

Chapter 5

The Energetics and Biomechanics of Walking and Running



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Abstract This chapter is on walking and running, the present knowledge of which is due essentially to the School of Milano. After a short historical synopsis, the energetics of walking and running is discussed. In this context, after having introduced Margaria's concept of energy cost, the effects of incline, of the terrain, of pathological gaits and of body mass and aging are treated. In the second part, the contribution of the School of Milano to the knowledge of the biomechanics of walking and running is analyzed, with special attention to the fundamental role played by Giovanni Cavagna. The pendulum-like mechanism of walking and the elastic mechanism of running are described. Concepts like internal and external work and mechanical efficiency are discussed. Further, the transition between walking and running is discussed along the lines proposed by Alberto Minetti. Finally, the energetics of sprint running and the effects of acceleration are discussed.

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Three athletes during training for the marathon race of the 1896 Athens Olympic Games, on the road from Marathon, Greece. The athlete in the middle is Charilaos Vasilakos (1877–1964), a student from Athens, who ended at the second place, after the shepherd Spyridon Louis (1873–1940). Property of WikiCommons, in free domain

5.1 Introduction

The aim of the present chapter is to subsume under a coherent picture the vast collection of data on the bioenergetics and biomechanics of walking and running, arising from the numerous papers devoted to these topics by the School of Milano, along the lines of the seminal study by Rodolfo Margaria (1938) on the energy cost of walking and running. More specifically, after a brief historical note, we discuss the basic principles along which an analysis of human locomotion can be performed, and then we describe more in detail the energetics and biomechanics of walking and running. The effects of the incline are analyzed for both. Competitive walking is also considered. The School was active in the study also of other types of locomotion, both on land (speed skating, skiing, but mostly cycling) and in water (swimming, rowing and other forms of assisted locomotion), along the same general principles. These are discussed in Chap. 6.

5.2 The Founders

It is well known since the Hellenistic era that muscles are the site of animal movement. Herophilus ($\approx 325 - \approx 255$ B.C.), one of the founders of the medical school of Alexandria, was already aware that muscles can shorten and lengthen. Although he is credited to have been one of the first to establish a bridge between hard science and medical science, we are not aware as to whether he created what we would call nowadays a physical theory of animal motion. Most of his work has been lost and present information on him is indirect, from citation in other texts (Von Staden 1989). To set a theory of locomotion, we need an adequate physical system and the Hellenistic one was lost. It was only with the development of modern classical mechanics starting from the seventeenth century, and the creations of concepts like work and power, that we got an instrument for the analysis and interpretation of animal locomotion.

As already pointed out in Chap. 2, the second necessary instrument came in the eighteenth century, with the discovery of oxygen and carbon dioxide. Antoine-Laurent de Lavoisier (1743–1794) was the first to demonstrate that both gases are necessary to life, as humans consume oxygen and produce carbon dioxide; but even more important, he demonstrated, together with Armand Séguin (1767–1835), that oxygen consumption, carbon dioxide elimination and heat production all increase in exercise, in rough proportion between them (Perkins Jr 1964). This observation implies three consequences: (i) chemical energy transformation is an oxidation process of some “organic” fuel, with carbon dioxide as end product; (ii) there must be a tight coupling of oxygen consumption to fuel degradation, and (iii) the chemical energy transformation into mechanical energy occurs during muscular contraction. The basis for an energetic analysis and interpretation of human locomotion was set.

It does not come as a surprise that the earlier attempts at describing the energetics of human locomotion in quantitative terms were devoted to walking. Indeed, in the second half of the nineteenth century, several authors determined the energy expenditure during level walking, wherefrom the energy cost of walking (C_w) on the level at speeds between 3.8 and 4.8 km h⁻¹ (1.05–1.33 m s⁻¹) can be calculated (Katzenstein 1891; Smith 1859; Sondén and Tigerstedt 1895). The obtained values were astonishingly close to the currently accepted ones (from 0.32 to 0.51 kcal kg⁻¹ km⁻¹, i.e., from 1.34 to 2.13 J kg⁻¹ m⁻¹). The mechanical efficiency of uphill walking, as obtained from the ratio of the potential energy (E_p) changes to the corresponding metabolic energy expenditure, was also determined, obtaining values ranging from ≈ 0.20 to ≈ 0.37 (Katzenstein 1891; Löwy et al. 1897; Schumburg and Zuntz 1896). At the beginning of the twentieth century, Brezina and Kolmer (1912) reported that the energy cost of level walking, per unit of transported mass and distance, increases sharply at speeds > 1.33 m s⁻¹. Shortly afterward, Barkan et al. (1914) observed that the energy expenditure of level walking at speeds between 0.8 and 1.3 m s⁻¹, at the altitude of the “Laboratorio Angelo Mosso” (2900 m above sea level, see Chap. 1), was essentially equal to that observed by others at sea level

(0.37–0.55 kcal kg¹ km¹). Similar results were reported also by Benedict and Murschhauser (1915).

The energy cost of running (C_r) can be assessed from the studies by Waller (1919) and by Liljestrand and Stenström (1919), whence values ranging between 0.80 and 1.30 kcal kg¹ km¹ were obtained, again not far from the presently accepted ones; whereas Hill (1928) was probably the first to investigate the effects of the air resistance in running. However, as mentioned above, the most comprehensive study on the energy cost of walking and running was undertaken by Margaria (1938). Margaria's study was a turning point of the history of the energetics of human locomotion, for the formalization of the concept of energy cost (C), which is still at the core of our interpretation of the energy transformations during walking and running, and actually during any type of locomotion.

The study of the biomechanics of human locomotion took great advantages from the technological revolution that occurred in the second half of the nineteenth century, thanks to the dramatic development of photography. Several attempts at reproducing movement using photographic tools preceded the Lumière brothers' invention of what we call *cinema*. Two men, interested in understanding human movement, had a major role in these developments: Etienne-Jules Marey (1830–1904), a French physiologist, and Eadweard Muybridge (1830–1904), a British photographer who practised in the USA, who, amazingly enough, shared the years of birth and death. The former invented the chronophotographic gun, a tool that allowed taking sequences of 12 frames per second reproduced on the same plate (classical movie cameras filmed at a frequency of 24 images per second); with this technique, Marey (1878) decomposed animal movement to get detailed analysis of it. Similarly, Muybridge placed 12, then 24 cameras at given distances, taking pictures at given predetermined times along the path of a moving animal. He copied his images onto a spinning disc allowing projection at predetermined speed of the sequence of images through a source of light: by doing so, he reproduced motion at a pre-cinematographic speed (Muybridge 1887).

Their techniques opened the way not only to modern cinema, but also to the cinematographic techniques of locomotion analysis, which allowed Wallace Fenn (1893–1971) to perform the first computations of mechanical work during walking and running (Fenn 1930a, 1930b). Pretty much as Margaria's 1938 study for the energetics, Fenn's papers represented a turning point of the history of the biomechanics of human locomotion. Incidentally, Margaria and Fenn were friends. Fenn later created Rochester, which then spread to Buffalo: their friendship is the base of the Buffalo—Milano connection.

5.3 Definitions and General Concepts

The maximal absolute velocities in human locomotion encompass a wide range of values (Fig. 5.1), whereas the maximal muscular power of the athletes competing in the different events, for any given effort duration, is substantially equal. Thus, the

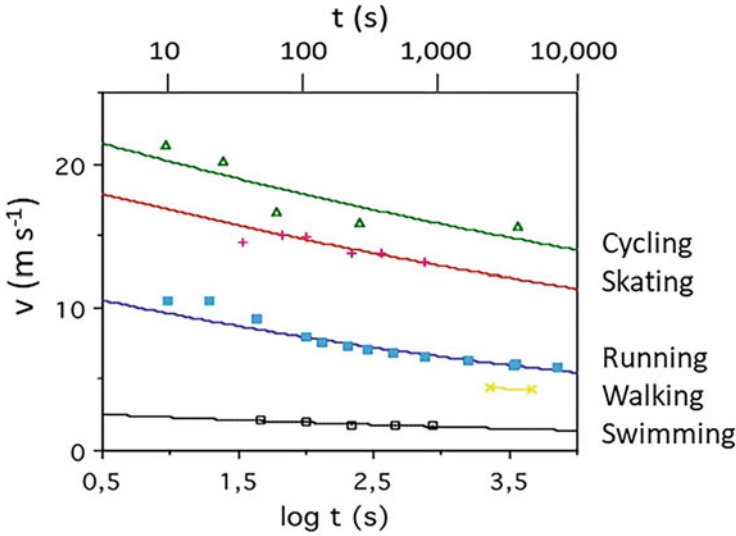


Fig. 5.1 Average speed (v) of some extremely high performances, or 2014 world records, as a function of time in the indicated forms of human locomotion. Since we refer to records, walking is competitive walking. The time is expressed in seconds (upper abscissa, log scale) or as the corresponding logarithm, lower abscissa. Modified after di Prampero 2015

above speed differences cannot be attributed to the athletes’ “engine”; on the contrary, they depend on the set of intrinsic characteristics of any given form of locomotion that determine C , is usually expressed in kJ km^{-1} . However, to compare subjects of different body size, it is often convenient to express C per kg of body mass ($\text{J kg}^{-1} \text{m}^{-1}$). It should also be pointed out that $1 \text{ kcal} = 4.186 \text{ kJ}$, and that the consumption of 1 L of oxygen in the human or animal body yields $\approx 5 \text{ kcal}$ ($\approx 21 \text{ kJ}$), the precise value ranging from 4.68 to 5.05 kcal L^{-1} depending on the substrates utilized, and hence on the respiratory quotient (Margaria 1975).

The rate of energy expenditure per unit of time (metabolic power, \dot{E}) is the product of C times the velocity (v):

$$\dot{E} = C v \tag{5.1}$$

Equation 5.1 tells that, in any form of locomotion, and for any given C value, the maximal attainable speed (v_{max}) is directly proportional to the subject’s maximal metabolic power (\dot{E}_{max}). Solving Eq. 5.1 for v_{max} , we obtain:

$$v_{max} = \frac{\dot{E}_{max}}{C} \tag{5.2}$$

Equation 5.2 applies regardless of the energy sources yielding \dot{E}_{max} ; however, it becomes particularly useful in long-duration aerobic performances, wherein \dot{E}_{max} is

well defined and is represented by the subject's maximal oxygen consumption ($\dot{V}O_2^{max}$, see Chap. 7). Hence:

$$v_{max} = \frac{\varphi \dot{V}O_2^{max}}{C} \quad (5.3)$$

In this specific context, v_{max} is tantamount to the maximal aerobic speed, whereas φ is the fraction of $\dot{V}O_2^{max}$ that can be sustained throughout the entire performance. We note that, for effort durations between ≈ 30 minutes and ≈ 2 hours, φ depends on the characteristics of the power-time relationship yielding the so-called critical power (Moritani et al. 1981).

The three quantities φ , $\dot{V}O_2^{max}$ and C , combined as in Eq. 5.3, explained about 70% of the performance variability in a group of long-distance runners (di Prampero et al. 1986). So, Eq. 5.3 provides a satisfactory description of the energetics of endurance running. Moreover, we can reasonably assume that the type of analysis expressed formally by Eq. 5.3 can be profitably applied to the analysis of any standardized form of locomotion, wherein the speed: (i) is the only criterion for evaluating performances, and (ii) depends directly on the subject's metabolic power. Thus, Eq. 5.3, the first formulation of which we owe to Margaria (1938), has been the basis for the analysis of the energetics of human locomotion carried out in the last 80 years within the School of Milano, as discussed in the next paragraphs.

In all forms of terrestrial locomotion, a fraction of C is utilized to overcome non-aerodynamic forces. This is defined as the non-aerodynamic energy cost ($C_n - a$) and includes the fraction of C that is necessary to overcome (i) gravity, to lift and lower, and inertia, to accelerate and decelerate the body center of mass at each stride; (ii) the friction of the point of contact with the terrain, whenever there is motion of one in respect to the other; (iii) the internal work necessary to move the limbs in respect to the subject's center of mass; (iv) the static muscular contractions to maintain the body posture; (v) the work of the respiratory muscles and of the heart to sustain respiration and circulation.

