SPECIAL ARTICLE

Human Locomotion

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ABSTRACT

The development of bipedal plantigrade progression is a purely human, and apparently learned, accomplishment. Experimental findings confirm the hypothesis that the human body will integrate the motion of various segments of the body and control the activity of muscles to minimize energy expenditure.

Movements which are integrated for this purpose include vertical displacement of the body, horizontal rotation of the pelvis, mediolateral pelvic tilt, flexion of the knee, plantar flexion of the ankle and foot, lateral displacement of the torso and rotation of the shoulder girdle.

Raising and lowering the body results in gains and losses of potential energy, and acceleration and deceleration result in gains and losses of kinetic energy. The motions are so co-ordinated that a transfer of energy back and forth from kinetic to potential occurs during walking, which tends to minimize total energy expenditure as well as muscle work.

SOMMAIRE

L'évolution du déplacement du plantigrade bipède est un phénomène purement humain et, semble-t-il, acquis. Les constatations expérimentales confirment l'hypothèse que l'organisme de l'homme peut intégrer les mouvements de diverses parties du corps et répartir l'activité musculaire de façon à réduire au minimum la dépense d'énergie.

Les mouvements qui concourent à ce but comprennent: les déplacements verticaux du corps, la rotation horizontale du bassin, la bascule latérale du bassin, la flexion des genoux, la flexion de la cheville et du pied, le déplacement latéral du torse et la rotation de la ceinture scapulaire.

L'élévation et l'abaissement du corps se traduisent par des gains et des pertes d'énergie potentielle et l'accélération et le ralentissement par des gains et des pertes d'énergie cinétique. Les mouvements sont synchronisés de telle façon que le passage de l'énergie potentielle à l'énergie cinétique se produise au cours de la marche, ce qui permet de réduire au minimum la quantité totale d'énergie dépensé et le travail musculaire.

THE development of bipedal plantigrade progression is a purely human accomplishment. We share two-legged locomotion with some flightless birds, such as the ostrich, and an arched plantigrade foot with the bear. I sometimes think that we have also retained other characteristics of these animals—namely our ability to bury our heads in the sand and, too often, to act in a "bearish" manner toward our fellow men. However, the orthograde position is exclusively human and permits us, literally, to view the world in an upright manner, although not always acting in an upright way. Perhaps I should apologize for these asides, but I do wish to emphasize the unique character of human locomotion within the animal kingdom.

Human locomotion appears to be a learned process. No one can watch the struggles of an infant as he first attempts to stand, holding onto the edge of a chair or tightly grasping in his hand the supporting fingers of a doting parent, without feeling that this is pure experimentation rather than the maturation of an inborn reflex. After the first few faltering steps, with the many inevitable falls, greater stability and precision are rapidly acquired. T. Popova,[1] working with Professor N. A. Bernshtein in Moscow, has studied the mechanism of walking in the growing child. She identifies three stages and points out that the characteristic patterns of locomotion that are seen in the adult are not achieved until the child reaches the age of 7 to 9 years. Apparently prior to this age the child is experimenting with his neuromusculoskeletal system, modifying the displacements that occur in various segments with the changes in bodily proportions, and developing improved neural controls.

If walking is a learned activity, it is not surprising that each of us displays certain personal peculiarities superimposed upon the basic pattern

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of bipedal locomotion. They are sufficiently characteristic that we are often able to recognize a friend even at a great distance. However, these individual variations tend to disappear when measurements are averaged, and we end up with a description of an "average" man who is exceedingly difficult to find in real life.

One need not belabour the point of individual dissimilarities in walking; the only reason for so doing is to emphasize that any serious description of human locomotion should attempt an explanation of the dissimilarities as well as of obvious similarities. Finding such an explanation, of course, necessitates searching for a basic principle or fundamental concept, the application of which might reveal the reasons why we employ a basic pattern, modify it with growth, and superimpose individual variations upon it.

Unfortunately, a fundamental concept does not emerge automatically or spontaneously through the accumulation of more and more data. Somewhere in the course of the investigation a hypothesis must be formulated so that deductions from the hypothesis can be compared with the measured observations. Agreement adds support to the hypothesis, and consideration of the hypothesis suggests new directions for future investigations.

A hypothesis is easily formulated which as far as we can see now seems to explain most of our observations, including the peculiar behaviour of the major segments of the body during walking.

This hypothesis states that the human body, if not influenced markedly by internal or external factors, will integrate the motion of the various segments of the body and control the activity of the muscles so that the energy required for each step is minimal.

In a presentation such as this, I must deviate from the traditional procedures followed in the delivery of a purely scientific paper. Customarily, methodology is discussed first, then the recorded data are presented, and a conclusion is drawn. I shall reverse this order. Having expounded a hypothesis, I will now proceed to present the supporting data from a variety of observations.

