

# A new definition of mechanical work done in human movement

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WINTER, DAVID A. *A new definition of mechanical work done in human movement.* J. Appl. Physiol.: Respirat. Environ. Exercise Physiol. 46(1): 79-83, 1979. —The definition of efficiency of human movement has often been unable to cope with activities such as level gait because the numerator of the efficiency equation includes only external work done by the body on an external load. The major purpose of this paper is to propose a definition that not only accounts for any external work but also for the internal work done by the limbs themselves. The internal work involves a new biomechanical analysis that takes into account all potential and kinetic energy components, all exchanges of energy within and between segments, and both positive and negative work done by the muscles. This analysis was applied to a study of over-ground level gait on eight subjects walking at different walking speeds. The internal work/stride as calculated from the sum of segment energies was compared with the same calculation on the body's center of mass energy. The latter was found to be in error (low) by 16.2% and could be low by as much as 40%. The average internal work per body mass per distance walked was 1.09 J/kg · m.

efficiency of movement; internal work; human gait

IN THE ASSESSMENT of the energy of human movement it is important to have an accurate measure of the mechanical work done by the body. A variety of analysis techniques and definitions have evolved producing anomalous results and differing conclusions. The differences have centered mainly on how to calculate the internal work done by the limbs themselves during any activity. This is especially true in level running or walking when the body returns to the same energy level once per stride. We need a nonzero mechanical work value to use in the efficiency calculation. Similarly, it is desirable to have a correct measure of internal work even when external mechanical work is being done.

The first purpose of this paper is to propose a rigorous definition of internal work that is applicable to any activity. The features of the biomechanical technique that is proposed will account for 1) all potential and kinetic energy components; 2) exchange of mechanical energy within a segment; 3) exchange of mechanical energy between segments; and 4) both positive and negative work done by muscles. As a result, it is maintained that more meaningful and consistent efficiency assessments can be made, and in a wider variety of movements.

The second purpose is to draw attention to the error

in the assumption that the trajectory of the body's center of mass contains the necessary information to calculate the internal work done by the body. This error is particularly important in symmetrical or reciprocal type movements such as running or walking. Symmetrical movements of limb segments, in opposite directions, do not result in a center of mass change; yet distinct kinetic energy changes have taken place.

The basis of any internal work calculation is a total body energy curve versus time. Fenn (10) was probably the first to attempt an accounting of mechanical energy changes. Using cine data of a sprinter he calculated the kinetic and potential energy of each segment, and stated that the work done was equal to the sum of the increases of each of these energies for all segments. Unfortunately, Fenn's calculations ignored two important physical principles: energy exchange within segments and between adjacent segments. Thus his mechanical work calculations were predictably high, and yielded a mechanical power of three horsepower! Post World War II brought considerable impetus because of the needs of the young amputee. Bresler and Berry (2) developed the Newtonian equations for the energy of normal gait in three dimensions. Some of their simplifying assumptions were correct, such as the lateral kinetic energy being negligible. For slow gait they assumed the rotational kinetic energy,  $\frac{1}{2}I\omega^2$ , was small, but in running it cannot be ignored (17, 22). In their summation of energy components, they recognized the energy exchange within segments, but did not analyze the energy of head, arms, and trunk (HAT).

Margaria (13) in a study of uphill, level, and downhill gait on a treadmill arrived at efficiencies ranging from 25% on the uphill, 0% on the level, and -118% for downhill. Such anomalous results point to the need for a measure of mechanical work which is positive for all kinds of activity and does not result in physically impossible efficiencies less than zero. Cavagna and colleagues (4-6) utilized data from force plates to calculate directly the energy of the body's center of mass. The time integral of the horizontal ground reaction force divided by the body mass yielded the forward velocity of the body center of mass. The horizontal work,  $E$ , was calculated from:  $E = \frac{1}{2} (\text{body mass}) \times (\text{horizontal velocity})^2$ . Similarly, the second integral of (vertical reaction force - body weight) gave the vertical work,  $W = mgh$ . The total body energy was calculated equal to  $W + E$ . This calculation recognized an exchange of energy between components. However, there

was a major assumption that was not stated: that the energy of the body's center of mass represents the sum of all segment energies. As indicated previously, reciprocal movements are not accounted for in these force-plate curves. Also, the force plate does not record any measure of segment rotational kinetic energy.

