ASPECTS OF THE ENERGETICS AND THE MECHANICS OF HUMAN LOCOMOTION

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Locomotion forms the essence of many sports. However, this analysis will concentrate only on walking and running. These are the most natural forms of locomotion in man, and have been so far much more studied than any other type of progression, because their intrinsic importance in the everyday life. Moreover they represent a fascinating aspect of the study of man, and many famous scientists of the past, like Marey, Fenn, Hill and Margaria, to name just a few, have devoted part of their life to the study of walking and running.

Methodological problems.

The study of the human locomotion could appear a relatively easy task, but its only simple aspect is that the movements to be analysed are repetitive and can be reproduced in a laboratory without many difficulties. Historically human locomotion has been studied starting from two different approaches: some devoted to assess its energetic aspects, some others the mechanical ones. When the speed of progression is constant and does not imply the contribution of the anaerobic sources the energy consumption of walking and running is easily determined with one simple treadmill and few relatively inexpensive instruments. On the contrary during rapid transients the instrumentation for the analysis becomes very sophisticated and when the aerobic sources play a significicative role, as for splints or high speed of running or when walking on steep gradients, one has to rely on a number of assumptions. On the other hand, the measurement of the mechanical work is rather complicated, the instrumentation is very expensive and sophisticated and not always the movernent can be performed on a treadmill, so that the speed is less easily kept constant.

To Sully understand human locomotion and to define the relationship between energetics and mechanics, the ideal approach should be the integrative one. Everybody can read on a dictionary that work done divided by energy expended is equal to efficiency. However such a simple definition does not seem to satisfy those who study the human movement, and in particular walking and running. Many authors have discussed this problem and a number of definitions of efficiency have been proposed. So 'muscle efficiency' has not the same meaning of 'muscular efficiency'. 'Muscle efficiency', measured on the isolated muscle, is the product of the phosphorilative-coupling efficiency and of the contraction-coupling efficiency. 'Muscular efficiency' refers to the muscular work performed in the execution of a movement and to the associated energy expenditure. According to how both encrgy and work are calculated the efficiency has been defined in different ways (Stainsby et al., 1980). One major problem is the correction for the encrgy base-line value: first it can he somewhat arbitrary to deline the appropriate exercise 'zero-load' condition and the cost of maintaining a given body posture and therefore the relative base-line (this seems particularly difficult for walking and running, while it is easier for free wheeling cycling); second the level of the base-line may change, especially during a prolonged exercise, due to the increased body temperature and the related increased work of the

heart and of the respiratory muscles. The cost of an exercise may also depend on the fibre types of the muscles involved: as it is well known the efficiency of the contraction is different for slow and fast muscle fibre types. The anaerobic contribution to the overall energy expenditure is difficult to measure, as it has been already mentioned, and in addition it has been questioned if the efficiency of the anaerobic work is similar to that of the aerobic work. Finally it has been also demonstrated that even psychogenic factors, cognitive, affective and perceptual, can influence resting and exercise metabolism through a modification of the synipathetic activity.

As for the mechanical work the methodological and, at time, philosophical issues are even more. The problem has already been discussed thoroughly by others and here it will be briefly summarised. In some instance it can be demonstrated that the work measured is not equal to the work actually performed by the muscles. Not all the energy expended ends up in some kind of measurable mechanical work, but can be used in isometric contractions or co-contractions for the fixation of the joints in the most appropriate posture. The second point is represented by the arbitrary, yet useful division of the mechanical work into two parts, external work and internal work. In particular at slow walking or running speed the work done to raise and lower the limbs is not measured neither as external nor as internal so that the total work could be less than the true work of the muscles. According to Cavagna and Kaneko (1977) in walking, at 3.5 $km.h^{-1}$, and in running, at 9 $km.h^{-1}$, the underestimation can be as high as 15%. On the contrary at high speeds its is possible that the work measured with this method is more than the true work since the energy of the limbs is sufficient to raise them against gravity. According to the same authors in running at over 30 $km.h^{-1}$ this overestimation can be about 12%. This introduces the third point that is related to the transfer of energy between segments of the body. The positive power resulting from energy transfer could be evaluated from the exact calculation of muscle moments and joint forces, and this is a rather complicated procedure. Transfer of energy can also occur between the subject and the environment: the effects of the track surface or of shoes materials have been already tested in many studies. Another source of energy that cannot be quantified is the elastic energy stored in muscles and tendons. This implies that the muscles must be active and forcibly stretched, a likely occurrence in running but not in walking. From this in turn comes the next problem which is the cost of the eccentric contractions. Many figures have been so far proposed for the relative efficiency of negative to positive work ranging from 1 to 5, considering only the most reasonable estimates. Mechanical energy may also decrease as an effect of some non-muscular source, like anatomical limitation to the joints range of motion or like muscle friction.

