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Positive and Negative Work Performances and Their Efficiencies in Human Locomotion* **

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Energy Cost of Walking

The energy cost of walking a given distance at a steady state has been found to reach a minimum value at an optimum speed, which, for walking on the level is about 4 km/h. For a wide range of speed values around this, the energy cost of walking does not change sensibly: only at a very high or very low speed of walking does it increase appreciably (Fig. 1). Walking uphill, the energy cost per km increases, while walking downhill a minimal energy requirement is met at an incline of about — 9%, to increase again on steeper ground.

Efficiency of Walking and Running

When the efficiency of walking is calculated by considering as mechanical work, only the final energy change, which, when walking at a constant speed, is given only by the body lift, and neglecting the rapid energy changes taking place within a step, a value of 0 is obviously found walking on the level: it tends to a value of 0.25, walking uphill, and to a value of about —1.2 walking downhill (see Fig. 2). This last value is meant as the ratio of the mechanical work performed to the energy expenditure (chemical) by the muscle, which only improperly can be referred to as "efficiency". When walking on the level the body is subjected to kinetic and potential energy changes, but since the energy changes in one direction (positive work performance) are met with energy changes in the opposite direction (negative work) within the step, the overall energy level does not change: in other words, positive work is performed which is followed by an equivalent amount of negative work.

When walking uphill the negative work performed decreases progressively with increasing incline, and positive work is in excess, which

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results in an increase of the potential energy. When walking downhill, the opposite takes place: the positive work done by the muscles decreases because the energy necessary for progression is met by the gravitational pull, and only negative work is performed by the muscles, this resulting in a decrease of the energy level of the body.

In Fig. 3 the energy expenditure in cal per m covered both for walking at the most economical speed, and for running, is plotted as a function of the incline of the ground; this last can also be visualized as the work

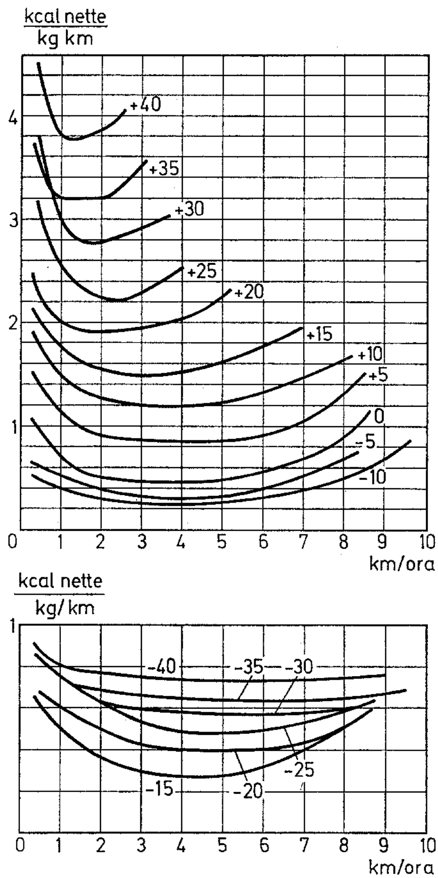

Fig. 1

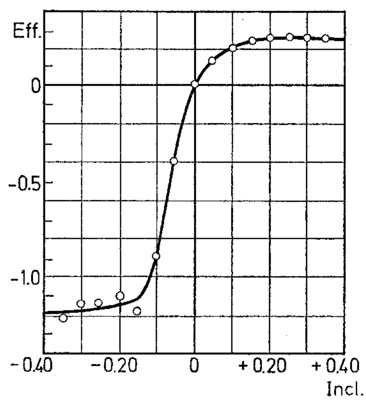

Fig. 2

Fig. 1. The energy expenditure of a man walking on a treadmill has been measured and the basal value subtracted to obtain the net cost of walking: by dividing this value by the speed, the energy expenditure per km is obtained: this, related to 1 kg of body weight (ordinate) is plotted as a function of the speed in km/h (abscissa) at different inclines in uphill (+) and downhill (—) walking as indicated (from MARGARIA, 1938)

Fig. 2. Efficiency defined by the ratio of the mechanical work, as given by the body lift, and the energy expenditure (chemical), as a function of the incline of the ground (from MARGARIA, 1938)

done in kgm per m covered and per 1 kg of body weight. Isoefficiency lines can then be drawn, showing, as in Fig. 2, that when performing positive work the "efficiency", as defined above, tends to 0.25, and in negative work to —1.2: a negative value for downhill walking is due to the fact that also negative work requires energy expenditure. The energy expenditure data for walking both uphill and downhill lie on an iso-efficiency line except in the range near level walking: their independence from the incline of the ground, for a wide range of incline values, seem to indicate that these efficiency values are the actual ones for positive and negative work.

