Changes in Internal Mechanical Cost during Overground Running to Exhaustion

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ABSTRACT

SLAWINSKI, J. S., and V. L. BILLAT. Changes in Internal Mechanical Cost during Overground Running to Exhaustion. Med. Sci. Sports Exerc., Vol. 37, No. 7, pp. 1180–1186, 2005. Purpose: The purpose of this study was to determine, during an overground supra-threshold run, whether a change in the internal mechanical cost could occur during an exhaustive run and whether this change was related to the increase in the energy cost of running (C_r). Methods: The C_r of 14 endurance runners was measured from pulmonary gas exchange using a breath-by-breath portable gas analyzer (Cosmed K4b², Rome, 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 third 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 ≤ 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_pe and C_KE 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 overground 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

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 center 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 VO₂. Therefore the increase in C_r observed at the end of supra-lactic threshold exercise may be related to the variation in mechanical energy.

Some studies have significantly related the differences in C_r to the energy variations of the center 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 center 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 third minute 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 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 center of mass, which is called the internal mechanical cost ($C_{int}$).

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 overground 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 third minute of a supra-lactic threshold exercise is associated with a modification of $C_{int}$.

**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 yr) 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 summarizes this information. Before 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 St. Louis.

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 ($VO_{2max}$). This parameter was defined as the highest 30-s $VO_2$ value attained during the test. The velocity associated with $VO_{2max}$ (v$VO_{2max}$) (9). The velocity at the lactate threshold (v$LTL$) was defined as the speed measured at $VO_2$ value that corresponds to the starting point of an accelerated lactate accumulation between 3.5 and 5 mmolL$^{-1}$ (1).

An exhaustive run at 95% of v$VO_{2max}$ until exhaustion (tlim95). Throughout the test, 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 m from the left of the runner. Two consecutive steps were analyzed at the beginning of the test (during the second lap of the track, around the third minute 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 ($C_{e}$) was also evaluated throughout the exercise, by the oxygen uptake measurement.

**Materials**

**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$^2$, Rome, Italy). Before each test, $O_2$ and $CO_2$ analyzers 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, WA). The accuracy of this system has been tested and is acceptable for $VO_2$ and $VCO_2$ measurement during supra-lactic threshold exercise (23).

**Mechanical measurement.** The video sequences obtained during the tlim95 were digitized 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 analyzed on a screen of a regular PC. ANIMAN3D 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 differences.
ent segments of the manikin (Fig. 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 that must coincide with some equivalent points of MAN3D. There are five particulars points that help the researcher to project MAN3D on the runner. These points are represented in the following picture (Fig. 2).

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 are out of direct view (as in Fig. 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 center of mass and the trajectories of the limb centers of mass to be obtained. The uncertainty in the determination of the different centers of mass trajectories depends on the resolution of the video camera used.

Data Analysis

Energy cost (C_r). 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 that 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).

\[
\dot{V}O_2(t) = y_0 + A_1 \times (1 - e^{-(t - TD1)/r_1}) \times U_1 \text{(fast component)}[1] \\
+ A_2 \times (1 - e^{-(t - TD2)/r_2}) \times U_2 \text{(slow component)}[2]
\]

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\(^{-1}\)), \(r_1\) and \(r_2\) are the time constants (min), and TD1 and TD2 are the time delay from the onset of exercise (s). \(U_1 = 0\) for \(t < TD1\) and \(U_1 = 1\) for \(t \geq TD1\); \(U_2 = 0\) for \(t < TD2\) and \(U_2 = 1\) for \(t \geq TD2\).

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

\[
C_r = \dot{V}O_2(t) \times EO_2 \times V_{95}^{-1} \times M^{-1} [3]
\]

where EO_2 (21.3 J.mL\(^{-1}\).O_2) is the energy equivalent of 1 mL.O_2 for a respiratory exchange ratio of 1 (12), and \(V_{95}\) is the velocity during the test tlim95 (measured with the video camera).

Mechanical cost. All the trajectories of the different centers of mass of the model (segments and body centers of mass) were smoothed using a polynomial method in order to obtain by derivation the speed displacement of the different centers 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 (Fig. 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 controlled 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 center of mass of each subject. Variations of potential and kinetic energies ($\Delta E_{ke}$ and $\Delta E_{pe}$ respectively) were then calculated (in joules).

\[
\Delta E_{pe} = M \times g \times (H_{max} - H_{min}) \quad [4]
\]

\[
\Delta E_{ke} = 1/2M \times (V_{max}^2 - V_{min}^2) \quad [5]
\]

$M$ 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 center 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$^{-1}$).

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 (Fig. 1) is composed of 17 different segments. The variation of internal energy ($\Delta E_{int}$) is calculated as the maximal minus the minimal $E_{int}$ during the step.

\[
E_{int} = \frac{1}{2} \sum_{i=1}^{17} m_i V_i^2 + I_i \omega_i^2 \quad [6]
\]

where $s$ represents a segment, $m_i$ is the mass of the segment (kg) considered, and $I_i$ is the moment of inertia of the segment (kg m$^2$). $V_i$ is the velocity of the center of mass of the segment (m s$^{-1}$) with respect to the referential linked to the CM. $\omega_i$ is the angular velocity of the center 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 ($C_{ke}$, $C_{pe}$, and $C_{int}$; J kg$^{-1}$ m$^{-1}$) 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 third minute and the end of the exercise of $C_r$ and $C_{int}$ were also calculated ($\% \Delta C_r$ and $\% \Delta C_{int}$).

**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 velocity, stride rate (SR), 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 nonspecialist) and a Student test was used to compare both populations. The significance level was fixed at $P = 0.05$.

