CONSERVATION OF ENERGY IN AMBULATION [a b c]

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Within physical and physiologic limitations, the bones and muscles are used in walking so as to achieve the most efficient pattern of locomotion. Minimal energy expenditure would be achieved if human locomotion were in a straight line; progression at a constant velocity would then require only a force sufficient to keep going and to overcome friction. However, the line of progression of the body's center of gravity is not level and the body does not proceed at a constant velocity. It appears that in walking the body is constantly converting energy from potential to kinetic and then back to potential energy again.

AUTHOR'S NOTE: This discussion is a summary of research conducted at the Biomechanics Laboratory by a number of investigators; most of the results have been reported previouly (1–12).

When we at the Biomechanics Laboratory began the study of human locomotion, we thought that measurement of all the conceivable displacements or reactions, such as angular displacements and velocity, would enable us to understand what it is that constitutes human locomotion. However, when we averaged all our findings, we found that the values did not apply to any single one of our subjects. There is no such thing as an average man. We found that our average values for the major displacements of the larger joints, such as the hip, knee, and ankle, were reasonably representative, but when we measured smaller rotatory displacements, such as the rotation of the pelvis and the rotation of the leg about its long axis, we found that these rotations, as projected in the extremity, vary from 3 to 31 deg., or several hundred percent.

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It then became important for us to try to develop a concept of locomotion that could be applied to all human beings. We assumed that each individual employs whatever nature gave him in his attempt to function with the least expenditure of energy. In walking, the bones and muscles are used, within limitations imposed by the laws of physics and the laws of physiology, to achieve the most efficient pattern of locomotion.

I believe that this assumption has been confirmed in our later studies. Therefore, I would like to approach the problem from the standpoint of energy levels and the shift of energies back and forth in the extremities. It is perfectly obvious that minimal energy expenditure would be achieved if human locomotion were in a straight line; progression at a constant velocity would then require only a force sufficient to keep going and to overcome friction.

To achieve progression, however, force must be exerted on the object and must work against a fixed point, because for every force there is an equal and opposite force. If we examine patterns of human locomotion, it becomes evident that in this case the opposite force is the instantaneous reaction from the floor. First, what happens to the body as a whole can be determined by means of floor reactions as registered on a force plate, which records the instantaneous vertical loads, fore-and-aft shears, lateral shears, and torques.

The force-plate data show that as the heel strikes, the reaction from the floor increases, and that for parallelism, as the foot is loaded, a little more than body weight is carried. This occurs as a result of the impact of the foot on the floor. Then the center of gravity of the body starts to descend as it passes over the weight-bearing leg, and as this happens the force plate records less than body weight; in the next few instants, the value drops to as little as about 40 percent of body weight. This happens because the knees are bending and the ankles are plantar flexing. Then, at the time of push-off of the foot from the floor, the force plate again shows increasing load, indicating that, as the body is elevated, the floor reaction is greater than body weight.

A recording of this type indicates that people bounce up and down when they walk. Since the line of progression is not level, the question immediately arises of what would be the most efficient displacement pattern. Mathematically, it would be a sinusoidal curve, and this is precisely what we found—when vertical displacement is measured, the average curve follows approximately a sinusoidal path.

Force-plate records of fore-and-aft shears demonstrate that as the foot strikes the ground there is a negative shear (backward thrust), as the body passes over the leg the shear becomes neutral, and at push-off there is a positive shear (forward thrust).

This means that, in the first part of the phase, the foot is being pushed forward against the floor by the body, while, in the last part, the foot is pushing against the floor to move the body forward. Furthermore, direct measure-

ments of the forward progress of the body substantiate the force-plate recordings—human locomotion does not take place at a constant velocity, but moves faster at one point and slower at the next.

Is it possible that the body in locomotion, because it is moving up and down and because it is varying its horizontal velocity, is converting energy from potential to kinetic and back to potential? It appears that that is precisely what happens.

The proportionate energy transfer will be discussed later in the paper.