Over and above $C_n - a$, in all forms of terrestrial locomotion, an additional amount of energy is dissipated against the air resistance that increases with the square of v , where v is the velocity in respect to the air, not in respect to the terrain: these two velocities become equal in the absence of wind. In fact, the amount of C used against the air resistance, defined as the aerodynamic energy cost (C_a),¹ is given by:

¹In fact, C is a force. Dimensionally and conceptually, a force (F) is equal to the work (w) or energy per unit of distance (length, L): $F = w L^{-1}$. This depends on the fact that the work is defined as the product of the force and the distance along the direction of motion. Expressing the quantity in question as force opposing motion, or as work, or energy, per unit of distance, is therefore conceptually identical.

Table 5.1 Constant relating the energy cost (expressed per unit of distance and per m² of body surface area) to the square of the speed (k_e); non-aerodynamic energy cost per unit of distance and per kg body mass (C_{n-a} , J m⁻¹ kg⁻¹); overall energy cost per unit of distance for a man of 70 kg and 1.75 m (C , J m⁻¹) and aerodynamic coefficient (C_x) in the indicated forms of human locomotion on solid compact terrain at constant speed (v , in m s⁻¹) in the absence of wind at sea level (Pressure = 760 mmHg, Temperature = 20 °C). Cycling on a traditional racing bike in dropped posture. Data from di Prampero 1986

	Walking (competitive)	Running	Speed skating (ice)	Cycling
k_e	0.46	0.40	0.44	0.42
C_{n-a}	1.43 + 0.91 v	3.86	1.00	0.17
C	100 + 64 v + 0.83 v^2	270 + 0.72 v^2	70 + 0.79 v^2	13 + 0.77 v^2
C_x	1.10	1.10	0.50	0.75

$$C_a = k_e v^2 \quad (5.4)$$

where k_e is the proportionality constant relating the two variables. It depends on (i) the area projected on the frontal plane (A_f), (ii) the body shape, (iii) the air density (ρ), and (iv) the efficiency of transformation of the metabolic energy into mechanical work (η):

$$k_e = \frac{0.5 C_x A_f \rho}{\eta} = \frac{k_w}{\eta} \quad (5.5)$$

where k_w is the proportionality constant relating the force opposing motion to the square of the speed, and C_x is a dimensionless coefficient, which is smaller the more “aerodynamic” is the shape of the moving object. C_x is the ratio of the drags of two objects of equal A_f : one is the body at stake, the other is an object of standard shape with a squared frontal area. Indeed the drag of any given moving body varies as a function of the Reynolds number, and thus, ceteris paribus, it is greater, the higher is the speed of the body with respect to the fluid. When the drag of the body at stake is equal to that of the standard object, the C_x is equal to 1. This is the case for a cube. In the four forms of locomotion discussed in this Chapter and in Chap. 6, C_x ranges from ≈ 0.5 to ≈ 1 (Table 5.1), whereas in old fashion cars is ≈ 0.6 and slightly lower than ≈ 0.3 for contemporary streamlined cars.

To sum up, C is equal to:

$$C = C_a + C_{n-a} \quad (5.6)$$

Combination of Eqs. 5.4 and 5.6 yields:

$$C = k_e v^2 + C_{n-a} \quad (5.7)$$

A substantial body of data collected over the years has provided rather accurate values of k_e (Table 5.1). This table shows that C_{n-a} is independent of v in most

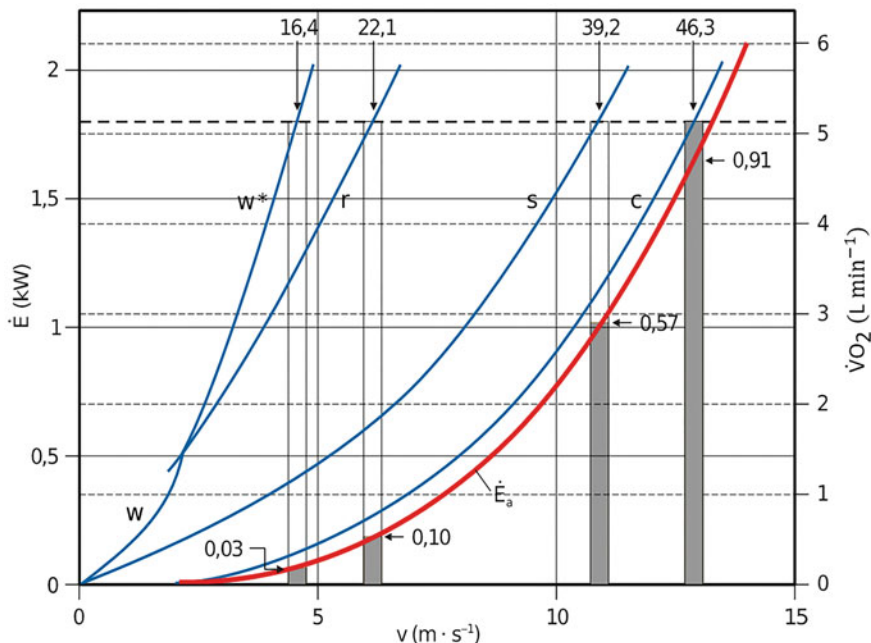


Fig. 5.2 Metabolic power (\dot{E} , kW, left ordinate) and corresponding oxygen uptake ($\dot{V}O_2$, L min $^{-1}$, right ordinate) above resting as a function of speed (v , m s $^{-1}$) during natural (w) or competitive (w^*) walking, running (r), ice speed-skating (s) and cycling (c) in a standard subject of 70 kg body mass, 1.75 m stature, at constant speed on flat compact terrain, at sea level in the absence of wind. The red curve (\dot{E}_a) describes the power dissipated against the air resistance, essentially equal in the four forms of locomotion. The vertical distance between the red curve and the blue ones is the power dissipated against non-aerodynamic forces (\dot{E}_{n-a}). The upper black broken horizontal line is the net maximal oxygen consumption of an elite athlete (1.8 kW, or 5.17 LO $_2$ min $^{-1}$). The intersection between this line and the blue ones is a measure of the maximal theoretical aerobic speed (vertical arrows and corresponding velocities, in km hr $^{-1}$) of this hypothetical athlete in the four forms of locomotion. The dark columns indicate the fraction of the overall power dissipated against the air resistance at the maximal aerobic speed. Modified after di Prampero 1986

forms of human locomotion on land. In this case, plotting C as a function of v^2 provides straight lines with slope equal to k_e and y-axis intercept equal to C_{n-a} . However, this is not so for competitive walking, because in this case C_{n-a} is a linear function of v . At variance, when we walk or run on a treadmill, C_a is nil, so that C corresponds to C_{n-a} .

The overall \dot{E} , as given by the product between C and v in the absence of wind (Eq. 5.6), is reported as a function of v in Fig. 5.2 for natural or competitive walking, running, ice speed-skating and cycling (for details on these last two forms of locomotion, see Chap. 6) (di Prampero 1986). The two components of the overall metabolic power (aerodynamic, \dot{E}_a and non-aerodynamic, \dot{E}_{n-a}) can be estimated for each form of locomotion, since the curve depicting the \dot{E}_a versus v relationship, in red on the graph, is essentially the same for all types of locomotion.

This figure shows that, in competitive walking as in running, since \dot{E}_a is but a minor fraction of \dot{E} , no substantial advantage can be obtained by ameliorating the subject's aerodynamic profile. On the contrary, as discussed in some detail in Chap. 6, an improvement of the aerodynamics of the bicycle provides astonishing increases of the speed on flat terrain, due to the large predominance of \dot{E}_a over \dot{E}_{n-a} .

Figure 5.2 shows also the maximal aerobic speed that a hypothetical elite athlete could achieve in these four forms of locomotion, were he/she able to compete with the same technical ability in all of them. Indeed, the maximal aerobic speed in each form of locomotion is set by the intersection between the horizontal line representing the subject's $\dot{V}O_2^{max}$ (above resting) and the appropriate metabolic power versus speed function.

It should finally be noted that all the functions shown in Fig. 5.2 for the reported locomotion modes had been obtained within the School of Milano, thanks essentially to the work of Rodolfo Margaria, Paolo Cerretelli, Pietro Enrico di Prampero, Gabriele Cortili (1939–2009), Piero Mognoni (1936–2008), and Franco Saibene (1932–2008). Figure 5.2 subsumes one of the most important legacies of the School of Milano to the physiological community: the theoretical and experimental basis of our understanding of the energetics of human locomotion, on which current studies still rely.

Combining Eqs. 5.1 and 5.4, one obtains:

$$\dot{E}_a = C_a v = k_e v^3 \quad (5.8)$$

It should be noted that Eq. 5.8, as such, applies only in the absence of wind. If this is not the case, the analysis becomes more complicated, as briefly discussed in Chap. 6.

A direct consequence of Eq. 5.8 is that, at speeds close to the maximal aerobic ones in elite athletes, \dot{E}_a varies greatly among different exercise modes. As an example, at the $\dot{V}O_2^{max}$ represented in Fig. 5.2, \dot{E}_a is almost negligible in competitive walking (≈ 0.066 kW or 0.19 L O_2 min^{-1}), rather small in level running (≈ 0.19 kW or 0.54 L O_2 min^{-1}), much higher in speed skating (up to ≈ 1.08 kW or 3.10 L O_2 min^{-1}), to reach about 90% of the total metabolic power in cycling (≈ 1.71 kW or 4.92 L O_2 min^{-1}).

5.4 The Energy Cost of Walking and Running

The relationship between C_{n-a} and v in natural level walking on the treadmill has a U shape with a minimum at a speed between 1.1 and 1.4 m s^{-1} (Fig. 5.3a). On the contrary, in level running, C_{n-a} is essentially constant and independent of the speed (Fig. 5.3b), amounting to about 3.8 – 4.1 $\text{J kg}^{-1} \text{m}^{-1}$, a value about twice that observed in level walking at the most economical speed (Margaria et al. 1963). However, above ≈ 2.2 m s^{-1} , the C_{n-a} of walking on flat terrain becomes higher than that of running. Indeed, it seems that, at speeds around 2.2 m s^{-1} , uninformed