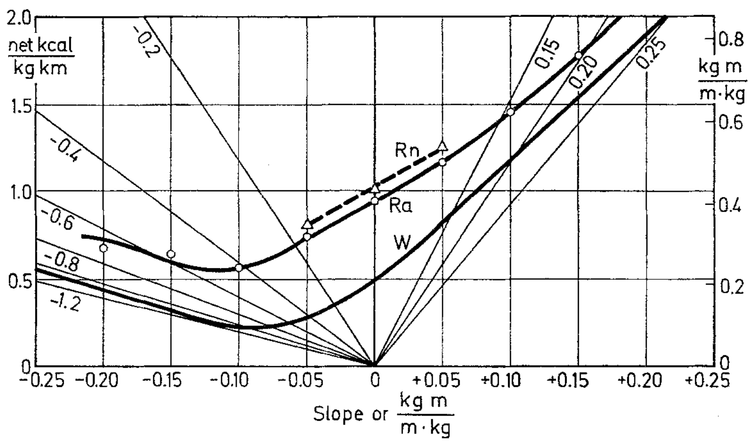

Fig. 3. Energy expenditure per kg of body weight and per m, walking at the most economical speed (*W*) and running (*R*), as a function of the incline of the ground: the data for running are valid for all speed values. *a* athletes, *n* non-athletes. Isoefficiency lines are also indicated (from Margaria et al., 1963)

Efficiency and Negative Work

Hill (1965) seems to raise some doubts about the validity of comparing the efficiency values for uphill and downhill walking, because the movements in the two kinds of exercise are not really similar: he thinks that a more reliable procedure would be to compare the data of uphill walking with those obtained in walking downhill backwards. In my opinion this last is a very unnatural exercise, and for being unhabitual it would take place probably at a low efficiency. On the other hand, there is no necessity for the movements to be really similar to obtain comparable data: the efficiency for positive work in all kinds of exercise that do not require a particular skill or training, such as walking uphill or bicycling or stair climbing, amounts to the same value of about 0.25, in spite of the evident dissimilarity of the exercise. As for the efficiency of negative work performance, from the experimental data of Abbott and Bigland (1953) collected on a subject performing positive and negative work on a bicycle ergometer, where the movements for both types of exercise are similar, the same values of "efficiency" for both positive and negative work as given by MARGARIA in 1938 in up- and downhill walking can be calculated. On this evidence I think that it can be stated with sufficient confidence that these are in reality the correct efficiency values.

Possible Work Performance in Walking

The net cost of the change of the energy level as due to the body lift (En_g) when walking or running at constant speed on an incline is then given by the isoefficiency straight lines of Fig. 3 indicated 0.25, resp. —1.2 which are defined by

$$En_g = \frac{1}{0.25}\ (+W) \text{ for uphill walking} \tag{1}$$

and by

$$En_g = \frac{1}{-1.2}\ (-W) \text{ for downhill walking} \tag{2}$$

where W is the incline (positive and negative), or the overall gravitational work per meter and per kg.

The difference between the actual experimental energy expenditure data (En_{exp}) and those given by the straight lines, i.e. $En_{exp} - En_g$ is spent in one or more of the following: a) internal work, b) work to sustain friction such as air resistance (which is nil walking on a treadmill), or friction of the foot on the soil, or within the joints and muscles, c) it is external work, which is performed in the same amount as positive and negative (W), within the step.

