Human Locomotion in Subgravity

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ABSTRACT

The validity of experimental models simulating subgravity on earth is discussed. The mechanical characteristics of human locomotion in subgravity are perhaps better described by extrapolating data obtained at $g = 1$.

Walking at $g = 1$ muscular energy is utilized substantially to lift the body (increase of potential energy) while the forward acceleration (increase of kinetic energy) is obtained mainly through the transformation of the potential energy into kinetic in the second phase of the step; kinetic and potential energy levels are thus mainly in phase opposition.

The shift from walking to running takes place at a critical speed, 8.5 km/hr at 1 g, at which the changes of kinetic energy attain too high a value to be sustained only by the changes of the potential energy which are necessarily limited. For a higher speed to be attained the forward acceleration must be sustained directly by the muscular push, at the initial phase of the step; this involves a simultaneous increase of both potential and kinetic energy: in running, therefore, kinetic and potential energies are substantially in phase.

Walking in subgravity, the lift of the body in the first phase of the step requires less energy: correspondingly less potential energy is available to sustain the forward acceleration of the body in the second phase of the step, and the critical speed at which walking is shifted to running will be correspondingly lower than on the earth. In gravity conditions such as the moon (0.16 g) walking should be practically impossible.

Also maximal speed of running is lower on the moon because, for the lower weight of the subject, the vertical component of the force may be too low to maintain the adherence of the foot on the ground and prevent skidding; this depends on the conditions of the soil: if this is hard, a maximal speed of running of about 13 km/hr can be achieved, if it is covered by a deep layer of dust, the maximal speed will be about 5 km/hr.

A higher speed of progression can be obtained by recurring to another mechanism, namely jumping, which involves a higher vertical component of the push exerted by the limb and obviously a decrease of the frequency of the steps, because of the increased parabula time. Through jumping, similar or higher speed of locomotion as on earth, can possibly be obtained on the moon, depending on the structure of the soil.

The possible utilization of the elastic energy of the contracted muscle is discussed: this, running on earth, is responsible for the 40 per cent of the work performed.

Due to the lower step frequency, the acceleration at the

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start will attain a very low value on the moon, as compard with the earth conditions.

As on the moon the work done against gravity is considerably reduced, the energy cost of speed maintenance per km covered and for a given speed value is much less than on earth.

THE MAIN FORCES acting in locomotion are: a) inertial as due to a change of the quantity of motion of the system relative to the surroundings and b) the body weight, P, which is constant. The wind resistance in still air is very small at all walking speeds, and can be neglected: such a resistance becomes appreciable only at speed values met in running.[1, 2]

The body weight is determined by the mass and the gravitation values as $P = M\ g$: the mechanics of locomotion will be affected differently if a given change of P is due to a change of M or of g.

In fact, for a given g value, the mechanics of locomotion of a 35 kg subject is substantially the same as that of a subject of 70 kg, i.e. of a mass M twice as great, the only difference being the value of the forces, both inertial and gravitational, acting during a step cycle. The 70 kg subject at $g = 0.5$ will weigh 35 kg, and in this condition his mechanics of locomotion will be very different from that of the 35 kg subject at 1 g

The prevalent importance of the value of g in locomotion is evident considering that the lowering of the center of gravity of the body, that takes place in the second phase of the step, both in walking and running, depends only on the acceleration of the gravity and it is independent of the body mass; on the other side a change of M implies proportional changes both of the body weight as of the inertial forces, F, that are responsible for the velocity changes a ($F = H \bullet a$), while a change of g is reflected on a change of the body weight, P, only, the inertial forces being unaffected.

The change of the relative importance of the body weight and the inertial forces is one of the main factors responsible for the change of the mechanics of locomotion at $g < 1$.

At the lower limit, $g = 0$, and therefore $P = 0$, a condition that is met in interplanetary space, and/or in parabolic flight for a short time, locomotion will not be possible.

Methods for studying locomotion in subgravity:— The mechanics of locomotion in subgravity may be analyzed: a) through models that simulate the condition of subgravity on the surface of the earth, and b) by analyzing quantitatively the mechanics of locomotion at $g = 1$ and by extrapolating then the data to $g < 1$, to obtain the possible changes of the mechanics of locomotion.

A real condition of subgravity can be obtained for a short time in parabolic flight: it is not easy however to have access to this technique.