But there is another problem. During the double weight-bearing phase there are two shears on the floor: a backward thrust of one leg with a forward shear on the floor, and a forward thrust of the other leg with a backward shear on the floor. This situation results in a force couple that acts on the pelvis and causes it to rotate first in one direction and then in the other. The changes in pelvic rotation occur during the double weight-bearing phase when each leg can contribute to the force couple. Whether certain muscles, either in the trunk or in the leg, may also be active in contributing to this pelvic rotation is, at present, not clear.

Since the forward velocity of the body is increasing during the latter half of the stance phase of one leg, while the other leg is swinging forward to be decelerated to almost zero velocity as it strikes the floor, the question is: How much of this forward force is due to the push-off—and how much is due to the deceleration of the swinging leg?

Electromyograms of muscles of the calf, when the individual walks at 75, 95, or 120 steps per minute, show very little increased activity, which is surprising. The question is: Where does the energy come from to increase the forward speed of the body, if not from a more forceful push-off? It comes from deceleration of the swinging leg. Our calculations indicate that this relation is about five to eight; that is, while five units of work are the result of the push-off, deceleration of the swinging leg contributes eight units. This explains two things. An increase in velocity does not require any increase in output from the calf group of muscles because the deceleration of the faster-moving leg provides the needed increased energy.

This phenomenon explains a common problem encountered in fitting prostheses to amputees. If a prosthesis is too light, the amputee usually does not like it. Most artificial legs feel very heavy to the average person, and a natural reaction is to inquire how the amputee can walk with such a heavy prosthesis. But, if there is too little weight in his prosthesis, the amputee develops less kinetic energy at the end of swing phase to be fed back into the body to maintain his forward velocity. On the other hand, if a leg is too heavy the initiation of swing requires more energy. So there must be a compromise. Ideally, the leg should be light when the swing phase starts, and it should be heavy toward the end of the swing. As yet, no prosthesis that has a changing mass has been developed. A good compromise weight can be calcu-

lated so the prosthesis will not be too heavy to start the swing, and yet will not be too light to feed back energy into the system. We have found that an above-knee prosthesis should weigh approximately 13 to 14 lb.

Energy expenditure has been mentioned briefly earlier in this paper. In order to provide an accurate analysis of human locomotion, it is necessary to combine knowledge gained from studies of energy expenditure with knowledge gained from the force-plate studies.

When engineers discuss energy, they analyze it purely from a mechanical standpoint, and they state that an individual, moving from one point to another and ending at the same elevation, exhibits no change in mechanical energy level even if he runs up and down or down and up a hill. He has done no extra mechanical work (Fig. 1).

The engineer's concept of energy is inadequate to explain the work done by man as a machine because man is also a biologic organism, and movement of his parts requires muscle energy, which requires that oxygen be consumed. We, at the Biomechanics Laboratory, decided to combine studies of the engineer's concept of energy with metabolic studies, in which expired air was sampled for its carbon dioxide content, and oxygen consumption was examined. Results were expressed as energy expended, or calories required per meter when walking at a fixed speed. If the value for energy expended by one individual is divided by his body weight, a value is obtained which can be compared with that for other individuals.

But an interesting phenomenon is observed: If an individual is walking at a low speed, the energy expended per step is relatively high. At a slightly faster walk, the energy used per step lessens, and finally, at a certain rate of speed, perhaps 4.5 km. per hour, a minimum of energy is used. If the subject walks faster, his energy requirements increase again. This fluctuation of energy requirement is quite characteristic of all individuals, men or women.