The fact that the energy expenditure line is a straight line for a wide range of incline values indicates, in my opinion, that the energy expended in level walking at the most economical speed is not due for an appreciable extent to internal work or to frictional resistance. In fact if this were the case, the same amount of energy would be spent walking uphill and downhill at about the same speed, and a constant "efficiency" value, of 0.25 or —1.2, could not be attained. On the other hand, frictional resistance would be largely affected by speed, which on the contrary seems to have very little influence on the cost of walking for a wide range of speed around the optimal, and no apparent influence at all in running, where considerably higher speed values are attained. The formulation given above for En_g, which is based on actual observations in the range of high values of incline, does not leave the possibility of any factor playing an appreciable role in the energy expenditure of walking and running, other than the performance of positive and negative work.

The conclusion can then be reached that the energy spent in level walking at low speed is not employed to overcome frictional resistances of any kind, or to perform an appreciable amount of "internal" work, but it may entirely be accounted for by the alternating positive and negative work performance within a step cycle, inherent in the peculiar mechanics of walking.

Walking uphill on an incline $> 22\%$ no negative work is performed and the energy expenditure is then given as from eq. (1). Walking downhill on an incline steeper than -9% no positive work is performed and the energy expenditure is given by eq. (2). At intermediate incline values both positive and negative work are performed within the step and the cost of walking is then given by both processes, i.e.

$$En_{exp} = \frac{+W}{0.25} + \frac{-W}{-1.2}. \tag{3}$$

The energy expenditure can then be visualized as the sum of two components, that responsible for the positive and that for the negative mechanical work. Walking or running on the level at a constant speed the energy gain is nil, as the positive work performed equals the negative, i.e. $(+W) + (-W) = 0$, and eq. (3) can then be written:

$$En_{exp} = W\left(\frac{1}{0.25} + \frac{1}{1.2}\right) = \frac{1}{0.207} W. \tag{4}$$

The mechanical work performed in walking can then be considered as made of two components: one appears as *energy gain* (or loss) and its cost is given by En_g as from eq. (1) (resp. eq. (2)): the other component is the work performed in the same amount as positive and negative and it can therefore be considered as *wasted* (W_w); its cost is given by eq. (4).

In general the energy expenditure is given by

$$En_{exp} = En_g + \frac{1}{0.207} W_w. \tag{5}$$

En_g is given by equation (1) when walking uphill by eq. (2) when walking downhill. The work wasted, W_w, expressed in kgm/m kg is given for all inclines in Fig. 4. Walking on the level it amounts to 0.044 kgm/m kg; this means that this is the positive mechanical work performed by the muscles to displace 1 kg of body weight for 1 m, and that an equivalent amount of resistant (negative) work is done by the contracted muscles of the limbs stretched by inertial or gravitational forces.

Cavagna and Margaria (1966) measured directly the positive and negative external work performed by man walking on the level at different speed values: the potential and the kinetic energy changes of the body were recorded, and the total energy change obtained. These data are given in Fig. 5, where it is shown that walking at 6 km/h the positive work involved per kg and per m is about 0.035 kgm, a value not too different from that calculated as above from the energy expenditure data only. The difference may be accounted for by the internal work employed in the acceleration and deceleration of the limbs. That the greatest part, at least, of the energy spent walking at low speed on the level is employed to accomplish positive and negative work, is thus confirmed by direct determinations.

This difference increases with increasing speed: walking on the level at 8.5 km/h, the energy cost per kg and per m amounts to 1 cal or

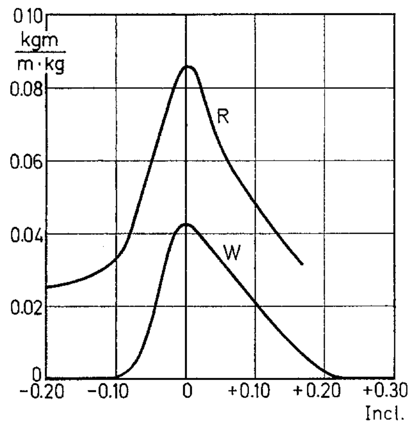

Fig. 4. Work wasted for being in equal amounts positive and negative (ordinata), walking (W) at the optimal speed, and running (R), uphill (+) and downhill (—) (abscissa)