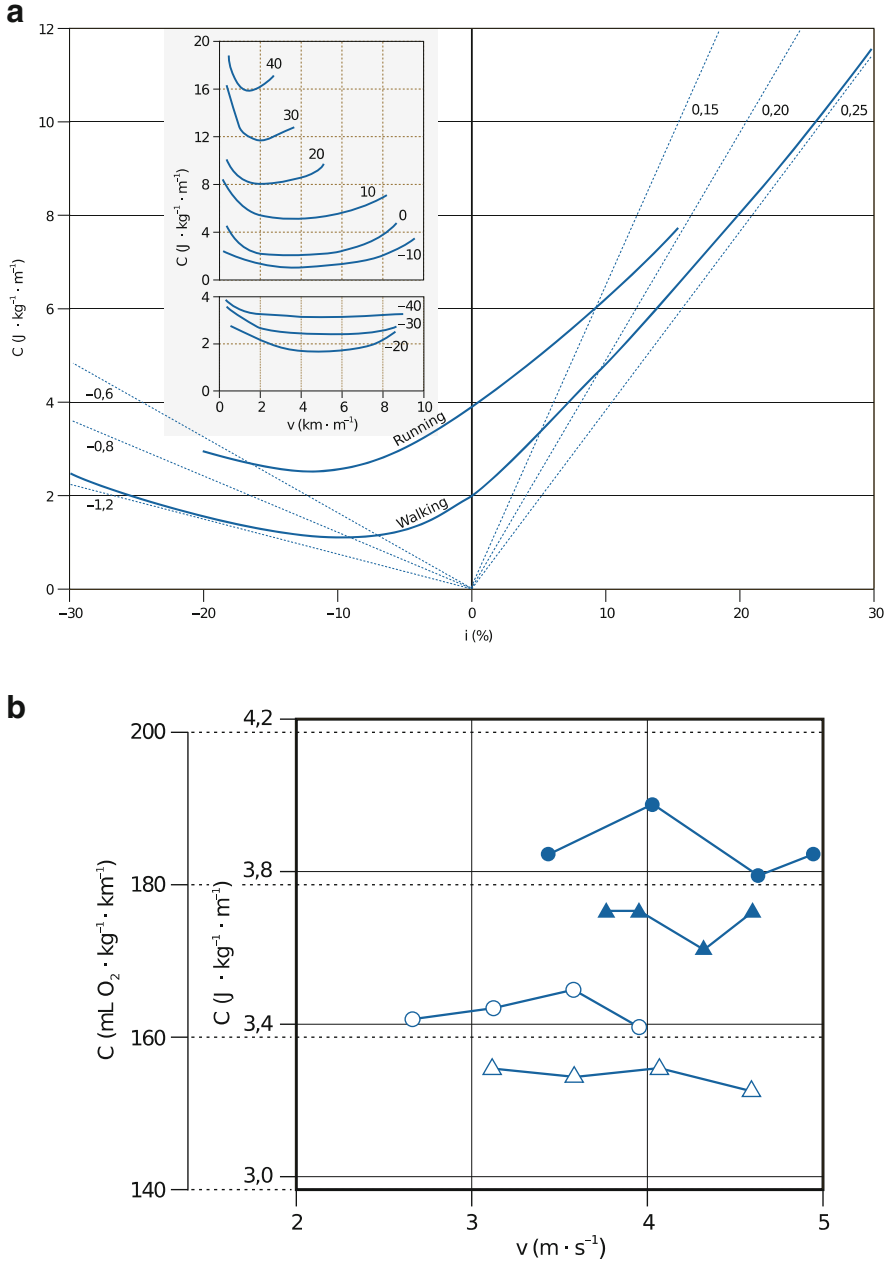


Fig. 5.3 (a) Energy cost of treadmill running, or natural walking, at the optimal speed (C , $\text{J kg}^{-1} \text{m}^{-1}$), as a function of the incline of the terrain (i , %). The energy cost of walking is a function of the speed (v , m s^{-1}), as indicated in the inset, whereas that of running, for any given incline, is constant. Modified after di Prampero 1986; data from Margaria et al. 1963. (b) Energy cost of treadmill running on the level as a function of the speed for the two most economical subjects (empty symbols) and the two less economical ones (filled symbols) of a group of 37 amateur marathon runners. Data from di Prampero et al. 1986

subjects shift spontaneously from walking to running (or vice-versa, if the speed is decreasing). The way this transition occurs is discussed more in detail in Sect. 5.6.

The same applies, in an even more elaborate way, in animals, like dogs and horses, characterized by three gaits: pace, trot, and gallop. The shift from one to the other of these forms of locomotion, as a function of the speed, occurs always in such a way as to select the most economical gait at the speed in question.

However, with a little bit of patience, it is possible to persuade humans or horses to utilize un-economical gaits: trot races for horses, competitive walking for humans. In this latter case, C , even if higher than that of running, is nevertheless substantially lower than could be expected from the extrapolation to high speeds of the C versus v relationship for natural walking. This feat is obtained thanks to the well-known technique of locomotion of competitive walking (Cappozzo et al. 1976; Cavagna and Franzetti 1981; Marchetti et al. 1983), somewhat funny at first glance, but energetically more economical than natural walking at the competition speed, even if not as much as level running.²

As far as C_a is concerned, Eq. 5.7 applies to running as well, as demonstrated on top-level marathon runners from Kenya (Tam et al. 2012), who could be investigated up to speeds as high as $5.0\text{--}5.5\text{ m s}^{-1}$ ($18\text{--}20\text{ km h}^{-1}$) in fully aerobic conditions. Concerning natural walking, C_a is so small, that it can be practically neglected, so that the C versus v relationship on a flat terrain (an athletic field, for instance) is essentially the same as that on the treadmill.

5.4.1 The Effect of the Incline

As mentioned above, in 1938, Margaria investigated in depth the energetics of walking and running at speeds between 0.14 and 2.64 m s^{-1} and slopes between $+40$ and -40% in walking and between 1.80 and 4.20 m s^{-1} from $+15$ to -30% in running, respectively. His data are reported in Fig. 5.3a. This Figure shows that C_{n-a} , as expected, increases uphill and decreases downhill; in this latter case, however, if the slope becomes steeper than -15% , C_{n-a} increases again. It shows also that in walking, the optimal speed, yielding the minimum C_{n-a} , is smaller, the steeper the incline (Fig. 5.3a). In running, at all slopes, the C_{n-a} is independent of the speed (Fig. 5.3b). Finally, the C_{n-a} of running turns out always higher than that of walking at the optimal speed; on flat terrain, as mentioned above, the former is about two times higher than the latter.

Minetti et al. (2002) studied C_w or C_r uphill or downhill in a much larger range of slopes than did Margaria, i.e., from -45% to $+45\%$. The so obtained data, on the one side, confirmed the data reported by Margaria (1938), as did also Minetti et al.

²At the 2014 European Championships in Zürich, Yohann Diniz from France established the current world record in the 50 km distance, which he completed in 3 h 32 min and 33 s. His average speed corresponded to 14.11 km h^{-1} or 3.92 m s^{-1}

(1994a), and, on the other side, have shown that the C_{n-a} of treadmill running is independent of v even at these very steep uphill or downhill slopes. This has allowed condensing these data into one and the same empirical relationship (independent of the speed) between the net C_{n-a} (in $\text{J kg}^{-1} \text{m}^{-1}$) and the incline of the terrain (i):

$$C_{n-a} = 155.5 i^5 - 30.4 i^4 - 43.3 i^3 + 46.3 i^2 + 19.5 i + 3.6 \quad (5.9)$$

where i is the tangent of the angle β between the terrain and the forward direction of the treadmill's movement (positive for uphill and negative for downhill), and 3.6 is the C_{n-a} value observed on their subjects during level running at constant speed.

Knowledge of $i = \tan \beta$ allows a trigonometric computation of the vertical distance h , whence the work against gravity (Mgh , where M is the body mass and g is the gravity acceleration) can be obtained. In fact h is equal to:

$$h = L_{ho} \tan \beta = L_t \sin \beta = L_{ho} i \quad (5.10)$$

where L_{ho} is the distance covered on the horizontal plane (that of the floor on which the treadmill is placed) and L_t is the distance covered along the treadmill's axis (direction of movement),³ so that:

$$L_t = L_{ho} \frac{\tan \beta}{\sin \beta} \quad (5.10a)$$

Equation 5.10 shows also that i is the h per unit L_{ho} , so that the abscissa of Fig. 5.3a is a representation of h , and thus, for any given human on Earth, of Mgh . The ordinate of this same figure reports the corresponding C_{n-a} , so that, when both C_{n-a} and Mgh are expressed per unit of distance, their ratio is the reciprocal of the apparent net mechanical efficiency of the vertical work (η_v) of walking (at the optimal speed), or of running. Thus, in Fig. 5.3a, we can draw a family of isopleths departing from the origin of the axes (three of which are shown in the Figure), along which η_v is constant. However, h is expressed per unit of L_{ho} , whereas C_{n-a} is expressed per unit of L_t . For this reason, since, when $\beta > 0$, and thus $L_t > L_{ho}$, the nominal η_v turns out larger than the real η_v , by a factor equal to $\tan \beta / \sin \beta$ (Eq. 5.10a). For inclines ≤ 0.25 , corresponding to $\beta \leq 14.04$ deg., $\tan \beta / \sin \beta \leq 1.03$. Hence, within this range of inclines, the above approach does not lead to

³Consider as an example a 10% slope: under these conditions the subject, for $L_{ho} = 1$ m, lifts his body mass by 0.1 m; as a consequence, the mechanical work performed against gravity (Mgh), expressed per unit body mass and distance, amounts to: $(9.81 * 0.1) = 0.98 \text{ J/kg}^{-1} \text{m}^{-1}$. The y axis of Figure 5.3a shows that the energy cost corresponding to $i = 0.10$ amounts to 4.70 and 6.18 $\text{J kg}^{-1} \text{m}^{-1}$ of L_{ho} , for walking and running, respectively. Hence, since $L_t = L_{ho} \frac{\tan \beta}{\sin \beta}$ (Eq. 5.10a), the corresponding efficiencies (η_v) amount to $(0.98 * 1.005) / 4.70 = 0.210$ for walking at the optimal speed and to $(0.98 * 1.005) / 6.18 = 0.159$ in running. Neglecting $\frac{\tan \beta}{\sin \beta}$, one would obtain $\eta_v = 0.98 / 4.70 = 0.208$ for walking at the optimal speed and to $0.98 / 6.18 = 0.158$ in running, a very negligible difference indeed.

any gross over-estimates of η_v ; for steeper slopes, this error turns out important, so that it becomes necessary to apply this correction procedure.

When walking or running downhill, Mgh is negative, in so far as it is performed by gravity on the mass of the subject, whose muscles contract eccentrically to apply a brake to the fall of the body, thus absorbing mechanical work: hence the resulting η_v is also negative.

During locomotion on flat terrain at constant speed, both in walking and in running, η_v is nil, because no net vertical work is performed. On the contrary, when moving uphill, η_v does increase, tending to a value of the order of 0.25 for i values close to 0.25 in both walking and running (Fig. 5.3a). The η_v at these slopes corresponds well to the maximal efficiency of isotonic muscle contractions, in which the muscle performs only positive (concentric) work. Similarly, when moving downhill, η_v becomes progressively more negative, tending to a value between -1.0 and -1.2 for i values close to -0.20 (Minetti et al. 2002). This η_v corresponds well to the maximal efficiency of isotonic eccentric muscle contractions, in which the muscle performs only negative work. It is therefore reasonable to assume that, at the inclines of the terrain at which these asymptotic values of η_v are attained, the muscles perform only positive or negative work.

This state of affairs is likely the consequence of the biomechanics of walking and running. Indeed, when walking or running on flat terrain, the subject's center of mass is lifted and lowered in the vertical plane at each stride, over the same distance upward and downward (see Sect. 5.5). On the contrary, when moving uphill, the ascent of the body center of mass is greater than the subsequent descent, the opposite being true during downhill locomotion. It seems therefore reasonable to assume that, at the inclines at which the efficiency attains its asymptotic values, the descent (in uphill walking or running) or the ascent (in downhill walking or running) of the center of mass cease altogether.

5.4.2 *Effects of the Terrain*

The data reported so far, and summarized in Figs. 5.2 and 5.3, and in Table 5.1, were obtained during natural or competitive walking and in running on the treadmill or on smooth compact terrain. On irregular or soft terrain, such as on sand, grass, or snow, C increases by an amount that depends on the terrain characteristics. An example thereof is reported in Fig. 5.4 for natural walking and running on dry sand. Under these conditions, at variance with what happens on compact terrain, C_w increases monotonically with the speed and is 2 to 3 times greater than on compact terrain. Similarly, also C_r is about 1.5 times larger than on compact terrain (Lejeune et al. 1998; Pinnington and Dawson 2001; Soule and Goldman 1972; Zamparo et al. 1992).