A condition of subgravity can be simulated in the Laboratory by applying to the subject a force opposing the body weight: this can be obtained by sustaining the subject by means of springs or light gas filled balloons,[4] or by immersion in water;[5, 6] in this last case the condition of subgravity may be simulated satisfactorily, only a new factor is introduced, i.e. the resistance to progression due to the high viscosity of the surrounding: because of this, locomotion in immersion

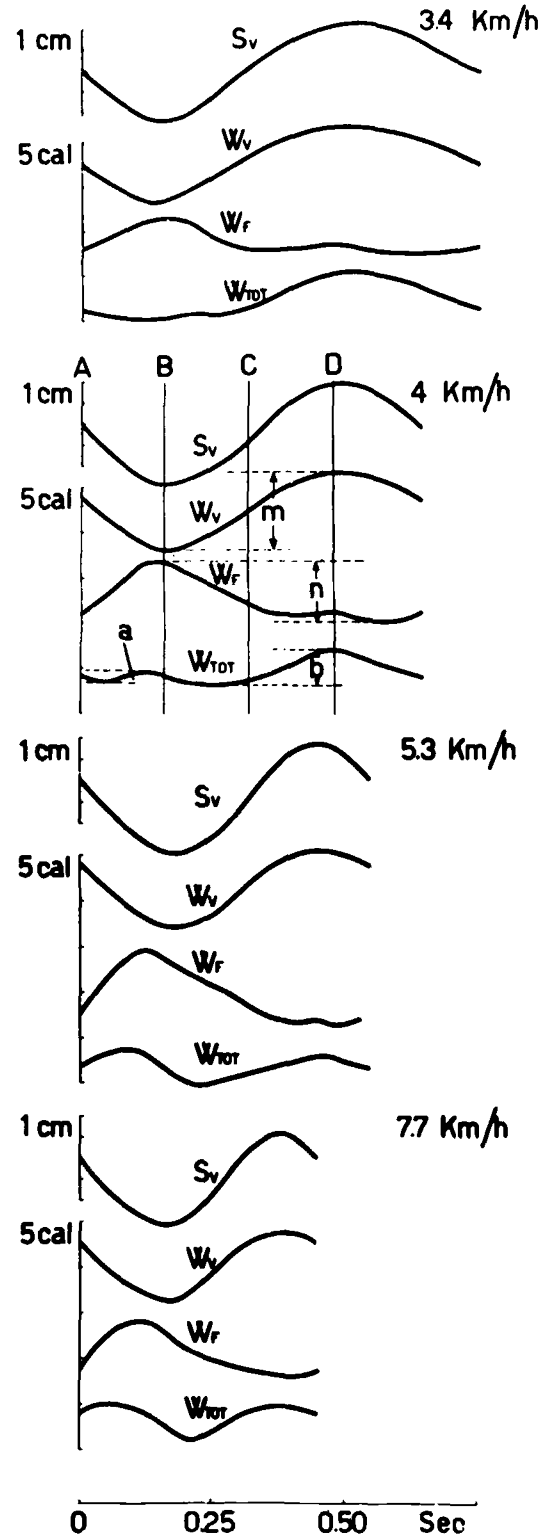

Fig. 1. Curves of the potential, W_V, and kinetic, W_F, energy of the body during a step cycle walking at 3.4, 4.0, 5.3 and 7.7 km/hr. W_V is calculated from the vertical displacements of the center of gravity, S_V; W_F from the speed changes in forward direction. W_{TOT} is the sum of the two curves W_V and W_F. m is the work done against gravity, n the work due to velocity changes in forward direction; $a + b$ is the total external work. The scale for W is 5 cal between marks, for S_V 1 cm between marks. (From Cavagna, Saibene and Margaria, 1963).

will differ appreciably from locomotion in a gas medium or in vacuum.

The suspension of the body with springs or balloons, simulates the condition of subgravity only partially a) because the forces cannot be applied to the center of gravity of the body and have to be applied to one or more points of the trunk. During the step cycle the center of gravity moves within the trunk: if the line, connecting the center of gravity of the body with the point of application of the resultant of the forces acting in opposition to the body weight is not a vertical one, a couple is formed which tends to put the subject out of balance; furthermore b) it becomes technically very difficult to apply these forces uniformly to the whole body, particularly to the limbs, that, during locomotion, are subjected to displacements relatively independent of the trunk.

In conclusion, the mechanics of locomotion in conditions of subgravity may perhaps be better analyzed by extrapolating at $g<1$ the quantitative data obtained in locomotion at $g=1$, rather than by experimental models which are necessarily dissimilar from the real conditions met in subgravity.

