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Difference in mechanical and energy cost between highly, well and non trained runners.

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Abstract

Introduction: Recently it has been shown that endurance training decreases the variability in stride rate. This decrease would lead to a reduction in the mechanical and the energy cost of running. **Purpose: T**his study therefore aims to compare the mechanical and the energy cost of running according to the training status of the runner (highly, well and non trained endurance runners). **Methods:** The kinetic, potential and internal mechanical costs (C_{ke}, C_{pe} and C_{int}) were measured with a 3D motion analysis system (ANIMAN3D). The energy cost of running (C), was measured from pulmonary gas exchange using a breath by breath portable gas analyser (Cosmed K4b^2, Roma, Italy). All the parameters were measured on track, for a speed of 4.84 ± 0.36 m.s^{-1}. **Results:** Highly trained runners did not exhibit *significantly* lower C compared to well or non trained runners (4.46 ± 0.38; 4.33 ± 0.32; 4.46 ± 0.46 J.kg^{-1}.m^{-1}, *respectively*; $p = 0.75$). However, C_{pe} was significantly lower in highly and well trained runners compared to non trained runners (0.43 ± 0.07; 0.45 ± 0.05; 0.54 ± 0.08 J.kg^{-1}.m^{-1}, *respectively*; $p < 0.05$). In contrast, C_{int} was significantly higher in highly trained runners compared to well and non trained runners (respectively 0.80 ± 0.12; 0.60 ± 0.09; 0.59 ± 0.10 J.kg^{-1}.m^{-1}; $p < 0.05$). **Conclusion:** *Although there is a significant difference in C$_{pe}$ and in C$_{int}$ between runners of various training status, there is no difference in C. Differences in C$_{pe}$ and C$_{int}$ may be associated with the same self-optimizing mechanism which contributes to a reduction in the impact loads during the initial portion of the support phase of the stride.*

Keys-words: oxygen uptake, biomechanics, training, running.

Introduction

Paragraph Number 1

In middle and long distance events, maximal performance depends on the optimisation of aerobic and biomechanical factors. The energy cost of running, defined as the amount of energy spent per unit of distance (18), reflects the sum of both aerobic and biomechanical demands. In aerobic conditions, the metabolic power can be estimated by oxygen uptake ($\dot{V}O_2$). Among long distance runners with comparable maximal oxygen uptake ($\dot{V}O_{2\,max}$), the energy cost of running (C) is a discriminating parameter in endurance performance (18). While various factors have been found to affect C (28), little is known about training effect on C. It seems that the use of interval training sessions over a long period (14 weeks to 5 years) brings about a decrease in C (5, 31, 33). However, many studies did not find any link between these parameters, so the reasons for C improvement with training are not well known.

Paragraph Number 2

Biomechanical parameters have been identified as factors that could influence C. Williams and Cavanagh (37) demonstrated that 54% of the inter-individual variability of C could be explained by kinematic variables. These authors demonstrated that the more economical runners possess a characteristic running style. They present numerous differences in kinematic variables and some of them are correlated with C. The mechanical cost of the movements of the centre of mass has also been identified as a potential biomechanical parameter that could explain the inter-individual variability in C [8, 9]. Indeed, C represents the energy used by the active muscle to produce mechanical work. Thus, the inter-individual differences in C have to be related to the variation in mechanical energies associated with the movement of the different segments of the body during running. Some studies have found a significant

relationship between the inter-individual differences in C and the variation in mechanical energies of the centre of mass during running [8, 9]. Recently, Borrani et al. [7] suggest that the modification of C could be related to a modification of an index of the internal cost. Therefore, in order to understand why there are significant differences in C among runners of different training status, there is a need to compare kinetic, potential, and internal energies indices in addition to the overall energy cost. However, effects of endurance training on these biomechanical factors have been poorly investigated. Indeed, most of the current studies have focused on the effect of training on simple mechanical stride parameters such as stride rate or stride length (1, 37). More recently, a study performed in our laboratory (31), showed that endurance training leads to a decrease in the stride rate variability. It has been hypothesised that the decrease of the stride rate variability would induce a decrease in the mechanical cost of running by reducing the amplitude of movement of the centre of mass. However, direct measurements of the effect of the training on kinetics, potential and internal mechanical cost (C_{ke}, C_{pe} and C_{int}) are not available.

