A MODEL FOR THE CALCULATION OF MECHANICAL POWER DURING DISTANCE RUNNING

KEITH R. WILLIAMS
Physical Education Department, University of California at Davis, Davis, CA 95616, U.S.A.

and

PETER R. CAVANAGH
Biomechanics Laboratory, The Pennsylvania State University, University Park, PA, 16802, USA.

Abstract—Because widely varying estimates of mechanical power have been calculated for a given speed of running by previous investigators, the effects of various assumptions necessary for mechanical power calculations were evaluated via a segmental energy analysis using 3-D cine data from 31 well-trained subjects running overground at 3.57 m s⁻¹. The magnitude of power calculated was very dependent upon assumptions involving the amount of between segment energy transfer occurring, the relative metabolic cost of positive vs negative work, the amount of the total negative work attributed to muscular work, the effects of elastic storage of energy and on the choice of cutoff frequency in filtering the coordinate data. Mechanical power values ranged from 273 to 1775 W depending on the particular assumptions made and computational methods employed giving efficiency ratios from 0.31 to 1.97. These results point to a need for more definitive research into the role played by energy transfer, negative work, and elastic storage of energy before confidence in measured mechanical power can be established.

Previous research dealing with the calculation of mechanical power output during distance running has utilized two primary analysis procedures, one involving movements of the center of mass alone, often termed 'external' work, and the other utilizing a segmental approach, termed 'internal' work. Table 1 summarizes the results of a number of studies which have produced measures of mechanical power during running at approximately the speed used in the present investigation (3.57 m s⁻¹). It is obvious from Table 1 that an extremely wide range for mechanical power has been found previously for running at approximately 3.6 m s⁻¹, even when using the same computational method for determining power. Since efficiency ratios are determined by dividing mechanical power by metabolic work rates, the efficiency ratios would be greatly affected by this wide range of values. Clearly, some systematic investigation into these differences is needed.

When work is done on a body segment, the energy

Table 1. A survey of mechanical power values obtained in previous studies calculated using a variety of computational methods. In some cases the data were extracted from graphs and should only be considered approximations. Original units have been converted to watts.

<table>
<thead>
<tr>
<th>Method*</th>
<th>Approx speed (m s⁻¹)</th>
<th>Mechanical power (W)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fukunaga et al. (1978)</td>
<td>3.6</td>
<td>343</td>
</tr>
<tr>
<td>Cavagna et al. (1977)</td>
<td>3.6</td>
<td>556</td>
</tr>
<tr>
<td>Norman et al. (1976)</td>
<td>3.6</td>
<td>172</td>
</tr>
<tr>
<td>Gregor &amp; Kirkendall (1978)</td>
<td>3.9</td>
<td>165</td>
</tr>
<tr>
<td>Luhtanen &amp; Komi (1978)</td>
<td>3.9</td>
<td>931</td>
</tr>
<tr>
<td>Luhtanen &amp; Komi (1980)</td>
<td>3.9</td>
<td>1650</td>
</tr>
<tr>
<td>Winter (1979b)</td>
<td>1.4</td>
<td>141</td>
</tr>
<tr>
<td>Pierrynowski et al. (1980)</td>
<td>1.5</td>
<td>166</td>
</tr>
<tr>
<td>Zarrugh (1981)</td>
<td>1.5</td>
<td>71</td>
</tr>
</tbody>
</table>

*The various methods used were: 1. Center of mass (CM) alone; 2. CM + movement of limbs relative to CM; 3. Pseudowork—see Appendix; 4. Segmental analysis—see Text; 5. Walking.

Received for publication 1 November 1982.
level of that segment is altered. The instantaneous energy level can be defined as the sum of the potential and kinetic (both translational and rotational) energies of the segment. These changes in energy levels can result from a variety of sources, as illustrated in Fig. 1. The most obvious source of mechanical power during running is muscular activity, but it is important to realize that the relationship between mechanical and metabolic measures of power will differ depending upon whether the contraction is concentric or eccentric. For a given magnitude of mechanical power, the metabolic cost of negative power is markedly less than that for positive power (Abbott and Bigland, 1953; Nagle et al., 1965). If an activity consists of appreciable positive and negative components, some method is needed to modify the mechanical power calculations to reflect these differences.

A second source of mechanical power is the release of energy previously stored in the elastic tissues of the musculo-skeletal system (Asmussen and Bondesson-Peterson, 1974; Cavagna et al., 1964, 1965, 1968, 1971, 1977). In an activity such as distance running, the greatest potential for storage of elastic energy comes from within the active muscles and their tendinous attachments. Some passive storage in joint ligaments during some phases of the running cycle is also theoretically possible. In order for energy to be stored elastically and subsequently recovered, the muscles involved must remain continuously active or the energy will dissipate as heat. If movement conditions permit the stored energy to be released, positive power will result but no additional metabolic cost will be incurred. The metabolic source of this positive mechanical power comes, indirectly, from negative muscular work. Clearly, if appreciable use of elastic energy is involved in an activity, comparisons of mechanical and metabolic power must account for elastic contributions.

A third major contributor to mechanical power during running is transfer of energy between segments. If one segment loses energy and another gains energy, it is possible that the positive changes resulted from energy transfer and not from concentric muscular activity. In such a case mechanical power calculations must again be adjusted to account for the contribution coming from energy transfer between segments. An important question concerns the factors which can cause a segment’s energy to decrease, since it is only then that there is the possibility for energy to be transferred. The dominant factor is again likely to be eccentric muscular contractions involving dissipation of power (negative power), with other possible contributors being joint motion limitations and perhaps to a lesser extent muscle viscosity.