Let us begin by considering the energy requirements of a normal adult male, walking at varying speeds on the level. Dr. Henry J. Ralston[2] of the Biomechanics Laboratory, University of California School of Medicine, has published some very illuminating findings. If energy expenditure, calculated on the basis of oxygen consumption and expressed as calories/m./kg. of body weight, is plotted against speed of walking, a curve results which passes through a minimum. Walking faster or slower requires more energy per step. While this finding is of interest, the most impressive observation is that if the subject is permitted to choose his own speed he will invariably adopt the speed which corresponds to the minimum.

The same holds true for amputees wearing prostheses or pylons, or using crutches.[3] The curve based on oxygen consumption, while differing from the normal in total values, shows a similar minimum. Again the speed selected as the easiest and most comfortable is the one requiring the minimal expediture of energy per step (Fig. 1).

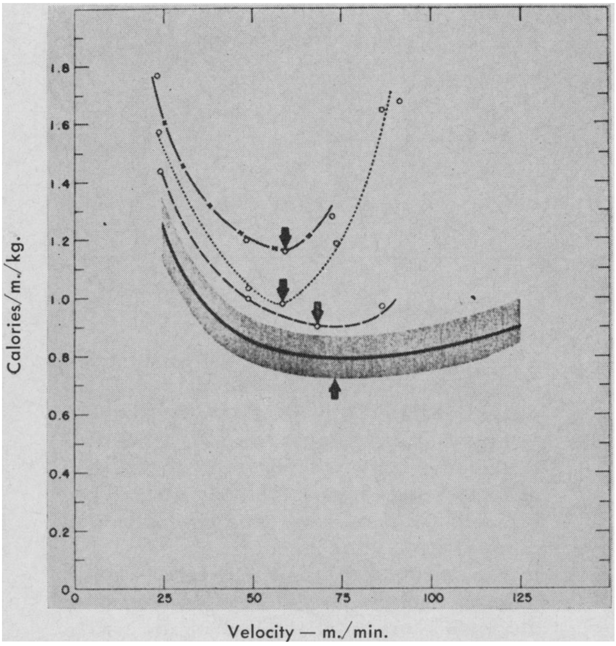

Fig. 1.—Comparison of the energy (expressed in terms of cal./m./kg.) expended during walking by normal subjects, and by amputees using various assistive devices. Solid line: average energy expenditure of normal subjects walking at various speeds. Stippled area: approximately one standard deviation. Broken line: amputee walking with suction-socket prosthesis. Dotted line: amputee walking with pylon. x — x — x —x: amputee using forearm crutches. Arrows point to natural walking speeds. (Reproduced with permission from Bard, G. and Ralston, H. J.: *Arch. Phys. Med.*, 40: 415, 1959.)

To me it is a source of wonderment that within our body there is a "computer" which so integrates the total behaviour of our musculoskeletal apparatus that each individual unconsciously adopts a gait which requires minimal energy per step.

We shall now examine this integrative process in more detail.

Since the body is moving forward during locomotion, the pathway of the centre of gravity of the body becomes of interest from the standpoint of energy requirements. It might be assumed that the centre of gravity should remain level, thus nullifying the force of gravity. However, this could have been achieved only if nature had developed a wheel with the centre of gravity in a fixed relationship to the axle. We are, however, committed to bipedal locomotion, which necessitates a considerable vertical displacement of the body with each step. The centre of gravity falls to its lowest point when the feet are most widely separated in the line of progression (as weight is transmitted from one foot to the other) and rises to its highest level as the body is propelled over the extended leg. We bounce up and down as we walk. The amount of this vertical displacement is between 4 and 5 cm.; therefore, the body must be raised and lowered this distance with each step.