Paragraph Number 3

Therefore, this study aims to examine *the differences of mechanical and energy cost* for groups of runners with different levels of training. The hypothesis being that the lower energy cost in highly trained runners would *be associated with* a lower mechanical cost. In order to test this hypothesis, C, C_{ke}, C_{pe} and C_{int} were measured in three populations with different training status.

METHODS

Paragraph Number 4

Subjects

Three groups took part of the experimental protocol:

- Seven highly trained (3 men and 4 women) runners (170 ± 7 cm; 55.7 ± 9.2 kg), who were members of the national French marathon team (mean performance *2 h 27 min 16 s ± 11 min 02 s*). They train about 12 times a week between 60 and 100% of the maximal oxygen uptake ($\dot{V}O_{2max}$).

- Eight well trained runners (169 ± 9 cm; 57.2 ± 7.7 kg), who have already participated to a national competition. They train about 5 times a week between 60 and 100% of $\dot{V}O_{2max}$.

- Six non-trained runners (175±5 cm; 68.8±6.5 kg), physical education students who were occasional runners. They train about 2 times a week at long slow distance running (60% of $\dot{V}O_{2max}$).

All subjects were informed of risks and stress associated with the experimental protocol and gave a written voluntary informed consent in accordance with the guidelines of the hospital of Paris S[t] Louis.

Paragraph Number 5

Experimental design

The energy cost of running (C), the kinetic and potential mechanical cost associated with the movements of the centre of mass (C_{ke} and C_{pe}), and the internal mechanical cost associated with the movements of the body's segments around the centre of mass (C_{int}) were measured during a constant load running exercise (V = 4.84 ± 0.36 m.s^{-1}).

The energy cost of running (C), the kinetic and potential mechanical cost associated with the movements of the centre of mass (C_{ke} and C_{pe}), and the internal mechanical cost associated with the movements of the body's segments around the centre of mass (C_{int}) were measured during a constant load running exercise (V = 4.84 ± 0.36 m.s^{-1}). Highly trained runners carried out a 30 minute run on a level road at a constant velocity (table 1). The velocity was set at the average velocity sustained during their best marathon race. Runners followed a pacing cyclist traveling at the required velocity. The cyclist was equipped with a speedometer with a speed precision of ± 0.1 km.h^{-1}. This protocol allowed us to measure C, C_{ke}, C_{pe}, C_{int} and to estimate $\dot{V}O_{2max}$ and the velocity associated with the achievement of $\dot{V}O_{2max}$ (v$\dot{V}O_{2max}$).

Table 1: Characteristics of the different populations (highly, well and non-trained): maximal oxygen uptake ($\dot{V}O_{2max}$), the speed associated to $\dot{V}O_{2max}$ (v$\dot{V}O_{2max}$) and the speed of the constant load exercises.

	Highly trained (±SD)	Well trained (±SD)	Non-trained (±SD)	ANOVA
Height (cm)	169±9	171±7	175±5	0.27
Weight (kg)	55.7±9.2	57.2±7.7	68.8±6.5[†§]	0.02
v$\dot{V}O_{2max}$ (m.s^{-1})	6.12±0.44 (estimated)	5.30±0.30[†] (measured)	4.79±0.33[†§] (measured)	≤0.01
$\dot{V}O_{2max}$ (ml.kg^{-1}.min^{-1})	79.0±7.3 (estimated)	65.7±6.1[†] (measured)	57.2±7.7[†§] (measured)	≤0.01
Running speed (m.s^{-1})	4.87±0.42	4.96±0.31	4.65±0.32	0.28

[†]Significantly different from highly trained runner (p≤0.05).
[§] Significantly different from well trained runner (p≤0.05).

Paragraph Number 6

The well trained and the non trained subjects performed two exhaustive exercises. The first exercise was an incremental test allowing $\dot{V}O_{2max}$, v$\dot{V}O_{2max}$ and the velocity at

the lactate threshold (vLT) to be determined. The running speed of this test was progressively increased from 12 $km.h^{-1}$ to exhaustion. The velocity increments between the stages (3 min duration) were set at 1 $km.h^{-1}$. All stages were followed by a 30-s period of rest. During this period, a fingertip capillary blood sample was collected in order to calculate the energetic equivalent of lactate *(EEL)*. The second exercise was a test to exhaustion at the velocity corresponding to 50% of the work rate difference between vLT and $v\dot{V}O_{2\,max}$ (vΔ50) for the well trained runners. For the non trained runner, the velocity of the exercise was set at 95% of $v\dot{V}O_{2max}$. C, C_{ke}, C_{pe} and C_{int} were determined during the last minute of the exercise. All test sessions were completed on a 400-m covered synthetic track. Throughout the tests, the subjects adopted the required velocity using an audio rhythm which gave the time to cover 25-m. Visual marks were set at 25-m intervals along the track (inside the first lane).