An amputee walking on a treadmill shows exactly the same pattern of energy expenditure as a normal individual. If the amputee is wearing a pylon, the energy curve is elevated slightly, but it still has a minimum, with

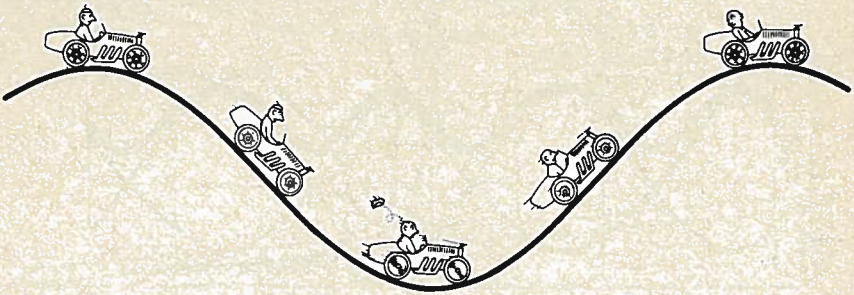

FIGURE 1.—If friction is ignored, no mechanical work has been done because the kinetic energy lost is equal to the potential energy gained.

a sharp rise immediately after the minimum because the pylon has no foot and the amputee therefore, has to climb "out of a hole," which requires additional energy. An individual on crutches will provide the same type of curve. The speed that is adopted by an individual as his most comfortable speed is that at which walking requires the minimal energy per step.

The basal metabolic rate is about 18 calories per minute per kg. of body weight. At zero velocity, that is, with the person standing still, we find that the rate rises to about 21. Walking at a normal pace requires about one and one-half times that, and walking with crutches requires almost three times as much energy.

How can the body integrate its activities and shift mechanical energy back and forth so the most efficient speed is unconsciously adopted? How much conversion back and forth between kinetic and potential energy is provided by the swinging legs and the changing velocity of the body in its forward progression with its up-and-down motion?

Some interesting relationships have been established. If the change in forward velocity is plotted as velocity squared, the curve produced is 180 deg. out of phase with the curve produced by plotting the vertical displacement of the body. If these curves are added algebraically, a curve is obtained which indicates the amount of energy conserved by this transfer (Fig. 2). Approxi-

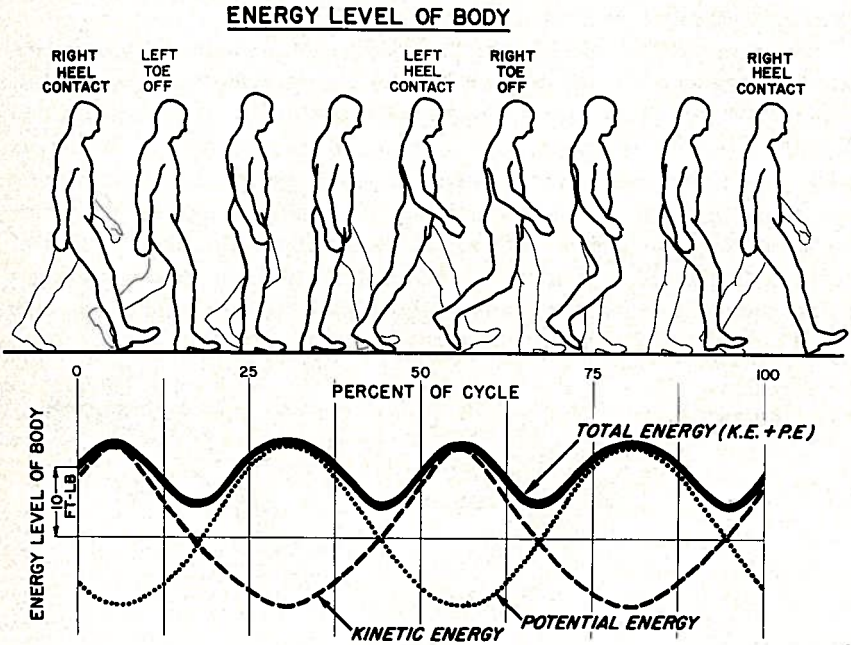

FIGURE 2.—Curves of kinetic energy (forward velocity) and potential energy (vertical displacement) of the body are shown in relation to percent of the walking cycle. The total energy curve is obtained by algebraic addition.

mately 50 percent of the required total energy is transferred (and thus conserved). This explains why it is easy to walk down a slight grade and why it is difficult to walk up it; when walking up a hill, a person raises his body a certain amount. Because of the slope, the body does not fall as far with each step as it is raised. Thus, there is no opportunity to recover as much of the potential energy and convert it into kinetic energy, so even a slight gradual slope requires additional work (Fig. 3). Interestingly enough, there is a linear relationship between grades and energy requirements (within the limits of slopes between +4 and −4 deg.). If the grade is twice as great, the energy requirements are twice as much, indicating that this relationship is probably a mechanical one and not based on any obscure, esoteric physiologic function. What happens when a person walks downhill? Just the opposite curve is produced. Here the center of gravity is raised, and as a person steps forward there is greater potential energy to be transferred into kinetic energy; energy is being fed into the system (Fig. 4).