In 1969 Gersten and colleagues (12) utilized a triaxial accelerometer attached to the trunk near the body's anatomic center of gravity and calculated the body's energy from this data. Such an approach yields the energy changes of the trunk only, the energy changes of the limbs remain unknown. From later work (17, 22) it was subsequently shown that the energy changes of the legs in gait far exceed those of the trunk. Ralston and Lukin (17) analyzed the energy of treadmill gait using displacement transducers attached to the centers of mass of the foot, shank, thigh, and trunk. They were able to calculate the potential and horizontal translational kinetic energy of the trunk plus the horizontal translational kinetic energy of the thigh, shank, and foot. These were the more important energy components. What was not obtained were the potential, vertical kinetic and rotational kinetic energy components of all lower limb segments. Also, the string displacement technology associated with this study confined the analysis to gait on a treadmill.

The technique used as a basis of this study is an advanced version of the instantaneous energy calculations made by Winter, Quanbury, and Reimer (22). Such an analysis does not ignore any of the energy components and takes into account energy exchanges within and between segments. Norman and colleagues (14) did a similar segment-by-segment analysis. The only difference in their results was in the way the energy summation was taken. They calculated that total work done assuming no energy exchange between segments. Their approach yielded some very interesting results regarding the efficiency of treadmill running and gave some new approaches about the possible causes of inefficiency.

#### THEORY

The definition proposed for mechanical efficiency,  $\eta_m$ , is one that will be more rigorous under all conditions

$$\eta_m = \frac{\text{internal} + \text{external mechanical work}}{\text{metabolic cost}} \times 100\% \quad (1)$$

We are aware of the dialogue that continues (7, 11, 14, 16, 18) concerning the denominator of the equation. This paper is not addressed to the metabolic cost as a variable, but rather to the more variable and, sometimes, anomalous numerator. This definition may look somewhat similar to others proposed in the past, but is quite different in the way internal work is defined in Eq. 4. If we are interested only in the efficiency of the body to perform external work Eq. 1 becomes work efficiency

$$\eta_w = \frac{\text{external work}}{\text{metabolic cost}} \times 100\% \quad (2)$$

External work is easy to measure, and usually comes directly from the output to an ergometer load, pushing or pulling a load, or lifting a weight. Internal work, on the other hand, is not easy to calculate. It can only be determined from the sum of all energy components (potential and kinetic) of all body segments. This summation yields a total energy curve as a function of time, and for an  $N$  segment model the body energy,  $E_b(t)$ , is

$$E_b(t) = \sum_{i=1}^N PE(i,t) + \sum_{i=1}^N TKE(i,t) + \sum_{i=1}^N RKE(i,t) \quad (3)$$

where  $PE(i,t)$  is the potential energy of the  $i$ th segment at time  $t$ ;  $TKE(i,t)$  is the translational kinetic energy of the  $i$ th segment at time  $t$ ; and  $RKE(i,t)$  is the rotational kinetic energy of the  $i$ th segment at time  $t$ . If we first sum the energy components within any given segment over time we can get the total energy and see the exchange of energy within that segment (22). Then if we complete the summation across all segments to get  $E_b(t)$  we can see evidence of energy exchanges between segments.

To demonstrate the use of this approach an analysis of gait was done using a seven-segment model: three segments for each leg plus one for HAT. The analysis assumes the following: 1) symmetrical gait in the sagittal plane; 2) that HAT can be considered one segment and can be defined by two body markers, one on the pelvis and the other at the mid-trunk region; as all subjects were instructed not to swing their arms excessively the energy of the arms was neglected (2, 3, 7); 3) that energy components in the medial-lateral directions are negligible; and 4) loss of energy due to ground and air friction is negligible. If a more rapid or more complex movement is to be analyzed all that is required is a model and data to include all important components. Equation 3 would still apply.

The time course of  $E_b(t)$  contains the information vital to the calculation of the net internal work done by all body segments. If net positive work is done by muscles then  $E_b(t)$  increases; similarly, a decrease in  $E_b(t)$  is due to negative work by muscles. The total internal work done during a given time, or in our example, during one stride, is

$$W_i = \sum_{i=1}^k |\Delta E_i| \quad (4)$$

where  $\Delta E_i$  is the total body energy change during the  $i$ th period of time; and  $k$  is the total number of sample periods during one stride and is usually defined by the sampling period of the imaging system (cine, TV, optoelectric).