This state of affairs is likely due to the fact that, on soft terrain, the pendulum-like mechanism that leads to the transformation of potential energy into kinetic energy, and vice-versa, in natural walking, and the recovery of elastic energy in running, are

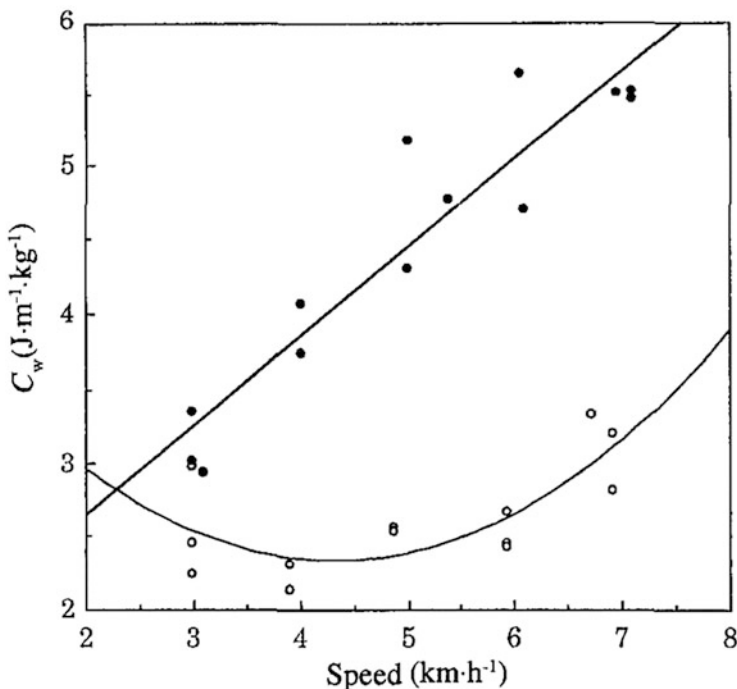


Fig. 5.4 Energy cost of natural walking (C_w , $\text{J kg}^{-1} \text{m}^{-1}$) on compact terrain (empty symbols), or on dry sand (filled symbols), as a function of the speed. From Zamparo et al. 1992

less effective than on compact terrain (see Sect. 5.6) (Pinnington and Dawson 2001). These mechanisms act optimally only if there is a firm grip of the foot on the ground. In the absence of this, the deficit of elastic energy recovery in running on sand implies increased muscle activation, associated with greater hip and knee range of motion than on firm terrain (Pinnington et al. 2005). On grass, C_r is about 20% larger than on compact terrain; this lesser increase, as compared to dry sand, is probably because grass is less compliant than dry sand, thus permitting a greater recovery of elastic energy (Pinnington and Dawson 2001).

5.4.3 Pathologies of Locomotion

C_w increases substantially also in numerous pathologies, both neurological (multiple sclerosis, Parkinson's disease, hemiplegic paralysis) and orthopedic (hip or knee prosthesis) (Fusi et al. 2002; Maggioni et al. 2012; Olgiati et al. 1986; Zamparo et al. 1995), by similar amounts at all walking speeds.

When comparing the C_w in pathological conditions to the normal physiological values, the effects of v cannot be neglected. To take this into account, Fusi et al.

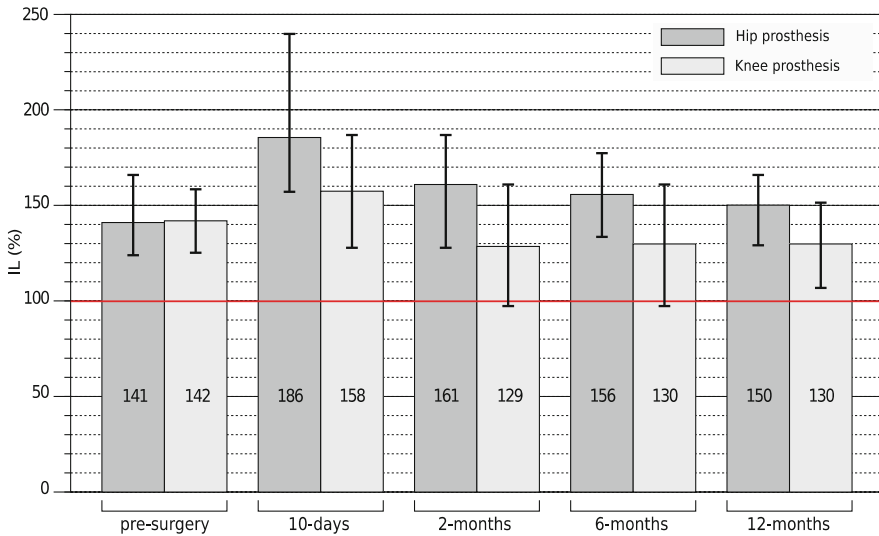
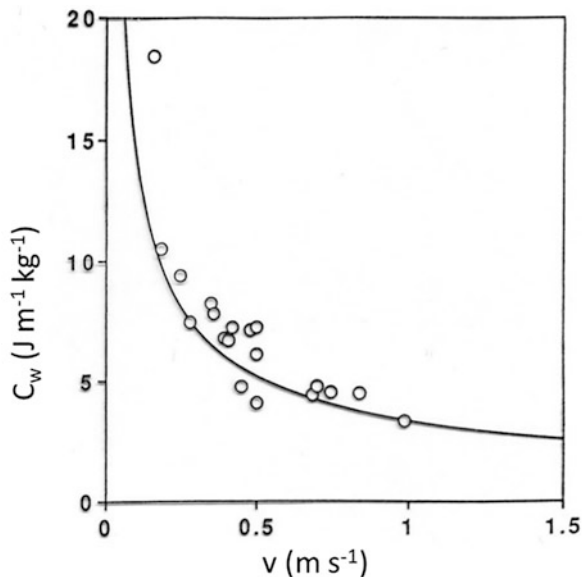


Fig. 5.5 “Index Locomotorius” (IL) before and after hip or knee prosthesis. Vertical bars indicate 1 standard deviation. Red horizontal line: IL in healthy subjects. From Fusi et al. 2002

(2002) proposed to utilize the so-called locomotor index, defined as the ratio between the energy cost in the investigated pathology and that observed in healthy subjects at the same speed. The evolution of the locomotor index as a function of time after surgical intervention is reported in Fig. 5.5 for hip or knee prosthesis carriers. It is noteworthy that, about 6 to 12 months after hip or knee prosthesis, these patients still have a locomotor index of 1.3–1.4, i.e., significantly higher than the physiological value of ≈ 1.0 , even if the patient has completely recovered from surgery and is considered clinically “healthy.” This is probably due to an abnormal gait pattern that the patient has acquired to minimize pain in the long period preceding the implant of the prosthesis (in the vast majority of instances the implant of the prosthesis is due to long-duration arthrosis processes of the hip or knee joint). This interpretation suggests that, in spite of the clinical recovery, the patient is not able, at least over relatively short periods of time, to resume the normal neuromuscular gait pattern.

On the contrary, in hemiplegic patients, the locomotor index is only marginally increased (≈ 1.1). This can presumably be attributed to the fact that the affected limb, even without contributing energetically to the progression, is nevertheless an effective “pillar” permitting the pendulum-like mechanism, an essential biomechanical mechanism optimizing C during natural walking. However, the muscular insufficiency of the affected limb necessarily leads to a slow speed; hence, the corresponding C moves up the ascending part of the curve relating C and v , thus leading to a larger energy expenditure per unit of distance (Fig. 5.6). As a consequence, in these patients, the overall C is greater than in normal subjects because of

Fig. 5.6 Energy cost of natural walking (C_w) in hemiplegic patients, as a function of the speed (v). Average energy cost of healthy patients is also indicated (continuous curve). From Zamparo et al. 1995



their impossibility to attain the optimal walking speed (v_{opt}), a fact that inevitably leads to a greater sense of fatigue and hence to a sedentary life style.

5.4.4 The Effect of Body Mass and Age

In several animal species, the C_r per unit of body mass decreases with increasing the animal's mass, as indicated in Fig. 5.7 for a mass range from 20 g to 4000 kg. The relationship has an allometric exponent of -0.316 , slightly higher than that calculated by Taylor et al. (1970) in the mass range from 10 g to 1000 kg (-0.40). However, within a given species, three of which are represented in the figure: humans, horses, elephants, C is essentially constant and independent of body mass. Coherently, Taboga et al. (2012) observed that, in severely obese subjects, whose body mass ranged from 109 to 172 kg, the C_r on the treadmill at 2.2 m s^{-1} , expressed per kg of body mass, was similar to that observed in non-obese subjects ($4,10 \pm 0,30 \text{ J kg}^{-1} \text{ m}^{-1}$, obese, $3,90 \pm 0,35 \text{ J kg}^{-1} \text{ m}^{-1}$, non-obese). This is a common phenomenon when studying the effects of body mass, since allometric cross-species relationships encompass a very wide range of body mass values (in Fig. 5.7, the biggest body mass is 200,000 times larger than the smallest one), whereas within-species relationships cover a by far smaller body mass range (the body mass of the obese subjects was less than 60% higher than that of non-obese subjects in the study by Taboga et al. 2012).

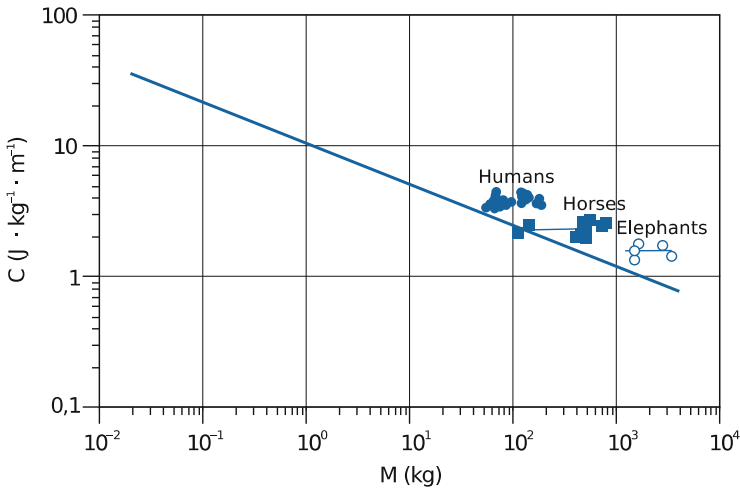


Fig. 5.7 Energy cost (C) of running in humans (full dots), horses (filled squares) and elephants (open dots) as a function of the body mass (M). Logarithmic coordinates. Straight line, described by $C = 10.7 M^{-0.316}$, indicates the energy cost of running, as a function of the body mass, in several species of mammals. Modified after di Prampero 2015, data from Griffin et al. 2004; Langman et al. 2012; Taboga et al. 2012

Table 5.2 Energy cost of running and walking at the optimal speed on compact flat terrain at various ages. Mass and optimal walking speed are also indicated. Modified after di Prampero 2008

Age (years)	Cost of running ($\text{ml kg}^{-1} \text{m}^{-1}$)	Mass (kg)	Cost of walking at optimal speed ($\text{ml kg}^{-1} \text{m}^{-1}$)	Optimal walking speed (m s^{-1})
5	0.390	20	0.09	1.0
7–10	0.245	28	0.09	1.3
11–13	0.212	37	0.09	1.3
14–16	0.195	60	0.10	1.4
Adult	0.182	70	0.10	1.4

At variance with these data, and in apparent contrast with the above considerations, other studies, all from the same group (Bourdin et al. 1993; Lacour et al. 1990; Padilla et al. 1992) observed a substantial reduction of C_r with increasing body mass (from about 30 to about 80 kg) in basketball players and in long-distance runners, similar to, albeit somewhat larger, than reported in Fig. 5.7. However, the high C_r observed by Bourdin et al. (1993) in their smallest subjects may be due, at least in part, to the fact that these subjects were also the youngest of the investigated group. Indeed, since the C_r in children and adolescents is greater than in adults (Table 5.2), we cannot exclude that the differences reported by these authors be due, at least in part, to the physiological variations of C_r itself with age.

Finally, Thorstensson (1986) showed that, both in adults and in children (10 years of age, 30 kg body mass), C_r decreases by 3–7% when the overall mass is artificially increased by 10% by adding an external load, provided that the added mass is placed

at the level of the body center of mass. On the contrary, as shown by Soule and Goldman (1969), an additional mass on the hands or feet leads to a substantial increase of C_w per unit of overall transported mass (body mass plus added load). The increase of C_w becomes particularly relevant when the additional mass is positioned on the head or in backpacks, as it happens in many African or Alpine populations (Bastien et al. 2005; Lloyd et al. 2011; Maloij et al. 1986).