Now, if we calculate the energy levels of every segment, including the foot, the knee, the thigh, the torso, the arm, and the head, we come out with a very complicated graph. The HAT (head + arms + trunk) rides up and down in the sinusoidal curve of vertical displacement. The curve of the kinetic energy due to the changes in the forward velocity of the body is 180 deg. out of phase. If we summate these curves, the result is a HAT total that is almost a straight line, with a slight elevation indicating change in energies when weight is transferred from one foot to the other and when the rotation of the pelvis begins to shift (Fig.

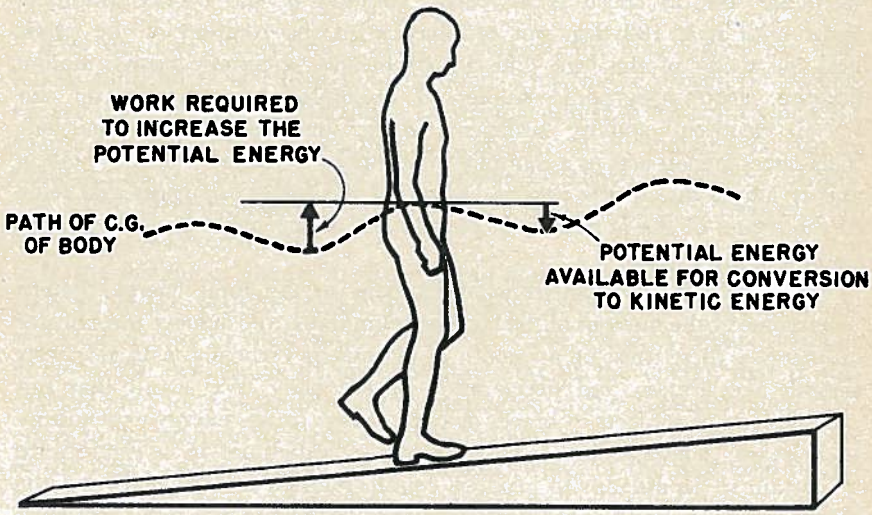

FIGURE 3.—Less potential energy is recovered during walking up a slope; therefore, additional work is required in order to move the body at the same velocity.

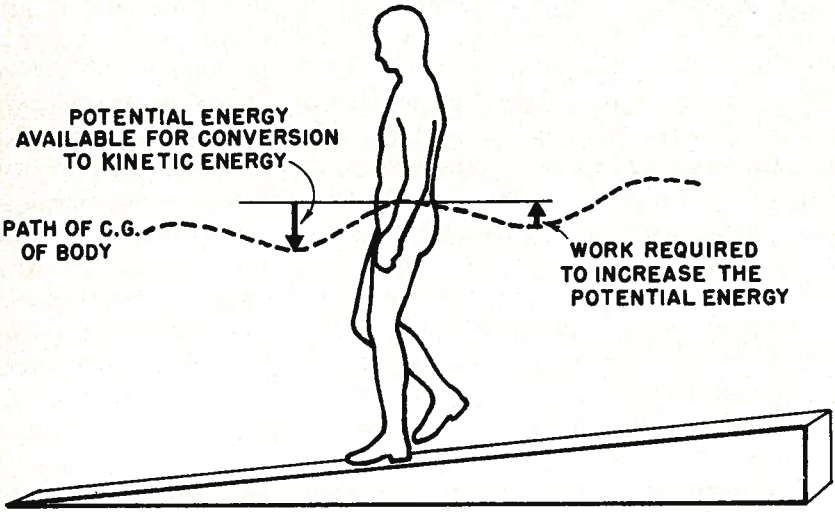

FIGURE 4.—Walking down a hill causes additional potential energy to be fed into the system. A greater velocity can be achieved with the same amount of work.

