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The energy cost of walking or running on sand

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Summary. Oxygen uptake ($\dot{V}O_2$) at steady state, heart rate and perceived exertion were determined on nine subjects (six men and three women) while walking (3–7 km·h^{-1}) or running (7–14 km·h^{-1}) on sand or on a firm surface. The women performed the walking tests only. The energy cost of locomotion per unit of distance (*C*) was then calculated from the ratio of $\dot{V}O_2$ to speed and expressed in J·kg^{-1}·m^{-1} assuming an energy equivalent of 20.9 J·ml O$_2^{-1}$. At the highest speeds *C* was adjusted for the measured lactate contribution (which ranged from approximately 2% to approximately 11% of the total). It was found that, when walking on sand, *C* increased linearly with speed from 3.1 J·kg^{-1}·m^{-1} at 3 km·h^{-1} to 5.5 J·kg^{-1}·m^{-1} at 7 km·h^{-1}, whereas on a firm surface *C* attained a minimum of 2.3 J·kg^{-1}·m^{-1} at 4.5 km·h^{-1} being greater at lower or higher speeds. On average, when walking at speeds greater than 3 km·h^{-1}, *C* was about 1.8 times greater on sand than on compact terrain. When running on sand *C* was approximately independent of the speed, amounting to 5.3 J·kg^{-1}·m^{-1}, i.e. about 1.2 times greater than on compact terrain. These findings could be attributed to a reduced recovery of potential and kinetic energy at each stride when walking on sand (approximately 45% to be compared to approximately 65% on a firm surface) and to a reduced recovery of elastic energy when running on sand.

Key words: Sand – Energy cost – Walking – Running – Perceived exertion

Introduction

The energy expenditure during walking or running on the level, uphill or downhill, carrying loads or on irregular terrain has been thoroughly investigated (Bobbert 1960; Givoni and Goldman 1971; Hughes and Goldman 1970; MacMahon and Green 1979; Soule and Goldman 1972). Relatively little is known, however, about the energetics of walking or running on sand, under which conditions the mechanics of both these forms of locomotion are presumably markedly affected. Indeed, the extensive investigations of Cavagna and coworkers (Cavagna et al. 1976, 1977; Cavagna and Kaneko 1977), and by others (Margaria et al. 1963; Kaneko 1990), have shown that when walking on the level at constant speed (*v*), at each stride a substantial interchange between kinetic (E_k) and potential energy (E_p) (and vice versa) takes place. In contrast to walking, during running on the level at constant *v* no interchange between E_k and E_p can occur; in running, however, a remarkable recovery of elastic energy (E_e) takes place at each stride. Both these mechanisms, that lead to a substantial reduction of metabolic energy expenditure, are very likely to be reduced when walking or running on sand. Under these conditions therefore, the energy cost of these two forms of locomotion can be expected to be larger than on firm surfaces.

The present investigation examined the metabolic cost of running and walking per unit of distance, on sand and compared the results to those obtained on firm surfaces.

Methods

Subjects and protocol. The energy cost of walking per unit of distance (C_w) and running (C_r), on sand or on firm surfaces was determined on nine subjects (six men and three women) whose anthropometric characteristics are given in Table 1. The selected *v* ranged from 3 to 7 km·h^{-1} when walking and from 7 to 14 km·h^{-1} when running (the women performed the walking tests only).

The following parameters were measured: cardiac frequency, oxygen consumption ($\dot{V}O_2$), venous blood lactate concentration ([la$^-$]$_b$) and ratings of perceived exertion (RPE).

