Changes in internal mechanical cost during over-ground running to exhaustion

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Abstract

Objective: The purpose of this study was to determine, during an over-ground supra-threshold run, whether a change in the internal mechanical cost could occur during an exhaustive run and if this change was related to the increase in the energy cost of running (C_r). **Methods:** The C_r of fourteen endurance runners was measured from pulmonary gas exchange using a breath by breath portable gas analyser (Cosmed K4b^2, Roma, Italy), at the third and the last minute of an exhaustive exercise performed at their velocity corresponding to 95% of the maximal oxygen uptake (4.88 ± 0.38 m.s^{-1}). At the same time, potential, kinetic and internal mechanical costs (C_{pe}, C_{ke} and C_{int}) were measured with a 3D motion analysis system (ANIMAN3D). **Results:** C_{int} and C_r increased significantly within the 3rd minute and the end of the supra-threshold exercise (respectively 0.55 ± 0.07 vs 0.60 ± 0.07 J.kg^{-1}.m^{-1} and 4.10 ± 0.39 vs 4.32 ± 0.42 J.kg^{-1}.m^{-1}; $p \leq 0.03$). However, the percentage of variation of C_{int} and C_r were not correlated ($r = 0.06$; $p = 0.84$). Contrary to C_{int}, C_{ke} and C_{pe} remained constant during the exercise (respectively 1.33 ± 0.33 vs 1.38 ± 0.29 J.kg^{-1}.m^{-1} $p = 0.79$ and 0.47 ± 0.11 vs 0.48 ± 0.10 J.kg^{-1}.m^{-1}; $p = 0.67$), but both parameters were significantly correlated with C_r ($r = -0.43$; $p = 0.03$ and $r = 0.40$; $p = 0.03$). **Conclusion:** During over-ground running to exhaustion a significant increase in C_{int} occurred, but this did not account for the increase in C_r. Moreover, the increase in C_{int} has yet to be explained.

Key words: Energy cost, oxygen slow component, mechanical work and fatigue.

Introduction

Paragraph Number 1

The process of determining the energy cost of running (C_r) during an exercise of moderate intensity is based on two assumptions. The first is that C_r is independent of running time for constant-speed running of 3-30 minutes duration. The second is that a steady-state of oxygen uptake ($\dot{V}O_2$) occurs following 3-4 min of exercise (25). However, during constant-load exercise of supra-lactic threshold intensity, the steady-state of $\dot{V}O_2$ is delayed after 3-4 min. A number of physiological factors have been postulated as contributing to this delayed steady state of $\dot{V}O_2$ during a supra-lactic threshold exercise (8, 13, 20). However, biomechanical factors have received less attention as potential causes which could partially explain this increase in C_r.

Paragraph Number 2

In running studies, biomechanical factors have often been used to address the differences in C_r among individuals (17, 35). Kram (22), as well as Farley and McMahon (19), had shown that C_r could be determined by the force generated by the muscle during running. Others have also shown that an inverse relationship exists between the stiffness of the body and the C_r (15). However, the interactions between mechanical and metabolic variables appear to be very complex. A general mechanical approach has been based on the observation of the mechanical energy change of the centre of mass and of the limbs of the body (14, 34). Indeed, the mechanical energy change associated with the movement of the different segments of the body during running, represents the energy used by the active muscle. Poole et al. (26) have demonstrated that 86% of this increase in C_r was related to the increase in active muscle $\dot{V}O_2$. Therefore the increase in C_r observed at the end of supra lactic threshold exercise may be related to the variation in mechanical energy.