The negative mechanical power measured may or may not involve metabolic cost, depending on whether the related decrease in segmental energy is due to eccentric muscular contraction, or to the other factors which do not involve active musculature. It would be desirable to partition the negative power into its various muscular and non-muscular sources.

**CENTER OF MASS POWER CALCULATIONS**

In 1930, Fenn (1930 a, b) evaluated the power involved in sprint running using movements of the center of mass as well as movements of the limbs relative to the center of mass. He obtained an estimated mechanical power of 2200 W (2.95 horsepower). Cavagna and his colleagues (1964, 1968, 1976, 1977) have variously used movements of the center of mass either alone or in conjunction with limb movements relative to the center of mass to calculate mechanical power during running, finding values ranging from 240 to 500 W. Fukunaga et al. (1978) using measures derived from the center of mass alone found mechanical power values ranging from approximately 340 to 650 W (70 to 134 cal kg\(^{-1}\) min\(^{-1}\)) for running speeds.
from 3 to 9 m s\(^{-1}\). Winter (1978) has criticized mechanical power calculations using the center of mass alone because it does not measure the 'internal' work done by the limbs. Cavagna (1977) has acknowledged that even his method which includes limb movements may underestimate the total work done by up to 12.5\%, because only increases in the kinetic energy of the limbs, and not decreases, are included. It is likely, then, that the values show in Table 1 which were derived from either the center of mass alone or in conjunction with movements of the limbs relative to the center of mass are likely to be underestimates of the total work performed for running at approximately 3.6 m s\(^{-1}\).

**SEGMENITAL POWER CALCULATIONS**

There have been several methods used in the past for the calculation of mechanical power using a segmental approach. Though all the techniques use changes in the instantaneous energy of each segment, they differ in the precise method by which the changes are summed. Among the first to use a segmental approach were Bresler and Berry (1951) who calculated segmental energy levels, joint power and energy transfer for the legs during walking. Many of the ideas presented were built upon by later investigators. Norman et al. (1976) developed an analysis procedure, termed pseudowork, which has subsequently been used by Gregor and Kirkendall (1978), and Luhtanen and Komi (1978, 1980). In this method the absolute changes in the instantaneous energy of a segment's potential energy (PE), translational kinetic energy (TKE) and rotational kinetic energy (RKE), are summed together over the entire cycle. (Computational formulae for this and other methods are listed in the appendix.) Winter (1978) has pointed out that the pseudowork method does not allow for between segment energy transfer and thus can lead to an overestimation of the work done. Because the absolute values of energy changes for each segment are added in individually, there is no chance for an increase in energy from one segment to be accounted for computationally by a decrease in energy from another segment. This situation therefore prohibits between segment energy transfer.

Another consideration that is equally important, at least for running, is that the pseudowork method does not allow for energy exchange between energy forms (PE, RKE, TKE) within a segment (Pierrynowski et al. 1980). This leads to an even greater overestimation of the amount of work done. As an example of this, if the PE of a segment decreased by 5 J and all of this energy were transferred into 5 J of kinetic energy for the same segment, as could occur during free fall, no net work would have been done. The pseudowork method, however, would add the absolute value of the decrease in PE | = 5 J | to the increase in kinetic energy (5 J) to show a total of 10 J of work being done—an obvious error. Since there is an appreciable amount of time during which the body is in free fall during the running cycle it is likely that such anomalies greatly affect the final results.

It is certain then that the pseudowork method for calculating mechanical power will significantly overestimate the power generated. The results from four studies using this method are listed in Table 1 and show an unexpected range from 163 to 1650 W for running at approximately the same speed. These values are even more surprising when compared to power calculated using the center of mass methods which were thought to be underestimates of the total generated. The reasons for these discrepancies between studies utilizing identical methodologies are unclear.

Winter (1978, 1979a, 1979b) has proposed a refinement of the methods of segmental energy analysis which attempts to account for energy transfers both within and between segments. (See Appendix.) In his total transfer algorithm, transfer of energy between segments occurs when the total instantaneous energy of one segment decreases. The energy lost is transferred through the musculoskeletal system to another segment, which shows an increase in total segment energy. Several questions can be raised concerning this analysis procedure.

First, in accounting for transfer of energy between segments the total transfer equations developed by Winter allow exchange to occur between any segments of the body. In an extreme case, if the left foot decreased its total energy during a given time interval and the energy of the right forearm increased by the same amount, while all other segments remained at the same energy level, the equations used in this method would assume that complete transfer of energy had occurred between the two widely separated segments. An alternative explanation, which cannot be directly evaluated, would be that the decrease in energy of the foot was absorbed by musculature of the leg, and that the increased energy of the forearm was due to active contractions of arm muscles. In this case both positive (forearm) and negative (foot) muscular work has been done, but no net mechanical power would be recorded if complete between segment energy transfer is assumed. The extent to which this type of exclusion of power may be prevalent in an actual locomotor situation cannot be ascertained directly. It may in fact be minimal, but is sure to occur to some extent and is likely to be dependent on speed.

The second possible area of confusion in the algorithm presented by Winter involves two different considerations of the role of negative power. First, it has been shown that during cyclic activities such as running or walking the total negative power is equal in absolute magnitude to the total positive power (Winter, 1979b; Zarragh, 1981). Though Winter (1978) does recognize that the relative metabolic costs of each type of power can be accounted for by assuming different efficiencies for positive and negative power, his total transfer equations as usually presented do not incorporate such a scheme. Instead, the entire absolute value of his measure of negative power is added to net
positive power (Winter, 1978, 1979b). This procedure has been changed somewhat in later work to which he was a contributor (Pierrynowski et al. 1980).