In this connection, the study of C_w and C_r in children is particularly interesting; indeed, in children, both C_w and C_r are greater than in adults, due to their little size; it decreases with age along the entire childhood, to reach, at puberty, the adult value, which is maintained until old age (Table 5.2). However, the increase of C_r in children is substantially higher than expected from their smaller body mass alone (by 70 to 90% at the age of 5 years). It is therefore possible that the observed increase, or at least a large fraction of it, be due to the biomechanical characteristics typical of the pre-pubertal age, e.g., as concerns the relative size of the limbs, as compared to the whole body, and/or to the different elastic characteristics of the muscle tendon complex. A school backpack on children's shoulders increased C_w by about 7% (Merati et al. 2001), which appears in line with the observations on adults who carried additional loads far from the body center of mass (Maloij et al. 1986; Soule and Goldman 1969).

To conclude this section, we note that Askew et al. (2011) showed that wearing medieval armors, the weight of which was on the order of 30–50 kg, led to an increase of C_w or C_r of about 1.9-to-2.3 times, as compared to “free” locomotion at the same speed. And this, without considering that a tight armor may also generate lung and chest wall restriction, with reduction of total lung capacity, inspiratory flow limitation and acute hypoventilation. It does not seem appropriate to open here a chapter on the “Physiology of History”; nevertheless it is interesting to consider whether and to what extent this enormous metabolic extra-load (for warriors and horses alike!) may have influenced the final outcome of the battles and wars, and hence of the history, of medieval times.

5.5 The Biomechanics of Walking and Running

5.5.1 *Definitions; Efficiency of Locomotion, Internal Work and External Work*

The quantitative assessment of the mechanical work performed, either absolute or per unit of distance, is often rather complicated. In all forms of locomotion, a fraction of the overall mechanical work is not utilized against external forces, nor does it lead to any changes in the position of the body center of mass in the vertical or horizontal plane (e.g., when an upper or lower limb is projected forward and the other symmetrically backwards). This fraction of the overall mechanical work, generally defined internal work (w_i), can only be assessed by means of graphical (video)

analyses. Moreover, w_i includes the mechanical work of breathing and of the heart pump. The remaining fraction of mechanical work, called external work (w_e), can be determined not only by means of graphical (video) analyses, but also by means of traditional ergometric approaches and/or by means of force platforms (Cavagna 1975). Obviously enough, the overall mechanical work performed (w_{tot}) by the subject is the sum of internal and external work:

$$w_{tot} = w_i + w_e \quad (5.11)$$

This section is devoted to an analysis of w_i and w_e , and hence of w_{tot} , as a function of the speed during natural walking and running, based essentially on the data reported in a remarkable series of studies by Cavagna and co-workers that followed two seminal papers by Cavagna, Saibene, and Margaria (Cavagna et al. 1963, 1964). These papers initiated a glorious, long-lasting, highly influential scientific line of the School of Milano, the flag of which is still carried by Alberto Minetti, Paola Zamparo and their collaborators.

5.5.2 *Walking and Running on Earth*

In these two forms of locomotion, the center of mass of the body is lifted and lowered in the vertical plane, and accelerated and decelerated in respect to the average speed in the horizontal plane, throughout each stride. In this section, we consider only walking or running on flat terrain and at constant speed, in which case the lifting and lowering of the center of mass, as well as the acceleration and deceleration within each stride are equal in absolute terms.

At any given time instant, the total energy of the center of mass in motion is given by the sum of the changes (Δ) in kinetic energy (E_k) and in potential energy (E_p) (thus, ΔE_k and ΔE_p , respectively), in respect to a pre-defined reference value. If, in any given phase of the stride, the overall energy increases, we state, by definition, that w_e has been performed by the muscles on the center of mass. On the contrary, if the overall energy decreases, the system or parts thereof have absorbed external work; in this case we state, somewhat loosely, that the muscles have done negative w_e . Hence, the overall w_e performed at each stride can be expressed by (Cavagna 1969):

$$w_e = \Delta E_p + \Delta E_k \quad (5.12)$$

As such, w_e takes into account the work performed against gravitational and inertial forces, as well as that performed against the air resistance. Indeed, at each stride, the deceleration in the forward direction is greater, the greater the air resistance; as a consequence, at constant average speed the greater must also be the

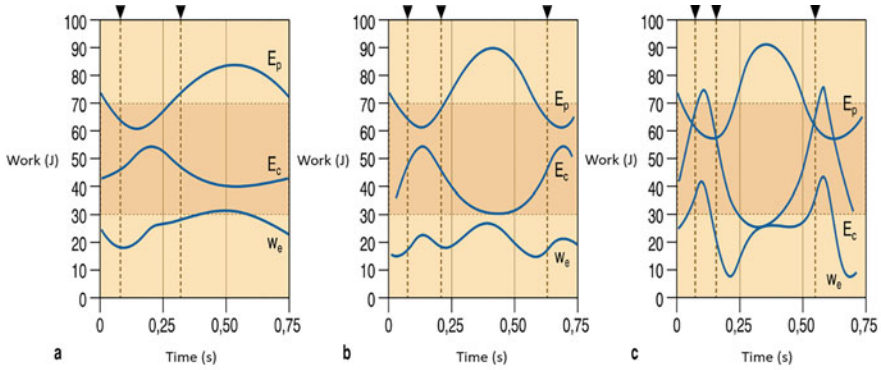


Fig. 5.8 Potential (E_p) and kinetic (E_c in the Figure, E_k in the text) energy (in J) of the body center of mass as a function of time (s) during walking at 0.9, (a) 1.4, (b) and 2.2, (c) m s^{-1} . At any given time during the stride cycle, the external work (w_e) is the sum $\Delta E_p + \Delta E_k$ (Eq. 5.12). The instant at which one foot touches the ground is indicated by the first arrow (and vertical dotted line); that at which the other foot is lifted above the ground is indicated by the second arrow (and vertical dotted line). Modified after Cavagna et al. 1963, Figure taken from di Prampero 2015 with the kind permission of Raffaello Grandi, Edi Ermes

subsequent acceleration, thus leading to an increased value of ΔE_k , and hence of w_e at each stride.

As mentioned above, after a given number of strides on flat terrain, the overall net external work is nil, since positive and negative work are equal in absolute terms. However, this is strictly true only if the air resistance is neglected; nevertheless, at the speeds prevailing in natural walking, the air resistance is so small, that its effects can indeed be neglected.

During natural walking, the center of mass is lifted in the initial phase of the stride, in which its E_p increases at the expense of the simultaneous decrease of E_k due to decreased forward velocity: hence, in this phase, ΔE_p is positive, whereas ΔE_k is negative. The so accumulated E_p is utilized in the immediately following phase to increase the forward velocity of the body: hence, in this second phase, ΔE_p is negative, whereas ΔE_k is positive.

In 1963 Cavagna, Saibene, and Margaria did show that, at v_{opt} , the E_p reaches its maximum almost at the very moment at which E_k attains its minimum and vice-versa (Fig. 5.8). Hence, the biomechanics of walking is characterized by pendulum-like energy exchanges, as in an inverted oscillating pendulum, or in an egg rolling on its major axis. In fact, in an oscillating pendulum, E_p attains its maximum when the sphere is at its highest position and stops (E_k is nil). This occurs at the two extremes of the trajectory of the pendulum, when the sphere is still, or when the major axis of the egg is vertical. On the opposite side, at the lowest point of the trajectory, the translational velocity is maximal (maximal E_k) and the E_p attains its minimum (lowest position of the sphere) (Fig. 5.9).

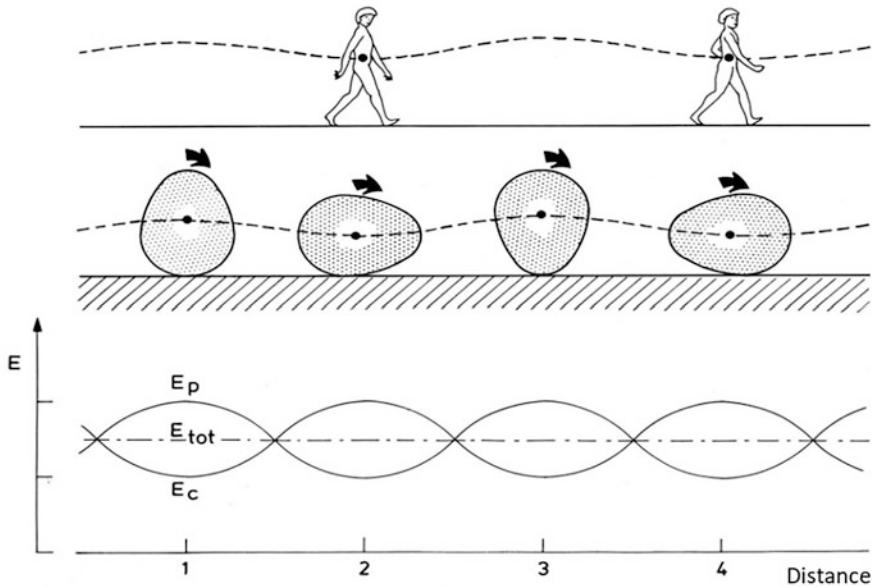


Fig. 5.9 Schematic representation of the potential, kinetic, and total energy (E_p , E_k and E_{tot} , respectively, arbitrary units) of the body center of mass as a function of the distance (arbitrary units) during walking. An egg rolling on its major axis represents a simplified model of walking at the optimal speed. In the rolling egg, as well as in walking, E_p attains a maximum when the center of mass reaches the highest point of its trajectory; at this same instant, E_k attains a minimum. In the absence of any frictional forces, as in an ideal pendulum, E_{tot} (as given by the sum of E_p and E_k) is constant, and the egg, once set in motion, would keep rolling forever thanks to the transformation of one energy form into the other. Redrawn after di Prampero 2015

In an oscillating pendulum, the curves of E_p and E_k are in perfect opposition of phase and of identical amplitude. Thus, in vacuo, were it possible to reduce the friction to zero, the total energy (sum of E_p and E_k) would be constant, so that an ideal pendulum would oscillate *in aeternum*. Obviously enough, this is not the case in natural walking, wherein ΔE_p and ΔE_k do not completely compensate each other, in so far as the respective curves are slightly out of phase and not perfectly symmetrical (Fig. 5.8). Therefore, the overall energy, as given by the sum of E_p and E_k , would decrease at each stride, were it not for the appropriate muscle work, performed on the center of mass, which is equal to the algebraic sum of the two curves. Hence, the w_e in natural walking depends on the absolute values of ΔE_p and ΔE_k , indicating the total w_e , as well as on the respective phase of the two curves (Fig. 5.8), indicating how much of the total w_e comes from the transformation of E_k into E_p and vice-versa. The difference between these two values is equal to the amount of energy that muscle contraction must add to keep w_e , and thus the average forward speed, constant. We define this extra-energy as w_m .

To express quantitatively this state of affairs, Cavagna et al. (1976) proposed to evaluate the efficacy of the transformation of E_k into E_p and vice-versa, which they defined Recovery, as follows:

$$Recovery = \frac{|\Delta E_p| + |\Delta E_k| - |w_m|}{|\Delta E_p| + |\Delta E_k|} \quad (5.13)$$

where the symbol $|$ indicates that the quantities are expressed in absolute values, regardless of the sign, positive, or negative. Eq. 5.13 shows that, were $w_m = 0$, as for an ideal pendulum in vacuo, the Recovery would attain 100%. At the other extreme, were $w_m = |\Delta E_p| + |\Delta E_k|$, the Recovery would be nil. As shown below, in running, ΔE_p and ΔE_k are essentially in phase, so that the Recovery is practically nil, whereas for natural walking the Recovery is about 0.65 at v_{opt} , being smaller above or below it (Fig. 5.10). As described above, the C_w on flat terrain attains a minimum at a speed of about 1.1–1.4 m s⁻¹ (v_{opt} , Figure 5.3a). Indeed, the two curves depicting the evolution of E_k and E_p (Fig. 5.8) are very nearly equal in amplitude and most closely in opposition of phase at v_{opt} . Hence w_m is at its minimum, whereas at greater or smaller speeds the two curves depicting E_k and E_p shift, one in respect to the other, and the more so the farther from v_{opt} (Fig. 5.8), thus leading to a progressively higher w_m and hence C_w than at v_{opt} . The relationship between Recovery and speed reported in Fig. 5.10 was obtained on young adults of average body size. However, in order to eliminate the effects of inter-individual differences, it can be normalized, expressing the speed itself as a function of the subjects' size. To this aim, we can use the theory of dynamic similarity, allowing a comparison of the behavior of objects of different size, the motion of which depends on the cyclic transformation of E_p into E_k and vice-versa, as typically happens in natural walking (Alexander 1989; McMahon and Tyler Bonner 1983). According to this theory, two geometrically similar objects of different size behave similarly when they move at the same Froude number (Fr):

$$Fr = \frac{v^2}{Lg} \quad (5.14)$$

where L is the length of a relevant body segment (the lower limb in this specific instance). The Froude number, so defined in honor of the naval engineer William Froude (1810–1879), who utilized it to infer the characteristics of actual ships as obtained from small-size models, is a non-dimensional quantity, corresponding to the ratio of E_k to E_p .