External[1] *mechanical work walking and running at* $g=1$:—In human locomotion the speed in forward direction is not constant, but changes at each step oscillating from a maximal to a minimal value; the center of gravity of the body, on the other side, both in walking and running, is subjected to vertical displacements at each step. Neglecting the work necessary to sustain the lateral displacements, which is very small, the external mechanical work performed during walking or running can be calculated if a) the speed changes in forward direction, namely the changes of kinetic energy, and b) the vertical displacements of the center of gravity, namely the changes of potential energy, are known.

The curves of the kinetic energy, W_F, and of the potential energy, W_V, during a step cycle, walking at different speed values on the earth surface, as obtained from actual measurements, are given in fig. 1.[7] It is evident that in walking the two curves of the kinetic and of the potential energy of the body, during the step cycle, are substantially in opposition of phase. The external positive work, which is given by the increments *a* and *b*, indicated on the curve giving the total energy, $W_{TOT}=W_V+W_F$, is less either than the work done against gravity alone, *m*, indicated on the curve W_V or than the work due to the changes of speed in forward direction, *n*, measured on the curve W_F. In other words during walking, some of the kinetic energy of the subject is turned into potential energy during the lifting of the body, and vice versa, in the last phase of the step, when the center of gravity of the body is lowered, the potential energy is turned into kinetic, as evidenced by the forward acceleration of the body.[7] The greater part of the external positive work, *b*, is performed during the last phase of the body lift (time C-D): evidently the kinetic energy of the body is not enough to lift the body to the required height, and an additional push from the limb muscles is required. The external positive work, *a*, in the phase A-B (fig. 1) is on the other side the expression of a forward push of the foot before leaving the ground: the net effect of this is to increase the kinetic energy above the value due to the transformation of the potential energy.

The change of the kinetic into potential energy and vice versa during walking is responsible for the low value of the external mechanical work and of the low energy cost of this exercise. The external work done in walking amounts to $a+b=0.1$ kcal/kg km, a very small amount, necessary to maintain the energy transformation cycle as described.

With increasing the speed of walking, the inertial forces, which are mainly directed forward, increase, and the work necessary to sustain the speed changes, *n*, in fig. 1, is increased correspondingly.

Obviously the work done against gravity, *m*, cannot increase indefinitely, but it has limitations due to the anatomical conditions of the subject, particularly of the

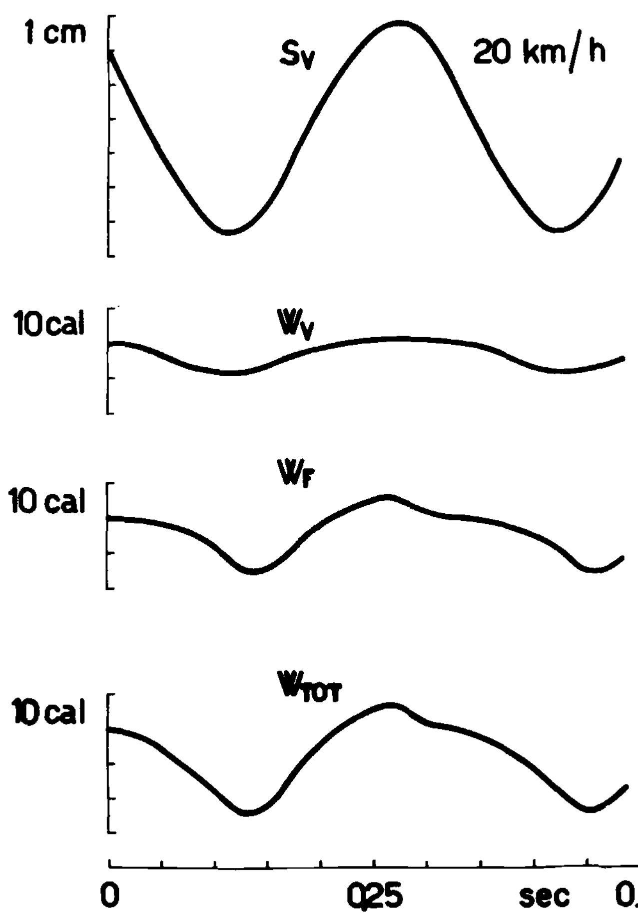

Fig. 2. Curves of potential, W_V, and kinetic, W_F, energy during a step cycle running at 20 km/hr; same indications as for fig. 1. The scale for W is 10 cal between marks, for S_V 1 cm between marks (from Cavagna, Saibene and Margaria, 1964).