Secondly, it would also appear that the means by which between segment energy transfer is accounted for prevents some amount of negative power generated from being included. As an example, consider the situation described previously where one segment loses 5 J of energy and another gains 5 J. Winter's method adds the energy changes from all segments and would result in a net change of zero for this simple example. Though the increase in segmental energies due to energy transfer should not be attributed to the muscles, if it is assumed that eccentric muscular action caused the 5 J decrease in one segment's energy, then this amount of negative mechanical power should somehow be incorporated into the total power calculated. Winter's method of calculation mathematically cancels both out. It should be noted, however, that some portion of the negative mechanical power is likely to result from non-muscular factors. Though the effects of muscle viscosity or friction have been in question for a long time, the relative importance of such factors are still unknown (Pierrynowski et al. 1980) though likely to be small. Another factor which could contribute to negative mechanical power when a joint is near either of its extremes of motion would be passive ligamentous restriction to joint motions. Again, the relative contribution of such factors to the measured negative power is unknown.

Table 1 includes results from several walking studies using Winter's methods or modifications of them. Since results using these methods have not been published for running, the walking data are useful for comparative purposes. Pierrynowski et al. (1980) calculated mechanical power during walking at 1.5 m s\(^{-1}\) using three methods, one which allowed no energy exchange (pseudowork = 501 W), one which allowed within segment exchange but no transfer between segments (340 W), and the last which allowed total energy transfer between and within a segment (166 W). Energy transfer thus accounted for 67\% of the total power derived using pseudowork (32\% from within and 35\% from between segment transfer). These results highlight the importance of energy transfer.

Zarrugh (1981) employed a three-dimensional analysis of leg motion, combined with changes in the HAT (head, arms, and trunk) considered as a unit, to provide measures of mechanical power during walking. The algorithm employed was similar to that used by Winter (1978), but the metabolic cost of negative work was assumed to be zero and thus he derived a measure of the average positive power during the gait cycle. This value represents a lower bound for the mechanical power generated. The effects of this assumption on the results can be seen in Table 1, where Zarrugh's mechanical power value of 71.4 W is approximately one-half that found by Pierrynowski et al. (1980) and Winter (1978).

### ELASTIC STORAGE OF ENERGY

The extent to which elastic storage of energy contributes to measured mechanical power during an activity such as running is unclear, but it is certain that not all the negative power is dissipated as heat. Isolated muscle experiments have shown elastic storage to be a substantial contributor to positive work (Cavagna et al., 1965, 1968), but the magnitude of the contribution to more complex activities is very difficult to determine. Cavagna et al. (1964, 1971) have attributed as much as 50\% of the total cycle mechanical power to reuse of elastic energy for some faster speeds of running, but these estimates come from indirect reasoning rather than direct calculation. Thys et al. (1972) and Asmussen and Bondé-Peterson (1974) have attributed 22–26\% of the work performed in a test situation involving knee bends to elastic storage of energy. Unfortunately no viable method has yet been devised for quantifying directly the extent of elastic storage of energy during running. Measures of mechanical power will therefore overestimate the amount of positive power performed by the muscles themselves as long as no means of estimating elastic storage is included.

### THE PRESENT STUDY

In an attempt to investigate some of the discrepancies found in the literature, the present study examined the mechanical power generated in distance running at a speed of 3.57 m s\(^{-1}\) by using a variety of computational methods. The effects of assumptions involving the relative cost of positive and negative work, the contributions of energy transfer, and the influence of elastic storage of energy are considered. The basic segmental methodology has been modified and expanded to provide a measure of power which provides the opportunity to account for the effects of negative work and elastic storage. Various alternatives to the assumption of complete energy transfer are also discussed. While segmental methods incorporating between and within segmental energy transfer have been applied extensively to walking, the literature contains no studies where they have been used for a mechanical power analysis of distance running as has been done in this work. In addition, the use of three-dimensional cinematographical techniques has allowed for a more accurate analysis of total body power than has been available previously since movements out of a sagittal plane are accounted for, and no assumption of symmetry between right and left sides is needed.

#### Data collection

Techniques of three-dimensional cinematography were used to obtain kinematic data for segmental movements from thirty-one well-trained runners during overground running. Figure 2 illustrates the indoor experimental area and shows the locations of...
Calculation of mechanical power during distance running

the 4 Locam cameras used. Film was obtained at a nominal rate of 100 fps from each camera as each subject ran through the experimental area at a speed of 3.57 m s⁻¹ ± 5%. Three dimensional calibration of a volume of space large enough to include one complete running cycle (0.8 x 2.0 x 3.8 m) showed rms errors of 0.0034, 0.0036, and 0.0034 m in the x, y and z directions for a prediction of the known coordinates of small spheres spread throughout the field.

Cine film for one trial for each subject was digitized using a Bendix data grid digitizer on-line to a PDP 11/34 mini-computer. Data was obtained from each camera from 10 frames prior to the first left foot contact until 10 frames after foot strike of the subsequent left foot contact. The coordinates for twenty locations on the runner's body were obtained from each frame, primarily using visual estimation of joint centers. A series of anthropometric measurements were made on the subjects and subsequent body segment parameters for a twelve segment model were derived using the regression equations from Clauser et al. (1969) for segment mass and center of mass locations, and from Whittsett (1963) for segmental moments of inertia. Corrections were made to include the influence of shoe mass on foot parameters. Segments included the head, trunk, and upper arm, forearm plus hand, thigh, shank, and foot from both sides of the body. Segment lengths were fixed for each frame to mean values from the entire cycle. Three dimensional coordinates were obtained using the DLT algorithm of Abdel-Aziz and Karara (1971). After digital filtering at 5 Hz, the data were analyzed for translational velocities of the center of mass of each segment, and for segmental angular velocities. Calculation of the instantaneous potential, translational kinetic and rotational kinetic energies were then obtained for each segment for each frame of data during one complete cycle for each subject (see Appendix).