Experimental procedure. The subjects walked or ran at constant *v* on approximately oval shaped paths of 200-m length on a sandy beach or on the firm ground of a nearby camp site at Belvedere (about 40 km south of Udine, Italy). The *v* was set by acoustic

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Table 1. Anthropometric characteristics of the subjects. Percentage fat was obtained according to Durnin and Womersley (1974) from the triceps, biceps, suprailliac and subscapular skinfold thicknesses

	Age (years)	Body mass (kg)	% Fat
Men			
Mean	30.0	75.7	17.4
SD	4.5	11.4	4.2
n	6	6	5
Women			
Mean	25	68.3	32.8
SD	1.7	1.5	2.3
n	3	3	3

signals (Balise Temporelle, Baumann CEM, Fleurier, Switzerland) whose frequency was such that, whether walking or running at the appropriate v, at each signal the subject was passing equally spaced (10 or 20 m) markers.

The expired air was collected, by means of standard light weight respiratory valves and hoses (4.0-cm internal diameter), in a 100-l rubber bag placed on the subjects shoulders. A three-way valve operating a stopwatch allowed the expired air to be collected into the bag for known periods of time. At each v the collection of expired air was started after about 4 min, at which time the subject, upon a vocal signal from the experimenter, turned the three-way valve and started the gas collection. When the bag was full, as judged by the experimenter, and upon a second vocal signal, the subject ended the air collection by operating again the three-way valve. The expired air collection times ranged from 40 to 75 s.

Metabolic measurements. The volume of the expired gas was determined by means of a dry gas meter (MC-6, S.I.M. Brunt, Milan, Italy) and the corresponding O_2 and CO_2 fractions assessed by a previously calibrated paramagnetic O_2 meter (Oxynos 1-C, Leybold Heraeus, Zurich, Switzerland) and an infrared CO_2 meter (Binos 1, Leybold Heraeus, Hanau, FRG). The $\dot{V}O_2$ and CO_2 production [standard temperature and pressure (dry)] were then determined according to standard open circuit procedures.

The cardiac frequency was continuously recorded during the test (portable cardiometer Baumann CEM) and was plotted off line after exercise was over (Brother M-1109, interface and printer, Baumann CEM).

The $[la^-]_b$ was determined by an enzymatic method (Henry 1968) in blood samples from the antecubital vein obtained at rest and between the 5th and 7th min after the highest walking v or after the two highest running v under which conditions, as judged by the individual's heart rate and $\dot{V}O_2$ values, lactate production was likely.

The water content of the sand was determined by weighing a given amount of it before and after 4 h in a dessicator at 150° C (four samples per day were collected during the tests). The loss of mass ranged from 0.64% to 4.88% and amounted on average to 3.3% on the 1st experimental day and to 0.88% on the 2nd. This difference had no effect on the data collected during the 2 days; so it has not been taken into account in the results and discussion.

The RPE were assessed after each running test using the CR-20 ratio scale (Borg et al. 1985). This was represented graphically on a sheet of paper on which 20 horizontal lines were drawn. The separation between the lines became progressively smaller from 0 to 20 (i.e. from the bottom to the top of the sheet). Eight verbal expression, from "nothing at all" to "extremely hard" were marked in juxtaposition to the appropriate lines (e.g. line 3 = moderate; line 6 = hard; line 12 = very hard), as proposed by Borg et al. (1987). The subjects were asked to mark the position corresponding to their perceived exertion. A written instruction for the use of this scale was given before the test (Noble et al. 1973).

The C_w or C_r was determined from the ratio of steady-state $\dot{V}O_2$ (above resting, assumed for all subjects as equal to $4\ \mathrm{ml \cdot min^{-1} \cdot kg^{-1}}$) to v:

$$C_w \text{ or } C_r = \frac{\dot{V}O_2}{v} \tag{1}$$

C_w or C_r were then expressed in $\mathrm{J \cdot m^{-1} \cdot kg^{-1}}$ on the assumption that 1 ml O_2 consumed in the human body yields 20.9 J (which is strictly true only if the respiratory quotient equals 0.96).