Paragraph Number 7

Energy cost measurement (C).

Throughout the constant velocity exercises, the respiratory and pulmonary gas exchange variables were measured using a breath-by-breath portable gas analyzer (Cosmed $K4b^2$, Roma, Italy (26)). Before each test, O_2 and CO_2 analyser were calibrated using ambient air and sample gas references. The flowmeter was calibrated with a 3-l syringe (Quinton instruments, Seattle, USA). Blood lactate concentration was measured for the three groups of runners, before and after the constant velocity exercises.

Paragraph Number 8

The breath-by-breath oxygen uptake data were reduced to 5-s stationary averages. These data were then smoothed, using a 3-step average filter, to reduce the noise, so as to enhance the underlying characteristics. These data were finally fitted to

mathematical exponential models (2) using an iterative nonlinear regression on Sigma Plot software (SPSS, Chicago, IL, USA). A single-exponential model (eq. 1) and a double-exponential models were used, comprising two exponential terms which start at two distinct time delays from the onset of exercise (eq. 2). The Fisher test, which was performed by the Sigma Plot software, was used to choose the model for which the fit was associated with the highest F value (2).

$$\dot{V}O_2(t) = A_0 + A1 \times (1 - e^{-(t-TD1)/\tau_1}) \times U_1$$

<div align="center">(linear and fast component)   [1]</div>

$$+ A2 \times (1 - e^{-(t-TD2)/\tau_2}) \times U_2$$

<div align="center">(slow component)   [2]</div>

With:

A_0: the basal metabolic rate (ml.min^{-1}).

A1 and A2 : the asymptotic amplitudes for the exponential terms (ml.min^{-1}).

τ_1 and τ_2: the time constants (s).

TD1 and TD2: the time delay from the onset of exercise (s).

C was expressed in J. kg^{-1}.m^{-1} and computed from the following equation:

$$C\,(J.kg^{-1}.m^{-1}) = \dot{V}O_2(t) \times E_{O_2} \times V^{-1} \times M^{-1}$$

To calculate the energy expenditure, an energy equivalent of oxygen (E_{O_2}) was applied. E_{O_2} depends on the respiratory quotient. For elite runners E_{O_2} was equal to 20.9 J. mlO$_2^{-1}$, for the other runners E_{O_2} was equal to 21.3 J. mlO$_2^{-1}$. "V" is the running speed during the test (expressed in m.min^{-1}) and "M" is the subject's mass. *EEL was equal to 3 mlO$_2$.kg^{-1}.mmol^{-1}.l^{-1} (9), this value was added to C in order to estimate the contribution of the anaerobic pathway (C+EEL).*

Paragraph Number 9

$\dot{V}O_{2max}$ *and* $v\dot{V}O_{2max}$ *measurement.*

Well trained and non trained runners performed an incremental exercise, so $\dot{V}O_{2max}$

and $v\dot{V}O_{2max}$ were directly measured from gas exchanges. The elite runners did not

participate in the incremental exercise, therefore $\dot{V}O_{2max}$ and $v\dot{V}O_{2max}$ were estimated

from the maximal fraction of $\dot{V}O_{2max}$ that can be maintained throughout the duration

of the effort (F expressed in %). The quantification of F follows the equation (17):

$$F = 0.94 - 10^{-3} \times T \qquad\qquad [3]$$

Where "T" is the best performance time (min) achieved in an endurance race. The

intensity of the 30 min test was set at the average velocity sustained during the best

marathon race of each runner. Therefore, F can be deduced from the best time

achieved during the best marathon. From F and the oxygen uptake $\dot{V}O_2(t)$ measured

during the 30 min test, it was easy to calculate $\dot{V}O_{2max}$ and $v\dot{V}O_{2max}$:

$$\dot{V}O_{2max} \ (ml.kg^{-1}.min^{-1}) = \frac{\dot{V}O_2(t)}{F} \times M^{-1} \qquad\qquad [4]$$

$$v\dot{V}O_{2max} \ (m.min^{-1}) = \frac{\dot{V}O_{2max}}{\dot{V}O_2(t) \times V^{-1} \times M^{-1}} \qquad\qquad [5]$$

Where "V" is the average velocity of the 30 min test, (expressed in m.min^{-1}) and "M"

is the subject's mass.