When the Recovery is expressed as a function of Fr , the resulting relationship is substantially equal for children (aged 1 to 12 years), normal-size adults, hypophysarian dwarves and pygmies (Cavagna et al. 1983; Minetti et al. 1994c, 2000). In all these subjects, the Recovery attains a maximum on the order of 0.70 for $Fr \approx 0.25$ (Saibene and Minetti 2003). In addition, since v_{opt} corresponds to the speed at which the Recovery attains its maximum (Fig. 5.10), and, as mentioned above, this occurs at $Fr \approx 0.25$, we can write:

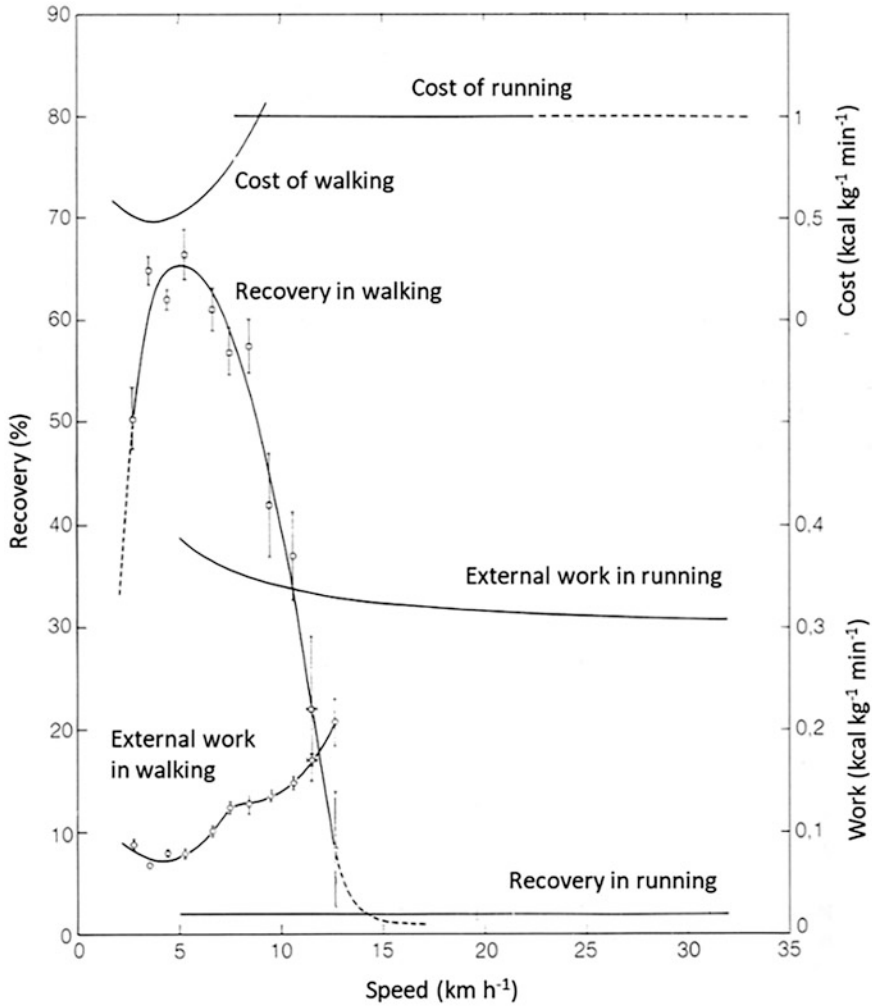


Fig. 5.10 Energy Recovery (see Eq. 5.13), external work and energy cost as a function of the speed in walking and running. From Cavagna 1988

$$\frac{v_{opt}^2}{Lg} = 0.25 \tag{5.15}$$

whence

$$v_{opt} = 0.5 \sqrt{Lg} \tag{5.16}$$

Assuming $L = 0.9$ m (average lower limb length of adult males), Eq. 5.16 yields $v_{opt} = 1.49$ m s⁻¹ (5,36 km h⁻¹), close to the value reported in Figure 5.3a. However,

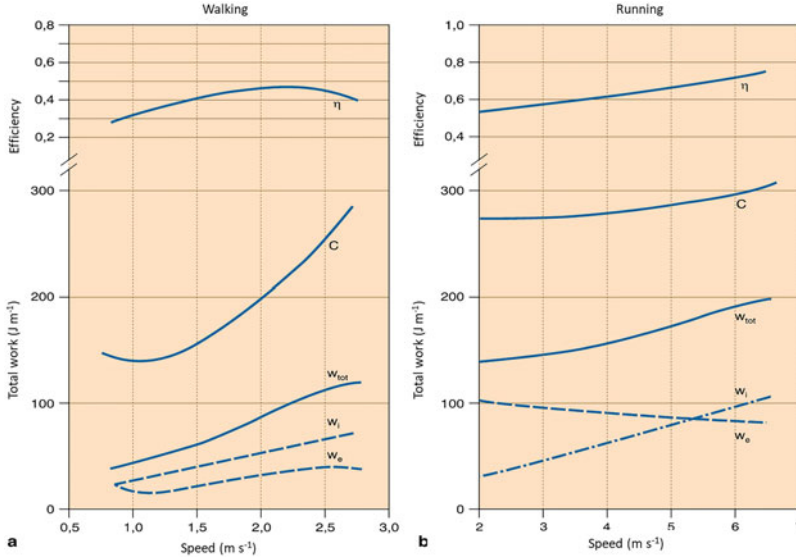


Fig. 5.11 Total mechanical work expressed per unit of distance (w_{tot}), external work (w_e), internal work (w_i), energy cost (C) and mechanical efficiency ($\eta = w_{tot} C^{-1}$) during walking (a) and running (b) on flat terrain as a function of the speed for a 70 kg subject. From di Prampero 2015; data of w_{tot} , w_e and w_i are from Cavagna and Kaneko 1977 and Cavagna et al. 1977; C is from di Prampero 1986. With the kind permission of Raffaello Grandi, Edi Ermes

for children below the age of 6, the v_{opt} value obtained from Eq. 5.16 is larger than the actually determined one. Indeed, for 3-years old children and $L \approx 0.45$ m (for a stature of ≈ 0.95 m), theoretical v_{opt} (1.06 m s^{-1}) is about 40% larger than the experimental one (0.75 m s^{-1} , Cavagna et al. 1983). This suggests that children below age 6 may not be dynamically similar to adult humans.

Cavagna and Kaneko (1977) and Cavagna et al. (1977) analyzed in detail E_p , E_k (and hence w_e , see Eq. 5.11), as well as w_i , during walking and running on the level. The so obtained data, summarized in Fig. 5.11, show that, in walking, w_{tot} increases with v :

$$w_{tot} = w_e + w_i = 0.07 + 0.6 v \quad (5.17)$$

where w_{tot} , w_e and w_i are expressed in $\text{J kg}^{-1} \text{ m}^{-1}$ and v in m s^{-1} .

Since C_w as a function of v is known, Eq. 5.17 allows a calculation of η , as the ratio between w_{tot} and C_w (see Sect. 5.5.1). As shown in Figure 5.11a, η attains a maximal value of about 0.48 in a range of speeds between 2 and 2.5 m s^{-1} . This value is greater than that observed during isotonic muscular contractions (≈ 0.25). As v is increased, the Recovery diminishes: at the speed of spontaneous transition between walking and running, it is about 0.50, and therefore, η is slightly lower than at v_{opt} (0.40 instead of 0.48).

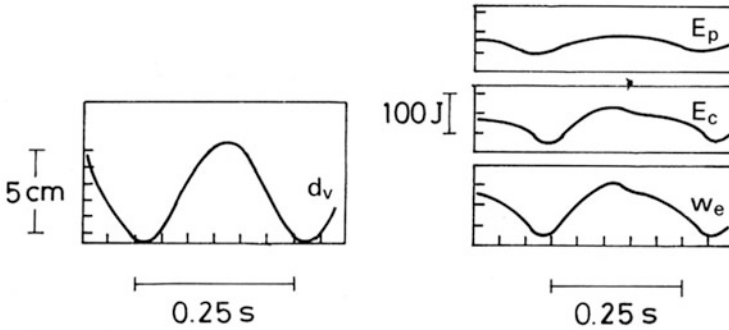


Fig. 5.12 Potential (E_p) and kinetic (E_c in the Figure, E_k in the text) energy, external work (w_e , J) and vertical displacement of the body center of mass (d_v , cm) as a function of time during running at 5.56 m s^{-1} . From Cavagna et al. 1964

When running on the level, at the onset of each stride the body center of mass is projected upwards and forwards by the muscle activity of the “pushing” limb. In the subsequent phase, after a brief time interval in which both feet are off the ground, the center of mass is lowered and decelerated, thanks to the muscle action of the “braking” limb. At the onset of the subsequent stride, the “braking” limb becomes the “pushing” limb. It follows that ΔE_p and ΔE_k are always in phase (Fig. 5.12). Hence, at variance with walking, the E_p accumulated in the initial phase of the stride cannot be used to accelerate the body forward in the subsequent phase: no transformation of one type of energy into the other is possible, and the Recovery, as described by Eq. 5.13, is always nil (see Fig. 5.10).

Also in running, as in walking, w_e is the sum of ΔE_p and ΔE_k (Eq. 5.12). However, since in running ΔE_p and ΔE_k are always in phase, at the onset of the stride, w_e has a large positive value, to reach an equally large negative value at the end of the same stride. Therefore, the active muscles must consume energy in the initial phase of the stride (push phase) to perform positive work, as well as in the final phase (braking phase) to absorb negative work. In the latter phase, a fraction of the negative work is stored in the series elastic elements of the contracting muscles.⁴ The so accumulated elastic energy is utilized in the subsequent rebounding phase, when the absorbing limb becomes the pushing one. This leads to a substantial economy of metabolic energy, as shown by the high values of η observed in running (see Figure 5.11b). Hence, the biomechanics of running is similar to the bouncing of a rubber ball on the terrain. When the ball hits the ground, it is initially compressed, because of the simultaneous decrease of E_p and E_k , leading to a large negative value of w_e ; in this phase, however, the decrease of w_e is partly counterbalanced by an increase of the energy stored in the elastic structures of the ball itself. In the following phase, this elastic energy is released with a simultaneous increase of both E_p and E_k (Fig. 5.13), allowing the ball to rebound. Cavagna et al. (1968) demonstrated a similar

⁴About 30% of the overall elastic energy is stored and released by the elastic structures of the arch of the foot (Ker et al. 1987).