From this concise review turns out that the exact amount of work done by the muscle during walking and running is difficult, if not impossible to determine; and equally difficult is to assess the relative importance of the transfer of energy, of the elastic storage and release of energy, and the cost of the negative work. Cavanagh and Williams (1983) tried to assign some value to these factors, but most of their so-called 'reasonable' coefficients were derived from metabolic measurements. In a way it appears that to gain some insight on the mechanics of locomotion is necessary to rely on its energetic counterpart.

Cost of transport.

In the study of locomotion instead of the efficiency the physiologists, using a financial analogy, refer to the 'economy' which is defined as the rate of energy expenditure at a given speed. More than 50 years ago, Margaria (1938) proposed a similar parameter, the net energy ex-

pended per unit distance. This has been called later, in a number of studies on animal locomotion and on the effect of the size on the energy expenditure, the 'cost of transport'.

In walking the cost of transport shows a minimum that corresponds approximately to the speed normally observed in unaware, unrestrained subjects. The mechanical work per unit distance, on the contrary, does not show a minimum but increases as the speed increases, as its external component displays indeed a minimum at about the same speed of the energy cost, but the internal one increases with the speed (Cavagna and Kaneko, 1977). The increase of the speed is in fact obtained by both an increase of the step length and the step frequency, the former affecting the external work, as vertical displacements and forward speed changes of the centre of mass are greater with longer step length, and the latter the internal one, as the work done in accelerating the limbs relative to the centre of mass increases with greater step frequency. On the other hand the exchange of potential and kinetic energy that takes place at each step is maximum at the optimal speed. From this findings it appears that both metabolic and mechanical factors affect the choice of our spontaneous walking speed. Other factors can however, influence the speed of walking. An interesting finding shows that the average walking speed of people of different towns and cities is also a function of the population size, increasing linearly with the logarithm of the number of the inhabitants (Bornstein and Bornstein, 1976). Apparently, beside energetics and mechanics, also cognitive and behavioural adaptation, which should minimize environmental stimulations, can determine the normal walking speed.

In running the energy cost per unit distance is more or less constant throughout the range of speeds at which the energy metabolism is considered to be practically only aerobic. So in running is almost equally expensive to run a kilometre at 10 or at 20 $km.h^{-1}$ (air resistance, which is not taken into account in the measurement, can be considered negligible at the above mentioned speeds) and from this point of view, one cannot speak of a natural speed of running. Running is not the commonest fonn of locomotion for man and the choice of the speed is not based on economical considerations. The cost of running is highly variable between subjects ranging from 160 to 220 nil O_2 per kg and per km. It is not clear however which arc the factors mostly responsible for this variability. Sprinters and long distance runners appear to have a different cost of running, this has been explained on the basis of different muscle fibre type composition, however other reports do not show a clear difference in the cost of mnning between athletes of different specialities, who clearly should have quite different muscle fibre types. In a very accurate and complete study, unfortunately at only one speed, Williams and Cavanagh (1983) analyzed a number of structural, functional and biomechanical parameters with the purpose to find some relationship between these and running economy and performance. They concluded that no one single variable can explain differences in economy between individuals, even if they could have potential influence on the cost of mnning: each individual adopts the specific movement pattern best suited to his anatomical and physiological characteristics. The cost could derive from the weighted sum of the el'fects of many variables, in particular three of them seem to better explain the greater part of the variance in the economy: one is the net positive power and the others are measures of angular kinematics. Furthermore in a small, selected group of highly trained and experienced subjects of similar VO_2max running economy has been shown to account for two thirds of the variation observed in performance on a 10 km race (Conley and Krahenbuhl, 1980), this finding however has never been confirmed. Nonetheless it must also be pointed out that performance in many events must not be dictated solely by economy, but mechanical power output

should be privileged in order to win.