Paragraph Number 10

Mechanical cost measurement

During the constant load exercise, runners were filmed by a digital video camera

(Sony, Japan, TRV 900) using a sampling frequency of 25 Hz. Two consecutive steps

were analysed at the end of the exercise (figure 1). The video sequences were digitised on a computer using a video card (Perception Video Recorder, Digital System Inc.), and then transformed into a set of bitmap pictures. The parametric trajectories of the anatomical points of the runner were determined using a motion analysis system, ANIMAN3D (34). This system uses a numerical manikin "MAN3D" (figure 2). The morphology of this numerical manikin integrates inertial properties of the different segments. The morphology of this numerical manikin could be adjusted to each runner from their height and weight. This model measures the 3D positions of the body, during running. In the present work, the lateral displacements of the different centres of masses have not been directly measured because only one camera was used. All the trajectories of the different centres of mass (segments and body centre of mass) were smoothed using a polynomial method in order to obtain by derivation the speed displacement of the different centres of mass. Variations of potential and kinetic energies (ΔE_{pe} and ΔE_{ke} respectively) were then calculated (in joules).

$$\Delta E_{pe} = M \times g \times \left(H_{max} - H_{min}\right) \qquad [6]$$

$$\Delta E_{ke} = \frac{1}{2} M \times \left(V_{max}^2 - V_{min}^2\right) \qquad [7]$$

"M" is the body mass (kg), "g" is the gravitational acceleration (9.81 m.s^{-2}), "H_{max} and H_{min}" are the 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 11

The variation of the internal energy (ΔE_{int}) represents the variations in mechanical energies associated with the movement of the different segments of the body around

the CM. The present model used in this work (figure 2) is composed of 17 different segments. The variation of internal energy (ΔE_{int}) is calculated,

$$\Delta E_{int} = \Delta \frac{1}{2} \sum_{i=1}^{17} \left(m_s V_s^2 + I_s \omega_s^2 \right) \qquad [8]$$

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 velocities 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 ΔE_{ke}, ΔE_{pe} and ΔE_{int} divided by the mass of the subject and his step amplitude. These parameters were measured during the steady state of $\dot{V}O_2$, at the end of the exhaustive run.
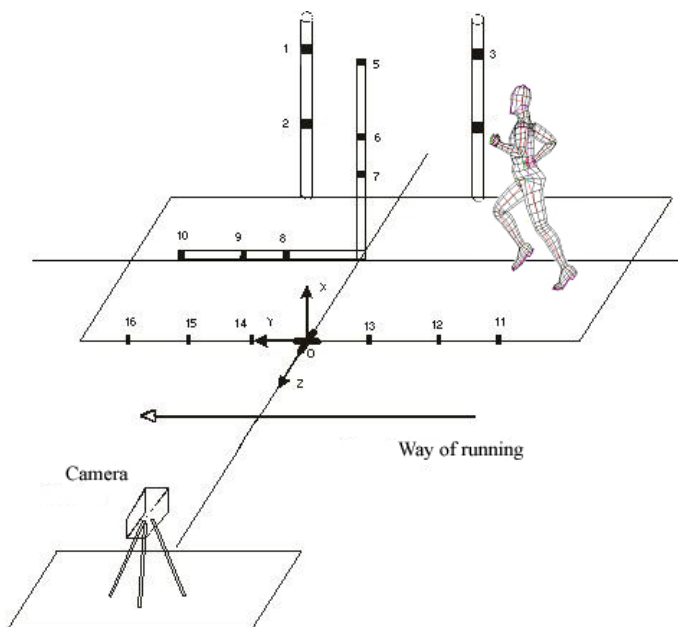