Paragraph Number 3

Some studies have significantly related the differences in C_r to the energy variations of the centre of mass during running (11, 12). Above the lactic threshold and under the influence of fatigue, the mechanical cost associated with the movements of an anatomical point taken as equivalent of the body centre of mass of the runner, has been significantly correlated with C_r and increased significantly between the beginning and the end of the exercise (12). Even if the interactions between biomechanical and physiological factors are still open to debate, this result suggests that the increase in C_r, generally observed after the 3^{rd} min of a supra-lactic threshold exercise, may be due to a combined action of both physiological and mechanical mechanisms. Recently, Borrani et al. (10) and Avogadro et al. (2) suggested that the increase in C_r in running did not result from a change in the external mechanical cost under the effect of fatigue. Nevertheless, the decrease in stride frequency suggested an alternative mechanical explanation such as a modification of the mechanical cost associated with the movements of the limbs around the centre of mass which is called the internal mechanical cost (C_{int}).

Paragraph Number 4

Therefore, in order to complete the understanding of the relationship between mechanical and metabolic variables, this study aims to determine whether a change in C_{int} could occur during an exhausting over-ground run and whether this change is related to a modification of C_r. The hypothesis was that the increase in C_r, generally observed after the 3^{rd} min of a supra-lactic threshold exercise, is associated with a modification of C_{int}.

Paragraph Number 5

Methods

Subjects and protocol

Fourteen subjects (mean height 1.73 ± 0.06 m, mean body mass 62 ± 9 kg, and mean age 21.9 ± 2.8 yrs) volunteered to participate in this study. This population was composed of 3 females and 11 males. Five subjects were physical education students (soccer, rugby and tennis players), the others subjects trained regularly in running (they had a national or a regional level of competition). Table 1 summarises this information. Prior to participation, all the subjects were informed of risks and stress associated with the experimental protocol and gave a written voluntary informed consent and approval received by ethics committee in accordance with the guidelines of the hospital of Paris S^{t} Louis.

	Specialist of running (n = 9)	***Non specialist of running (n = 5)***	***Total (n = 14)***
v$\dot{V}O_{2max}$ (m.s^{-1})	5.31 ± 0.34	4.75 ± 0.35†	5.10 ± 0.43
$\dot{V}O_{2max}$ (ml.kg^{-1}.min^{-1})	57.1 ± 8.5	67.6 ± 6.3†	63.8 ± 8.6
vLT (m.s^{-1})	4.43 ± 0.46	3.70 ± 0.45†	4.23 ± 0.55
tlim (s)	369.8 ± 52.7	374.4 ± 90.8	372.8 ± 77.0
Height (m)	1.72 ± 0.06	1.74 ± 0.05	1.73 ± 0.06
Age (yr)	20.4 ± 2.1	24.6 ± 1.5†	21.9 ± 2.8
Body mass (kg)	58.9 ± 8.1	68.6 ± 7.2†	62.4 ± 8.9

†Significantly different from the specialist of running ($p \leq 0.05$).

Table 1: Anthropometrical and physiological variables of the fourteen subjects: the maximal oxygen uptake ($\dot{V}O_{2max}$), the velocity associated to $\dot{V}O_{2max}$ (v$\dot{V}O_{2max}$), the velocity at the lactate threshold (vLT) and time to exhaustion (tlim).

All subjects performed two exhaustive tests.

- An incremental test (3-min stages) to exhaustion (the voluntary stop of the exercise). This test was performed on a track in order to determine the maximal oxygen consumption ($\dot{V}O_{2\,max}$). This parameter was defined as the highest 30 s

$\dot{V}O_2$ value attained during the test. The velocity associated with $\dot{V}O_{2\,max}$ ($v\dot{V}O_{2\,max}$) (9). The velocity at the lactate threshold (vLT) was defined as the speed measured at $\dot{V}O_2$ value which corresponds to the starting point of an accelerated lactate accumulation between 3.5 and 5 $mmol.L^{-1}$ (1).

- An exhaustive run at 95% of $v\dot{V}O_{2max}$ until exhaustion (tlim95).