It should be noted that  $W_i$  includes both positive and negative work and is so defined because both types of muscle contractions contribute to the metabolic cost that is seen in the denominator of the efficiency equation. However, there is no difficulty in separating the positive and negative components in Eq. 4, if it is desired.

## METHODS

Coordinate data were obtained from eight subjects walking at different speeds in the Gait Laboratory in the Dept. of Kinesiology at the University of Waterloo. Each subject had reflective markers attached on the following anatomic landmarks: toe, metatarsophalangeal (m-p) joint, heel, ankle (lateral malleolus), lateral head of fibula, lateral epicondyle of femur, greater trochanter, iliac crest, and midtrunk region. Each subject wore his own footwear, and walked on a raised walkway while a tracking cart, carrying a TV and cinecamera, was guided on a track at a distance of 4 m. Background markers on the wall beside the walkway gave a "yardstick" reference so that body coordinates could be properly scaled, and obtained as absolute coordinates (20).

Coordinates of the body and background markers were extracted from cinefilm using a Numonics Digitizer interfaced with a Nova 1200 computer. Raw coordinate data were corrected for parallax error between the plane of progression of the subject and the plane of the background, then transferred to an IBM 370 computer for kinematic processing. The "noise" in the coordinate data, mainly due to the digitizing process, has been calculated to have an rms error of 2 mm. Prior to link segment energy analyses the coordinates were digitally filtered (23) using a fourth-order, zero-lag, low-pass Butterworth filter cutting off at 5 Hz. Validation for the filtering and finite difference calculation of velocities and accelerations is supported by the study by Pezzack, Norman, and Winter (15). For each subject anthropometric data were obtained using tables provided by Dempster (8), based on the subject's height and weight.

Data were digitized for one and one-half strides, and based on the assumption of symmetrical gait, data recorded for the right leg became the data for the left leg after it was shifted in time exactly one-half stride. In this way one complete stride was analyzed, and care was taken that the stride to be analyzed was symmetrical as far as stance and swing times would indicate. Based on this model the energy was calculated two ways. First,  $E_b(t)$  was calculated using Eq. 3. Second, the height and velocity of the body's center of mass was calculated, which yielded its potential and translational kinetic energies. The sum of these two energy components gave the total energy of the body's center of mass, similar to that calculated by Cavagna and colleagues (4-6) using force-plate data. From each of the two body energy curves the internal work per stride was determined using Eq. 4; then the work per unit distance per unit of body mass was tabulated.

## RESULTS

The two total body energy curves for one of the subjects is presented in Figs. 1 and 2. Figure 1 shows the net energy of the left and right leg, HAT, and the total body segment energy. Figure 2, for the same data, gives the kinetic and potential energies of the body's center of mass plus the total of these two components. A comparison of these total body energies, calculated the

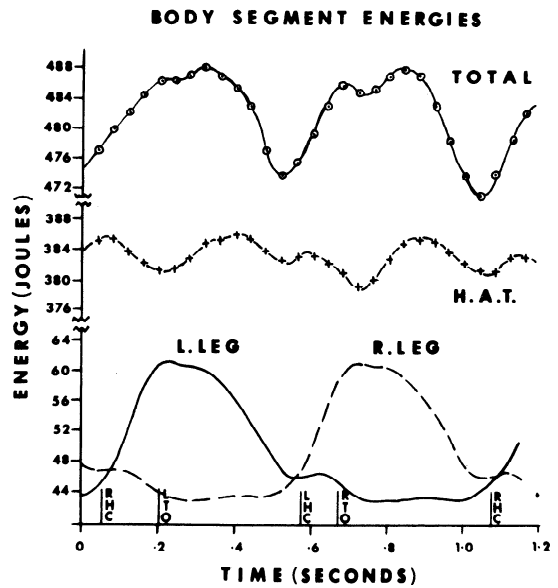


FIG. 1. Energy of leg and HAT segments of the body during level overground walking. Total body energy reflects exchanges of energy between segments. See text for detailed discussion.