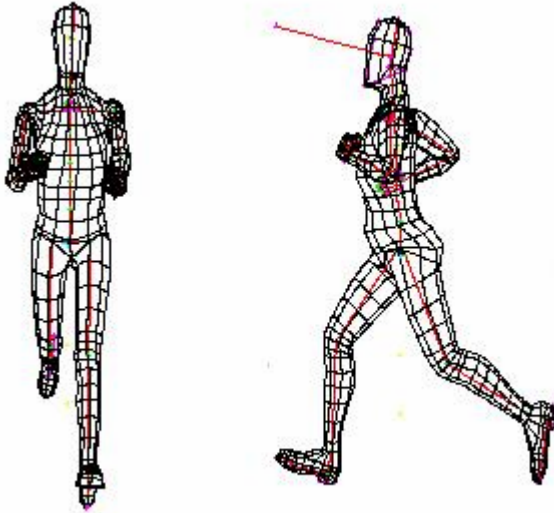Fig. 1: Representation of space calibration and of the field of the camera

Fig. 2: MAN3D human manikin representation.

Paragraph Number 12

Statistics

An ANOVA permitted to compare C_{pe}, C_{ke}, C_{int}, C, $\dot{V}O_{2max}$, $v\dot{V}O_{2max}$, the running test speed, the *weight* and the height of the different populations. A post hoc test was used (PLSD Fischer test) to identify differences between the *groups*. Pearson's correlation coefficients were used to evaluate the relationships among variables.

RESULTS

Paragraph Number 10

Characteristics of the highly, well and non trained runners

$\dot{V}O_{2max}$ and $v\dot{V}O_{2max}$ were significantly greater in trained subjects. Indeed, both parameters were greater for highly trained runners compared to well trained runners or compared to non-trained runners (table 1).

The speed of the constant load exercise was not significantly different between the groups (p=0.33). The different measures obtained from the different populations, during the constant load exercise (C_{pe}, C_{ke}, C_{int} and C), were performed for similar running speeds (table 1).

Paragraph Number 13

Effect of the endurance training status on C, C_{pe}, C_{ke}, C_{int} and the step rate.

The metabolic cost of running reported in table 2 is the "gross" value, including the O_2 consumption at rest. The less trained runners do not consume more energy than the highly trained runners. Indeed, in order to move forward at the same running speed (table 2) the highly trained runners present a same C *as well-trained, or non-trained* runners. Moreover, when the energetic equivalent of lactate (EEL) is added to C there is also no difference between the groups.

Table 2: Effects of the endurance training status on the gross energetic cost (C), the gross energetic cost plus the energetic equivalent of lactate (C + EEL), the step rate (SR), the step length (SL), the kinetic, potential and internal mechanical costs (C_{ke}, C_{pe}, C_{int}, respectively).

	Highly trained (±SD)	Well trained (±SD)	Non trained (±SD)	ANOVA
C_{ke} (J.kg^{-1}.m^{-1})	1.54±0.70	1.41±0.40	1.43±0.33	0.89
C_{pe} (J.kg^{-1}.m^{-1})	0.43±0.07	0.45±0.05	0.54±0.08[†§]	0.02
C_{int} (J.kg^{-1}.m^{-1})	0.80±0.12	0.60±0.09[†]	0.59±0.10[†]	≤0.01
C (J.kg^{-1}.m^{-1})	4.46±0.38	4.33±0.32	4.46±0.46	0.75
C + EEL (J.kg^{-1}.m^{-1})	4.56±0.39	4.75±0.32	4.89±0.44	0.30
R	0.94±0.08	1.00±0.03	1.06±0.05[†]	<0.01
SR (Hz)	3.21±0.22	3.01±0.11[†]	2.96±0.21[†]	0.05
SL (m)	1.52±0.14	1.66±0.08[†]	1.58±0.12	0.09

[†]Significantly different from highly trained runner (p≤0.05).
[§] Significantly different from well trained runner (p≤0.05).