**RESULTS**

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

Within the third 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 $\pm$ 0.33 J kg$^{-1}$ m$^{-1}$ to 1.38 $\pm$ 0.29 J kg$^{-1}$ m$^{-1}$ ($P = 0.78$) and $C_{pe}$ varied from 0.47 $\pm$ 0.11 J kg$^{-1}$ m$^{-1}$ to 0.48 $\pm$ 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.

However, significant correlations have been established between $C_r$, $C_{ke}$ or $C_{pe}$ ($r = 0.43$ and $P = 0.03$; $r = 0.40$ and $P = 0.03$; Fig. 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 $C_r$.

The internal mechanical cost ($C_{int}$), contrary to $C_{ke}$ and $C_{pe}$, increased significantly between the third and the last minute of the exercise ($P \leq 0.05$, Table 2). The average percentage of variation of $C_{int}$ ($\% \Delta C_{int}$) was 9.7% with a great interindividual variability. Indeed, 11 runners presented an increase of $C_{int}$ (comprised) of between four and 35% and three 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 $C_{int}$ ($\% \Delta C_{int}$) was significantly different between the specialist and the nonspecialist of running ($P = 0.03$). Indeed, the nonspecialists increase $C_{int}$ by 20%, within the third and the last minute of exercise, whereas the specialists do not increase it (4%).

Finally, there was no correlation between the $C_r$ and $C_{int}$ (Fig. 4C) or between $\% \Delta C_r$ and $\% \Delta C_{int}$ ($r = 0.06$; $P = 0.84$). The increase in $C_r$ observed after the third minute of a supra-lactic threshold exercise is not associated with a modification of $C_{int}$.

**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.**
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 Cr and Cint increase, Cr is only correlated with C_ke and C_pe, and not with C_int. Thus, this slight increase in Cr is not associated with a modification of the mechanical work produced in running.

In the present study, during the supra-threshold exhaustive run, C_t increased within the third and the last minute of the exercise. This increase in C_t 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 VO2 slow component after the third minute of exercise above the lactate threshold (3,8,13,33). This VO2 slow component explains this increase up to exhaustion of Cr (6). A number of metabolic factors have been postulated as contributing to this VO2 slow component (see for review Gaesser and Poole (20) and Xu and Rhode (38).

This increase in Cr between the third and the last minute of exercise is not accompanied by an increase of C_ke and C_pe. Therefore, the increase in C_t cannot be related to C_ke or C_pe. Following the idea that smaller vertical oscillation of the center of mass is associated with a low Cr, there was a significant correlation between Cr and C_pe (Fig. 4B). As already demonstrated in the literature (11,12), low but significant correlations have been established between Cr and C_ke or C_pe (Fig. 4A and B). Although there was a significant correlation between Cr and C_ke or C_pe, the increase in Cr could not be related to the mechanical cost associated with the movements of the center of mass during the step.

A detailed analysis of mechanical data showed that the mechanical cost associated with the movements of the limbs around the center of mass (Cint) increases significantly by 9.7% within the third and the last minute of the exercise. This increase in Cint during track running has never been described and depends on mechanical adaptations that have yet to be explained. Numerous factors influence Cint, speed (34), load, gradient, gait, or stride frequency (24). To simplify the calculation of Cint (W), this has been modeled by Minetti and Saibene (24) as:

\[
C_{\text{int}} = SR \cdot \frac{V^2}{2}\left[\frac{mL^2 + g^2}{(a^2 + g^2)} + mU + b \cdot mL\right]
\]

This equation shows that Cint mainly depends on the SR, and on the running speed (V). However other parameters influence Cint, including the mass of the lower and upper limb (mL and mU), the fractional distance of the lower limb center 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).

Thus, the internal mechanical cost depends on the speed and on the mass of the segments, as well as on the segmental organization during running. Using this equation, Borrani et al. (10) have recently showed that on the treadmill, Cint 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 Cint increased within the third 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 overground running. Therefore, the differences observed between both studies may be explained by specific mechanical adaptations induced by treadmill or overground running (18,32). This increase in Cint could be linked to an increase in the leg speed during the stride or to a change in the segmental organization. The stability of SR, observed in the present study, was not consistent with an
increase in the leg speed. As Cke or Cpe, the stride rate (SR) was not modified during an exhaustive run. Therefore, during overground running, the lack of any change did not support a role for SR during fatigue as a mechanism for the increase in C, as previously proposed by Borran 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 during strenuous exercise (3,7) have already demonstrated that in cycling as in running, the increase of C was not influenced by cadence.

Thus, the increase in Cint after the third minute 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 Cint could depend on the level of experience in running. Indeed, the Student test has showed that the great variability in the %ΔCint depends on the skill/experience of the runner. On track, the nonspecialists increase Cint by 20%, within the third and the last minute of exercise, whereas 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).

The present results showed that both Cint and the energy cost of running (Cr) increase within the third 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 Cr and Cint. Indeed, the study of individual variations of C and Cint shows that some runners who displayed an increase in Cint did not display an increase in Cr. This result showed that the increase of Cr could not be related to the increase in Cint and that two independent mechanisms might explain the increase in Cr and in Cint.

The results reported in this study showed that during track running, exhaustion has no effect on Cpe or Cke. Only the Cr and Cint increased significantly at the end of a supra-lactic threshold exhaustive run. However, the C is only correlated with Cke and Cpe, and not with Cint. Thus, the increase in Cr is not associated with a modification of the mechanical work produced in running. The increase in Cint after the third 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 Cint 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 Cint during overground running to exhaustion has yet to be explained.

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