In order to provide some quantitative measure of the effects of elastic storage of energy on performance, the contribution of elastic energy to the work done in knee bends was assessed using the techniques of Thys et al. (1972) and Asmussen and Bonde-Pedersen (1974). The specific methods used are detailed elsewhere (Williams, 1980). One method of performing knee bends could utilize elastic storage while the other could not, and percent differences in Vo₂ between the two conditions during steady-state was used as a measure of elastic contributions. While utilization of stored elastic energy in knee bends in this experimental procedure is likely to be somewhat different than that used in running, the results provide an order of magnitude estimation of possible contributions during running and give some input as to variability among individuals.

In order to provide an indication of the suitability of the various mechanical power methods, the subjects were divided into three significantly different (p < 0.01) physiological efficiency groups based on net submaximal oxygen consumption (Vo₂) obtained while running at 3.57 m s⁻¹ on a treadmill. Divisions for each group were: (1) < 3.80, (2) between 3.80 and 40.0, (3) > 40.0 ml kg⁻¹ min⁻¹. Methods of Vo₂ collection were typical and are described elsewhere (Williams, 1980). An analysis of variance was applied to the various mechanical power methods across the three groups to delineate any relationship existing between mechanical and physiological efficiency.

## TOTAL CYCLE ENERGY ANALYSIS

### Methods from previous investigations

Once instantaneous energies for all segments were derived for all subjects, total cycle power was calculated using a number of methods for comparison. In addition to the approach developed in this paper, the pseudowork method of Norman et al. (1976), the methods of Winter (1978b) and modifications of them (Pierrynowski et al., 1980; Zarrugh, 1981), and analyses involving the work done by the center of mass alone were also applied to the data. Details of these calculations are found in the Appendix.
Total cycle power

Before comparisons can be made between mechanical and metabolic power outputs, it is necessary to adjust the total mechanical power to reflect the influence of the between segment energy transfer, elastic storage of energy, the difference in metabolic cost between positive and negative muscular work, and passive musculoskeletal resistance to motion in the limbs. The following equation to be explained in detail below was developed to serve as a model for the mechanical power that is directly associated with muscular work:

\[ PTOT = (1 - a_i)(1 - b_j)TPOS + \frac{c_i TNEG}{d_j} \]  

(1)

TPOS is the total positive power assuming complete within segment energy exchange, but not accounting for the other factors described previously. TNEG is the total negative power. If power by the CM alone is being calculated, TPOS and TNEG represent the sums of positive and negative energy changes of the CM across frames, respectively. The coefficients, \( a_i \) and \( b_j \), provide the means for adjusting the total power to account for between segment energy transfer, elastic storage, passive musculoskeletal resistance in the limbs, and the relative metabolic cost of positive and negative muscular work, respectively.

PTOT then is the total measured mechanical power output adjusted for these factors. The assumptions behind values ascribed to each of the four coefficients will be discussed in detail subsequently and are defined as follows:

\( a_i \) — the fraction of TPOS attributable to between segment energy transfer in the \( i \)-th condition \((i = 1, 4)\) of allowable energy transfer;

\( b_j \) — the fraction of \((1 - a_i) \times (TPOS)\) attributable to elastic storage of energy in the \( j \)-th condition \((j = 1, 4)\) of the allowable elastic storage;

\( c_i \) — the fraction of the total negative power which is the result of eccentric muscular contraction rather than passive resistance within the musculoskeletal system in the \( k \)-th condition \((k = 1, 3)\) of eccentric muscular contributions;

\( d_j \) — the relative metabolic efficiency of negative to positive muscular power, used to adjust the negative power output to reflect metabolic differences between the two modes of work for condition \( l (l = 1, 4)\).

Between segment energy transfer

The new approach to mechanical power calculations derived in this study followed the basic algorithm of Winter (1979b) with several modifications to the way negative power is calculated, and to assumptions used for between segment energy transfer.

In determining the positive mechanical power attributable solely to concentric muscular sources (NETPM) both transfer of energy and elastic storage of energy must be considered. Because the exact amount of positive power that results from energy transfer cannot explicitly be measured, four progressively restrictive schemes of transfer were applied to the data which involved limiting the segments between which transfer was assumed to occur. Four possible values for the power transferred (ETR\(_i\)) resulted for each subject individually depending upon the transfer criteria selected. The most restrictive condition assumed no between segment energy transfer (NOTR) and the least restrictive allowed total transfer between all segments (TOTTR), the same transfer criterion used in the total between segment transfer and no between segment transfer methods suggested by Winter (1979b). Intermediate between these extremes, two other conditions were imposed. One assumed energy transfer could occur only between adjacent body segments (SEGTR) while the second was somewhat more liberal in that it allowed transfer between segments of a given limb or to the trunk, but not across the trunk to another limb (LIMBTR). By determining the amount of power transferred under any of these transfer criteria (ETR\(_i\)), coefficient \( a_i \) for each subject can be calculated by dividing ETR\(_i\) by TPOS.

\[ a_i = \frac{ETR_i}{TPOS} \]  

(2)

Thus, net positive power after energy transfer is accounted for (NETPTR\(_i\)) would be derived from the equation:

\[ NETPTR_i = (1 - a_i)TPOS \]  

(3)

The four transfer criterion used allowed for four values \((i = 1, 4)\) to be determined for each subject for coefficient \( a_i \) for use in equation (1). It should be noted that even though positive power attributed to energy transfer is effectively subtracted out, the energy transfer process is not without metabolic cost. Instead it is included in the calculations for negative power since it results indirectly from eccentric contractions. These transfer conditions allowed for a more detailed examination of the effect of energy transfer on mechanical power calculations with the intent of suggesting which condition was most likely to be representative of the actual situation.