Paragraph Number 14

C_{pe} was significantly lower in highly and well trained runners compared to non trained runners (20%). Inversely, the step rate (SR) was significantly higher in highly trained runners compared to well and non trained runners. Moreover, there was an inverse correlation between SR and C_{pe} or the vertical displacement of the centre of mass (CM)(respectively r = - 0.63; p = 0.001 and r = - 0.81; p ≤ 0.0001). Figure 3 shows that runners who present the greatest vertical displacement of the CM also possess the weakest limb displacement speed around the CM. Indeed, the vertical displacement of the CM for the different group is 6.7 ± 0.9 cm for the highly trained runners compared

to 7.7 ± 0.7 cm for the well trained runners, and 8.3 ± 1.3 cm for the non trained
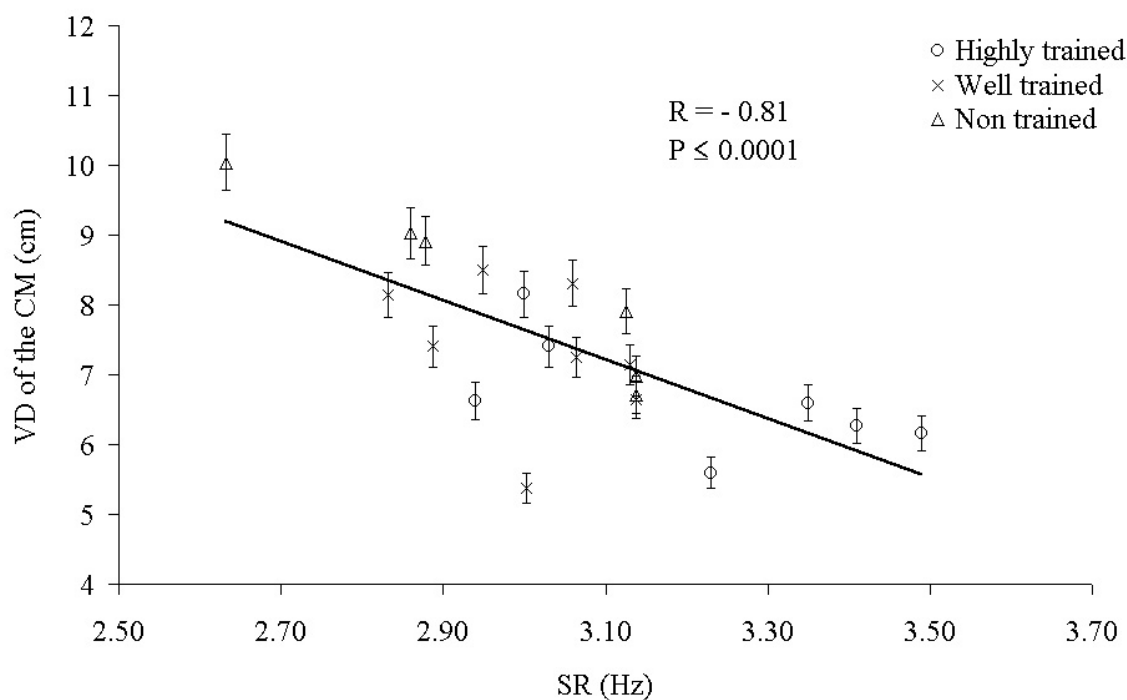
runners (p = 0.02).

Fig. 3 : Correlation between the vertical displacement of the centre of mass (VD of the CM) and the step rate (SR). The verticals bars represent the standard error of measure.

Paragraph Number 15

C_{int} was also significantly higher in highly trained runners: 30% greater in comparison

with well trained runners and 37% greater in comparison with non trained runners. C_{int}

was correlated with the vertical displacement of the CM (r = - 0.46; p = 0.03), but not

with SR (r = 0.41; p = 0.07) or with C_{pe} (r = - 0.32; p = 0.16).

Paragraph Number 16

The running speed was similar in all the runners, therefore C_{ke} was not significantly

different in the three populations of different training status (p = 0.89).

Paragraph Number 17

Relationship between C, C_{ke}, C_{pe}, C_{int}, SR and $\dot{V}O_{2max}$.

