males when compared at the same speed [6]. However, in this study percentage of $\dot{V}O_2max$ and RPE are similar between groups indicating that they ran at the same relative intensity. It has been reported that $C_R$ is the same between males and females when compared at the same relative intensity [7,15].

The present values for $C_M$ were similar to those previously reported for middle-level triathletes [8], but greater than those reported for runners [19]. To the best of our knowledge, $C_M$ has not previously been reported for elite triathletes.

### *Potential mechanisms of the lower changes in $C_R$ for the elite athletes*

One could argue that part of the changes observed during the second run could also be induced by the fatigue of the first run. However, the blood lactate concentration lower than 3 mmol × l$^{-1}$ and the RPE values lower than 13 at the end of the first run (see Table **3**) indicated a relatively easy exercise and suggested a small effect on the second run.

Moreover, the middle-level triathletes are long-term trained (at least for 5 years) and performed at regional to national level; thus the role of the long-term adaptation is unlikely to explain the difference of $C_R$ changes between the two groups.

### Energy cost of the respiratory muscles

This study found that the estimated running $\dot{V}RMO_2$ increased significantly more after cycling ($P < 0.05$) for middle-level ($46.3 \pm 27.5\ mlO_2 \times min^{-1}$) than for elite triathletes ($19.2 \pm 16.5\ mlO_2 \times min^{-1}$). It has been argued that the increase in $\dot{V}RMO_2$ could partly account for the increase in $C_R$ with short-term fatigue [8,34]. In the present study, the 38% rise in $\dot{V}RMO_2$ for middle-level explained 8.5% of the increase in $C_R$, a value similar to the 8–14% obtained from calculations with the data presented in previous studies [20–23]. The fatigue of the inspiratory muscles could be influenced by the training status [28] and could then explain the fact that middle-level triathletes increased significantly more the oxygen consumption of respiratory muscles than their elite counterparts.

### Mechanical alterations

It has been hypothesied that the elite triathletes experienced a lower increase in $C_R$ and $C_M$ than the middle-level triathletes. Surprisingly, $C_R$ and $C_M$ tended to decrease for elite (–3.7 ± 4.8% and –4.3 ± 5.3%); $C_R$ increased (2.3 ± 4.6%) and $C_M$ remained stable (–0.1 ± 4.3%) for the middle-level. The relationship between $C_R$ and mechanical variables is still unclear [30,31,38]. $C_R$ has not been found to be influenced by a single mechanical factor [38]. Because of the step variability during running, it has been proposed that part of the weak relationship between $C_R$ and mechanical variables could be due to the limited number of steps typically analysed [2]. Using a KA to analyse 48 ± 4 steps, Candau et al. [8] have observed a significant increase in $C_M$ with short-term fatigue. However, the increases in $C_M$ and $C_R$ were not correlated, suggesting that the alteration in movement pattern for the centre of mass was not only responsible for the rise in $C_R$ with fatigue. Previous studies [22,23,35] focusing on the kinematic parameters (stride length, stride rate, joint angles) changes showed no major alterations. Quigley and Richards [35] found no changes in running mechanics immediately following 30 min of bicycling compared with an isolated run and concluded that the perception of discomfort during the first minutes following the cycle-run transition was not related to alterations in the running pattern. With the exception of a more forward leaning posture, Hausswirth et al. [22] reported low mechanical alterations in the running part of a triathlon compared with a marathon of the same duration. Also, no relationship between changes in a single kinematic variable and increases in $C_R$ was found in this latter study. Hue et al. [23] confirmed that no changes occur in stride length and rate. Nevertheless, none of the experiments above studied kinetic parameters. Despite the use of a global kinetic descriptor, the mechanical cost, the present study confirmed previous findings, i.e. no significant alterations in running mechanics after cycling.

### Storage and re-use of elastic energy

While the mechanisms explaining an enhanced work output from movements utilising a stretch-shortening cycle (SSC) are still under discussion [37], it seems evident that elastic energy plays a role in the conservation of mechanical energy. It has been shown that energy stored in muscle structures during an eccentric contraction can be re-used in the subsequent concentric contraction. Storage and reutilization of this elastic energy improves the efficiency of repetitive SSC movements such as running [9,31]. The quantity of elastic energy stored and recovered is influenced by leg stiffness [10].

One could argue that the change in $C_R$ might be related to alterations in muscle-tendon stiffness. In a non-fatigued running state, $C_R$ has been shown to be significantly related to the stiffness of the propulsive leg [14]. A decrease in the stiffness results in less efficient storage and recoil of elastic energy, and thus an increase in $C_R$. In the present study, a trend towards an increase (4.0 ± 8.9%) in $\Delta H_{STRIKE}$ (i.e. vertical displacement in CG during the braking phase) after cycling among middle-level triathletes supports the speculation that there might have been a decrease in the muscle-tendon stiffness after exhaustive cycling in this group. In contrast, the decrease (–4.2 ± 8.3%) for the elite triathletes suggests a better stiffness regulation after cycling; i.e. in specific conditions. Elite triathletes are more experienced at the cycling-running transition and may be more capable of reorganising their stride patterns when running after exhaustive cycling. Nevertheless, it remains to be addressed whether there are alterations in lower limb stiffness after exhaustive cycling, and whether such a change is a determinant of performance.

### *Practical implications*

To the best of our knowledge, no previous studies have reported the influence of performance level on running economy under a specific fatigue state. There was no significant overall effect of exhaustive cycling on $C_R$ observed in this study. This finding is comparable to one study [16], while others [20–23,26] have observed an increase in $C_R$ after cycling. Based on the alterations of $C_R$, it could be estimated from the equation of di Prampero et al. [18] that the 10 km running time after fatigue from cycling is increased for middle-level (74 ± 63 s) and slightly decreased (–12 ± 18 s) for elite triathletes. The recognition that the influence of exhaustive cycling on the energy cost of running varies among triathletes may have practical importance relative to physiological testing. For instance, the performance of running tests after exhaustive cycling rather than in the rested state may be more valuable for the purposes of monitoring the adaptations to training in triathletes.

In conclusion, a significant effect of the triathlon performance level on the change of the running energy cost after cycling has been identified. A lower rise in oxygen consumption of the respiratory muscles, a tendency to a decrease of the mechanical cost associated to a suggested better stiffness regulation was observed among the elite triathletes but not among their less successful counterparts. Nevertheless gender influence can not be totally excluded to explain the difference of cycling effects on running economy. Further studies are needed to confirm the present results.

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