Throughout the tests, the subjects adopted the required velocity using an audio rhythm which gave the time to cover 20-m. Visual marks were set at 20-m intervals along the track with audio signals determining the speed needed to cover 20-m intervals. To estimate the kinetic, potential and internal mechanical cost of running (C_{ke}, C_{pe} and C_{int}), the mechanical analysis was performed during the tlim95. The runners were filmed by a video camera using a sampling frequency of 25 frames per second (Sony, Beta SP VCRs, resolution of 572 lines). The camera was positioned 9 meters from the left of the runner. Two consecutives steps were analysed at the beginning of the test (during the second lap of the track, around the 3rd min after the beginning of the exercise) and two more steps at the end of the test (during the last lap of track, around the last minute of the exercise). The running speed was documented with the video camera, for each time the runner crossed in front of the camera (Table 2). The energetic cost of running (C_r) was also evaluated throughout the exercise, by the oxygen uptake measurement.

	3^{rd} min (n = 14)	*End (n = 14)*
Velocity ($m.s^{-1}$)	4.87 ± 0.40	4.89 ± 0.37
SR (Hz)	2.98 ± 0.12	3.00 ± 0.16
SL (m)	1.62 ± 0.14	1.63 ± 0.11
C_{ke} ($j.kg^{-1}.m^{-1}$)	1.33 ± 0.33	1.38 ± 0.29
C_{pe} ($j.kg^{-1}.m^{-1}$)	0.47 ± 0.11	0.48 ± 0.10
C_{int} ($j.kg^{-1}.m^{-1}$)	0.55 ± 0.07	0.60 ± 0.07†
C_r ($j.kg^{-1}.m^{-1}$)	4.10 ± 0.39	4.32 ± 0.42†

†Significantly different from the 3rd minute of the exercise ($p \leq 0.05$).

Table 2: Changes in the stride rate (SR), the stride length (m), the velocity of the exercise, kinetic (C_{ke}), potential (C_{pe}), internal mechanical cost (C_{pe}) and energetic cost of running (C_r) between the 3rd and the last minute of the exercise.

Paragraph Number 6

Material

Oxygen uptake measurement. Throughout the exercises, the respiratory and pulmonary gas exchange variables were measured using a breath-by-breath portable gas analyzer (Cosmed K4b^2, Roma, Italy). Before each test, O_2 and CO_2 analysers were calibrated using ambient air and sample gas references of 16% O_2 and 5% CO_2. The flowmeter was calibrated with a volume of air of 3-l (Quinton instruments, Seattle, USA). The accuracy of this system has been tested and is acceptable for $\dot{V}O_2$ and $\dot{V}CO_2$ measurement during supra-lactic threshold exercise (23).

Paragraph Number 7

Mechanical measurement. The video sequences obtained during the tlim95 were digitised without distortion on a PC as a series of bitmap images by a Perception Video Recorder card from Silicon Co. Then the images recorded were displayed and analysed on a screen of a regular PC. ANIMAN 3D uses the numerical human model MAN3D (27, 28, 30) which is delimited by an envelope composed of 155 crowns. These crowns are superimposed on the different segments of the manikin (figure 1). The position and posture of MAN3D can be adjusted to each runner. The morphological properties of MAN3D are deduced from the size and the weight of the subject. The inertial properties of the segments are from works of Dempster and Gaughran (16). Then MAN3D is projected onto images. When the projections of MAN3D were superimposed onto the images of the runner, the position and posture of the runner were the same as that of MAN3D. Posture and position adjustments were optimized by locating the positions of some particular points of the runner on the images which must coincide with some equivalent points of MAN3D. There are 5 particulars points which help the researcher to project Man3D on the runner. These points are represented in the following picture (figure 2):

- The top of the head.
- The hand in direct view.
- Two points on the back.
- The end of the foot in direct view.