Elastic storage of energy

The net positive power after energy transfer has been accounted for (NETPTR\(_i\)) can be assumed to result from either concentric muscular contraction or elastic storage of energy. The proportional contributions from either of these unfortunately cannot be measured directly. By assuming that elastic storage contributes as a given fraction \((b_j)\) of NETPTR\(_i\), an estimate of the fraction of NETPTR\(_i\), attributable to muscular work can be determined \((1 - b_j)\). The net positive power due to concentric muscular contractions (NETPM\(_{ij}\)) would then be given by the equation:

\[ NETPM_{ij} = (1 - b_j)\text{NETPTR}_i = (1 - a_i)(1 - b_j)TPOS \]  

(4)

which is the first term on the right side of equation (1).
**Negative work due to non-muscular sources**

For a given interval between frames, the change in each segment's total instantaneous energy was determined to give the work done involving that segment for each increment in time. The decreases in energy for all segments were added together to give a measure of the total negative work (TNEG) done for a given frame interval. When summed over the entire cycle and divided by time this gives the total negative power. Winter's (1979b) method for total between segment energy transfer simply sums the negative work algebraically with positive work allowing some arbitrary portion of the negative work to disappear from the total. This assumes either (1) that all the negative work involved is due to non-muscular sources, an unlikely occurrence, or (2) that the metabolic cost of the negative work by the muscles is zero. Clearly, when eccentric contractions are involved this will result in an underestimation of the mechanical power attributable to the muscles.

If $c_k$ is assumed to be that portion of the power due to muscular sources, the net negative power due to muscular activity (NETNM$k$) is derived by:

$$\text{NETNM}_k = c_k |\text{TNEG}|$$

(5)

where the absolute value is used for TNEG since this is a negative number but the muscular energy cost is a positive value.

**Relative metabolic cost of negative work vs. positive work**

When the intent of determining mechanical power is for comparison with metabolic work rates, some scheme must be used to account for the smaller metabolic cost of negative vs positive muscular work. Pierrynowski et al. (1980) have suggested an equation which will do this, but details showing how the relationship was developed are lacking. Negative muscular work may result in positive mechanical power being performed, as in the case of between segment energy transfer and elastic storage of energy, or it may simply result in heat dissipation. To show how the differing metabolic cost of negative and positive work can be accounted for, consider the following. (To avoid confusion with terminology previously defined, new terms will be temporarily used.)

Assume the total metabolic work (Met$^{tot}$) could be partitioned into positive (Met$^+$) and negative (Met$^-$) components which resulted during periods of positive (Mech$^+$) and negative (Mech$^-$) mechanical work. The mechanical work terms are general and could be any of those described previously. Then:

$$\text{Met}^+ + \text{Met}^- = \text{Met}^{tot}$$

(6)

$$\text{Mech}^+ + |\text{Mech}^-| = \text{Mech}^{tot}$$

(7)

where the absolute value of Mech$^-$, a negative number, is taken so that the mechanical work portions do not cancel out. During positive muscular power output, some portion ($f_1$) of the metabolic energy involved in the production of positive muscular work will be converted into positive mechanical power. Because eccentric muscular work costs relatively less than concentric work, a different portion ($f_2$) of the negative metabolic energy will result in negative mechanical power.

$$\text{Mech}^+ = f_1 * \text{Met}^+$$

(8)

$$|\text{Mech}^-| = f_2 * \text{Met}^-.$$  

(9)

Substituting (8) and (9) into (6) yields:

$$\frac{\text{Mech}^+}{f_1} + \frac{|\text{Mech}^-|}{f_2} = \text{Met}^{tot}$$

(10)

But, for a given metabolic energy expenditure of positive or negative work, $d$ times as much negative mechanical work would result in comparison to positive work. In other words, negative work is $d$ times as efficient as positive work. Thus, this relative efficiency of negative to positive work, $d_i$, stated mathematically is:

$$d_i = f_2 / f_1.$$  

(11)

Substituting (11) into (10) and rearranging yields:

$$\text{Mech}^+ + \frac{|\text{Mech}^-|}{d_i} = f_1 \text{Met}^{tot}$$

(12)

the same relationship suggested by Pierrynowski et al. (1980) where $f_1$ can be thought of as an efficiency value for positive work. Under these considerations, the correct way to derive an adjusted mechanical power resulting from both positive and negative muscular work would be given by:

$$\text{Mech}^{tot} = \text{Mech}^+ + \frac{|\text{Mech}^-|}{d_i}$$

(13)

where Mech$^{tot}$ is a measure of mechanical power adjusted only for the differences between positive and negative muscular work. Thus, it is represented by PTOT in equation (1). Mech$^+$ represents the first half of the right side of equation (1) while $|\text{Mech}^-|$ corresponds to $c_k |\text{TNEG}|$.