The mechanical work per unit distance in running increases almost linearly with the speed, being 25% higher at 20 $km.h^{-1}$ than at 10 $km.h^{-1}$. This is due to the increase of the internal component which also increases almost linearly with the speed, being twice as much higher at 20 $km.h^{-1}$ than at 10 $km.h^{-1}$. ln fact the external component decreases only slightly, about 7%. from 10 to 20 $km.h^{-1}$.

ln a way it is puzzling that the pattern of the cost of walking and running at the different speeds is roughly paralleled by the pattern of the external work per unit distance: in walking both show a minimum at the same speed, in running both vary little with the speed (Cavagna et al., 1964). This could be interpreted as if the energy cost of the external work would be the most important contributor to the overall energy cost of locomotion.

Walking and running with weights: cost of the internal work.

How to assess the cost the internal work? Some authors have indirectly approached this problem in different ways. As it is well known the internal work is mainly done in overcoming the inertia of the limbs that are accelerated and decelerated with respect to the centre of mass of the body. Assuming that the whole limb rotates around its proximal joint as a rigid pendulum the kinetic energy necessary to move the limb is equal to product of its moment of inertia times the square of its angular velocity, moreover the moment of inertia is equal to the product of the mass of the limb and the square of the distance between the centre of mass of the limb and the joint. It turns out that, for limbs of equal length, by varying, at given speed, the mass of the limb (assuming that is concentrated as close as possible to the centre of rotation) the kinetic energy. and hence the internal work, will change proportionally. On this ground Taylor and co-workers (1974) measured the rate of energy expenditure of cheetahs, gazelles and goats, running on a treadmill up to 20 $km.h^{-1}$. These mammals have a very similar body weight and limb length, but differ in the mass of the limbs and in the distance of the limb joints (shoulder and hip) from the centre of mass of the limbs. So the gazelle should runs at a lower cost than the cheetah. The results have shown that in a comparable range of speeds, where the stride rate was similar, the energy expenditure was approximately the same. These authors concluded that the cost of accelerating and decelerating the limbs is a minor fraction of the overall energy expended for running, unless the higher limb mass, as for the cheetah, is compensated by a higher elastic storage of energy.

Many authors (Claremont and Hall , 1988; Datta and Ramanathan, 1971; Martin, 1985; Myers and Steudel, 1985; Soule et al., 1978; Steudcl. 1990) have measured the increase of the rate of oxygen consumption when an external load was added to the mass of a subject walking or running so that the total weight to displace was increased. They have observed in animals of various size, rat, dog, horse, but also in man, that the ratio of energy expenditure, loaded to unloaded, $Etot/Eo$, increased in direct proportion with the ratio of weights, loaded to unloaded, $Ptot/Po$, up to 60% of the body weight. This is more true when not only the speed of walking or running is the same, but when also the stride frequency does not change, so that the kinematics of the centre of mass and its vertical displacements should not be affected by the load carrying and the work against gravity increases proportionally with the increase of the weight. However these experiments are contradicted by others showing that the cost of carrying loads is heavily dependent on the carrying modes. When the same weight was carried by hands to a P_{tot}/P_o equal to 1.1,

