Difference in Mechanical and Energy Cost between Highly, Well, and Nontrained Runners

JEAN S. SLAWINSKI and VERONIQUE L. BILLAT
Department STAPS, UFRSFA University d’Evry-Val d’Essonne, Batiment des Sciences, Evry, FRANCE

ABSTRACT
SLAWINSKI, J. S., and V. L. BILLAT. Difference in Mechanical and Energy Cost between Highly, Well, and Nontrained Runners. Med. Sci. Sports Exerc., Vol. 36, No. 8, pp. 1440–1446, 2004. 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: This study therefore aimed to compare the mechanical and the energy cost of running according to the training status of the runner (highly, well, and nontrained 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 K4b², Rome, 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 with well or nontrained 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 with nontrained 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 with well and nontrained 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 that contributes to a reduction in the impact loads during the initial portion of the support phase of the stride. Key Words: OXYGEN UPTAKE, TRAINING, RUNNING, CENTER OF MASS, BIOMECHANICS

In middle and long distance events, maximal performance depends on the optimization of aerobic and biomechanical factors. The energy cost of running (C), 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 (V\(_{\text{O}_2}\)). Among long distance runners with comparable maximal oxygen uptake (V\(_{\text{O}_2}\)max), C is a discriminating parameter in endurance performance (18). Although 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 wk to 5 yr) 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.

Biomechanical parameters have been identified as factors that could influence C. Williams and Cavanagh (37) demonstrated that 54% of the interindividual 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 center of mass has also been identified as a potential biomechanical parameter that could explain the interindividual variability in C (8,9). Indeed, C represents the energy used by the active muscle to produce mechanical work. Thus, the interindividual 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 interindividual differences in C and the variation in mechanical energies of the center 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, 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 hypothesized 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 center of mass. However, direct measurements of the effect of the training on kinetics, potential and internal mechanical cost (C_{kin}, C_{pot}, and C_{int}) are not available.

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. To test this hypothesis, C, C_{kin}, C_{pot}, and C_{int} were measured in three populations with different training status.

**METHODS**

**Subjects.** Three groups took part of the experimental protocol:

Seven highly trained (three men and four 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× wk^{-1} between 60 and 100% of the maximal oxygen uptake (VO_{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× wk^{-1} between 60 and 100% of VO_{2max}.

Six nontrained runners (175 ± 5 cm; 68.8 ± 6.5 kg) physical education students who were occasional runners. They train about 2× wk^{-1} at long slow distance running (60% of VO_{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 St Louis.

**Experimental design.** The energy cost of running (C), the kinetic and potential mechanical cost associated with the movements of the center of mass (C_{kin} and C_{pot}), and the internal mechanical cost associated with the movements of the body’s segments around the center 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-min 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_{kin}, C_{pot}, C_{int} and to estimate VO_{2max} and the velocity associated with the achievement of VO_{2max} (vVO_{2max}).

The well trained and the nontrained subjects performed two exhaustive exercises. The first exercise was an incremental test allowing VO_{2max}, vVO_{2max}, and the velocity at the lactate threshold (v_{LT}) 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. The second exercise was a test to exhaustion at the velocity corresponding to 50% of the work rate difference between v_{LT} and vVO_{2max} (vΔ50) for the well-trained runners. For the non-trained runner, the velocity of the exercise was set at 95% of vVO_{2max}. To calculate the energetic equivalent of lactate exchange variables were measured using a breath-by-breath portable gas analyzer (Cosmed K4b², Rome, Italy (26)).

Before each test, O₂ and CO₂ analyzers were calibrated using ambient air and sample gas references. The flowmeter was calibrated with a 3-L syringe (Quinton Instruments, Seattle, WA). Blood lactate concentration was measured for the three groups of runners, before and after the constant velocity exercises.

The breath-by-breath oxygen uptake data were reduced to 5-s stationary averages. These data were then smoothed, using a three-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). A single-exponential model (Eq. 1) and a double-exponential models were used, comprising two exponential terms, which start at two distinct time delays (3).

Table 1. Characteristics of the different populations (highly, well, and nontrained): maximal oxygen uptake (VO_{2max}), the speed associated to VO_{2max} (v VO_{2max}), and the speed of the constant load exercises.