[1] "External" work is that fraction of total mechanical work necessary to sustain the displacements of the center of gravity. "Internal" work is that fraction that does not lead to a displacement of the center of gravity of the system and which is required a) to overcome muscle viscosity and joint friction, b) to sustain isometric contractions, and c) those movements of the limbs which do not lead to a displacement of the center of gravity.

limbs, which limit the maximal lift of the center of gravity of the body. If the work necessary to sustain the speed changes in forward direction, n, tend to increase above the potential energy, m, stored during the body lift, this last will not be sufficient any more to provide for the forward push. This will be therefore sustained directly by a proper frontal component of the push. As this has also necessarily a vertical component, the kinetic and potential energy levels of the body will increase at the same time. This is what in effect takes place in running. In this exercise the curves of the potential and of the kinetic energy in the step cycle are substantially in phase (fig. 2), this being the main difference from walking. A consequence of this is that in running the external mechanical work is correspondingly greater (about 0.25 kcal/kg km).[8]

The shift from walking to running takes place at such a speed value, 8.5 km/hr, at which the potential energy, m, accumulated during the body lift, about equals the kinetic energy variations, n, necessary to sustain the forward speed changes in the step cycle.[8]

Walking in subgravity:—In subgravity the work done against gravity is obviously less: therefore correspondingly less will be the potential energy available to accelerate the body forward (increase of kinetic energy) and the shift from walking to running will take place at a lower speed value.

Let us assume for example that locomotion takes place on the surface on the moon where $g = 0.16$: in such conditions the curve W_V of fig. 1 will be flattened and the value of m will be reduced to 0.16 of the value on earth: the potential energy of the body in these conditions will not be enough to account for the kinetic energy changes, n, which are due to inertial forces only and are not affected by a change of g. The change of the potential energy into kinetic and vice versa, a fundamental characteristic of walking as described above, will therefore not be possible on the moon surface, except at a speed of progression lower than 1 km/hr.

It is very likely that on the moon surface walking will be unpractical, and locomotion will be possible only through a mechanics similar to that of running, in which the two energy components, potential and kinetic, will increase at the same time as an effect of the muscular push.

Let us consider the case of the change of the body weight, P, of the subject as an effect of the change of M instead of g: this can be done comparing two subjects of different masses or observing the effect of the application of a weight evenly distributed on the subjects' body. When M is less, the curve W_V of fig. 1 again will appear flattened because the potential energy gained by the body during the lifting phase of the step will be less: in this case, however, also the curve W_F will be flattened, because also the kinetic energy is proportional to M, and the conversion process of kinetic to potential energy and vice versa will not be affected appreciably.

In conclusion in subgravity one of the factors most responsible for the change of the mechanics of locomotion is the change of the ratio between inertial and gravitational force, or, in other words, between kinetic and potential energy level of the body.

As in subgravity the range of speed, in which walking is possible, is very limited, it is necessary to analyze how the mechanics of running is changed in subgravity.

Mechanics of running in subgravity:—It has been mentioned above that in running the kinetic and the potential energy of the body are substantially in phase, both increasing at the beginning of the step, as a consequence of the muscular push. This push, when $g = 1$, is directed forward and upward at an angle with the horizontal of about 75°-85°. The frontal component of the speed v_F is a function of the frontal component alone f_F of the inertial forces, f_{TOT}: if the vertical component f_V is great enough to raise the body from the ground, this will describe a parabula, the length and duration of which will increase with f_V. A higher duration of the parabula implies a lower step frequency, and therefore a decrease of the number of forward pushes applied to the body in the unit time. From this point of view therefore the vertical component of the push tends to decrease the speed of progression v_F.

The influence on the speed of progression of the duration of the parabula described by the center of gravity of the body can be quantitatively analyzed considering that during the step cycle in running the body decelerates progressively between two successive pushes. The maximum speed in forward direction impressed to the body, at the end of a push, will be

$$V_{F\,max} = V_{O_{TOT}} \cos \alpha \qquad (1)$$

where $V_{O_{TOT}}$ is the speed magnitude at the beginning of the parabula and α the angle included between the direction of the push f_{TOT} with the horizontal.