1.2, 1.6, corresponded an Etot/Eo respectively equal to 1.17, 1.36, 2. Myers and Steudel (1985) estimated the changes in the energy expenditure of four subjects running unloaded or loaded at about 10 km.h⁻¹. They produced alterations in body mass, limb mass, moment of inertia and centre of mass of their subjects by adding 3.6 kg load around the waist, or 1.8 kg load around each upper thigh, each upper shank or each ankle. The subjects were able to keep a constant stride frequency in all conditions. They observed that when the load was located near the centre of mass (waist) the percentage increase of the energy expenditure over the unloaded condition was only 3.7%, but became 9.4%, 12.1% and 24.3% for the thigh, shank and ankle location respectively. In subsequent experiments on dogs Steudel (1990) demonstrated that while the increase of the rate of the energy expenditure due to the external work with speed parallels the increase of the rate of the external work, the increase of the rate of the energy expenditure due to the internal work with speed is much less than the increase of the rate of the internal work. In a range of speed, from the fastest walking gait to the fastest trotting gait, at which limb loading did not affect locomotion, to an increase of the internal work of 3.2 times corresponded an increase of the energy expenditure of 1.8 times. Furthermore while the rate of internal work increased as a power function of the speed, the rate of energy expenditure increased linearly with the speed. On the contrary both the rate of external mechanical work and the related rate of energy expenditure increase linearly with the speed. As a consequence the cost of transport, is almost constant at all speeds.

From these data it appears that in locomotion the internal work, which is an important fraction of the total work, is decoupled from the energy metabolism and some mechanism for powering internal work in addition to the muscular contribution becomes increasingly important as the speed increases. This mechanism can be either the storage and recovery of elastic energy in muscles and tendons, either the transfer of energy within and between body segments.

Choice of the stride frequency in walking and running.

In walking and in running at a given speed infinite combinations of stride length and stride frequency can be adopted, however every individual chooses the particular combination that suits him best. No systematic measurements of the energy expenditure have been made on subjects walking at forced frequencies. Zarrugh and Radcliffe (1978) observed that the rate of energy expenditure when walking at 5.4 km.h⁻¹ at different frequencies shows a minimum near the frequency spontaneously adopted by the subjects. On the other hand Cavagna and Franzetti (1986) measured the external mechanical power at three different walking speeds maintained at different step frequency, and calculated the corresponding internal mechanical power from previous measurements. They found that the total power (external plus internal) reached a minimum at a step frequency, which they called optimal frequency, that was 20-30% less than the step frequency freely chosen at the same speed, in the fact while external mechanical power decreases, the internal mechanical power increases with the step frequency. In our laboratory we have recently measured simultaneously energy expenditure and mechanical work, and its two component, on subjects walking on a treadmill at different speeds at their freely chosen step frequency and at forced ones, and proposed a mathematical model that predicts how external and internal mechanical work affect the choice of a particular step frequency, when walking at constant speed, have been recently investigated in our laboratory (Minetti and Saibene. 1992). The function relating energy expenditure to frequency shows a much more marked curvature than the corresponding function for mechanical work, in other words a departure from the freely chosen frequency im-

plies a significant increase of energy expenditure, while the mechanical work is slightly affected. It is worth noting that the transfer of work against gravity into work for accelerating the centre of mass and vice versa, is maximum at intermediate step frequency and decreases at lower and higher frequencies. At low frequency work against gravity and work of acceleration, although opposite in phase, are of different amplitude, at high frequency they are no more in opposition of phase. Furthermore the mechanical work displays a minimum at a lower frequency and the energy expenditure at a slightly higher frequency than the freely chosen one. Possible reasons for such discrepancies could be methodological and/or physiological. As already mentioned there is a fraction of the internal work that cannot be measured. This is likely to occur mainly at low frequencies: including this fraction in the computation would shift the minimum mechanical work towards a higher frequency. Furthermore if one admits that part of the total (kinetic plus potential) energy of the centre of mass is transferred to the limbs it is possible that at the higher frequencies the total mechanical work is decreased so that its minimum is shifted closer to the freely chosen frequency. On the energetic side it is possible that at the highest frequency the anaerobic metabolism is also involved increasing the total amount of energy expended: this would shift the energy expenditure curve towards lower frequencies. Again metabolism seems to better satisfy optimization criteria. However not necessarily metabolic and mechanical factors are the only one to dictate the frequency normally adopted by a subject. The minimization of the average forces applied by the muscles during walking could well be another possibility, this is also a metabolic factor which privileges the cost of developing and maintaining force rather than the cost of performing work (Kram and Taylor, 1990).