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>Highly Trained (± SD)</th>
<th>Well Trained (± SD)</th>
<th>Nontrained (± SD)</th>
<th>ANOVA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Height (cm)</td>
<td>169 ± 9</td>
<td>171 ± 7</td>
<td>175 ± 5</td>
<td>0.27</td>
</tr>
<tr>
<td>Weight (kg)</td>
<td>55.7 ± 9.2</td>
<td>57.2 ± 7.7</td>
<td>68.8 ± 6.5†§</td>
<td>0.02</td>
</tr>
<tr>
<td>v VO_{2max} (m·s^{-1})</td>
<td>6.12 ± 0.44 (estimated)</td>
<td>5.30 ± 0.30†§ (measured)</td>
<td>4.79 ± 0.33†§ (measured)</td>
<td>≤0.01</td>
</tr>
<tr>
<td>VO_{2max} (mL·kg^{-1}·min^{-1})</td>
<td>79.0 ± 7.3 (estimated)</td>
<td>65.7 ± 6.1†§ (measured)</td>
<td>57.2 ± 7.7†§ (measured)</td>
<td>≤0.01</td>
</tr>
<tr>
<td>Running speed (m·s^{-1})</td>
<td>4.87 ± 0.42</td>
<td>4.96 ± 0.31</td>
<td>4.65 ± 0.32</td>
<td>0.28</td>
</tr>
</tbody>
</table>

† Significantly different from highly trained runner (P < 0.05).
§ Significantly different from well-trained runner (P < 0.05).
\[ VO_2(t) = A_0 + A_1 \times (1 - e^{-(T_1/T) \cdot t}) \times U_1 \]

(linear and fast component) \[ VO_2(t) = A_2 \times (1 - e^{-(T_2/T) \cdot t}) \times U_2 \]

(slow component) \[ F = 0.94 - 10^{-3} \times T \]

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 VO_2(t) measured during the 30-min test, it was easy to calculate VO_{2max} and vVO_{2max}:

\[ VO_{2max}(mL \cdot kg^{-1} \cdot min^{-1}) = \frac{VO_2(t)}{F} \times M^{-1} \]

[5]

\[ v \text{VO}_{2max}(m \cdot min^{-1}) = \frac{V}{VO_2(t) \times V^{-1} \times M^{-1}} \]

[6]

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

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).

With:

- \( A_0 \): the basal metabolic rate (BMR) (mL·min\(^{-1}\)).
- \( A_1 \) and \( A_2 \): the asymptotic amplitudes for the exponential terms (mL·min\(^{-1}\)).
- \( \tau_1 \) and \( \tau_2 \): the time constants (s).
- TD1 and TD2: the time delay from the onset of exercise (s).

C was expressed in joules per kilograms per meter and computed from the following equation:

\[ C(J \cdot kg^{-1} \cdot m^{-1}) = VO_2(t) \times E_O \times V^{-1} \times M^{-1} \]

[3]

To calculate the energy expenditure, an energy equivalent of oxygen (E_O) was applied. E_O depends on the respiratory quotient. For elite runners, E_O was equal to 20.9 J·mLO_2\(^{-1}\), for the other runners E_O was equal to 21.3 J·mLO_2\(^{-1}\). “V” is the running speed (m·min\(^{-1}\)) during the test 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 to estimate the contribution of the anaerobic pathway (C+EEL).

**VO_{2max} and vVO_{2max} measurement.** Well-trained and untrained runners performed an incremental exercise, so VO_{2max} and vVO_{2max} were directly measured from gas exchanges. The elite runners did not participate in the incremental exercise; therefore, VO_{2max} and vVO_{2max} were estimated from the maximal fraction of VO_2 that can be maintained throughout the duration of the effort (F expressed in %). The quantification of F follows the equation (17):

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

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 VO_2(t) measured during the 30-min test, it was easy to calculate VO_{2max} and vVO_{2max}:

\[ VO_{2max}(mL \cdot kg^{-1} \cdot min^{-1}) = \frac{VO_2(t)}{F} \times M^{-1} \]

[5]

\[ v \text{VO}_{2max}(m \cdot min^{-1}) = \frac{V}{VO_2(t) \times V^{-1} \times M^{-1}} \]

[6]

where “V” (m·min\(^{-1}\)) is the average velocity of the 30-min test, and “M” is the subject’s mass.