Our method has been compared with the measure of a force plate-form (29). The results have shown that the difference between both systems on the computation of the mechanical energy was about 11% and remains constant for different running speeds. When the segments (hand, forearm and arm) are out of direct view, the system allows Man3D to be projected onto a partially hidden segment with accuracy. Indeed, when the elbow is in direct view, it is possible to deduce the position of the forearm and of the arm with accuracy. However, when the elbow and the forearm is out of direct view (as in figures 1 or 2) the system does not allow one to deduce with the same accuracy the position of the hand, the forearm or the arm. But this case (when the arm is totally hidden) does not represent more than one or two images during one step. Moreover, the position of the hidden arm can be deduced from the previous and the following positions of the arm. This procedure allows the trajectory of the body centre of mass and the trajectories of the limb centres of mass to be obtained. The uncertainty in the determination of the different centres of mass trajectories depends on the resolution of the video camera used.

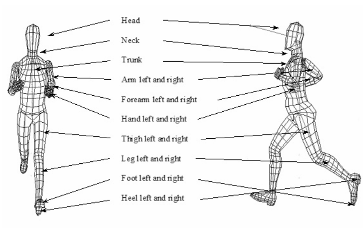

Figure 1: MAN3D human model representation and its 17 segments.

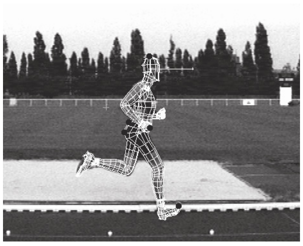

Figure 2: Example of projection of Man 3D on the runner, with the 5 particulars points (black).

Paragraph Number 8

Data analysis

<u>Energy cost (C_r).</u> The breath-by-breath oxygen uptake data were reduced to 5-s stationary averages in order to reduce the noise so as to enhance the oxygen kinetics characteristics. These data were finally fitted to two exponential functions using a least square fit method: a single-exponential function comprising a delayed linear component (eq. 1) and a double-exponential function comprising two exponential terms which start at two distinct time delays from the onset of exercise (eq. 2) (4). The Fisher test was used to choose the model for which the fit was associated with the highest F value (4).

$$\dot{V}O_2(t) = y_0 + A_1 \times (1 - e^{-(t-TD1)/\tau_1}) \times U_1$$

(fast component) [1]

$$+ A_2 \times (1 - e^{-(t-TD2)/\tau_2}) \times U_2$$

(slow component) [2]

Where y_0 is the baseline $\dot{V}O_2$ ($ml.min^{-1}$), A_1 and A_2 are the asymptotic amplitudes for the exponential terms ($ml.min^{-1}$), τ_1 and τ_2 are the time constants (min), and TD1 and TD2 are the time delay from the onset of exercise (s).

$$U_1 = 0 \text{ for } t < TD1 \text{ and } U_1 = 1 \text{ for } t \geq TD1$$

$$U_2 = 0 \text{ for } t < TD2 \text{ and } U_2 = 1 \text{ for } t \geq TD2$$

The energy cost of running (C_r) was evaluated, 3 mins after the beginning of the exercise and 1 min before its end (12):

$$C_r = \dot{V}O_2(t) \cdot E_{O_2} \cdot V_{95}^{-1} \cdot M^{-1}$$

Where E_{O_2} (21.3 $J.ml\,O_2^{-1}$) is the energy equivalent of 1 mlO_2 for a respiratory exchange ratio of 1 (12), and V_{95} is the velocity during the test tlim95 (measured with the video camera).

Paragraph Number 9

Mechanical cost. All the trajectories of the different centres of mass of the model (segments and body centres of mass) were smoothed using a polynomial method in order to obtain by derivation the speed displacement of the different centres of mass. The speed of running was measured with the video camera after the trial. In the referential of the camera, the horizontal position of the CM increases linearly according to time (figure 3). The slope of the relationship between time and the horizontal position of the CM allows one to calculate the speed of the CM of the runner. Moreover, the speed was measured with photo cells placed in the field of the camera. The polynomial method used was a polynomial of high multiple order. After plotting the residual according to the order of the polynomial (37), the polynomial degree was determined individually for the trajectory of the centre of mass of each subject. Variations of potential and kinetic energies (ΔE_{pe} and ΔE_{ke} respectively) were then calculated (in joules).

$$\Delta E_{pe} = M \times g \times \left(H_{max} - H_{min}\right) \quad [3]$$

$$\Delta E_{ke} = \frac{1}{2} M \times \left(V_{max}^2 - V_{min}^2\right) \quad [4]$$

"M" is the body mass (kg), "g" is the gravitational acceleration (9.81 $m.s^{-2}$), "H_{max} and H_{min}" are maximal and minimal heights of the body centre of mass (CM) during one step (m). "V_{max} and V_{min}" are the maximal and minimal horizontal velocities of the CM during one step ($m.s^{-1}$).