Also in running there is a preferred frequency at each speed. Forty years ago Hogbergh (1952) observed in one subject at different running speeds that slight deviations from the freely chosen stride length produced little variations in energy expenditure, but with larger deviation the cost increased disproportionately. In a thorough investigation on 10 male runners Cavanagh and Williams (1982) observed that the freely chosen step length at 13.8 km.h^{-1} was for most subjects only slightly longer than optimal and that over a range +/- 10% of the preferred step length the oxygen uptake increased of about 6%, varying considerably between individuals. Kaneko and co-workers (1987) measured the mechanical work on 4 subjects running on a track at three different speeds from 9 to 16 km.h^{-1} and on a treadmill, at the same speeds, the energy expenditure. They found that also in running the departure from the optimal step frequency implies a much greater increase in the energy expenditure than in the mechanical work and that, in the range of the speeds observed, the optimal frequency remains constant and close to the freely chosen one so that the speed is increased only by progressive longer steps. Cavagna and co-workers (1986, 1991) observed that the frequency corresponding at the minimum power, contrarily to what happens in walking, decreases as the speed increases, as a consequence there is only a limited range of speed, around 13 km.h^{-1} at which the optimal frequency matches the freely chosen one. They argue however that at high speed running is not the work calculated over the whole step that must be considered, but rather the work performed during the push phase. The minimum push power is of course much higher and increases more with the speed than the minimum step power. Considering the push power, the optimal frequency is also higher and decreases less with the speed and corresponds to the freely chosen frequency at about 22 km.h^{-1}. The step power, which is limited by the aerobic metabolism, sets the freely chosen frequency at intermediate speeds, while the push power, which derives from the anaerobic sources, determines the frequency adopted at

high speed of running.

Speed of transition from walking to running.

Finally another problem concerning both energetics and mechanics of locomotion is why one changes spontaneously gait, from walking to running and vice versa at a certain speed, although it would bc possible to maintain that gait at a higher (or a lower speed). On the average this speed corresponds to about 7 km.h, varying considerably among individuals, depending on stature, age, sex, etc. The measurements of the energy expenditure show that there is a speed at which is equally expensive to run or to walk, but from the data available it turns out that this speed does not corresponds to that of the spontaneous transition, but it is higher, between 8 and 9 km.h^{-1}. Very recently with an elegant approach Mognoni (personal communication) has shown that the speed of equal energy expenditure for walking and running does not change significantly with the incline of the terrain from +15% to -15% despite a more than threefold difference of oxygen uptake, a finding that appears also from the data of Margaria (1938). However Mognoni has shown that the speed of the transition increases progressively from the positive to the negative slope, at a slope of +15% one begins to run at a speed at which it would have been more economical to walk. This finding shows clearly that the metabolic factors are not the sole responsible for the change of gait, and in fact it is difficult to imagine how a change in the energy request can be sensed so promptly to deserve such an immediate response. Furthermore mechanical data (Cavagna and Kaneko, 1977; Minetti and Saibene, personal observations) show that the speed at which the total mechanical power of walking and running coincide is even higher than that at which the two metabolic powers are equal. So it seems that also the mechanical power can be ruled out as the prime determinant of the transition from one gait to the other. Thorstensson and Roberthson (1987) on 18 subjects observed that the speed of transition is slightly higher during the acceleration than during the deceleration, as if some kind of hysteresis is operating to blunt the change of gait, so that one has not to switch frequently from walking to running and vice versa when is around the transition speed.

In summary it seems reasonable to assume that the transition speed represents a compromise deriving from many factors including energy expenditure, mechanical work, stress on the skeletomuscular structures, informations from peripheral receptors, all concurring to determine an ill-deiined subjective feeling of comfort.

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