**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 analyzed at the end of the exercise (Fig. 1). The video sequences were digitized 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” (Fig. 2). The morphology of this numerical mannequin 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 centers of masses have not been

**FIGURE 1**—Representation of space calibration and of the field of the camera.
directly measured because only one camera was used. All the trajectories of the different centers of mass (segments and body center of mass) were smoothed using a polynomial method in order to obtain by derivation the speed displacement of the different centers of mass. Variations of potential and kinetic energies ($\Delta E_{pe}$ and $\Delta E_{ke}$, respectively) were then calculated (7).

$$\Delta E_{pe} = M \times g \times (H_{\text{max}} - H_{\text{min}})$$  \[7\]

$$\Delta E_{ke} = \frac{1}{2}M \times (V_{\text{max}}^2 - V_{\text{min}}^2)$$  \[8\]

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

The variation of the internal energy ($\Delta E_{\text{int}}$) 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 (Fig. 2) is composed of 17 different segments. The variation of internal energy ($\Delta E_{\text{int}}$) is calculated,

$$\Delta E_{\text{int}} = \frac{1}{2} \sum_{i=1}^{17} (m \cdot \dot{V}_{i}^2 + I \cdot \dot{\alpha}_{i}^2)$$  \[9\]

where “s” represents a segment, “m,” is the mass of the segment (kg) considered, and “I” is the moment of inertia of the segment (kg m$^2$). “$\dot{V}_{i}$” is the velocity of the center of mass of the segment (m s$^{-1}$) with respect to the referential linked to the CM. “$\dot{\alpha}_{i}$” is the angular velocities 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 expressed in joules per kilograms per meter ($C_{ke}$, $C_{pe}$, and $C_{\text{int}}$) are equal to the positive variation of $\Delta E_{ke}$, $\Delta E_{pe}$, and $\Delta E_{\text{int}}$ divided by the mass of the subject and his step amplitude. These parameters were measured during the steady state of VO$_2$, at the end of the exhaustive run (3,4).

**FIGURE 2—MAN3D mannequin representation.**

**Statistics.** An ANOVA permitted to compare $C_{pe}$, $C_{ke}$, $C_{\text{int}}$, $C$, VO$_{2\text{max}}$, $\nu$VO$_{2\text{max}}$, the running test speed, and the weight and the height of the different populations. A post hoc test was used (PLSD Fisher test) to identify differences between the groups. Pearson’s correlation coefficients were used to evaluate the relationships among variables.

**RESULTS**

**Characteristics of the highly, well and nontrained runners.** VO$_{2\text{max}}$ and $\nu$VO$_{2\text{max}}$ were significantly greater in trained subjects. Indeed, both parameters were greater for highly trained runners compared with well-trained runners or compared with nontrained 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 ($C_{pe}$, $C_{ke}$, $C_{\text{int}}$, and $C$), were performed for similar running speeds (Table 1).

**Effect of the endurance training status on C, C_{pe}, C_{ke}, C_{\text{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, to move forward at the same running speed (Table 2), the highly trained runners present a same C as well-trained or nontrained runners. Moreover, when the energetic equivalent of lactate (EEL) is added to C there is also no difference between the groups.

$C_{pe}$ was significantly lower in highly and well-trained runners compared with nontrained runners (20%). Inversely, the step rate (SR) was significantly higher in highly trained runners compared with well and nontrained runners. Moreover, there was an inverse correlation between SR and $C_{pe}$ or the vertical displacement of the center of mass (CM) (respectively $r = -0.63$; $P = 0.001$ and $r = -0.81$; $P \leq 0.0001$). 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 with 7.7 ± 0.7 cm for the well-trained runners, and 8.3 ± 1.3 cm for the nontrained runners ($P = 0.02$).

$C_{\text{int}}$ was also significantly higher in highly trained runners: 30% greater in comparison with well-trained runners and 37% greater in comparison with nontrained runners. $C_{\text{int}}$ 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 $C_{pe}$ ($r = -0.32$; $P = 0.16$).