Although C_{pe} and C_{int} were significantly different according to the training status of the runners, there was no correlation between C and C_{pe} or C_{int} (figure 4). The correlation coefficients were near r = 0.05 and p = 0.83 for C_{ke}, r = - 0.13 and p = 0.58 for C_{pe} and r = 0.41, and p = 0.06 for C_{int}. Furthermore, there was no correlation between the SR and C (r = 0.15; p = 0.53). These results showed that the inter-individual variability of C can not be explained by biomechanical parameters such as SR, C_{pe}, C_{ke} or C_{int}. However, SR, C_{pe} and C_{int} were significantly correlated with $\dot{V}O_{2max}$ (respectively r = 0.58; p = 0.007; r = - 0.73; p = 0.0001; r = 0.60; p = 0.004).
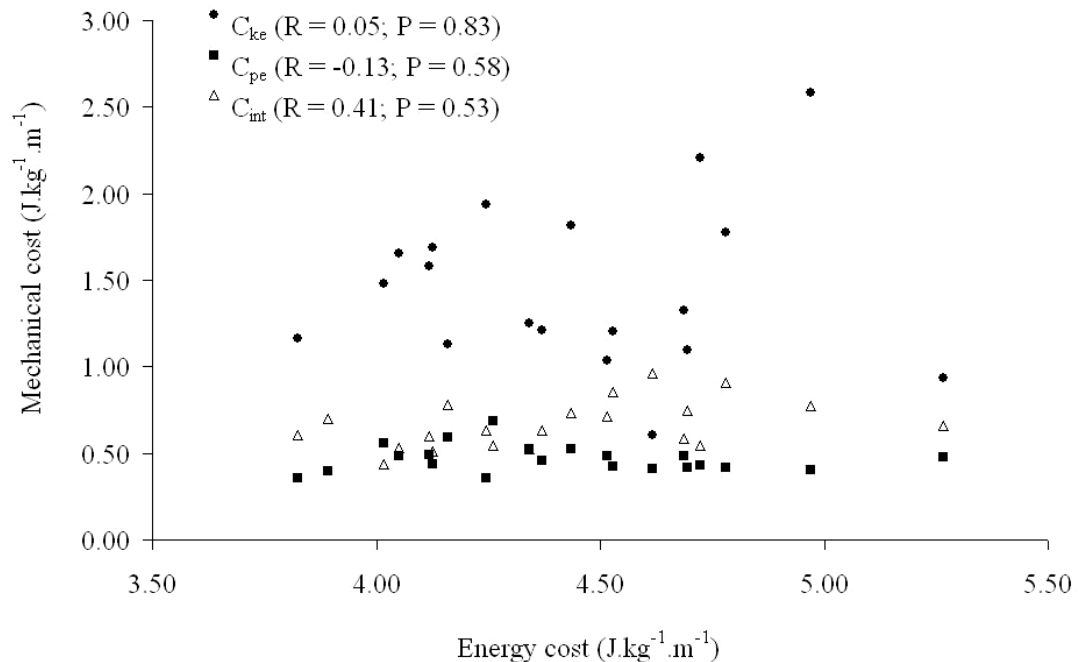

Fig. 4: Relationship between the energy cost of running (C), the kinetic mechanical cost (C_{ke}), the potential mechanical cost (C_{pe}) and the internal mechanical cost (C_{int}).

DISCUSSION

Paragraph Number 18

The purpose of this work was to test the hypothesis that the lower energy cost in highly trained runners is *associated with* a lower mechanical cost. To test this hypothesis, C, C_{ke}, C_{pe} and C_{int} were *measured in runners who differ in training status*. The results showed that contrary to our hypothesis, the energy cost of running was not different for runners with different training status. However, the mechanical cost is different for runners with different training status. Indeed, the mechanical cost associated to the vertical movements of the centre of mass (C_{pe}) was smaller in highly trained runners. Inversely, the mechanical cost associated with the movement of the segments around the centre of mass (C_{int}) and the step rate (SR) were greater.

Paragraph Number 19

There was no difference in the energy cost of running between the three groups, whereas such a difference would be expected and has been demonstrated in previous studies (5, 31, 33). Numerous mechanisms such as a decrease in the ventilation, an optimisation of the neuromuscular recruitment, an improvement in the transport of oxygen by the blood, the use of this oxygen by the active muscles or the increase of the muscular elasticity (12, 30) could be at the origin of the improvement in the energy cost with training. However, mechanisms associated with this decrease are not well known and numerous studies do not report any change after a period of training (13, 25, 31, 32, 36). Daniels and Daniels (12) have shown that for intensities typically used in races up through the marathon, no differences exist in C within the range of most intensities (80-100% of $\dot{V}O_{2\,max}$). In the present study, the range of intensities was comprised within 80% and 97% of $v\dot{V}O_{2\,max}$. Therefore, the lack of difference in C among runners of different training

levels may be associated with the fact that C is measured for speeds upper to speeds typically used during a marathon race.