The anaerobic contribution to the total energy cost due to lactate accumulation in blood, was calculated as follows. The net increase of $[la^-]_b$ was obtained subtracting the rest value from the peak attained in the recovery phase after the highest walking or running v. The energy value of $\Delta[la^-]_b$ was obtained assuming an equivalence of $3\ \mathrm{ml\ O_2 \cdot mmol^{-1} \cdot l \cdot kg^{-1}}$ (di Prampero 1981); it ranged from 2.6 to $29.7\ \mathrm{ml\ O_2 \cdot kg^{-1}}$ [mean 14 (SD 8.7), $n = 10$]. The total C_r and C_w above resting was then determined dividing the energy value of $\Delta[la^-]_b$ by the overall distance covered and adding it to the aerobic energy cost. At the highest v the lactate contribution was on average about 7% of the total energy cost and ranged from approximately 2% to approximately 7% in walking and from about approximately 7% to approximately 12% in running.

Results

Under all experimental conditions, the $\dot{V}O_2$ ($\mathrm{ml \cdot min^{-1} \cdot kg^{-1}}$) increased with the v and was substantially higher on sand than on firm ground. The relationships between $\dot{V}O_2$ and v were linear in running (under both experimental conditions) and in walking on sand. On firm surfaces, as found previously by others, the increase of $\dot{V}O_2$ per unit v was larger at higher walking v. Consistent with $\dot{V}O_2$ the heart rate also increased almost linearly with v, and was higher on sand.

The net C_w, when expressed per kg body mass, was essentially equal in men and women both on sand and on firm ground. All data were therefore pooled and plotted as shown in Fig. 1 as a function of v. On firm ground the individual values can be interpolated by a U

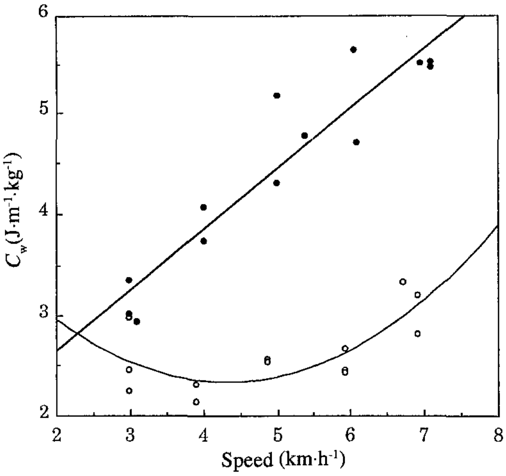

Fig. 1. Net (above resting) energy cost of walking (C_w, $\mathrm{J \cdot m^{-1} \cdot kg^{-1}}$) as a function of speed (v, $\mathrm{km \cdot h^{-1}}$) on sand (*full dots*: $C_w = 1.46 + 0.59\ v$, $r = 0.94$, $n = 13$) or on firm surfaces (*open circles*: $C_w = 4.5 - 0.99\ v + 0.11\ v^2$, $r = 0.75$, $n = 13$)

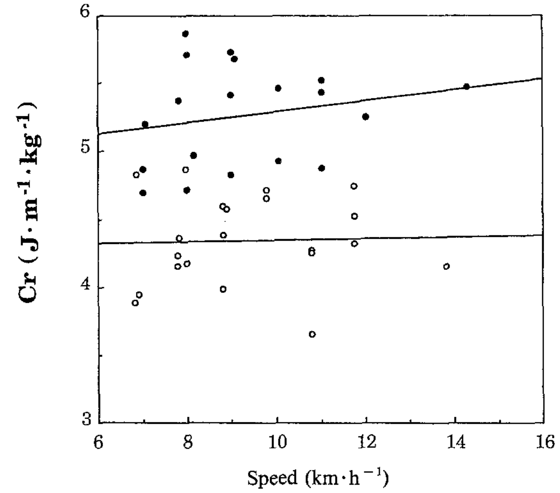

Fig. 2. Net (above resting) energy cost of running (C_r, J·m^{-1}·kg^{-1}) as a function of speed (v, km·h^{-1}) on sand (*full dots*: $C_r = 4.89 + 0.04\,v$, $r = 0.20$, $n = 20$) or on firm surfaces (*open circles*: $C_r = 4.89 + 0.005\,v$, $r = 0.03$, $n = 21$)