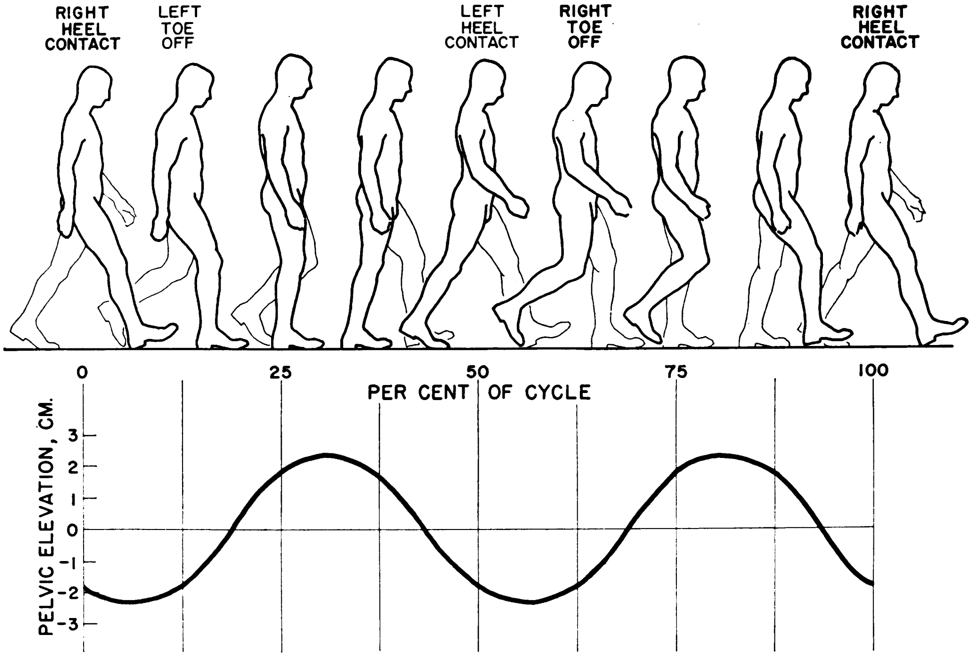

Fig. 2.—Pelvic elevation. Pathway of vertical displacement of the pelvis during the walking cycle as measured from a point opposite the second sacral segment.

The first question is what kind of vertical displacement pattern would require the minimal amount of energy. This is easy to answer on purely mathematical grounds—it would be a sinusoid of low amplitude. When we directly measure the vertical displacement of the centre of gravity we find that it approaches remarkably close to a sinusoidal curve (Fig. 2). On the basis of our original hypothesis, this is, of course, not at all surprising.

Our next question is how the motions of the various individual parts of the body are integrated so that they produce a sinusoidal displacement of the centre of gravity and restrict the amplitude of the vertical displacement to about 4 cm. This question can be answered by kinematic studies—considering only movement or angular displacements of the segments of the body and disregarding muscular or other forces that produce these movements.

Let me state at this juncture that the torso, head and arms do not appear to be involved in the attainment of the vertical sinusoidal displacement of the centre of gravity of the body. This statement is supported by the observation that the vertical displacement as measured at the top of the head is about the same as that at the sacrum. It is the correlated movements of the pelvis, hips, knees, ankles and feet that result in the sinusoidal curve with the small amplitude of 4 to 5 cm. While each part of the lower extremity is contributing its share toward achieving the smooth displacement of the centre of gravity, the direction of each contribution is somewhat different. The pelvis, hip and knee contribute more toward decreasing the amplitude of the vertical motion of the centre of gravity, while the knee, ankle and foot are more involved in smoothing a series of interrupted arcs into a sinusoidal curve.

Two motions of the pelvis are pertinent. The first is rotation of the entire pelvis in a horizontal plane. The extent of this rotation, although showing individual variations, is usually between 6° and 8° (Fig. 3). The rotation occurs alternately about each weight-bearing hip joint. The pelvis on the side of the swinging leg starts to rotate forward at the time of toe-off. As the leg continues to swing forward, the pelvis on the same side continues to rotate forward. Pelvic rotation in this direction abruptly slows at the time of heel strike and it is reversed as full weight is placed upon the foot. The reversal is necessary, for as this foot receives the body weight the contralateral foot is leaving the ground and the pelvis on that side must start rotating forward with it. The effect of these pelvic rotations in the horizontal plane is to lessen the amount of fall of the centre of gravity with each step. How this is accomplished may become clearer if we take two extreme examples. If there were no pelvic rotation we would step forward like the opening blades of a pair of scissors. With the blades apart the handles of the scissors, representing the torso, would be lower than when the blades are closed. The degree of lowering of the handles of the scissors, of course, would be related to how much we opened the scissors, or the length of the step. On the other hand it is possible to make a compass, or pair of dividers, walk by rotating it alternately about each leg. In this example there is no true hip movement, as the pivot of the compass may not move up and down at all. When we walk we adopt partly a "scissors" gait with flexion and extension at the hips and partly a "compass" gait with pelvic rotation. It is the latter