**Center of mass alone**

In calculating the power generated by the center of mass (WCM), first changes in instantaneous kinetic and potential energies between frames were calculated. This resulted in separate sums for positive power, TPOS, where the CM energy increased between frames, and for negative power, TNEG, where the CM energy decreased between frames. In the total power equation, coefficient $a$ would be zero since the method does involve the between segment energy transfer considerations of a segmental analysis. Coefficients $b$, $c$, and $d$ could be applied as previously discussed.

**RESULTS**

**Instantaneous segmental energies**

Mean patterns of energy changes from 31 subjects for individual segments are shown in Figs 3a and 3b.
Fig. 3. Mean instantaneous segmental energy patterns from 31 subjects during one complete running cycle for the (a) head, trunk, right upper arm, and forearm, and (b) right thigh, shank and foot.

over the entire running cycle. These curves represent the total instantaneous energy of the segments at each point in time, with no transfer of energy between segments accounted for. As expected, leg segments have higher energy levels during swing, and lower levels during support, with arm instantaneous energies highest during swing of the contralateral leg. The trunk energy decreases following foot strike and then increases during the push off phase. It should be remembered that it is the changes in segmental energies, and not their absolute magnitude, which are used to determine mechanical power. It is interesting to note that the total change in energy of the trunk during a half cycle is approximately the same as the changes in energy of a foot during the same time.

Estimation of coefficients $a, b, c, d$

Figure 4 shows mean instantaneous NETPTR$_i$ values during a half cycle of running plotted against time for each of the four between segment energy transfer criteria. The total cycle positive power which results from each of the transfer conditions is also listed in the figure. TOTTR which allows for the greatest amount of energy transfer, generally shows the least net positive power across the entire curve. Summing the net positive power over the complete running cycle resulted in mean NETPTR, values of 281.0, 511.8, 620.1, and 758.2 W for the transfer conditions TOTTR, LIMBTR, SEGTR and NOTR respectively. The period of non-support is the time where differences between the conditions is the greatest. Thus, mean TPOS from all subjects was 758.2 W. For TOTTR this meant that ETR$_i$ equalled 477.3 W which would give a value of 0.63 for $a_i$. Similar values for ETR, and $a_i$ for the other transfer criteria were 246.2 W and 0.32 (LIMBTR), 137.9 W and 0.18 (SEGTR), and 0.0 and 0.0 (NOTR). The calculated values $a_i$ could then be substituted into equation (1) to adjust PTOT to account for the effects of energy transfer on positive power.

Four estimates of elastic energy contributions were applied to the data. One was based on the results of the knee bend experiments, where $b_j$ values were derived for each individual from percentage differences in $V_O_2$ between the two knee bend methods. The mean contribution of elastic storage of energy in the knee bend experiment was 24% (SD = ±6.9 %) resulting in a mean $b_j$ value of 0.24. Other values used for $b_j$, assuming no individual variability in elastic use, were:

- 0.5 based upon the work of Cavagna et al. (1964) for sprint running;
- 0.0 which assumed no elastic storage of energy; and
- 0.35 included on the assumption that elastic energy used in distance running would be intermediate between that used in knee bends and sprint running.

Mean total negative power (TNEG) summed over the entire running cycle was -753.5 W. Though there is no direct evidence to suggest values which are appropriate for coefficient $c_b$, it seems likely that the majority of the negative mechanical power resulted from muscular rather than non-muscular sources. Three values were arbitrarily assigned to $c_b$ to illustrate possible effects of non-muscular sources of negative power on PTOT. One was 1.0, where all negative power was assumed to result from eccentric muscular work, one was 0.6 to represent a large non-muscular influence, and the last was an intermediate value of 0.85.

Four estimates of the relative efficiency of positive and negative muscular work were used for coefficient $d$, based upon suggestions from the literature. One
Calculation of mechanical power during distance running

assigned a value of 3 to $d_1$ (Nagle et al., 1965; Pierrynowski et al., 1980), inferring that negative work is three times more efficient than positive work. Other estimates for $d_1$ were 1, 2 and 5 as suggested by Winter (1979b), Pierrynowski et al. (1980), and Zarrugh (1981), respectively.

Estimates of total cycle power

Using the selected values for the various coefficients it is possible to calculate mean total power values and efficiency ratios for a running cycle under a series of possible assumptions (Table 2). One set of values was chosen as a reference against which to compare other estimates of power, and is listed as Condition A in Table 2. It is not suggested that this is the best estimate of mechanical power for running at this speed, but it appears at least to be a reasonable estimate. For this reference condition, of the total positive power ($TPOT = 758 \text{ W}$) 63% was calculated on average to come from between segment energy transfer ($ETR = 478 \text{ W}$). Of the remaining positive power ($NETPTR = 281 \text{ W}$) 35% was assumed to come from elastic storage of energy (183 W). Of the total negative power ($TNEG = -754 \text{ W}$), 15% was assumed to result from non-muscular sources (-113 W) and 85% from eccentric muscular contractions (-641 W). The efficiency of negative muscular work was assumed to be three times that of positive work. These various results combine using equation (1) to give a $PTOE$ value of 395.8 W. Since a mean net $VO_2$ value of 898 W (39.0 ml·kg$^{-1}$·min$^{-1}$) was found, this resulted in a net efficiency ratio of 0.44.