Assuming that the deceleration b is constant through all the parabula time, t_p, the minimal speed will be

$$V_{F\,min} = V_{F\,max} - bt_p \qquad (2)$$

as

$$t_p = \frac{2\ V_{O_{TOT}}\ \text{sen}\ \alpha}{g} \qquad (3)$$

equation 2) may be written as:

$$V_{F\,min} = V_{O_{TOT}} \bullet \cos \alpha - b\ \frac{2\ V_{O_{TOT}} \bullet \text{sen}\ \alpha}{g} \qquad (4)$$

It is evident that the speed $V_{F\,min}$ will be greater: 1) the smaller the angle α, 2) the higher g and 3) the lesser b.

As the vertical component of the speed $V_{O_{TOT}} \bullet \text{sen}\ \alpha$ is proportional to the vertical component f_V of the force, it can be deduced from equation 4) that an increase of f_V leads to a decrease of $V_{F\,min}$, and therefore of the mean speed of progression v_F, this being approximately $(W_{F\,max} + V_{F\,min})/2$.

Such a speed in fact will be at a maximum when the second factor of equation 4) will be nil, namely when the force applied to the center of gravity will be directed horizontally.

The body is permanently subjected to the acceleration of gravity, the force being given by his weight: besides this, in the first phase of the step the body will be subjected also to the inertial force given by the muscular push f_{TOT}, directed forward and upward.

It is necessary that the vertical component of the muscular push be equal to the body weight of the subject: it cannot be less, because the resultant will be directed downward, besides than forward, and the subject will fall on the ground: if it were higher, correspondingly greater will be the parabula time and the step frequency will be lower.

In effect, running at 1 g, the vertical component of the muscular push is approximately the same as the subject weight (see fig. 3). This force does not change

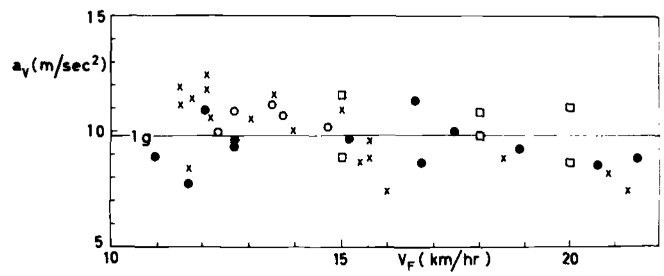

Fig. 3. Mean values of the vertical acceleration of the center of gravity of the body at each step (a_V) as a function of speed (v_F) running on the earth. A line has been drawn at the 1 g value.

appreciably with speed, which means that the subject exerts in all conditions the minimal and therefore the most economical force.

In conclusion, the direction of the push running on the earth surface is defined by the two components of the push, the vertical, which is constant and equal to the body weight, and the frontal which increases with speed. The angle formed by the push direction with the horizontal is therefore smaller the greater the speed, decreasing from 85° at 10 km/hr. to 75° at 20 km/hr.

Running in subgravity the muscular push must still be directed forward and upward: the vertical component of the push however will be reduced proportionally to the reduction of the acceleration of gravity.

The forward component of the push on the contrary, depending on inertial forces, for a given speed value, should be the same as for $g = 1$.

A decrease of the vertical component of the push, for a given forward component, implies a greater incline of the direction of the force, namely a decrease of the angle α. Very likely the lower limit of this angle will be conditioned by the frictional resistance of the foot on the ground. This resistance however will be lower in subgravity, because of the decrease of the body weight: the frictional force, F, in fact is approximately proportional to the vertical component, $P' = P + f_{TOT}$ sen α, of the total force exerted by the foot on the ground:

$$F = k\ P' \tag{5}$$

k, the coefficient of friction, depends on the physical state of the two bodies in contact and it is independent of the surface extent. Such coefficient is greater at the beginning of the movement. As evident from eq. 5), its value is defined by the maximal possible ratio between frontal and vertical components of the total force exerted on the ground by the foot; a higher ratio would involve skidding and the push would be inefficient.

The mean forward acceleration to which an athlete is subjected at the start of a top speed run (for exam. 100 mt race) is of the order of magnitude of 1 g.[9] If the vertical component of the muscular push is also 1 g (see fig. 3), the force P′ acting on the ground will amount to twice the body weight. If in such conditions no skidding takes place the friction coefficient at the start will be greater than 0.5.

The condition considered is probably a limiting one on ordinary ground, and an increase of the forward component of the push will lead to skidding: it is for this reason that the 100 mt race is performed on hard ground and the athletes wear nailed shoes.