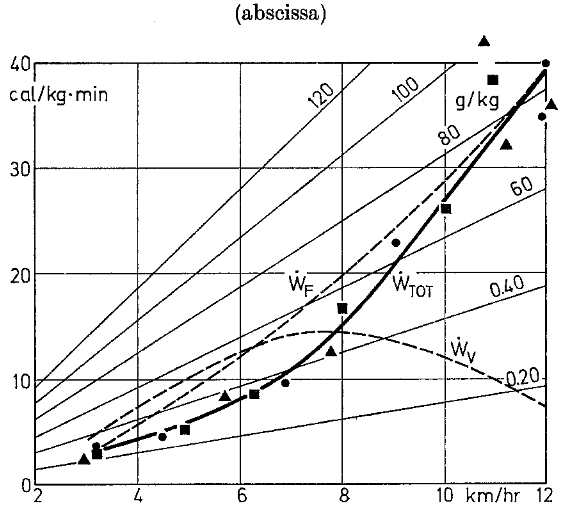

Fig. 5. Total external work in walking, in calories per minute and per kilogram of body weight, W_{tot}, as a function of the average speed of progression (full line). The broken lines are the single components, W_F (work necessary to sustain the velocity changes) and W_V (work performed against gravity), of the resultant W_{tot}. Different symbols refer to three different subjects (from CAVAGNA and MARGARIA, 1966). The lines radiating from the origin have been added: they indicate the mechanical work in gm per m covered and per kg of body weight, or the equivalent pull in g/kg

0.427 kgm, which at an efficiency of 0.207, as from eq. (4) corresponds to a constant pull of $0.427 \times 0.207 = 0.088$ kg, while the actual equivalent pull, as from Fig. 5 amounts to ab. only 50 g: the difference 38 g/kg, or 0.038 kgm/m kg is then to be accounted to internal work.

The Rate of Positive and of Negative Work in Walking

Walking uphill the increased energy level acquired during the positive work phase of the step is retained, at least in part, because of the decreased negative work in the following step phase. The negative work performed within a step cycle decreases with increasing steepness of the ground at such a rate that when walking on an about 22% incline, it is no longer appreciable. The positive work per step, on the contrary, increases progressively with increasing steepness.

Walking downhill the opposite takes place, only the energy expenditure data (En_{exp}) reach the isoefficiency line at a smaller (ab. —9%) incline value than walking uphill, thus making the curve of Fig. 4 appear asymmetrical.

As the values given on the ordinata of Fig. 4 are in kgm/m kg the same indication gives the pull in kg per kg of body weight in the direction of the progression to keep the body in motion: this is equivalent to a constant pull necessary to meet the resistance to progression.

A constant pull of the amount indicated would successfully replace the pull by the muscles, were this employed to meet a) a frictional, or b) a gravitational resistance. This, however, is not the case: walking downhill on a 4.4% incline, a constant pull of 44 g/kg of body weight is acting in the same direction of the movement, the same as that involved walking on the level: the work performed by the muscle is reduced to only 60%, as compared with walking on the level, and even a greater incline does not reduce the cost of walking to less than 50%.

That a constant pull cannot take over completely the pull by the muscles is a further evidence that the energy expended in level walking is not employed to meet any resistance to progression, but to perform positive and negative work within the step.

This would certainly be the case for other kind of locomotion, such as cycling or skating, skiing, swimming etc., where only positive work is performed and no negative work takes place in any phase of the exercise.

The muscular work done in walking or running, on the contrary, could be replaced only by alternating positive (in the direction of the movement) and negative pulls, given in the appropriate phases of the step cycle. A constant positive pull such as walking downhill can thus replace some or all the positive work performed by the muscles during the step cycle, but it will sum up with the inertial forces during the negative work phase of the step. To save muscular action in the negative work phase of the step, the pull should be reversed, and adjusted to the corresponding intensity. The intensity of the pull by the muscles, both the positive and the negative, is not constant, and therefore its replacement by an external force appears a very difficult task.

The Validity of the Efficiency Values for Positive and Negative Work Obtained Walking on an Incline

A schematic treatment of the effect and the efficiency of a constant external pull, such as when walking up- or downhill, may be made by assuming that the positive work is performed during the first 2/3 and the negative work during the last third of the step cycle, and that both of them change at a constant rate, as indicated schematically in Fig. 6.