5). But it looks to us now as if we are carrying head, arms, and trunk more or less as a flywheel, simply so we can convert the energy back and forth. The body above the umbilicus is not contributing anything to locomotion except by its weight.

An individual who walks very slowly rotates his thorax and pelvis in phase, but as speed is increased, rotation of the thorax gradually shifts until it is 180 deg. out of phase with the rotation of the pelvis and the swing of the legs. This is, we believe, a purely passive motion because electromyographic studies of abdominal musculature do not reveal electrical activity sufficient to account for this displacement This phenomenon acts as a damping mechanism to decrease pelvic rotation and is simply due to the passive linkage of the spinal ligaments and some of the tissues of the abdomen. It requires no muscle effort and contributes nothing to locomotion.

We also have investigated what happens to the total energy pattern when some of the motions of the body are eliminated. To achieve the transfer of energies, there must be a smooth displacement vertically, with relatively smooth acceleration and deceleration of the body. We found that immobilization of subjects in braces or casts always causes energy expenditure to increase, generally 10 to 15 percent. An individual in a rigid brace will strain in an attempt to produce counterrotation of the pelvis and the shoulders; complete immobilization of the shoulders not only produces awkward gait, but increases energy expenditure by about 16 or 17 percent.

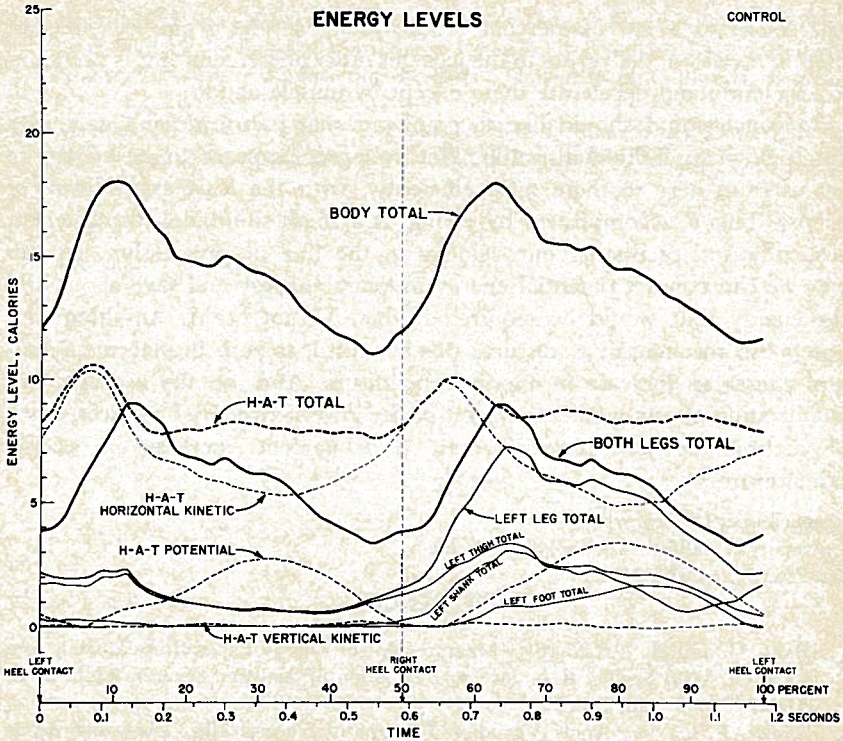

FIGURE 5.—Kinetic and potential energy levels of various segments of the body, measured at 0.02 second intervals during one walking cycle.

Now we have demonstrated that, in general, the body above the umbilicus contributes very little to locomotion. This can be proved by loading experiments. It requires 40 to 50 lb. of weights added to the belt to increase energy requirements by more than 16 percent; an individual can carry a considerable amount of weight at or above his center of gravity. Lifting this added weight requires a little increased energy, which is recovered as the weight is lowered again.