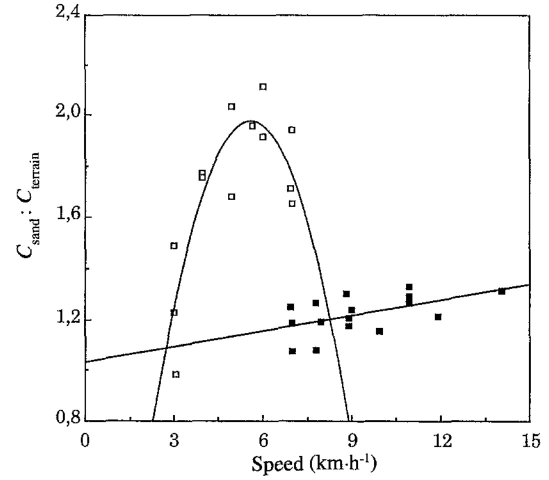

Fig. 3. The ratio r between the net energy cost of walking (*open squares*: $r = -1.4 + 1.21\,v - 0.11\,v^2$, $r = 0.87$, $n = 13$) and running (*full squares*: $r = 1.03 + 0.02\,v$, $r = 0.54$, $n = 19$) on sand or on firm terrain ($C_{sand} : C_{terrain}$) plotted as a function of speed (v, km·h^{-1}). The values reported on the *abscissa* represent the mean of v in the two conditions for each subject [the difference between the two v was 1.91% (SD 1.14), $n = 32$]

shaped curve showing a minimum of 2.3 J·m^{-1}·kg^{-1} (0.11 ml O_2·min^{-1}·kg^{-1}) at about 5 km·h^{-1}. In the same range of v on sand, C_w was substantially higher than on firm surfaces and did not show a minimum, the function being better approximated by a straight line.

The C_r, above resting was essentially independent of the v (Fig. 2); it amounted on average to 4.35 (SD 0.33; $n = 21$) J·m^{-1}·kg^{-1} on firm ground and to 5.33 (SD 0.47; $n = 20$) on sand. Thus, on sand, C_r was on average about 23% greater than on firm surfaces ($P \leq 0.0001$). The data of Figs. 1 and 2 show that at 7 km·h^{-1} on sand the C_w and C_r was about the same (approximately 5.2 J·m^{-1}·kg^{-1}); however, on firm surfaces at the same v, the C_w was still substantially lower than C_r (3 vs 4.2 J·m^{-1}·kg^{-1}). Thus, sand seems to be more detrimental, in terms of energy expenditure, in walking than in running. This is shown quantitatively in Fig. 3 where the ratio of the energy cost on sand to that on firm surfaces is plotted as a function of the v for both C_w and C_r. Running on sand led to an increased energy cost of about 10%–40%, while walking on the same surface produced increases ranging from about 60% to 200%, at least for v greater than 3 km·h^{-1}.

Under all experimental conditions, the stride length at a given v (and hence the stride frequency) was equal (Student's paired t-test not significant): it increased from about 1 m at 3 km·h^{-1} in walking to about 2.8 m at 14 km·h^{-1} in running.

The RPE in running on firm surfaces were rather low at all v [mean 3.9 (SD 1.2); $n = 17$]; on sand, however, the RPE increased markedly with the v attaining an average of 7.6 (SD 4.3) ($n = 16$) at the highest v tested, a difference that may well have been due to differing biomechanics and/or to the larger energy expenditure when running on sand.

Discussion

The values obtained in this study for C_w or C_r on firm surfaces are similar to those reported in previous studies (e.g. Margaria 1938; di Prampero 1986). Also the increase of C_w or C_r on sand is of the same order as found by other authors who have studied these forms of locomotion on soft terrains (Givoni and Goldman 1971; McMahon and Green 1979; Soule and Goldman 1972).