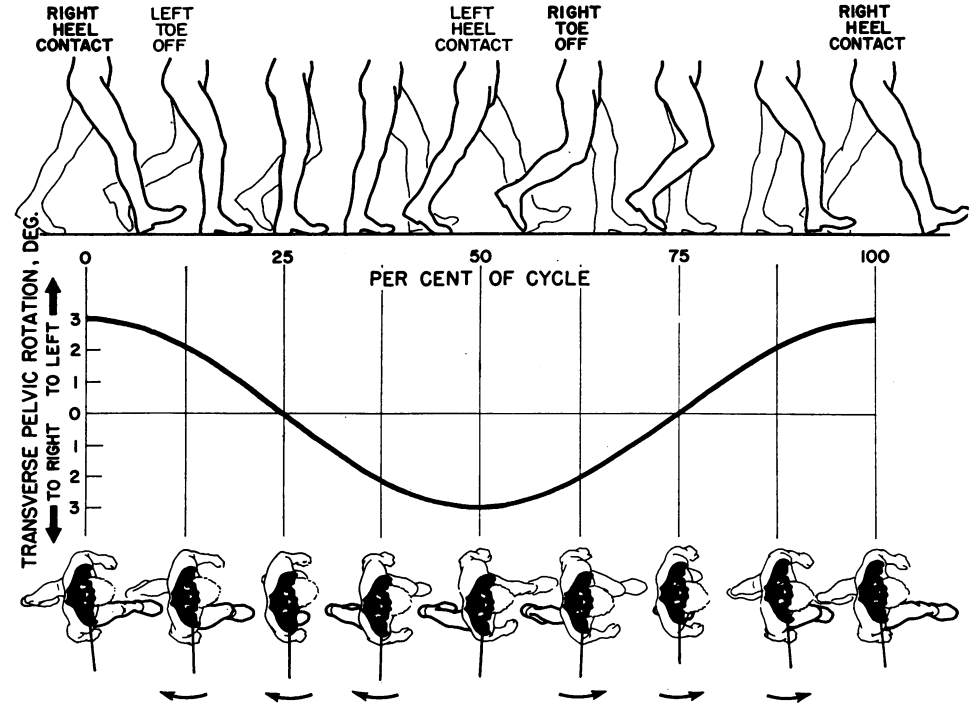

Fig. 3.—Transverse pelvic rotation during the walking cycle as measured in a horizontal plane.

motion that tends to decrease the amplitude of the vertical displacement of the body.

The second pelvic motion occurs in the frontal plane. It consists of permitting the pelvis to drop on the side of the non-weight-bearing, or swinging, leg (Fig. 4). We walk with a positive Trendelenburg. The amount of this pelvic tilt is variable but averages about 6° to 8°. Its effect is to decrease the amount that the centre of gravity must be raised as the torso is carried over the weight-bearing leg. This becomes clear if we recall that the centre of gravity is located in the midline of the body and midway between the hips. If one hip is raised and simultaneously the other hip is lowered the same amount, the effect on the centre of gravity will obviously be nil. During

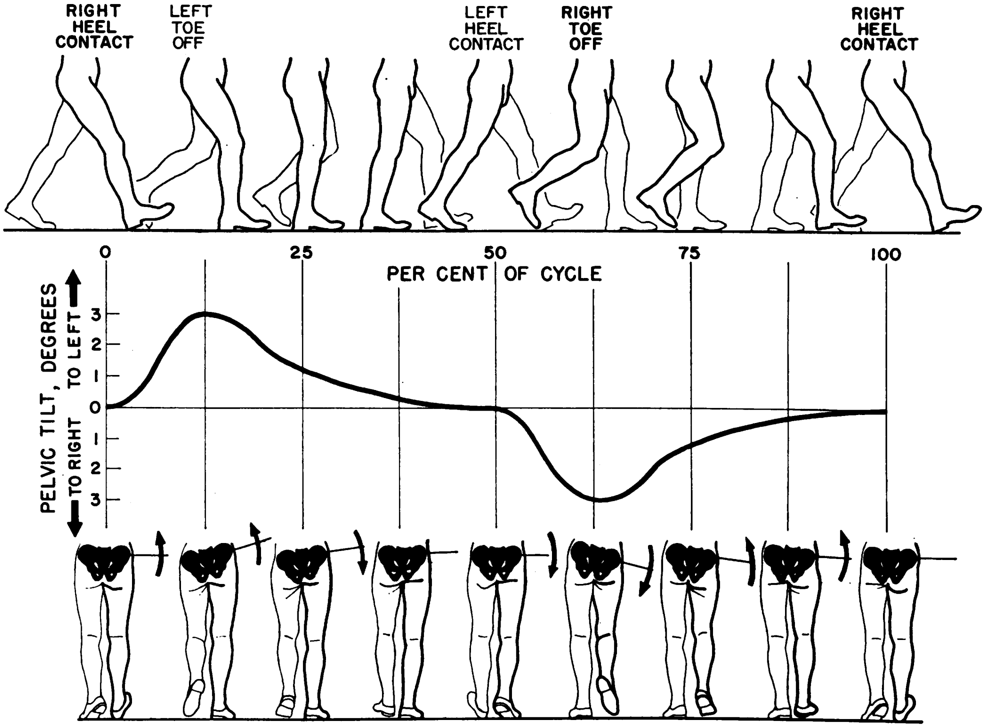

Fig. 4.—Pattern of pelvic tilt during the walking cycle. Note the relatively sudden drop toward the non-weight-bearing side, followed by gradual recovery.