On this assumption the angle of the push cannot be lower than 45°.

Running on the moon surface, being $g = 0.16$ and the vertical component of the push correspondingly reduced, if the forward component of the push is, for a given speed value, the same as on the earth, the angle as calculated turns out to be about 52°, running at 10 km/hr., 32° at 20 km/hr. and 23° at 30 km/hr.

The last two speed values cannot be reached running on the moon. In fact when the forward component of the push f_F has the same value as the vertical component and the angle α is 45°, the ratio between the frontal and vertical components of the force exerted by the foot on the ground is 0.5, i.e. the limiting value at which skidding takes place. A value of $f_F = 0.16$ however corresponds to a running speed of about 13 km/hr which is a maximum for this mechanism of locomotion. Higer speed can be achieved only through a mechanism of progression different from running, involving an appreciable lift of the center of gravity over the normal level.

Assuming that the moon soil is not compact, and that it is covered by a layer of dust or sand, the friction coefficient will be reduced. If this is assumed to be for example 0.2 the maximum speed of running is reduced to about 5.5 km/hr. In this case a limit to skidding would be given by the low friction coefficient of dust against the dust itself, rather than against the boots of the subject, and wearing nailed boots would be of no use.

The main peculiarities of the mechanics of running on the moon up to the speed values mentioned above are: a) a greater forward incline of the body during the push, b) a very sensible reduction of the force applied at each step because of the decreased vertical component: this involves less energy expenditure per km covered due to the decrease of work against gravity, c) a much lower maximum speed of running than a $g = 1$.

Progression by jumping:—To increase the speed of progression above 13, resp. 5.5 km/hr, an increase of the muscular push is required: only through this mechanism the forward component of the push f_F, on which only the speed of progression v_F depends, can be increased.

To avoid skidding, an increase of the muscular push f_{TOT} involves an increase of angle α. In fact the ratio between the forward and the vertical components of the total force exerted against the ground by the foot can be defined by:

$$R = \frac{f_{TOT} \bullet \cos\alpha}{f_{TOT} \bullet \operatorname{sen}\alpha + P} = \frac{\cos\alpha}{\operatorname{sen}\alpha + P/f_{TOT}} \qquad (6)$$

from which it appears that for $\alpha = \text{const}$, R increases with the muscular push, f_{TOT}. When f_{TOT} sen $\alpha = P$, and $\alpha = 45°$ R is 0.5, its maximum value. For this value not exceeding 0.5, an increase of the muscular push involves an increase of the angle α also.

Consequently the vertical component of the push will increase to a value higher than the body weight and a jump will result: the subject will describe a parabula the extent of which depends on the muscular push and on the angle α. This progression by jumps is substantially different from running. The value of the angle α, when running at 1 g, is plotted in fig. 4, as a function of the speed of progression v_F. The curve indicated $g = 0.16$ is calculated for running on the moon.

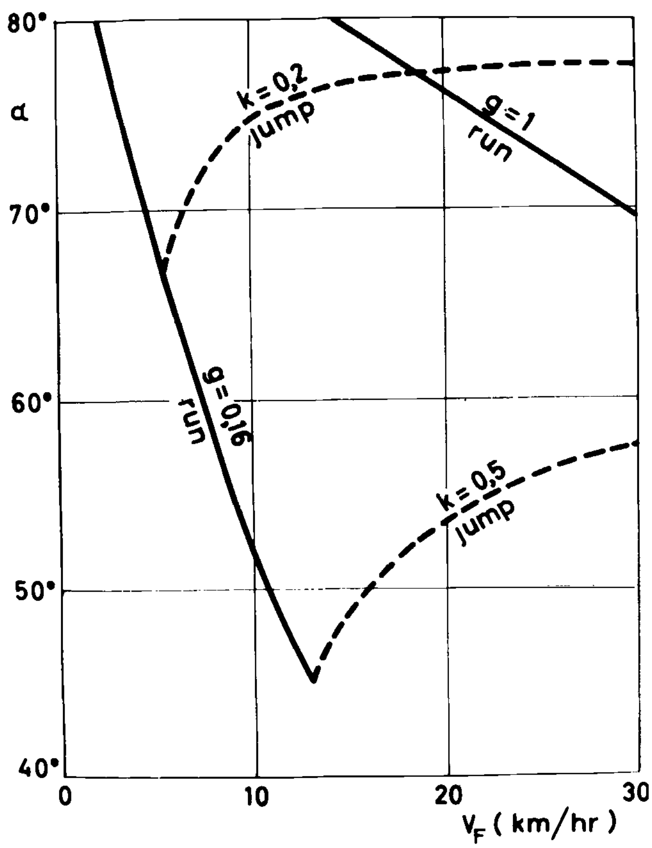

Fig. 4. The angle α formed by the direction of the push of the foot with the horizontal at each step is plotted as a function of the mean speed of progression, v_F. The line for $g = 1$ is constructed on experimental data, the line for $g = 0.16$ (moon surface) is calculated.