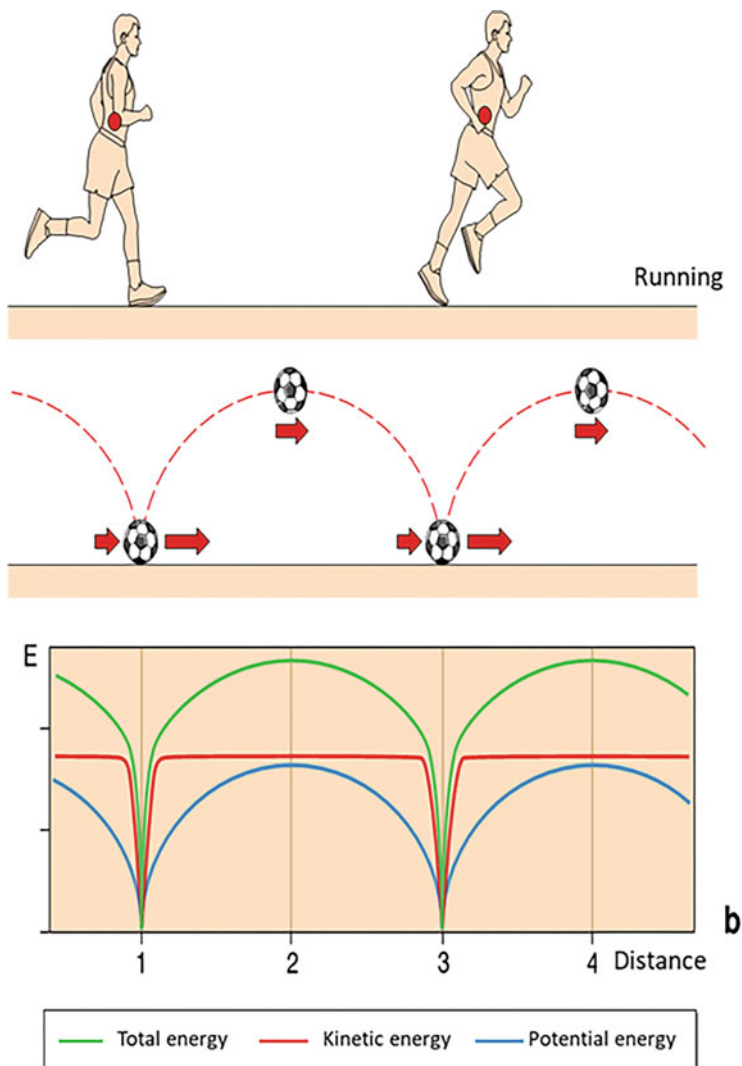


Fig. 5.13 A ball bouncing on the terrain represents a simplified model of running. When the ball hits the ground, the potential and kinetic energy attain simultaneously a minimum value and, for a very short time, the ball is motionless at the lowest point of its trajectory. In this phase, a fraction of the total energy is stored in the elastic structure of the ball itself; it is recovered in the immediately subsequent rebound phase, with a simultaneous increase of both potential and kinetic energy. In running, as well as in a bouncing ball, there cannot occur any transformation of potential into kinetic energy or vice-versa; however, the recovery of elastic energy in the rebound phase is a substantial “energy-sparing” mechanism. From di Prampero 2015, with the kind permission of Raffaello Grandi, Edi Ermes

mechanism in isolated muscles, which perform a greater work when they contract immediately after stretching: the elastic elements of muscle release the stored elastic energy at the onset of contraction.

A recovery of elastic energy analogous to that described above for running does occur also in other movements, in which the shortening of the muscle is immediately preceded by its stretching (eccentric contraction). For instance, a series of flexions and extensions of the knees performed without interruption, other things being equal, requires a lesser metabolic energy consumption than the same series of movements performed with a brief pause between flexion and extension. In this latter case, in fact, the elastic energy accumulated in the extensor muscles that during knee bending are forcefully stretched, is dissipated during the pause; hence, the concentric action that follows must be performed entirely at the expense of metabolic energy. As a consequence, the overall mechanical efficiency of the exercise is lower ($\eta = 0,19$) in this latter case, as compared to the same series of movements performed without interruption between flexion and extension ($\eta = 0,26$) (Thys et al. 1972). This shows that the recovery of elastic energy is possible only if the eccentric contraction (stretching of the muscle) is immediately followed by its concentric counterpart (shortening); if this is not the case, the elastic energy is dissipated as heat before the subsequent concentric contraction starts.

w_e and w_i are reported as a function of v during level running in Figure 5.11b (Cavagna and Kaneko 1977). Their sum (w_{tot}) is described by the following empirical equation:

$$w_{tot} = 0.66 v^{-1} + 1.19 + 0.24 v \quad (5.18)$$

where w_{tot} is in $\text{J kg}^{-1} \text{m}^{-1}$ and v in m s^{-1} . The sum of the first two terms of Eq. 5.18 is a measure of w_e , which is essentially independent of speed in physiological human running conditions, since in the velocity range ($2.8\text{--}8.3 \text{ m s}^{-1}$) investigated by Cavagna and Kaneko (1977), it decreases only from 1.43 to $1.27 \text{ J kg}^{-1} \text{m}^{-1}$. On the contrary, w_i , represented by the sum of the second and third terms of Eq. 5.18, increases linearly with v .

Knowledge of w_{tot} and of C_r allows calculation of η for level running: as shown in Figure 5.11b, η increases with v from ≈ 0.5 at $v \approx 2 \text{ m s}^{-1}$ to ≈ 0.7 at $v \approx 6.5 \text{ m s}^{-1}$. These high values of η , substantially larger than the maximal ones observed during purely isotonic muscle contractions, demonstrate that the recovery of elastic energy occurring at each stride in running is larger, the higher the running speed.

The recovery of elastic energy is an extremely useful mechanism for reducing C_r : it occurs to a various extent in several mammalian species (Cavagna et al. 1977), but it reaches an extraordinary extent in kangaroos, which can easily reach speeds of $40\text{--}50 \text{ km h}^{-1}$ ($11\text{--}14 \text{ m s}^{-1}$) that, however, they maintain for short time periods only (Dawson 1977). Indeed, at each bout, the thick tendon of the tail of the kangaroo becomes an effective spring (Alexander and Vernon 1975). Thanks to this “tail effect,” the recovery of elastic energy increases with the speed, so much so, that the $C_n - a$ of “running” (hopping) in this animal species decreases from \approx

$7.5 \text{ J kg}^{-1} \text{ m}^{-1}$ at 2.8 m s^{-1} to $\approx 2.8 \text{ J kg}^{-1} \text{ m}^{-1}$ at 6.4 m s^{-1} . It follows that, in this speed range, the \dot{E} of “running” in the kangaroo is constant, amounting to about 20 W kg^{-1} ($60 \text{ mlO}_2 \text{ kg}^{-1} \text{ min}^{-1}$).

The $\dot{V}O_2^{max}$ of contemporary top-level long-distance runners is $\approx 70 \text{ ml kg}^{-1} \text{ min}^{-1}$ above resting (Tam et al. 2012). Assuming that no recovery of elastic energy occurs during running, and thus $\eta = 0.25$, Eq. 5.18 shows that a hypothetical athlete with these characteristics would attain at $\dot{V}O_2^{max}$ a speed of 2.9 m s^{-1} , and thus would cover the 5.000 m distance in 28 min 44.14 s, as compared to the actual world record of 12 min 35.36 s. This back of the envelope calculation stresses dramatically the great importance of elastic energy recovery at each stride in running humans.

Recognizing the importance of the role of the recovery of elastic energy in setting C_r further highlights, in terms of athletic performances, the roles of training regimes leading to appropriate increases of the maximal muscular power. Indeed, muscle fiber composition and specificity of training do affect muscle performance as well, in so far as training may increase the number of active muscle fibers and lead to the metabolic potentiation of specific fiber types. Hence, since the mechanical characteristics of the various fiber types are diverse, especially in terms of maximal contraction velocity (Bottinelli 2001), it appears reasonable to suggest that the effects on the recovery of elastic energy provided by a training regime based on long-term high-intensity aerobic exercise, may be different from those provided by a training regime based on explosive exercise and force development.

The effects of the recovery of elastic energy on the running economy, and hence on performance, have also been discussed in terms of the potential advantage that artificial metallic prostheses, to be utilized only in competitions, may offer to athletes having undergone mono- or bi-lateral limb amputations. Indeed these prostheses may ameliorate artificially the athlete’s running economy thanks to an increased recovery of elastic energy (as compared to natural running), thus constituting a kind of “mechanical doping.” This line of reasoning led to the exclusion of athletes suffering from this type of handicap from competitions, as was the case of Oskar Pistorius being excluded from the 2008 Olympics in Peking.

5.6 The Spontaneous Transition between Walking and Running

In Sect. 5.5, we underlined that at speeds around 2.2 m s^{-1} , uninformed subjects shift spontaneously from walking to running (or vice-versa, if the speed is decreasing). This speed was defined as the speed of spontaneous transition between walking and running. The traditional interpretation assumes that humans always choose the most economical gait. On this basis, Margaria et al. (1963) hypothesized that at speeds higher than the spontaneous transition speed, C_r started to be lower than C_w , the opposite being the case at speeds below the transition speed.

The spontaneous transition between walking and running does not occur at a fixed speed, but in a speed range between 1.8 and 2.5 m s⁻¹ (Saibene and Minetti 2003). This may depend, at least in part, on the geometric characteristics of the subjects, since the spontaneous transition seems to occur at a speed that is lower, the shorter the limb (Thorstensson and Roberthson 1987).

Minetti et al. (1994b) carried out a systematic analysis of the transition speed during treadmill running. According to them, the speed of spontaneous transition is slightly lower than that at which walking and running have the same C_{n-a} . On this basis, they suggested that the transition may not have an energetic origin only. When passing from walking to running, there is a sudden significant, though small, increase of speed, and the subject suddenly moves at a higher step frequency. So, they proposed a hypothesis involving both mechanical and energetic factors. They plotted C as a function of v after expressing C in Joules per kg per step instead of J kg⁻¹ m⁻¹, as customary. Because of the differences in step frequency in the transition zone, it turned out that the speed of transition was the speed at which both walking and running had the same C per step (see Fig. 5.14). This observation is still partly compatible, although on a slightly different basis, with Margaria's hypothesis.

The question remains as to how a step can be "sensed" such as to determine a gait transition. More favorable patterns of neuromuscular activation during running at the transition speed and a possible mechanical reflex arising from lower limb proprioceptors have been hypothetically evoked (Prilutsky and Gregor 2001; Segers et al. 2013).

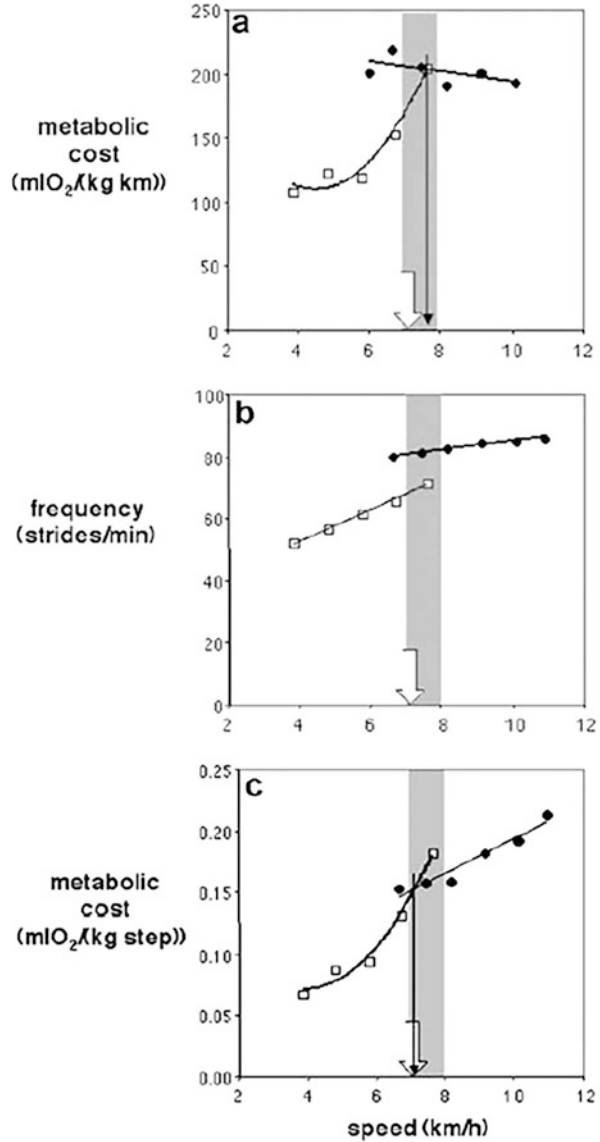
5.7 Sprint Running and the Role of Acceleration

The massive utilization of anaerobic sources and the short duration of sprint running events make any direct measurements of \dot{E} under these conditions rather problematic. So far, the energetics of sprint running has been mainly estimated indirectly from biomechanical analyses (Cavagna et al. 1971; Fenn 1930a, 1930b; Mero et al. 1992; Plamondon and Roy 1984). Otherwise, it was assessed by means of rather indirect procedures (Arsac 2002; Arsac and Locatelli 2002; di Prampero et al. 1993; van Ingen Schenau et al. 1991, 1994; Ward-Smith and Radford 2000).