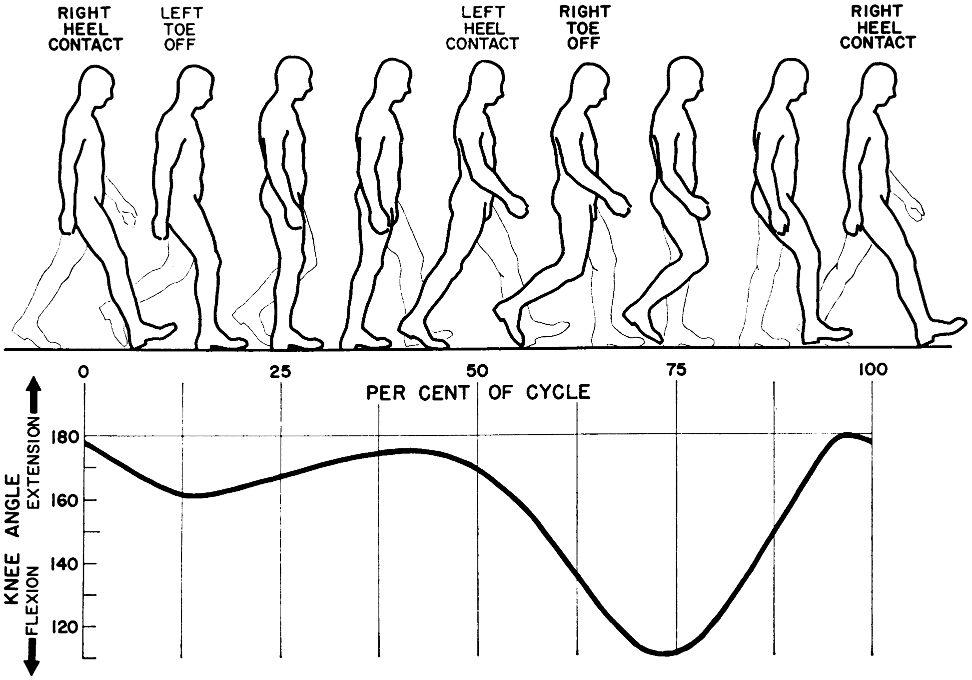

Fig. 5.—Measurement of the angular displacement of the knee. Note initial knee flexion after heel strike and incomplete knee extension during stance phase.

normal walking, however, the hip on the non-weight-bearing side does not fall nearly as much as the weight-bearing hip is elevated in midstance phase. However, any degree of lateral pelvic tilt will tend to decrease the amount that the centre of gravity and the torso must be elevated at each step.

Both these movements are readily detected in an unclothed individual, but watching nude people ambulate is not a common experience. However, the tightfitting apparel often worn by the female provides a close approximation. The pelvic rotation and the lateral pelvic tilt are readily discernible to any interested observer.

When walking on the level we do not walk over a completely extended knee joint. At heel strike the knee reaches its maximal extension and, as the body weight is transferred onto the foot, the knee flexes slightly, permitting the body to pass over the leg, which has been appreciably shortened through flexion at the knee joint (Fig. 5). If this did not occur we would be forced to vault over a fully extended leg in a manner similar to an above-knee amputee wearing a pylon. By means of slight knee flexion the body can move forward over a shortened leg and approach a more horizontal path.

The three factors of horizontal pelvic rotation, lateral pelvic list, and slight flexion of the knee combine to decrease the vertical displacement of the body. Theoretically, if these movements did not occur the vertical displacement of the body would be twice that of the measured 4 to 5 cm.

While the pelvis and knee are primarily involved in regulating the rise and fall of the torso, the forward progress of the body would still be accomplished in a series of interrupted arcs except that the combined movements of the knee, ankle and foot smooth the arcs into a sinusoidal curve.

As the heel strikes the ground, the ankle plantar flexes under control of the extensor muscles of the leg, and at the same time the knee flexes. Both motions tend to shorten the leg and absorb the impact of the body weight as the foot strikes the floor. As the foot is loaded it pronates, further easing the transfer of body weight. Then, as the body passes over the leg, knee extension and active plantar flexion of the foot cause the heel to rise and result in relative elongation of the leg. Thus the descending body weight is smoothly transferred to the opposite foot and the next cycle of elevation of the body is initiated.

The movements of the various parts of the lower extremity that function together to achieve the smooth sinusoidal path for the centre of gravity of the body are not completely independent variables. Suppression or exaggeration of motion of any one segment may be compensated for by altering motion of one or all of the others. This can readily be seen in a woman with high heels, who obviously walks differently from a person wearing low heels. The relative shortening of the foot and suppression of ankle motion is compensated for by exaggerated knee flexion and modification of pelvic movements. However, if the floor reactions are recorded it is found that in this respect there is very little difference between high heels and bare feet; also, the wearer still achieves a smooth sinusoidal displacement of the centre of gravity of the body. The change in manner of walking is compensatory and not an affectation.