Paragraph Number 20

Following this hypothesis, the present results show that the mechanical cost of the vertical movements of the CM (C_{pe}) is smaller in highly trained runners. This result is in accordance with the generally acknowledged principle which states that smaller verticals oscillations of the body centre of mass are associated with a high level of training (28, 37). However, there was no relationship observed between C_{pe} and C (figure 4). According to the training status, the variation in C_{pe} is not associated with the variation in C. Similarly, the kinetic mechanical cost (C_{ke}) or the mechanical cost of the movements of the segments around the centre of mass (C_{int}) were not correlated with C (figure 4). These results agree with numerous studies which have demonstrated that the relationships between C and the mechanical cost are both weak and inconsistent (11, 28, 37). The mechanical cost reflects a global and indirect expression of the muscular effort which explains why a low correlation is observed between C and the mechanical cost. Other mechanical parameters should be correlated with C. Indeed, it has been shown that less economical runners possess a more compliant running style during ground contact (11, 24).

Paragraph Number 21

Collectively, the results reported here, do not confirm our primary hypothesis and suggest that the mechanical cost (C_{pe} and C_{int}) is not correlate with C but with $\dot{V}O_{2max}$. The mechanism that explains the modifications of the mechanical parameters (SR, C_{pe} and C_{int}) is in relation with the level of training of the runners rather than their energy cost. However, this mechanism has to be elucidated.

Paragraph Number 22

If humans are self-optimizing machines, the minimal cost, being an optimally criterion, may be identified that governs the kinematic and kinetic detail of the performance. For example, it has been shown that adult and children tend to walk or run at frequencies that are determined by the oxygen cost (10). However, it is unlikely that the metabolic cost is the only optimality criteria adopted for human activity. The potential for injury may also result in the development of optimal criteria. Farley and Taylor (19) reported that horses naturally switch from a trot to a gallop actually increasing their metabolic cost but reducing the peak of forces on the muscles, tendons and bones. They suggest that this mechanism reduces the chance of injury for the horse. During human running, the body is subjected to high impact loads during the initial portion of the support phase of the stride. These impacts have magnitudes up to 2.3 times body weight (BW) with an impact load rate of 113 $BW.s^{-1}$ (29). Increases in impact shock can result from an increase in running speed (21), from running downhill (22), from an increase in stride length (15, 23) or fatigue (35). It would appear therefore, that impact shock attenuation may be an important factor on which individuals optimise. In a same way, Zamparo et al. (38) have recently demonstrated that the self selected speed of running depends *not only on cardiovascular factors*, but also on biomechanical factors.

Paragraph Number 23

The running style of the highly trained runners may be associated with the same self-optimizing mechanism which contributes to reducing the impact loads during the initial portion of the support phase of the stride. Indeed, this style is characterised by a high SR and a low C_{pe} and a low vertical displacement of the CM. Moreover, the figure 3 shows that the vertical displacement of the CM is inversely correlated to SR. This inverse relationship shows that a high stride rate is linked to a smaller vertical

displacement of the CM. During the flight phase, the CM of highly trained runners may reach a lower height (table 2), which decreases the impact shock when the foot hits the ground. This result is in accordance with the results of Farley and Gonzales (20) which show that at higher step rate, the initial vertical force peak is absent and that the vertical force peak is decreased. This style of running may be associated with the training mode of the runners. Indeed, the nature of the adaptive responses to training is specific to the training stimulus. Highly trained runners cover very long distances during training session, and perform a very high number of strides (more than 20 $km.day^{-1}$; (6)) compared to the other populations studied. For example, running 32 $km.week^{-1}$ will produce over 1.3 million impacts to the body over a period of one year (16). More frequent impacts will place greater stress on the muscles, tendons and bones resulting in an increased risk of injury and degenerative disease (15). Therefore, to attenuate this risk, mechanical adjustments such as a decrease in the vertical oscillation of the CM may take place with training. Following this hypothesis, the modification of the mechanics of running with the training status does not have any relationship with the energy cost of running (C).

Paragraph Number 24

To conclude, highly trained runners did not display a lower C. However, C_{pe} was 20% lower and C_{int} was 30% greater in highly trained runners. The endurance training leads to an increase of C_{int} and a decrease in C_{pe} without any modification of C. These mechanical adjustments may be associated with the same self-optimizing mechanisms which contribute to reduce the impact loads during the initial portion of the support phase of the stride.

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