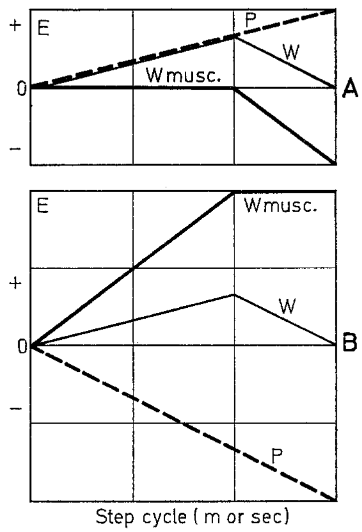

Fig. 6. Energy level in a single step cycle when walking on the level, W: A) when a steady positive pull is applied, leading to an energy change such as P, equivalent to the energy change taking place during the positive work phase of the step, and assuming that W is not changed as an effect of the pull, the work that must be accomplished by the muscles is $P - W = W_{\text{musc}}$. B) On the same assumption that W does not change when a negative pull is applied to the walking subject, such as when walking uphill, only positive work is performed by the muscles during the first 2/3 of the step, the negative work in the last 1/3 being made at the expenses of the negative pull. In A only negative work, in B only positive work is performed. At incline values higher than + 22 or —9 only one kind of work, either positive or negative, is performed within the step: then the efficiencies as calculated for the positive and negative work are the correct ones, because no mixture of positive and negative work takes place within the step

Assuming then that the pull forward, as it takes place in downhill walking, equals the pull of the positive work phase of the step, no positive work needs to be performed by the muscles: these will have to support only the negative work in the last third of the step phase. This is what seems to take place at an incline of ab. — 10%, namely at an incline value where the experimental curve (Fig. 3) meets the straight line.

Walking uphill the pull is in the direction opposite to progression, and only the negative work can be supported by such a pull. The experimental line meets the 0.25 isoefficiency straight line at an incline of +22% (Fig. 3), thus suggesting that about twice as great a pull is necessary to take over the negative than the positive work when walking on the level. Assuming that when walking on an incline the positive and the negative work maintain the same intensity and time course peculiarities as walking on the level, this seems to indicate that the negative pull in level walking is twice as great and it lasts only half the time (or it is carried for half a distance) of the positive pull. The more lasting positive work performance in the step cycle gives reason also of the asymmetry of Fig. 4, i.e. that a condition of minimal "wasted" work is reached at a lower incline in downhill than in uphill walking.

The Effect of a Steady Pull on the Energy Expenditure in Walking

In effect it appears from the work of Cavagna and others (1963, 1966) that the energy expenditure takes place in two distinct phases of the step cycle, as indicated by *a* and *b* of the curve E_{tot}. These two phases of positive work are often smoothed in a single phase, and no negative work is performed between the two, except, in the case described by Fig. 7, walking at 4.92 and 6.31 km/h. Walking at low speed the time of positive work performance is just about 2/3 of the cycle time, that of negative work being the remaining 1/3. At higher speed, the positive work phase is a progressively higher fraction of the cycle time and the E_{tot} line corresponding to the negative work becomes very steep.

As it is shown in Fig. 7 positive and negative work actually performed do not follow such a smooth curve as in the schema of Fig. 6; and even if the average rate of positive work performance walking on the level equals that due to the external pull, muscle activity is required when the increase of energy involved in a particular instant is higher than that due to the external steady pull: the same may be said about walking uphill, where a steady backward pull is active. In spite of this, however, the description above gives a quantitative sufficiently approximate explanation of the observed facts.