At this point I would like to consider two other related movements of the body. There is a side-to-

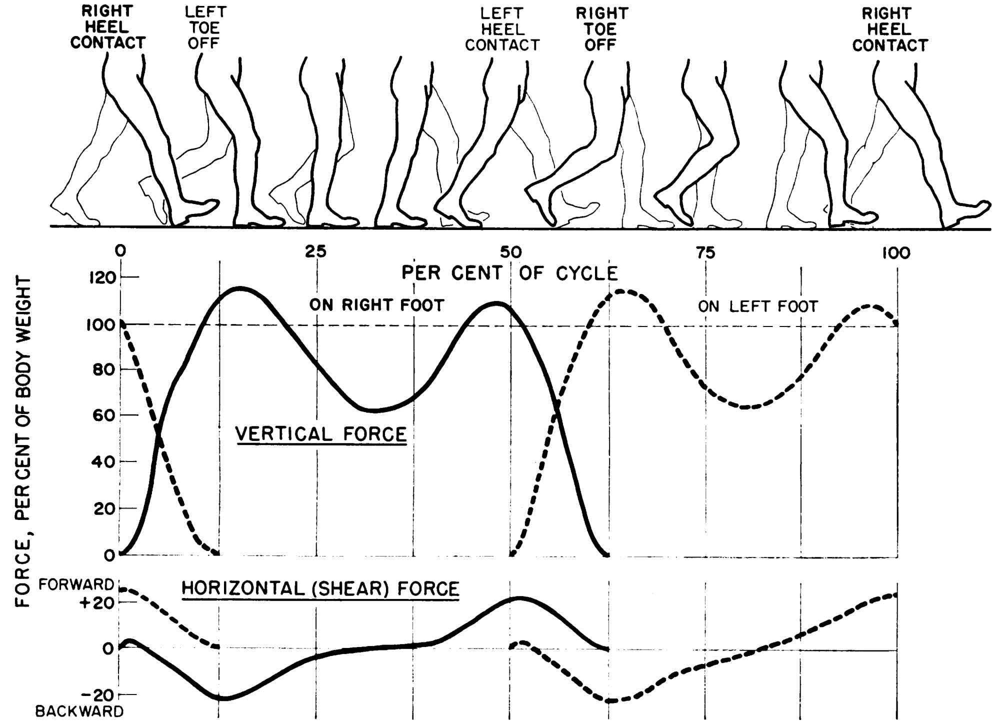

Fig. 6.—Floor reactions during the walking cycle as recorded from force plates.

side movement of the torso as weight is transferred from one leg to the other. This lateral displacement is 4 to 5 cm.; if the path of the centre of gravity is recorded in the horizontal plane, it is also sinusoidal, which again is not surprising.

The pelvic rotation discussed above produces certain effects upon both the legs below and the trunk above. It is found that the segments of the leg rotate in the same direction and in phase with pelvic rotation. While this is understandable, the surprising observation is that the amplitude of this rotation increases progressively from proximal to distal segments of the leg. Thus we find the tibia rotating about its long axis three times as much as the pelvis. This is an intriguing phenomenon and is intimately related to certain locking and unlocking mechanisms in the foot, which unfortunately we cannot discuss further in this communication.

Pelvic rotation produces some obvious movements in the upper part of the trunk, the shoulder girdle and the arms. If one walks very slowly the shoulders rotate in phase with the pelvis, but as the speed of walking increases, rotation of the shoulders begins to shift in its phasic relationship to the pelvis. At the speed of minimal energy expenditure, the shoulders and pelvis are approximately 180° out of phase. The arms, being hung from the ends of the rotating shoulder girdle, behave as pendulums and start to swing. It can be observed in anyone walking at his normal speed that the legs and arms are out of phase: As one leg swings forward the contralateral arm moves forward.

This arrangement between shoulder girdle rotation, with concomitant arm swing, and pelvic rotation seems to be a mechanism that damps pelvic rotation. Should the torso be immobilized in a brace or cast so that the trunk and shoulders are forced to rotate together and their out-of-phase rotation is prevented, walking at moderate or higher speeds becomes awkward and the energy requirements as measured by oxygen consumption rise sharply. It is, therefore, our present feeling that the counterrotation at the shoulders is a self-regulating mechanism for damping the excessive pelvic rotation which would otherwise occur in walking at higher speeds.

Man is a self-propelled machine with striated muscle as its sole source of power. The striated muscles, however, are so arranged that they can only produce rotatory movements of the segments of the body around the axes of the joints of the skeleton. If we were suspended off the ground, we could put the various parts of our bodies through all sorts of bizarre gyrations but would be totally unable to initiate and sustain a continuing forward movement of the body as a whole. To propel oneself through space requires some fixed point external to the body against which bodily forces can be exerted. In normal locomotion this fixed point is, of course, the floor.