Paragraph Number 10

The internal energy (E_{int}) represents the sum of the mechanical energies associated with the different segments of the body. The present model used in this work (figure 1) is composed of 17 different segments. The variation of internal energy (ΔE_{int}) is calculated as the maximal minus the minimal E_{int} during the step.

$$E_{int} = \frac{1}{2} \sum_{i=1}^{17} \left(m_s V_s^2 + I_s \omega_s^2\right) \quad [5]$$

Where "s" represents a segment, "m_s" is the mass of the segment (kg) considered and "I_s" is the moment of inertia of the segment ($kg.m^2$). "V_s" is the velocity of the centre of mass of the segment ($m.s^{-1}$) with respect to the referential linked to the CM. "ω_s" is the angular velocity of the centre of mass of the segment ($rad.s^{-1}$) with respect to the referential linked to the CM of the segment.

Kinetic, potential and internal mechanical cost expressed in $J.kg^{-1}.m^{-1}$ (C_{ke}, C_{pe}, C_{int}) are equal to the positive variation of E_{ke}, E_{pe} and E_{int} during one step, divided by the mass and the step amplitude of the subject.

The step rate (SR) was computed by counting the number of images for a stride and the step length (SL) was computed by dividing the running speed by SR.

The percentages of variation between the 3rd min and the end of the exercise of C_r and C_{int}, were also calculated ($\%\Delta C_r$ and $\%\Delta C_{int}$).

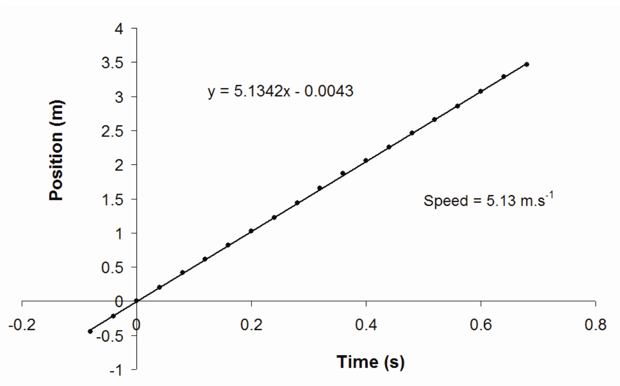

Figure 3: Example of horizontal position of the CM in the referential of the camera, and calculus of the speed of the CM of the runner.

Paragraph Number 11

Statistics

Relationships between the C_r and C_{pe}, C_{ke} or C_{int} were determined by standard linear regression and tested using a Spearman test. A paired Student test was also used in order to compare the average values for the velocity, the stride rate (SR), the stride length (SL), C_{pe}, C_{ke}, C_{int} and C_r obtained at the beginning and at the end of the tlim95 test. The runners were grouped by level of experience in running (specialist and non-specialist) and a Student test was use to compare both populations. The significance level was fixed at $P = 0.05$.

Paragraph Number 12

Results

During the constant load exercise, the subjects ran for 373 ± 77 s before exhaustion at a velocity of 17.6 ± 1.4 km.h^{-1} (4.88 ± 0.38 m.s^{-1}). During this constant load exercise, the energy cost of running (C_r) increased significantly within the 3rd and the last minute (table 2).