At a speed of progression higher than that indicated by the origin of the broken lines on the "run, $g = 0.16$" line, running, as conventionally defined, is no more possible, and progression takes place by jumping (broken line): the angle then increases with speed.

The two broken lines have been calculated by assuming two different friction coefficients of the lunar soil with the foot as indicated.

The point of intersection of this curve with the two broken lines is the maximal speed of running for the two extreme values considered of the friction coefficient 0.2 and 0.5.

For a given value of the frontal component of the component of the push being $f_V = f_F$ tg α, the vertical push f_F, namely of the speed of progression v_F, the angle α during running will be much less on the moon. Once the maximum speed of running is reached, to attain a higher speed, the subject recurs to the jumping mechanism and the angle α must increase as mentioned above, to allow a stronger muscular push. The frequence of the steps or of the jumps in subgravity can be calculated by assuming that the time of the push, t_{acc}, and the time of deceleration against the ground, $t_{dec.}$, for a given speed, be the same as found experimentally running at 1 g. An increase of the speed of progression, v_F, involves a decrease of the contact time of the foot on the ground, and therefore of both the time values t_{acc} and $t_{dec.}$ As these times are related only to the speed v_F and to the skeletal structure of the body, it is likely that they will not be influenced by a change of the acceleration of gravity. From the frontal component of the push f_F and from the angle α, the vertical component of the push being $f_V = f_F$ tg α, the vertical component of the acceleration is obtained $a_V = f_V$ / M. This value, multiplied by the time of the push,

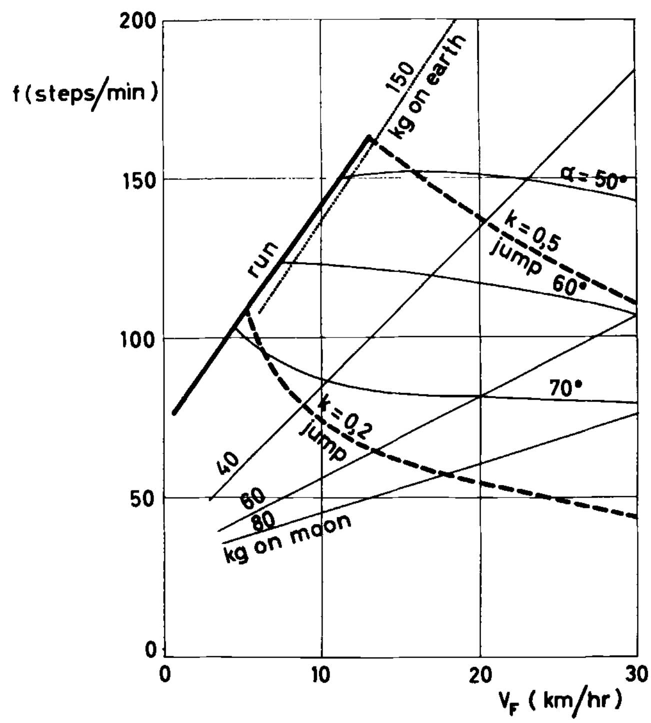

Fig. 5. Frequency of steps in running on earth as a function of the speed of progression (full thick line): the same line applies also to moon surface conditions, up to the maximal speed of running as given by the origin of the "jumps" (broken) lines. Step frequency in running increases with speed, in jumping it decreases with speed.

Iso-force lines are also drawn, indicating the total mean force exerted by the foot on the moon surface at each step (straight thin full lines), resp. on the earth surface (single dotted line).

Iso-angle lines are also drawn indicating the direction of the push of the foot, valid for $g = 0.16$.

gives the vertical component of the speed at the end of the push

$$a_V\, t_{acc} = V_{O_{TOT}} \operatorname{sen} \alpha \qquad (7)$$

From equation 7) the parabula time, t_p, can easily be calculated for a given value of g (eq. 3).