Newton's Third Law states that to every force there is an equal and opposite reaction. Therefore, the forces that resist the pull of gravity and push us forward produce equal and opposite forces exerted by the floor. These floor reactions may be measured with suitable instrumentation and they give us some interesting information on locomotion (Fig. 6).

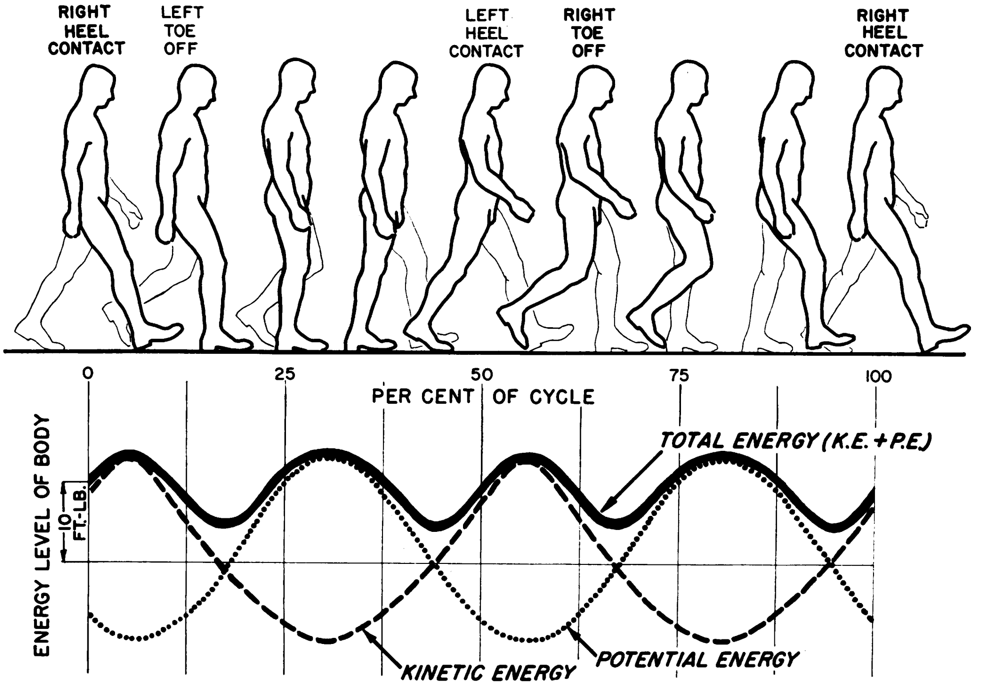

Fig. 7.—Idealized curves showing the transfer of energies within the body during the walking cycle. If the system were conservative, the total energy curve would be a straight line. The energy contributed by the musculature of the body is indicated by the difference between the total energy curve and a straight line.

The vertical floor reactions substantiate our previous observations that we move up and down as we walk.

As the body starts to rise over the single extended leg, it is subjected to an upward acceleration, reflected in an increase in the floor reaction, which is recorded as an apparent increase in body weight. Thus, during elevation of the body the force on the floor may exceed the body weight by 20% on each leg. Conversely, as the body falls the downward acceleration is recorded from the floor reaction as an apparent decrease in body weight, which may exceed 35%. This means that the potential energy of the body (weight x height), which was maximal at the highest elevation of the body, is being converted into kinetic energy as the body falls. This kinetic energy is partly diverted into forward propulsion of the body, increasing the velocity of forward movement by approximately 30%. With the next elevation of the body, the forward velocity decreases and the kinetic energy gained previously is reconverted into potential energy. Unfortunately, this transfer from potential to kinetic and back to potential energy is not completely efficient and requires additional energy output from the legs.

There are two sources of energy output from the legs. The first and most easily understood is the push-off that occurs through plantar flexion of the foot after the contralateral foot has struck the ground. It produces a thrust upward through the leg. Part of this force is transmitted to the body and assists it to "climb the hill" over the extended opposite leg; the remainder initiates hip and knee flexion on the same side and starts the leg swinging forward for the next step. Thus the swinging leg, through the initial push-off and with further assistance from the hip flexors, gains considerable kinetic energy as it moves forward. This kinetic energy is transmitted upward to the torso as the leg is decelerated through action of the hamstring muscles; the deceleration further assists in the forward propulsion of the body. Computations indicate that this deceleration of the swinging leg may contribute more to the forward movement of the body than does the push-off caused by plantar flexion of the ankle.