Table 2 shows the effects that the various assumptions have on $PTOT$ and the resulting efficiency ratios. Three of the coefficients have been held constant while the fourth was varied as described previously. Conditions A–D show the effects the various energy transfer criteria have on $PTOT$: $A$, $E$, $F$ and $G$ vary the elastic storage of energy contributions; $A$, $H$ and $I$ change the assumed proportion of the total negative work due to muscular sources; and $A$, $J$, $K$ and $L$ examine the effects of the various assumptions of the relative efficiency of positive and negative muscular work. Both the $PTOT$ and efficiency values are dramatically dependent upon the assumptions, with efficiency values ranging from 0.35 to 0.92. The results for $PTOT$ are shown graphically in Fig. 5, which also suggests a kind of sensitivity analysis, indicating which of the various assumptions introduce the largest sources of variation into $PTOT$. Clearly, energy transfer and the relative cost of positive and negative work are the most important areas.

Table 3 shows how the $PTOT$ values calculated by the model presented in equation (1) compare to values calculated by applying the methods developed by various other investigators to the data collected in this study. Though the model in equation (1) was not used to make these estimates, values are shown in Table 3 for coefficients $R$, $b$, $c$ and $d$ that would result based on the assumptions inherent in each method. Also included for reference are conditions labeled: $M$, considered a physiologically reasonable lower bound for $PTOT$; $A$, the condition described earlier as a reference (see Table 2); $O$, calculated for power measured by the center of mass alone; $R$, a physiologically reasonable upper bound for $PTOT$; and $S$, an absolute maximal

<table>
<thead>
<tr>
<th>Condition</th>
<th>Coefficient values</th>
<th>$PTOT$ (W)</th>
<th>Net efficiency ratio$^*$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$A$</td>
<td>0.63 0.35 0.85 3</td>
<td>395.8</td>
<td>0.44</td>
</tr>
<tr>
<td>$B$</td>
<td>0.32 0.35 0.85 3</td>
<td>548.6</td>
<td>0.61</td>
</tr>
<tr>
<td>$C$</td>
<td>0.18 0.35 0.85 3</td>
<td>617.6</td>
<td>0.69</td>
</tr>
<tr>
<td>$D$</td>
<td>0.0 0.35 0.85 3</td>
<td>706.3</td>
<td>0.79</td>
</tr>
<tr>
<td>$E$</td>
<td>0.63 0.50 0.85 3</td>
<td>353.7</td>
<td>0.39</td>
</tr>
<tr>
<td>$F$</td>
<td>0.63 0.24 0.85 3</td>
<td>426.7</td>
<td>0.48</td>
</tr>
<tr>
<td>$G$</td>
<td>0.63 0.0 0.85 3</td>
<td>494.0</td>
<td>0.55</td>
</tr>
<tr>
<td>$H$</td>
<td>0.63 0.35 1.00 3</td>
<td>433.5</td>
<td>0.48</td>
</tr>
<tr>
<td>$I$</td>
<td>0.63 0.35 0.60 3</td>
<td>333.0</td>
<td>0.37</td>
</tr>
<tr>
<td>$J$</td>
<td>0.63 0.35 0.85 1</td>
<td>822.8</td>
<td>0.92</td>
</tr>
<tr>
<td>$K$</td>
<td>0.63 0.35 0.85 2</td>
<td>502.6</td>
<td>0.56</td>
</tr>
<tr>
<td>$L$</td>
<td>0.63 0.35 0.85 5</td>
<td>310.4</td>
<td>0.35</td>
</tr>
</tbody>
</table>

$^*$ $TOTTR = 0.63$, $LIMBTR = 0.32$, $SEGTR = 0.15$, $NOTR = 0.0$.  
$^t$ $TPOS = 758.2$, $TNEG = -753.5$.  
$^\dagger$ Mean Net $VO_2 = 898 \text{ W}$.  
$^\ddagger$ A is the reference condition.  
| Boxes designate the coefficient which is being varied. |
Fig. 5. The effect of various assumptions on mechanical power (PTOT) calculated for a running cycle. Assumptions as to the amount of between segment energy transfer and the relative metabolic efficiency of negative to positive work can be seen to affect PTOT more than do assumptions of the contributions of elastic storage or of the percentage of negative work attributable to muscular rather than non-muscular sources. The shaded areas represent an estimated range for 'realistic' assumptions.

upper bound (when within segment energy transfer is assumed) where no between segment energy transfer, no elastic storage, no non-muscular sources of energy, and equal positive and negative metabolic work costs are assumed.

The segmental method from Winter (1979b) assuming total between segment energy transfer (α = 0.63, condition Q) resulted in a PTOT value of 557.8 W. The low value of 0.37 for coefficient cL is a consequence of the method by which negative and positive work are manipulated during the calculation of energy transfer as discussed previously. The modification of this method (Pierrynowski et al., 1980) where relative efficiencies are assigned to the metabolic costs of positive and negative work (condition P) yielded a PTOT value of 373.5 W when coefficient dL is assumed to be 3. Zarrugh's (1981) modification of Winter's (1979b) segmental method (condition N) gave a PTOT value of 280.5 W, one of the lowest values found. This is because the cost of negative work is assumed to be zero as evidenced by the zero values given to coefficients cL and dL. The pseudowork method (T) of Norman et al. (1976) gives an artificially high value for PTOT due to the lack of any correction for energy transfer. Power due to the center of mass alone (WCM, condition O), resulted in a PTOT value of 332.8 W. This is approximately 16% less than the corresponding segmental method (A).

Physiological efficiency groups

Figure 6 documents the effects that assumptions of total between segment energy transfer (coefficients α in Table 2) have on net positive power (NETPTR) when compared across the three significantly different (p < 0.01) physiological efficiency groups. Though no significant differences were found between NETPTR, in the three groups, the method using total transfer (TOTTR) showed the expected trends where the most mechanically efficient runners were the most efficient physiologically. The opposite trend was apparent for the no transfer method (NOTR). These differing trends were due to the amount of energy transferred between segments (ETR), also shown in the figure, where the more physiologically efficient runners were more effective at deriving positive power from energy transfer.