The most relevant observations emerging from the present study can be summarized as follows:

When walking on sand:

1. An optimal v at which C_w was minimal (4–5 km·h^{-1} on firm ground) was not discernible
2. The ratio of C_w on sand to C_w on firm surfaces increased markedly for v greater than 3 km·h^{-1}, to attain a value of about 2 for v approximately 5 km·h^{-1} and decreased again at higher v (Fig. 3).

In running on sand:

3. The C_r increased slightly with v, whereas on firm surfaces it was independent of v.

As a consequence:

4. The ratio C_r on sand to C_r on firm surfaces increased significantly ($P < 0.05$), albeit slightly, with v, from approximately 1.15 at 7 km·h^{-1} to approximately 1.4 at 14 km·h^{-1}.

Finally,

5. At a v of 7 km·h^{-1}, on firm surfaces, C_r was greater than C_w, whereas on sand at the same v C_r was smaller than C_w.

The paragraphs that follow are devoted to a brief discussion of the possible mechanisms underlying the above findings.

Walking

As shown by Cavagna et al. (1976), during walking on a hard surface at constant v on flat ground, the centre of mass of the body is raised and lowered and accelerated and decelerated (by equal amounts) at each stride. Obviously enough, no net gain of E_p, nor of E_k can occur. However, the changes of E_p and E_k at each stride are opposed in phase and of similar magnitude. Thus a conversion of E_p into E_k, and vice versa, can take place at each stride, the human body behaving like a pendulum. The exchange of E_p into E_k is not complete and the muscles perform a given amount of work at each stride to avoid a decrease in energy and hence a decrease in v. It has also been shown that the exchange between E_k and E_p is maximal, and the muscular work minimal, at the optimal v, i.e. at the v at which C_w is also minimal. At higher and lower v the exchange is lower and hence the work the muscles have to perform, as well C_w, is larger.

The interconversion of the two forms of energy involved can be expressed quantitatively by the ratio:

$$\%\,\mathrm{R} = \frac{W_f + W_v - W_{ext}}{W_f + W_v} \cdot 100 \tag{2}$$

which Cavagna et al. (1976) have introduced and defined as percentage of recovery (R). In Eq. 2, W_f is the work performed in the forward direction (to accelerate and decelerate the body), W_v the work done in the vertical direction inclusive of the vertical E_k change, a very small quantity at low v and W_{ext} is the external work performed.

Equation 2 shows that, were the system a frictionless pendulum %R would equal 100 since in this case W_{ext} would equal 0. At the other extreme, were W_f and W_v completely out of phase and of equal magnitude, then W_{ext} would equal W_f plus W_v and hence %R would equal 0. It was also shown by Cavagna et al. (1976) that %R attained a maximum of about 65% at a v of about 5 $\mathrm{km \cdot h^{-1}}$ and was less below and above this v (about 50% for $v = 3$ and about 40% for $v = 9\ \mathrm{km \cdot h^{-1}}$).

It can be tentatively assumed that, when walking on sand, the transformation of E_p into E_k at each stride was reduced because of the irregular and soft surface which did not allow a continuous and smooth muscle activity. This line of reasoning is qualitatively consistent with the observation that the ratio of C_w on sand to C_w on firm surfaces attained a maximum at the v at which, on firm surfaces, %R was also maximal. However, even when walking on sand, the %R must still have been relatively large, at least at v between 4 and 7 $\mathrm{km \cdot h^{-1}}$. Indeed, were %R reduced to zero, the C_w on sand could be calculated as:

$$C_{w\,sand} = C_{w\,terrain} \cdot \frac{100}{100 - \mathrm{R}} \tag{3}$$

where R is the value observed by Cavagna et al. (1976) on firm surfaces (60%–65% in the 4–7 $\mathrm{km \cdot h^{-1}}$ range of v). Equation 3 has been based on the assumption that the overall efficiency of muscle contraction did not change on sand as compared to firm surfaces, an assumption supported by the constancy of the stride frequency in both conditions. Inserting into Eq. 3 the %R values obtained by Cavagna et al. (1976), it can be calculated that C_w on sand should have increased from 6.5 $\mathrm{J \cdot kg^{-1} \cdot m^{-1}}$ at 4 $\mathrm{km \cdot h^{-1}}$ to 7.8 $\mathrm{J \cdot kg^{-1} \cdot m^{-1}}$ at 7 $\mathrm{km \cdot h^{-1}}$. These values are substantially higher than those actually obtained on sand which, in the same range of v, increased from 3.5 to 5.5 $\mathrm{J \cdot kg^{-1} \cdot m^{-1}}$ (see Fig. 1). Thus, also when walking on sand %R must have been substantially greater than zero. Indeed, inserting into Eq. 3 the values of C_w determined on sand and on firm surfaces, %R can be calculated to be in the range 43%–48%, compared with 60%–65% on compact ground (Cavagna et al. 1976).

Running

At variance with walking, during running on a hard surface the overall push of the active muscles is applied in an upward and forward direction, and as a consequence, E_k and E_p increase and decrease simultaneously. An appreciable exchange between these two forms of energy is therefore not possible (Cavagna et al. 1976; Cavagna and Kaneko 1977). However, at each stride, a certain amount of E_e is stored in the muscles and in the stretched tendons of the legs and is reutilized in the following stride. Thus, in running, the pendulum-like mechanism is replaced by a bouncing ball mechanism. Cavagna and Kaneko (1977) have shown that the greater the v, the higher the elastic recoil, the values of net efficiency ranging from approximately 40% to approximately 70% when the v is increased from 7 to 25 $\mathrm{km \cdot h^{-1}}$. When running on sand, the reutilization of E_e at each stride is presumably reduced. Indeed, to avoid backwards slipping of the foot, the push of the active muscles at each stride must be applied along a direction closer to the vertical. Thus whereas the E_k changes at each stride are not affected (the stride frequency is indeed equal), the changes of E_p at each stride become larger, thus leading to greater oscillations of the overall ($E_k + E_p$) energy. Because of the soft surfaces, however, these larger changes of the overall energy level cannot be entirely accumulated in the form of E_e, but are partially wasted. Hence the higher C_r on sand.

McMahon et al. (1987) have shown that running with flexed knees, "Groucho running", is a way to alter the temporary storage of E_e in the legs. Indeed, Groucho running resulted in a higher rate of $\dot{V}O_2$ compared to normal running at the same v (20%–30% on average and higher the deeper the knee flexion). It is remarkable, even if a coincidence cannot be excluded, that this is the very same increase of energy requirement as found in our study for running on sand (see Fig. 3).

An additional mechanism that may have led to an increased C_w and C_r on sand, was the tendency of the foot to slip backwards during the push phase of the stride. In this case, an amount of work (and hence of energy) proportional to the force applied in the horizontal direction times the backwards slipping of the foot would have been wasted thus increasing the energy cost of locomotion. For a given v, a backwards slipping of the pushing foot can be expected to have led either to an increased stride frequency or to an increased stride length. In our experimental conditions, the relationship between frequency and v was found to be the same on sand as on firm surfaces (see above), thus ruling out the first possibility. In addition, the experimentally observed identity of the frequency versus v relationship in the two conditions would imply also that, if the pushing foot was indeed moving backwards in the sand, the stride length would have been increased by the very same amount by which the foot had moved backwards, a rather unlikely possibility. It does seem plausible, therefore, to assume that in our experiments, the backwards slipping of the foot was of minor quantitative importance.

In conclusion, the present results showed that the C_w or C_r was increased over that observed on firm surfaces by 40% to 100% in walking and by 15% to 40% in running. These findings were attributed to a reduction of the recovery of E_e in running and of the transformation of E_p into E_k and vice versa in walking. The energy sparing effects of these two mechanisms were therefore substantially reduced and the energy cost was correspondingly increased.

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