The realization that the deceleration of the swinging leg transfers its energy to the torso and facilitates forward progression is important, particularly in relation to design of lower-extremity prostheses. One unfamiliar with artificial legs is usually surprised that they are so heavy. The average above-knee prosthesis may weigh between 10 and 15 lb. One may wonder how an amputee can walk with such a heavy artificial extremity; yet a prosthesis that is too light is not usually desired by him. These questions are easily answered by considering the following facts. First, the energy from the deceleration of the swinging leg contributes about half the energy needed for forward movement of the body. Second, kinetic energy is calculated by multiplying mass by the square of the velocity. If a normal person and an amputee walk at the same cadence, the angular velocities are approximately the same. The kinetic energies in the normal leg and the prosthetic leg will therefore be directly dependent upon their masses. If the artificial leg is too light, there will be little kinetic energy available at the end of the swing phase of the prosthetic leg to assist the body in its forward movement, and additional energy must be contributed by the normal leg.

Since the body is moving forward at changing velocities and since this can only be achieved by application of forces against the floor, the resulting floor reactions can be recorded as shears. These fore-and-aft shears are of considerable magnitude —when measured in pounds they approximate 25% of the total body weight (Fig. 6).

As the body is elevated, its forward progression slows and there is a negative shear recorded from the floor. At the time the centre of gravity passes over the weight-bearing foot, no shear is measured. As the centre of gravity of the body passes in front of the foot, it begins to fall. Midway in its fall, plantar flexion of the foot occurs. These two factors combine to initiate forward acceleration of the body. This acceleration is recorded as a positive shear on the floor.

Attention again should be directed to the effect of deceleration of the swinging leg and its contribution to the forward propulsion of the torso. Since its kinetic energy is transmitted upward to the trunk and involves changes in energy level within the body, little change in the shear forces exerted by the floor is recorded.

This transfer of energy back and forth from kinetic to potential within the body conserves energy and minimizes the work of the musculature (Fig. 7). To do this, however, requires that we raise and lower our bodies to gain or lose potential energy and that we move forward at varying velocities to gain or lose kinetic energy. Unfortunately, the system is not perfect; our present best estimate is that the transfer is about 50% efficient. The remaining energy must be supplied by muscle action.

Since bipedal locomotion has been imposed on us by evolution, it is amazing how nature has integrated our up-and-down bouncing with our progression forward in fits and starts. All these seemingly unnecessary and auxiliary motions of the body are required for the proper transfer of energies and the final achievement of a relatively efficient gait.

A major item has been omitted from this discussion: the behaviour of the muscles which constitute the power source for all movement. It should be pointed out here that muscles must act according to their own physiological laws and as a power source have definite limitations when considered from a pure engineering viewpoint. Nature has not ignored these limitations and in locomotion has employed muscles in a very specific manner so as to attain maximal efficiency from them. This, however, is another story—in many ways even more fascinating—but one which cannot be discussed here. In conclusion, let me simply state that the displacements of the body as a whole, the movements of the individual parts of the body, and the behaviour of the musculature all seem to be directed toward a single objective, to move us through space with the least amount of effort.

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PAGES OUT OF THE PAST: FROM THE JOURNAL OF FIFTY YEARS AGO

STAMPING OUT POVERTY

The factor of poverty in sanitary problems was discussed in Washington, November 26, by Surgeon General William C. Gorgas, whose success in cleaning up Havana and the Panama Canal zone have brought him recognition as America's leading sanitarian. His audience was the Clinical Society of Surgeons, assembled in their twenty-fourth annual meeting. Dr. Gorgas said: "Such sanitary work as is necessary in the tropics is inexpensive, but measures directed against special disease are not the greatest good that can be accomplished by sanitation. Before these great results that we can all now see are possible for the sanitarian, we shall have to alleviate more or less the poverty at present existing in all civilized communities.

Poverty is the greatest of all breeders of disease and the stone-wall against which every sanitarian must finally impinge. During the last ten years of my sanitary work I have thought much on this subject. Of what practical measure could the modern sanitarian avail himself to alleviate the poverty of that class of our population which most needs sanitation? It is evident that this poverty is principally due to low wages; that low wages in modern communities are principally due to the fact that there are many more men competing for work then there are jobs to divide among these men. To alleviate this poverty two methods are possible, either a measure directed toward decreasing the number of men competing for jobs, or, on the other hand, measures directed towards increasing the number of jobs.

"The modern sanitarian can very easily decrease the number of men competing for jobs; if by next summer he should introduce infected stegomyia mosquitos at a dozen places in the southern United States he could practically guarantee that when winter came we would have several million less persons competing for jobs in the United States than we have at present. This has been the method that man has been subject to for the last six or seven thousand years, but it does not appeal to me, nor, I believe, to yourselves. This method is at present being tried on a huge scale by means of the great war in Europe. I do not think that I risk much in predicting that, when this war is over and we shall have eliminated three or four million of the most vigorous workers in Europe, wages will rise and for a long time no man will be unable anywhere in Europe to get a job at pretty fair wages. But I am sure that every sanitarian would much rather adopt measures looking toward the increase of jobs rather than, as we have done in the past, submit to measurers that decrease the number of competitors for jobs."—Retrospect of Medicine, *Canad. Med. Ass. J.*, 6: 354, 1916.