If the weight is placed in other areas, the effect is different, but, in general, if the load is placed on the HAT it does not require much increased energy to walk on the level. Of course, changes occur in uphill or downhill locomotion. It appears that most of the energy that is still unaccounted for (remember that a summation of the potential-kinetic energies produced a curve that goes up and down) is caused by the oscillation of the legs. A summation of all the various swings of the right and of the left legs produces a curve which is similar to the earlier curve. This is almost entirely due to acceleration and deceleration of the swinging leg. At the present time, it appears that the transfer of energy from HAT to

legs conserves about 50 percent of the total energies required, but that there is no way of delivering to the legs this other 50 percent that is necessary to accelerate and decelerate them except by muscle action.

In conclusion I should like to point out that nature doesn't care very much how an individual walks. Nature's goal appears to be to try to get us from here to there most efficiently, with the least expenditure of energy. This is accomplished by giving us a small sinusoidal displacement vertically and oscillating our velocity in the line of progression. In this way we can convert potential energy to kinetic energy and save about half the energy that would be required if this did not occur. Anything that upsets this mechanism or disturbs this beautiful, smooth displacement pattern causes an increase in energy expenditure. And, on the average, immobilization of any segment or joint of the lower extremity by braces, casts, or arthrodesis, will require about a 10-percent increase in energy expenditures.

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REFERENCES

1. Bard, G. and H. J. Ralston: Measurement of Energy Expenditure During Ambulation, With Special Reference to Evaluation of Assistive Devices. Arch. Phys. Med., 40:415–420, Oct. 1959.
2. Berry, F. R., Jr.: Angle Variation Patterns of Normal Hip, Knee and Ankle in Different Operations. Technical Report, Series 11, Issue 21. Prosthetic Devices Research Project, Institute of Engineering Research, University of California, Berkeley, Feb. 1952, 5 pp.
3. Bresler, B. and J. P. Frankel: The Forces and Moments in the Leg During Level Walking. ASME Paper, No. 48–A–62. Trans. ASME, 72:27–36, Jan. 1950.
4. Cunningham, D. M.: Components of Floor Reactions During Walking. Technical Report, Series 11, Issue 14. Prosthetic Devices Research Project, Institute of Engineering Research, University of California, Berkeley, Nov. 1950, 3 pp.
5. Inman, V. T.: Human Locomotion. Canad. Med. Assoc. J., 94:1047–1054, May 1952.
6. Levens, A. S., V. T. Inman, and J. A. Blosser: Transverse Rotation of the Segments of the Lower Extremity in Locomotion. J. Bone & Joint Surg., 30–A: 859–872, Oct. 1948.
7. Lukin, L., and H. J. Ralston: Mechanical Efficiency of Human Locomotion. Fed. Proc., 25:334, Mar.-Apr. 1966.
8. The Pattern of Muscular Activity in the Lower Extremity During Walking: A Presentation of Summarized Data. Technical Report, Series 11, Issue 25. Prosthetic Devices Research Project, Institute of Engineering Research, University of California, Berkeley, Sept. 1953, 41 pp.
9. Ralston, H. J.: Energy-Speed Relation and Optimal Speed During Level Walking. Int. Z angew Physiol., 17:277–283, 1958.
10. Ralston, H. J.: Effects of Immobilization of Various Body Segments on the Energy Cost of Human Locomotion. Proc. 2nd IEA Conference, Dortmund, 1964. Ergonomics (Supplement), pp. 53–60, 1965.

11. Ryker, N. J., Jr.: Glass Walkway Studies of Normal Subjects During Normal Level Walking. Technical Report, Series 11, Issue 20. Prosthetic Devices Research Project, Institute of Engineering Research, University of California, Berkeley, Jan. 1952, 23 pp.
12. Saunders, J. B. deC. M., V. T. Inman, and H. D. Eberhart: The Major Determinants in Normal and Pathological Gait. J. Bone & Joint Surg., 35–A: 543–558, July 1953.