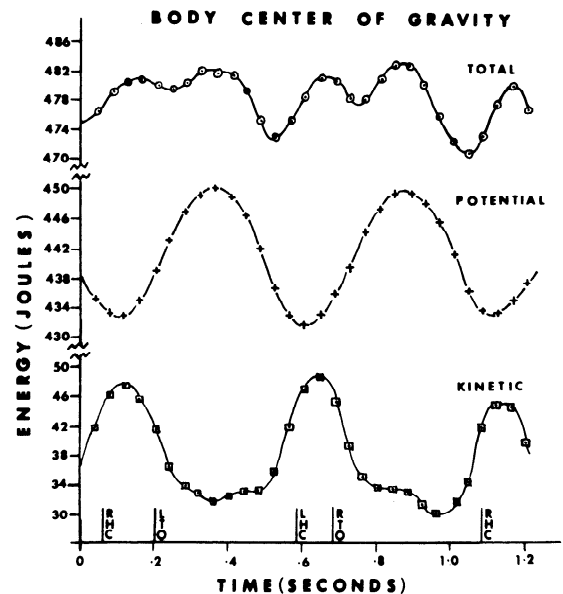


FIG. 2. Potential and translational kinetic energies of body's center of mass for same data as in Fig. 1. Total energy of body's center of mass reflects to a certain extent the kind of energy changes that are occurring within and between segments.

two different ways, is presented in Fig. 3. Finally, in Table 1 the results of the internal work per stride ( $E_q$ . 4) is tabulated.

The percentage error of the body center of mass approach was calculated and expressed as a percent of the sum of segment energies. The average error was 16.2% on the low side, and could be low by more than 40%. The average internal work done per unit mass and distance was  $1.09 \pm 0.26$  (SD) J/kg·m.

## DISCUSSION

The sum of segment energies as shown in Fig. 1 demonstrates the net changes in total body energy after

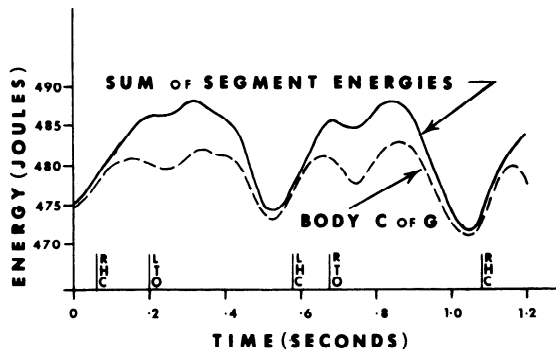


FIG. 3. Comparison of total body energy as calculated from body's center of mass and from sum of segment energies. Inability of body center of mass approach to detect energy changes due to reciprocal movement results in lower average energy and lower changes during gait stride. See Table 1 for differences based on gait analyses of 8 subjects.

TABLE 1. Mechanical energy per stride, mass, and distance for level walking

Subj No., Sex, Ht, Mass, Trial	Ctr of Grav Energy, J	Sum Seg Energies, J	Diff, %	Energy/Distance, J/m	Energy/Mass·Dist, J/Kg·m	Cadence, steps/min	
WN 21, M, 1.79 m, 80 kg	B	125.1	151.5	-17.4	96.3	1.20	89
	C	115.6	128.7	-10.2	91.6	1.14	85
	F	144.9	166.5	-13.0	104.7	1.31	106
	H	100.8	120.1	-16.1	75.6	0.95	84
	G	132.7	152.1	-12.7	91.0	1.14	124
WN 22, M, 1.85 m, 77 kg	A	159.2	163.1	2.4	104.2	1.36	108
	E	120.0	147.2	-18.5	92.6	1.21	122
	F	158.7	166.7	-4.8	102.3	1.33	112
	G	113.2	135.0	-14.9	81.1	1.06	120
	H	85.2	94.0	-9.4	60.3	.79	90
	I	216.7	251.7	-13.9	144.6	1.88	126
WN 23, F, 155 m, 50 kg	B	94.2	123.7	-23.8	81.3	1.63	166
	C	70.7	68.5	+3.2	51.5	1.03	130
WN 25, M, 1.73 m, 73 kg	A	65.2	111.8	-41.7	74.1	1.02	150
	B	78.6	123.7	-36.5	82.5	1.13	150
	C	93.6	88.8	+5.4	62.7	0.86	130
WN 27, F, 1.52 m, 55 kg	A	67.4	71.8	-6.1	57.5	1.05	115
	B	88.3	96.1	-8.0	86.0	1.56	97
	C	70.8	85.2	-16.9	66.1	1.20	133
WN 28, F, 1.57 m, 49 kg	A	59.1	78.4	-24.7	50.4	1.04	133
	B	47.6	66.4	-28.3	52.7	1.08	118
	C	32.8	48.5	-32.3	37.1	0.76	146
WN 29, M, 1.70 m, 66 kg	A	80.0	93.5	-14.5	60.1	0.91	113
	B	79.0	94.6	-16.5	65.7	1.00	100
	C	84.0	98.8	-15.0	63.7	0.97	125
WN 30, M, 1.82 m, 65 kg	A	77.9	94.1	-17.2	54.1	0.83	105
	B	88.1	116.8	-24.5	64.9	1.00	86
	C	83.1	106.3	-21.8	70.4	1.08	111
WN 20, M, 1.79 m, 79 kg	A		193.0		129.5	1.65	110
	B		130.0		85.2	1.08	102
	D		100.00		75.8	0.96	92
Avg ± SD			-16.2 ± 10.6		1.09 ± 0.26	119	