Energy Employment in Running

In running the energy expenditure per m covered is much higher, about twice as much. This is due to the fact that potential and kinetic energy increase at the same time, thus making impossible the trans-

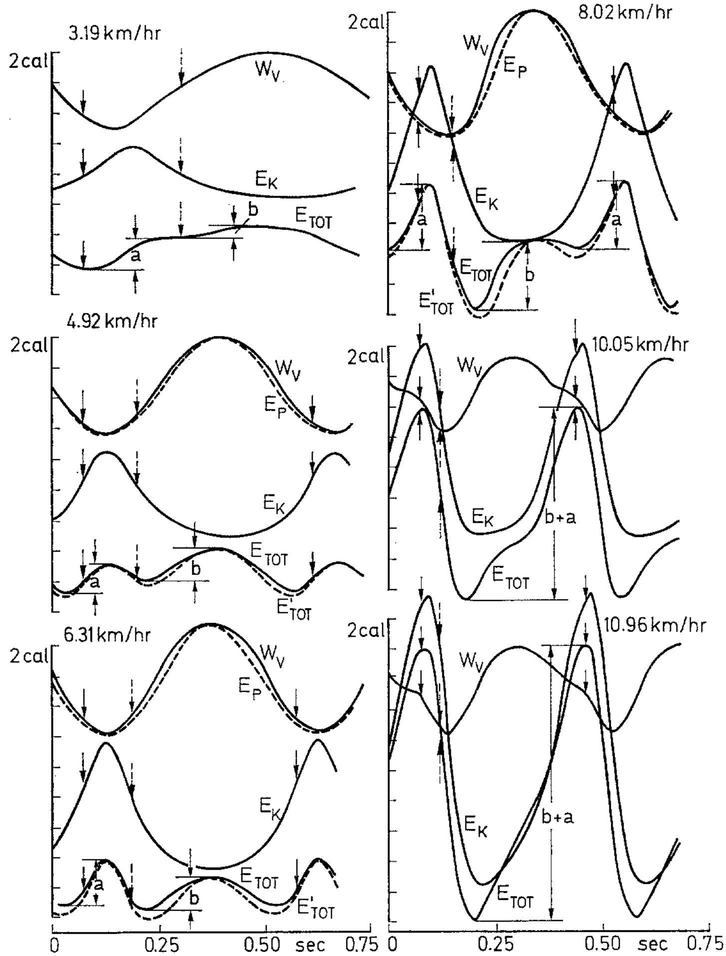

Fig. 7. Work against gravity (W_V), potential energy of the body (E_P, broken curve), kinetic energy of the body (E_K), and total energy changes, $E_{tot} = W_V + E_K$, walking at different speed, as indicated. E_{tot} (broken line) indicates the total energy level of the body as calculated by the sum $E'_{tot} = E_P + E_K$, the vertical component of the inertial forces being neglected. On the ordinate 2 cal between marks, on the abscissa time in seconds. The increments a and b of the curve E_{tot} indicate the positive external work performed at each step (from CAVAGNA and MARGARIA, 1966)

formation of one kind of energy into the other (CAVAGNA et al., 1964): the positive work performed E_{tot} is then the sum of the potential and the kinetic energy changes, while walking at ordinary speed it amounts to less than the energy change of each component, as it has been mentioned earlier.

When running on the level, the negative external work amounts to the same value as the positive; as they both require muscular energy, the total energy expenditure will necessarily be greater than in walking.

The Use of Elastic Energy Stored in a Contracted Muscle When Stretched

The positive work performed in a step cycle in running has been found to be very high as compared with the energy expended, and the efficiency, as calculated conventionally from the ratio of the positive mechanical work performed over the energy expended, reaches a value of 0.40—0.50, appreciably higher than the value found walking uphill, in which the internal work, because also of the slow movements involved, should be reduced to a minimum. This phenomenon, that appeared paradoxical at a first approach, has been discussed by Cavagna et al. (1964) and by Margaria et al. (1963) and interpreted as due, in part at least, to the elastic recoil of the contracted muscle stretched by inertial and gravitational forces.

It appears that in running, in the negative work phase of the step cycle, the work done by the muscles in active tension is stored as "elastic" energy: this can be utilized to perform positive work if the muscle is allowed to shorten immediately after, this summing up to the positive work performed by the shortening contracted muscle: on the contrary, it is converted into heat, if the muscle relaxes after the stretching.

Therefore E_{tot} of Fig. 8 in running does not give an exact indication of the total energy level of the body, because only the gravitational (potential) and kinetic energy levels have been taken into consideration, while the "elastic" energy changes could not be recorded.