An alternative approach is to assume that, during the acceleration phase, sprint running on flat terrain is biomechanically equivalent to uphill running at constant speed, the slope being dictated by the forward acceleration, and that, conversely, during the deceleration phase it is biomechanically equivalent to running downhill. Since the energy cost of uphill (downhill) running at constant speed over a fairly large range of inclines is rather well known (Minetti et al. 2002), the energy cost of accelerated (decelerated) running, can be easily estimated once the acceleration (deceleration) is known (di Prampero et al. 2005).

Figure 5.15 (left panel) shows that a runner accelerating on flat terrain leans forward, so that the angle α between the runner's mean body sagittal axis and the

Fig. 5.14 An analysis of the spontaneous transition speed (thick white arrow) between walking (unfilled squares) and running (filled circles). (a) The regression curves of energy cost per unit distance, intersect at a higher speed (thin arrow) than the spontaneous one. (b) Differences in stride frequency between walking and running are shown. (c) The energy cost is expressed per step, instead of per meter. In this case, the intersection between regression curves occurs at the same speed as for spontaneous transition. The grey area depicts the speed range at which humans may either walk or run. From Saibene and Minetti 2003; data from Minetti et al. 1994b



terrain (average throughout a whole stride) is smaller the greater the forward acceleration (a_f). Thus, this state of affairs is analogous to running uphill at constant speed, provided that α is unchanged (Fig. 5.15, right panel). It necessarily follows that the complement of α , i.e., the angle between the terrain and the horizontal plane ($90 - \alpha$), increases with a_f when running on flat terrain, or with the incline of the terrain when running uphill at constant speed.

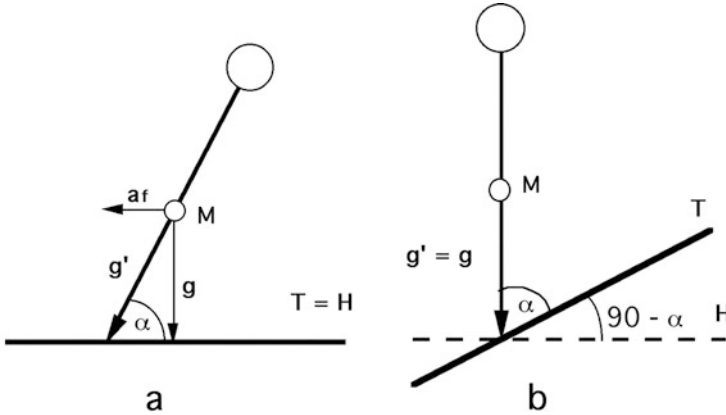


Fig. 5.15 The subject is accelerating forward while running on flat terrain (a), or is running uphill at constant speed (b). M , subject's body mass; a_f , forward acceleration; g , acceleration of gravity; $g' = \sqrt{a_f^2 + g^2}$, vectorial sum of a_f plus g ; T, terrain; H, horizontal; α , angle between the runner's mean body axis throughout the stride and T; $90 - \alpha$, angle between T and H. Note that, in this representation, the angle $90 - \alpha$ corresponds to the angle β of Eqs. 5.9 and 5.10, and in the footnote 3. See text for details. Modified after di Prampero et al. 2015

The incline of the terrain (i , see also Eq. 5.9) is generally expressed as the tangent of $90 - \alpha$ (β in Eq. 5.9). During accelerated running on flat terrain, i is equivalent to the ratio between a_f and g (Fig. 5.15, left panel):

$$i = \tan(90 - \alpha) = \frac{a_f}{g} = \text{ES} \tag{5.19}$$

Hence, the ratio a_f/g yields the tangent $90 - \alpha$, which makes accelerated running on flat terrain biomechanically equivalent to running at constant speed up to a corresponding slope (Fig. 5.15, right panel), defined as equivalent slope (ES).

Inspection of Fig. 5.15 also shows that accelerated running is characterized by yet another difference, as compared to constant speed running. Indeed, the acceleration, which the runner undergoes along the vertical axis of his/her body (g'), is greater than g , corresponding to the vectorial sum of a_f and g , which is equal to:

$$g' = \sqrt{a_f^2 + g^2} \tag{5.20}$$

It follows that the force that the runner must develop (average throughout a whole stride), as given by the product of the body mass and the acceleration, is greater in accelerated running ($= M g'$) as compared to constant speed running ($= M g$), because $g' > g$ (Fig. 5.15, left panel). Thus, accelerated running is equivalent to uphill running wherein, however, the body weight is increased in direct proportion to

the ratio g'/g . Because of Eq. 5.20, this ratio, defined “equivalent body mass” (EM), is described by:

$$EM = \frac{M g'}{M g} = \frac{\sqrt{a_f^2 + g^2}}{g} = \sqrt{\frac{a_f^2}{g^2} + 1} \quad (5.21)$$

Substituting Eq. 5.19 into Eq. 5.21, one obtains:

$$EM = \sqrt{\frac{a_f^2}{g^2} + 1} = \sqrt{ES^2 + 1} \quad (5.22)$$

It must also be pointed out that during decelerated running, which is equivalent to downhill running, and in which case ES is negative, EM assumes nevertheless a positive value, because ES in Eq. 5.22 is raised to the square.

In conclusion, if the time course of v during accelerated/decelerated running is determined, and the corresponding instantaneous accelerations/decelerations are calculated, Eqs. 5.19 and 5.22 allow computation of the appropriate ES and EM values, thus converting accelerated/decelerated running on flat terrain into the equivalent constant speed uphill/downhill running. Hence, if C_r at constant speed at any incline is known, the corresponding energy cost of accelerated/decelerated running can be easily obtained.

On these premises, the empirical equation described by Minetti et al. (2002) (current Eq. 5.9) can be used to compute the energy cost of running during acceleration/deceleration (C_{acc}), by substituting ES for i , denoting the energy cost of constant speed level running as C_r , and multiplying then the entire equation by EM:

$$C_{acc} = EM(155.4 ES^5 - 30.4 ES^4 - 43.3 ES^3 + 46.3 ES^2 + 19.5 ES + C_r) \quad (5.23)$$

In Eq. 5.19, only the forward acceleration is accounted for, whereas the effect of the air resistance is neglected. Therefore, only the non-aerodynamic component of ES (ES_{n-a}) is considered, as would be the case in treadmill running, so that $ES = ES_{n-a}$. To overcome the air resistance, the runner must lean forward more than indicated in Fig. 5.15 during running on a track, thus reducing angle α and increasing the ES by an amount, due to the air drag (aerodynamic ES, ES_a), which is equal to:

$$ES_a = \frac{k_w v^2}{g} \quad (5.24)$$

where v is the instantaneous velocity and k_w is the same constant as in Eqs. 5.5, however expressed per unit of body mass. Hence, the overall ES, as set by both a_f and the air velocity, i.e., by the sum of ES_{n-a} and ES_a , is given by:

$$ES = ES_{n-a} + ES_a = \frac{a_f}{g} + \frac{k_w v^2}{g} \quad (5.25)$$

Equation 5.25 tells that during accelerated running, the air resistance leads to an increase of ES, whereas the opposite is true in decelerated running, in which case a_f is negative.

The effects of the air resistance are rather minor, as compared to those due to the forward acceleration: indeed, assuming k_w (per unit of body mass) $\approx 0.0037 \text{ m}^{-1}$, in the range of speeds between 2 and $10 \text{ m}\cdot\text{s}^{-1}$, ES_a ranges from 0.15 to 3.8%. This is coherent with the usual practice of simulating the air resistance, when running on the treadmill at speeds of $5.55 \text{ m}\cdot\text{s}^{-1}$, by inclining it upwards by about 1%.

In conclusion, if the time course of velocity during accelerated/decelerated running is determined, and the corresponding instantaneous accelerations/decelerations are calculated, Eqs. 5.25 and 5.22 allow computation of the appropriate ES and EM values. Accelerated or decelerated running can then be easily converted into equivalent constant speed uphill or downhill running. Hence, the corresponding energy cost of accelerated/decelerated running can be obtained.

It should be noted here that the effects of the acceleration on C_r can be astonishingly high. Indeed, at the very onset of a 100 m dash, in medium-level sprinters, C_r attains about $50 \text{ J kg}^{-1} \text{ m}^{-1}$, as compared to about $4 \text{ J kg}^{-1} \text{ m}^{-1}$ for constant speed running on flat terrain (di Prampero et al. 2005). Furthermore, knowledge of C_r allows calculation of the corresponding metabolic power, as given by the instantaneous product of C_r and v . In medium-level sprinters, this attains a peak of about 80 W kg^{-1} , equivalent to an oxygen consumption of $230 \text{ ml kg}^{-1} \text{ min}^{-1}$ above resting, i.e., about four times larger than the $\dot{V}O_2^{max}$ of the investigated subjects.

Similar calculations can be made also on Usain Bolt during his 100 meters dash world record (9.58 s). However, because of his astonishingly high initial a_f , his ES falls largely outside the range of application of Eq. 5.9. Depending on how extrapolation of Eq. 5.9 is performed, the peak metabolic power, attained about 0.8 s after the start, may result as high as 160 W kg^{-1} (di Prampero et al. 2015).

5.8 Conclusions

Walking and running are natural forms of bipedal locomotion, as trotting galloping and ambling are natural forms of quadrupedal locomotion. There are more locomotion paradigms in quadrupedal than in bipedal locomotion, and their analogies were investigated by Alberto Minetti (Minetti 1998). Walking is characterized by the exchanges between E_k and E_p at each step in both cases. Running is an analogue of

trotting, both being characterized by storage and release of elastic energy at each step, whereas E_k and E_p vary in phase, so that no exchanges between these two forms of energy are possible indeed. Minetti (1998) proposed that skipping gaits are analogues of galloping and represent the third paradigm of bipedal locomotion. In fact, the simultaneous presence of pendulum-like and elastic mechanisms in skipping differentiates this gait from running. Gravity may matter in determining the predominance of skipping on other gaits, as long as skipping becomes the “natural” form of locomotion in low-gravity environments such as the Moon (Pavei et al. 2015), as originally suggested by Margaria and Cavagna (1964), well before the first manned flight to the Moon in 1969 (see Chap. 11).

The role of the School of Milano in the history of the physiology of locomotion is central. It sounds logical that scientists interested in exercise be attracted by the energetics and biomechanics of human locomotion. Yet few combined the two issues, exercise and locomotion, within the same cultural framework, and none in a systematic, programmatic manner as Margaria did. This is a further feature characterizing the exceptional, farseeing vision of Margaria. Along the groove traced initially by Marey and Muybridge, then by Fenn, Margaria started the study of the energetics and promoted the study of the biomechanics of human locomotion. Cavagna and Saibene in the latter, Cerretelli and di Prampero in the former took the relay. Cavagna generated a vassal kingdom at Leuven, Belgium, with Norman Heglund, Peter Willems and their successors; Saibene trained Minetti, who carries the flag of locomotion in Milano. Cerretelli and di Prampero left a patrol of scientific heirs (Carlo Capelli, Guido Ferretti, Bruno Grassi, Paola Zamparo) who ensures scientific continuity to the study of the energetics of muscular exercise and of human locomotion within the cultural framework of the School of Milano. No other School can compete in terms of impact, continuity and longevity with the School of Milano, as far as the study of the energetics and biomechanics of human locomotion is concerned.

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