Paragraph Number 13

Within the 3rd and the last minute of exercise the velocity of running, the stride rate (SR) and the stride length (SL) did not vary significantly (table 2). At the same time, C_{ke} and C_{pe} also remained constant (table 2). Indeed, C_{ke} varied from 1.33 ± 0.33 J.kg^{-1}.m^{-1} to 1.38 ± 0.29 J.kg^{-1}.m^{-1} (P = 0.78) and C_{pe} varied from 0.47 ± 0.11 J.kg^{-1}.m^{-1} to 0.48 ± 0.10 J.kg^{-1}.m^{-1} (P = 0.67). These results demonstrated that during track running there was no modification of SR, C_{ke} or C_{pe} at the end of an exhaustive exercise.

Paragraph Number 14

However, significant correlations have been established between C_r and C_{ke} or C_{pe} (r = 0.43 and P = 0.03; r = 0.40 and P = 0.03; figure 4A, B). They only explained 18 to 16% variance between measures. Therefore, such as it was calculated in the present work, C_{ke} or C_{pe} constituted a global descriptor of the C_r.

Paragraph Number 15

The internal mechanical cost (C_{int}), contrary to C_{ke} and $C_{pe,}$ increased significantly between the 3rd and the last minute of the exercise (P ≤ 0.05, table 2). The average percentage of variation of C_{int} (%ΔC_{int}) was 9.7% with a great inter-individual variability. Indeed, eleven runners presented an increase of C_{int}, (comprised) of between 4 and 35% and 3 runners presented a decrease of C_{int} (comprised) of between -4 and -15%. Moreover, no correlation was observed between C_{int} and C_{ke}, C_{pe} SR or SL (respectively, r = 0.07 and P = 0.73; r = -0.2 and P = 0.31; r = 0.06 and P = 0.77; r

= 0.13 and P = 0.50). This result showed that the increase of C_{int} was not associated to a modification of other mechanical parameters. However, the percentage of variation of C_{int} (%ΔC_{int}) was significantly different between the specialist and the non specialist of running (p = 0.03). Indeed, the non specialists increase C_{int} by 20%, within the 3rd and the last minute of exercise, while the specialists do not increase it (4%).

Finally, there was no correlation between the C_r and C_{int} (figure 4C) or between %ΔCr and %Δcint (r = 0.06; P = 0.84). The increase in C_r observed after the 3rd min of a supra-lactic threshold exercise is not associated with a modification of C_{int}.