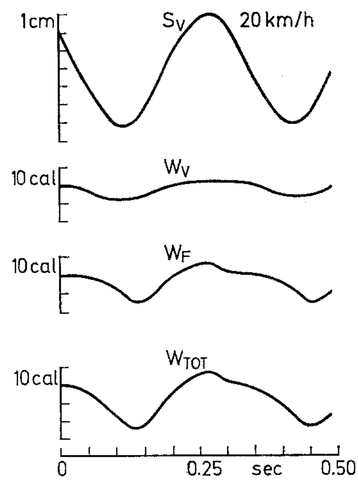

Fig. 8. Work due to the speed changes of the center of gravity of the body in forward direction, W_F, and work due to the vertical displacements, W_V, on level running at 20 km/h; W_{tot} ist the sum of the two. Displacements of the center of gravity of the body in vertical direction are given by S_V. The scale for W is 10 cal between marks, for S is 1 cm between marks

The curve of the "elastic" energy changes can be approximately visualized as being in opposition of phase with the potential and kinetic energy curves: in fact it increases (elastic energy is accumulated) at the moment the foot touches the ground, the muscles absorbing the energy of the impact, and it decreases (elastic energy is released) when the potential and the kinetic energy increase as an effect of the pull of the foot leaving the ground.

By summing the elastic to the gravitational and the kinetic energy components, the resulting curve would certainly show smaller waves than the curve E_{tot} of Fig. 8: and correspondingly smaller would appear the actual positive and negative work done by the muscles in a step cycle.

Work Balance in Running

The positive and negative work calculated from the energy expenditure when running on the level, amounts to 0.088 kgm/m kg (see Fig. 4), while it appears from direct measurements of the mechanical work performed to be 0.4—0.5 cal (CAVAGNA et al., 1964) or about 0.2 kgm/m kg. The difference 0.200—0.088 = 0.112 may, therefore, be considered the minimal amount of "elastic" energy which adds up to the energy provided by the muscle doing positive work: this appears to be a considerable fraction, more than a half, of the total mechanical work performed in running.

When running uphill the amount of "wasted" work decreases rapidly with increasing incline: it seems that a zero value would be reached at an incline of ab. + 0.30, too high to be tested experimentally because running involves a minimal speed, which in any case is too high to be supported by the energy expenditure of the subject exercising at steady state.

Running downhill a rapid fall of this "wasted" energy takes place (Fig. 4): only this seems to level off at an incline greater than 15%.

Why in running on a steep descent the energy expenditure is so high, is not very clear at present: it may be that either a) the high speed of progression involved in running on such an incline involves an appreciable amount of work to overcome frictional resistances, or that b) running in these conditions is an exercise performed less efficiently than running on the level or at a mild incline, requiring skill and training to be performed economically: the negative work performed in the deceleration phase of the step cycle may possibly be in excess, and the gravitational pull is then insufficient to provide the acceleration necessary to maintain the speed required: an additional positive work must then be performed by the muscles.

Summary

Walking at a constant speed on a steep incline, the ratio of the mechanical work performed, as calculated by the body lift, to the energy expended, as calculated by the oxygen consumption, generally referred to as "efficiency", is independent of the incline, and it amounts to 0.25 walking uphill and to —1.2 walking downhill. These values can be

regarded as the "efficiency" values for positive (uphill) and negative (downhill) work. Walking on the level or on a mild incline, both positive and negative work are performed within the step cycle. When an equal amount of positive and negative work is performed (level walking or running) the energy level of the body at the end of the performance does not change, and the "efficiency" as calculated amounts to 0.207. This work may be considered *wasted:* it reaches a maximal amount on the level of 0.044 kgm/m kg walking, and of 0.088 kgm/m kg running. For this reason a constant pull in the direction of the movement cannot replace completely the pull given by the muscles, as when other systems of progression such as cycling, skiing, skating etc. are adopted. By far the greatest amount of energy spent in walking or running at a constant speed is spent in positive work performance to counteract the deceleration (negative work) taking place at the end of each step. Very little energy is supplied for internal work, i.e. to meet the resistance to progression due to friction within the body or at the contact of the foot with the soil.

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