The duration of the jump, or of the step, can be obtained by adding the acceleration and the deceleration times, as determined experimentally during locomotion at the same speed at 1 g, to the parabula time.

In fig. 5 the step frequency in running, or progressing by jumps, on the moon surface, is plotted as a function of the speed of progression v_F.

The thick full line curve has been drawn on experimental data obtained on running at 1 g; they should hold to both earth and moon conditions. In fact in run the vertical component of the acceleration a_V is the same as the acceleration of gravity, g, (fig. 3) and therefore the time of parabula, t_p, as from equations 3) and 7),

$$t_p = \frac{2\ t_{acc}\ a_V}{g} = 2\ t_{acc} \qquad (8)$$

appears to be independent of the value of g. The validity of this equation is shown also by the fact that running at 1 g is always t_p twice the time of push, t_{acc}.

The broken lines refer to progression by jumping at a g value such as on the surface of the moon, in conditions of two different friction coefficients.

The straight thin lines in fig. 5 are the isoforce lines indicating the total mean force exerted at each step by the foot on the moon surface. The straight dotted line, near the line indicated "run," is also an isoforce line, valid only for the condition of 1 g.

The curved lines at the center of fig. 5 are the iso-angle lines of push, on the moon soil. It becomes thus possible to analyze the main characteristics of the human locomotion when progressing on the surface of the moon.

For example, when the friction coefficient is k = 0.2, and a push of 40 kg is exerted, a maximum speed of 9 km/hr. is reached. An increase of speed with the same push will be possible only if k is greater than 0.2, the maximal speed being 20.5 when k = 0.5: of course the angle of the push will then be decreased, as shown in the figure, from a value of about 73° to about 54°.

Higher speed values can be reached by increasing the force exerted by the foot and this involves an increase of the angle of the push, as illustrated in fig. 5. The step frequency necessarily decreases in this condition, because of the increased time of parabula.

Let us now assume that, the moon soil being compact (k = 0.5), a speed of progression of 20 km/hr is to be maintained. This can be achieved with 135 steps per min., the value of the push being 40 kg and the angle 55°, or the subject may give a push per step of 80 kg, the step frequency being 60 and the angle of the push about 75°. It depends mainly on the neural or better neuro-muscular coordination whether the subject will make the first or the second choice. The amount of work performed in the two cases seems to be of the same order of magnitude.

Running on the surface of the earth at 1 g, the push is much greater, i.e. of about 140 kg for a subject of 70 kg of body weight. As it can be seen in fig. 5, the force exerted by the foot on the ground, running at 1 g, is practically constant and independent of speed, only the frequency of the steps changing, besides the angle of the push (this last however does not change as described quantitatively in fig. 5 as the iso-angle curves of fig. 5 refer to the moon conditions only).

It is evident in fig. 5 that assuming that the moon soil is compact (k = 0.5) the same speed of progression as on the earth can be reached with a much lesser push, and a much lower step frequency: this implies a much lesser cost per km covered.

The possibility of making use of elastic energy:—It is not possible at present to predict whether on the moon a total force of the foot against the ground, averaging the same value as on the earth, of about 140 kg can be reached. It has been shown in fact that, running on the earth, such a high value is reached because to the muscular push as given by active muscular contraction, the elastic recoil is added of the contracted muscle which has been stretched immediately before, in the deceleration phase of the preceding step.[7] This fraction of the push which is not sustained by the active muscular contraction, amounts to about 40-45 per cent of the total push: its amount, however, is not constant, depending on the conditions at which the contraction takes place, and particularly on the total time of contraction and the sequence of the stretching-contraction process. It does not seem possible to predict at present to what extent this energy can be utilized, in the new conditions of frequency and of force of muscular contraction in the jump progression on the moon. If this fraction of energy will not be utilized, the maximal push exerted at each step, with the same energy consumption, will be appreciably reduced.

Acceleration at the start:—Running on the moon, the acceleration of the body at the start will be much less than on earth; in fact, for a given soil condition, a subject, on the earth, because of his greater weight, may use a much higher forward component of the push and maintain a higher step frequency. On the moon the same forward component as on the earth can be attained only by increasing the muscular push to obtain a higher vertical component, necessary to maintain adherence to the soil; this implies a higher parabula time, and therefore a low step frequency: acceleration at the start is obviously a function of the frequency of the steps. The time for the 100 mt race will be much higher on the moon than on earth.

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