The running speed was similar in all the runners; therefore, $C_{ke}$ was not significantly different in the three populations of different training status ($P = 0.89$).

**Relationship between C, C_{ke}, C_{pe}, C_{\text{int}}, SR, and VO_{2max}.** Although $C_{pe}$ and $C_{\text{int}}$ were significantly different according to the training status of the runners, there was no correlation between C and $C_{pe}$ or $C_{\text{int}}$ (Fig. 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 $P = 0.06$.
Significantly different from highly trained runner (P ≤ 0.05).
§ Significantly different from well-trained runner (P ≤ 0.05).

**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 respiratory quotient (R), the step rate (SR), the step length (SL), the kinetic, potential, and internal mechanical costs (C_{ke}, C_{pe}, and C_{int}, respectively).**

<table>
<thead>
<tr>
<th>Training Status</th>
<th>C (J kg(^{-1}) m(^{-1}))</th>
<th>C + EEL (J kg(^{-1}) m(^{-1}))</th>
<th>R</th>
<th>SR (Hz)</th>
<th>SL (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Highly Trained</td>
<td>1.54 ± 0.70</td>
<td>1.41 ± 0.40</td>
<td>0.94 ± 0.08</td>
<td>3.21 ± 0.22</td>
<td>1.52 ± 0.14</td>
</tr>
<tr>
<td>Well Trained</td>
<td>0.43 ± 0.07</td>
<td>0.45 ± 0.05</td>
<td>1.00 ± 0.03</td>
<td>3.01 ± 0.11†</td>
<td>1.66 ± 0.08†</td>
</tr>
<tr>
<td>Nontrained</td>
<td>0.80 ± 0.12</td>
<td>0.60 ± 0.09†</td>
<td>0.94 ± 0.08</td>
<td>3.21 ± 0.22</td>
<td>1.52 ± 0.14</td>
</tr>
</tbody>
</table>

† Significantly different from highly trained runner (P = 0.05).
§ Significantly different from well-trained runner (P ≤ 0.05).

**FIGURE 3**—Correlation between the vertical displacement of the center of mass (VD of the CM) and the step rate (SR). The vertical bars represent the SEM.

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

For C_{int}, furthermore, there was no correlation between the SR and C (r = 0.15; P = 0.53). These results showed that the interindividual 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 VO_{2max} (respectively, r = 0.58; P = 0.007; r = -0.73; P = 0.0001; r = 0.60; P = 0.004).

**DISCUSSION**

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 center of mass (C_{pe}) was smaller in highly trained runners. Inversely, the mechanical cost associated with the movement of the segments around the center of mass (C_{int}) and the step rate (SR) were greater.

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 ventilation, an optimization 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 (14) 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 VO_{2max}). In the present study, the range of intensities was comprised within 80% and 97% of VO_{2max}. 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.

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 center of mass are associated with a high level of training (28,37). However, there was no relationship observed between C_{pe} and C (Fig. 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 center of mass (C_{int}) were not correlated with C (Fig. 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).
weight (BW) with an impact load rate of 113 BW/stride. These impacts have magnitudes up to 2.3 times body loads during the initial portion of the support phase of the stride. During human running, the body is subjected to high impact forces on the muscles, tendons, and bones. They suggest that increasing their metabolic cost but reducing the peak 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 (11,24,27).

Collectively, the results reported here do not confirm our primary hypothesis and suggest that the mechanical cost (Cpe and Cint) is not correlated with C but with VO2max. The mechanism that explains the modifications of the mechanical parameters (SR, Cpe, and Cint) is in relation with the level of training of the runners rather than their energy cost. However, this mechanism has to be elucidated.

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 optimize. 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.

The running style of the highly trained runners may be associated with the same self-optimizing mechanism that contributes to reducing the impact loads during the initial portion of the support phase of the stride. Indeed, this style is characterized by a high SR and a low Cpe 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·d⁻¹; (6)) compared with the other populations studied. For example, running 32 km·wk⁻¹ will produce over 1.3 million impacts to the body over a period of 1 yr (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).

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

The authors gratefully acknowledge the Fédération Française de Ski and Michel Tavernier for their assistance during the experiment.

REFERENCES