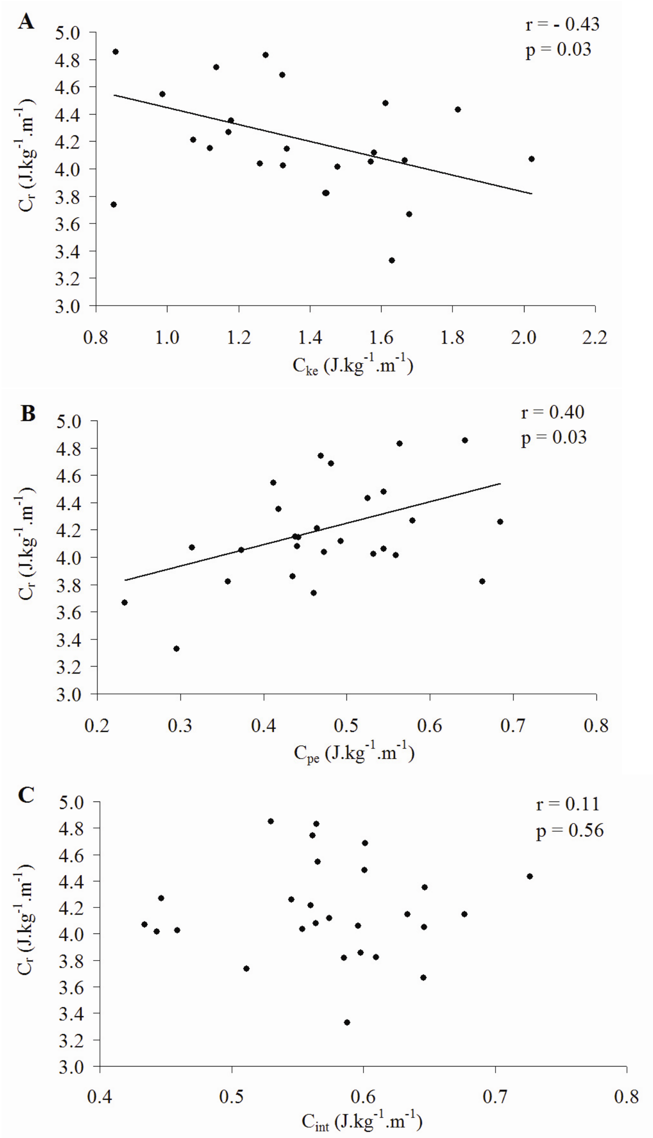

Figure 4: Correlation, between C_r and C_{ke} (A), C_{pe} (B) and C_{int} (C) measured in the fourteen runners, at the 3rd and the last minute of the exhausting exercise.

Paragraph Number 16

Discussion

This study aims to test the hypothesis that the increase in the energy cost generally observed at the end of a supra-lactate threshold run was associated with a modification in the internal mechanical cost of running. This study showed that during track running, exhaustion has no effect on C_{pe} or C_{ke}. Despite the fact that both C_r and C_{int} increase, C_r is only correlated with C_{ke} and C_{pe}, and not with C_{int}. Thus, this slight increase in C_r is not associated with a modification of the mechanical work produced in running.

Paragraph Number 17

In the present study, during the supra-threshold exhaustive run, C_r increased within the 3^{rd} and the last minute of the exercise. This increase in C_r has been well documented (20, 38) and depends on the physiological adaptations which are linked to the oxygen slow component. Indeed, several studies have reported the appearance of a $\dot{V}O_2$ slow component after the 3^{rd} min of exercise above the lactate threshold (3, 8, 13, 33). This $\dot{V}O_2$ slow component explains this increase up to exhaustion of C_r (6). A number of metabolic factors have been postulated as contributing to this $\dot{V}O_2$ slow component (see for review Gaesser and Poole (20); Xu and Rhode (38)).

Paragraph Number 18

This increase in C_r between the 3^{rd} and the last minute of exercise is not accompanied by an increase of C_{ke} and C_{pe}. Therefore the increase in C_r cannot be related to C_{ke} or C_{pe}. Following the idea that smaller vertical oscillation of the centre of mass is associated with a low C_r, there was a significant correlation between C_r and C_{pe} (figure 4B). As already demonstrated in the literature (11, 12), low but significant correlations have been established between C_r and C_{ke} or C_{pe} (figure 4A and B). Although there was a significant correlation between C_r and C_{ke} or C_{pe}, the increase in C_r could not be related to the mechanical cost associated with the movements of the centre of mass during the step.

Paragraph Number 19

A detailed analysis of mechanical data showed that the mechanical cost associated with the movements of the limbs around the centre of mass (C_{int}) increases significantly by 9.7% within the 3^{rd} and the last minute of the exercise. This increase in C_{int} during track running has never been described and depends on mechanical adaptations which have yet to be explained. Numerous factors influence C_{int}, speed (34), load, gradient, gait, or stride frequency (24). In order to simplify the calculation of C_{int} (in Watts), this has been modelled by Minetti and Saibene (24) as:

$$C_{int} = SR \cdot V^2 \frac{\pi^2}{2}\left[\left(a^2 + g^2\right)\left(m_L + b^2 m_U\right)\right]$$

This equation shows that C_{int} mainly depends on the SR, and on the running speed (V). However other parameters influence C_{int}, including the mass of the lower and upper limb (m_L and m_U), the fractional distance of the lower limb centre of mass from the proximal joint (a), the length of the upper limb as a fraction of the lower limb one (b) and the average radius of gyration of limbs, as a fraction of the limb length (g).