all energy exchanges within the body have been accounted for. The major increases are due to net positive work by several muscle groups at push-off and early swing, the major decreases occur in late swing and weight acceptance due to eccentric activity of several muscle groups absorbing mechanical energy. The com-

plete details of the mechanical power generation and absorption is beyond the scope of this paper, and has already been reported (19, 21). Both concentric and eccentric muscle activity have a metabolic cost and therefore must be included in any efficiency calculation. It is recognized that the efficiency of negative work is higher than that for positive work (1); thus any efficiency calculation using this definition of internal work will lie between the two efficiency extremes. It is interesting to work out a hypothetical example to see what additional interpretation can be gained. Suppose the positive and negative mechanical work per stride was 60 J each, and the metabolic cost per stride was 300 J. Using positive work only the efficiency would be 0.2; using both positive and negative work it would be 0.4. If we assume positive work is twice as efficient as negative work we would then calculate the positive work efficiency to be 0.3 and negative work efficiency to be 0.6.

The total body energy, as calculated from the center of mass (Fig. 2), was predictably quite similar to that calculated by Cavagna and Margaria (5) using force-plate data. As a result of the symmetry of the gait, two peaks occur per stride. Potential energy reaches a maximum as the body rises at midstance and falls during double support; the kinetic energy component has the opposite variations. As predicted, the center of mass energy is lower and shows less change than the sum of segment energies (Fig. 3). This error is due to the fact that the center of mass approach fails to account for energy changes present in reciprocal movements, clearly demonstrated by this example of gait. The individual energy components are scalar quantities (always positive); thus the energy associated with reciprocal movements always adds, whereas the center of mass approach adds vectors that can cancel. The integral of the energy changes (absolute value) during one stride, for this example analysis, was 62.2 and 51.3 J, the lower value being for the center of mass technique. The average error is shown to be low by 16.2% and can be as much as 40%.

Another significant error can be seen when assessing the technique used by certain researchers (12) who have attached a marker or accelerometer near the anatomic center of gravity. They have analyzed the data from an anatomic landmark located on the trunk and calculated the associated potential and kinetic energies. This would yield a total energy curve not unlike that for HAT as shown in Fig. 1. It is quite evident that this curve bears little relationship to the total body energy curve plotted immediately above it. The major changes due to each of the legs is not seen in the HAT energy curve; in fact, an accelerometer attached to the trunk can, at best, yield nothing more than the energy changes of that segment alone.

**Conclusions.** First, a new measure of internal mechanical work done is presented accounting for all energy exchanges within the body and for both positive and negative work. The same analysis permits, if desired, a separation of total positive and negative work components. Second, a new definition of efficiency of human movement is presented utilizing the internal mechanical work plus external work in the numerator.

This definition overcomes the anomalous situations in level and downhill gait which previously yielded efficiency values of zero or negative. Third, utilizing level overground gait as an example of reciprocal movement the error associated with the energy of the body center of mass was calculated to be low by 16.2%. Finally, the

internal mechanical work done per unit mass and distance walked was calculated to be 1.09 J/kg·m.

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