Paragraph Number 20

Thus, the internal mechanical cost depends on the speed and on the mass of the segments, as well as on the segmental organisation during running. Using this equation, Borrani et al. (10) have recently showed that on the treadmill, C_{int} decreases significantly from 0.90 (0.07) to 0.87 (0.04) $J.kg^{-1}.m^{-1}$ (3.5%) throughout the slow-component period. This decrease is mainly the result of the respective decrease in contact time (-2.6%) and stride frequency (-2%). Contrary to the results of Borrani et al. (10), the present study showed that C_{int} increased within the third minute and the last minute of the exercise. This difference can be explained by the method used. Indeed, the study of Borrani et al. (10) was carried out on a treadmill whereas the present results have been obtained during over-ground running. Therefore the differences observed between both studies may be explained by specific mechanical adaptations induced by treadmill or over-ground running (18, 32). This increase in C_{int} could be linked to an increase in the leg speed during the stride or to a change in the segmental organisation. The stability of SR, observed in the present study, was not consistent with an increase in the leg speed. As C_{ke} or C_{pe}, the stride rate (SR) was not modified during an exhaustive run. Therefore, during over-ground running, the lack of any change did not support a role for SR during fatigue as a mechanism for the increase in C_r, as previously proposed by Borrani et al. (10) and Avogadro et al. (2). Furthermore, two studies carried out in order to understand the possible influence of cadence on the increase of C_r during strenuous exercise (3, **7**) have already demonstrated that in cycling as in running, the increase of C_r was not influenced by cadence.

Paragraph Number 21

Thus, the increase in C_{int} after the 3rd min of exercise could be related to a change in the geometric configuration of the segments of the body. One probable hypothesis would be connected to the effect of fatigue on the biomechanical stride characteristic (21, 31). These effects of fatigue on C_{int}, could depend on the level of experience in running. Indeed, the Student test has showed that the great variability in the $\%\Delta C_{int}$ depends on the skill/experience of the runner. On track, the non specialists increase C_{int} by 20%, within the 3rd and the last minute of exercise, while the specialists increase it by only 4%. However, it is difficult to identify segments responsible for these modifications. Indeed, the use of a global method of calculation of the mechanical work does not allow one to determine precisely the segments responsible for the observed modifications. Only the use of a local method of the calculation of the mechanical work such as the method of calculation of powers developed in joints would allow a better understanding of the observed mechanical modifications. One of the perspectives of the present work would be to study the effects of fatigue in the mechanical work calculated by the method of the joints moments. Hence, the observed modifications of the style could be explained. However, the use of the joints method in running is limited to the study of the power developed at the level of the joints of lower limbs (5, 36).

Paragraph Number 22

The present results showed that both C_{int} and the energy cost of running (C_r) increase within the 3rd minute and the end of the supra-threshold exercise. However, contrarily to the hypothesis of the present study, the figure 4C showed that there was no correlation between C_r and C_{int}. Indeed, the study of individual variations of C_r and C_{int} shows that some runners who displayed an increase in C_{int} did not display an increase in C_r. This result showed that the increase of C_r could not be related to the increase in C_{int} and that two independent mechanisms might explain the increase in C_r and in C_{int}.

Paragraph Number 23

The results reported in this study showed that during track running, exhaustion has no effect on C_{pe} or C_{ke}. Only the C_r and C_{int} increased significantly at the end of a supra-lactic threshold exhaustive run. However, the C_r is only correlated with C_{ke} and C_{pe}, and not with C_{int}. Thus, the increase in C_r is not associated with a modification of the mechanical work produced in running. The increase in C_{int} after the 3rd minute of exercise could be related to a change in the geometric configuration of the segments of the body. The geometric configuration might depend on the skill/experience of the runner. The modification of C_{int} suggests that the technique of running is a basic component of the training of endurance runners and above all in fatigue status. However, the increase in C_{int} during over-ground running to exhaustion has yet to be explained.

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