Similar trends were also apparent when comparing results from the various methodologies across the physiological efficiency groups, as shown in Table 3. Measures which assume total transfer (A, M, N, O, P, Q) show the expected increased VO2 associated with high power outputs while those with no transfer (S, T) show the opposite trends. No definite relationship was found for the center of mass alone (O).

Table 3. Estimates of total cycle power (PTOT) for all subjects, and across physiological efficiency groups, and estimates of net efficiency ratios are shown for data analyzed using the methods from this study and methods from various other investigators

<table>
<thead>
<tr>
<th>Condition</th>
<th>Coefficients</th>
<th>PTOT (W)</th>
<th>Net efficiency ratio</th>
<th>PTOT (W kg(^{-1})) by physiological efficiency groups</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>α  b  c  d</td>
<td>Mean (SD)</td>
<td>High  Med.  Low</td>
<td>High  Med.  Low</td>
</tr>
<tr>
<td>M</td>
<td>Reasonable lower bound</td>
<td>0.63 0.50 0.00 5</td>
<td>272.2 (26.4) 0.30</td>
<td>3.31 3.43 3.48</td>
</tr>
<tr>
<td>N</td>
<td>Zarrugh (1981)</td>
<td>0.63 0.00 0.00 0</td>
<td>280.5 (48.6) 0.31</td>
<td>3.91 4.15 4.38</td>
</tr>
<tr>
<td>Z</td>
<td>CM alone (WCM)</td>
<td>0.35 0.85 3</td>
<td>332.8 (36.9) 0.37</td>
<td>4.75 5.01 4.92</td>
</tr>
<tr>
<td>P</td>
<td>Pierrynowski et al. (1980)</td>
<td>0.63 0.00 0.37 3</td>
<td>373.5 (61.9) 0.42</td>
<td>5.18 5.34 5.80</td>
</tr>
<tr>
<td>A</td>
<td>This study</td>
<td>0.63 0.35 0.85 3</td>
<td>395.8 (38.5) 0.44</td>
<td>5.75 5.89 5.91</td>
</tr>
<tr>
<td>Q</td>
<td>Winter (1979)</td>
<td>0.63 0.00 0.37 1</td>
<td>557.8 (89.8) 0.62</td>
<td>7.72 8.32 8.64</td>
</tr>
<tr>
<td>R</td>
<td>Reasonable upper bound</td>
<td>0.32 0.24 0.95 2</td>
<td>745.0 (64.2) 0.83</td>
<td>10.98 10.96 11.2</td>
</tr>
<tr>
<td>S</td>
<td>Absolute maximum</td>
<td>0.00 0.00 1.00 1</td>
<td>1511.8 (133.0) 1.67</td>
<td>22.73 22.52 21.75</td>
</tr>
<tr>
<td>T</td>
<td>Norman et al. (1976)</td>
<td>0.00 0.00 1.00 1</td>
<td>1775.1 (143.2) 1.97</td>
<td>26.67 26.27 25.77</td>
</tr>
</tbody>
</table>

*High efficiency indicates low VO2.
DISCUSSION

It is evident that a dramatically wide range of values for mechanical power can be obtained for running depending upon the particular assumptions made and computational procedures employed. For the present data for running at 3.57 m s\(^{-1}\) values from 273 to 1775 W were obtained. Even when the values are restricted to what might be considered reasonable upper and lower bounds (conditions M and R in Table 3) there are still values differing by 270%.

In order to determine the most appropriate mechanical measure of power output during distance running, it is vital that the conceptual basis for each method be examined and the various results interpreted in light of supporting data. The model presented in equation (1) and the coefficients \(a-d\) derived for each computational method provide a suitable means for comparing the fundamental assumptions inherent in each method. The coefficients used in condition A are suggested ones that at the present time might be termed 'working values' that represent current estimates of the conditions found in distance running. They should not necessarily be considered 'best' estimates.

Transfer of energy assumptions have been shown to have a substantial effect on final power output calculations, and in condition A it was assumed that total transfer between segments was the best choice of the four transfer criteria evaluated. It is useful to put these values in the perspective of the methods of other investigators included in this study. Pseudowork (T), which allowed no between or within segment energy transfer gave a mean value of 1775.1 W. Condition S, which is the same as the algorithm derived by Winter (1979b) which allowed complete within segment exchange but no between segment transfer yielded 1511.8 W, while Winter's method for complete within and between segment transfer (Q) resulted in 557.8 W. As more energy transfer is assumed in these three methods, net positive power (\(\text{NETPTR}_E\)) decreases as would be expected. Because the pseudowork method fails to account for any transfer of energy, it can be viewed as a measure of gross mechanical power without consideration for the influence of biological and mechanical factors resulting in energy exchange, and thus is not a realistic measure for an activity such as running. Its continued use cannot, therefore, be recommended.

If substantial between segment energy transfer does occur, as seems reasonable, it should be possible to show some experimental support for it. A possible approach is suggested by Fig. 7, which shows the instantaneous energy changes for both legs during a part of the running cycle. During this period the right (swing) leg was rapidly losing energy, while the left (support) leg was gaining energy, thus creating the situation in which energy transfer could have occurred. Bresler and Berry (1951) found similar potential for energy transfer between legs during the initial stages of double support in walking. It should be possible to get some indirect evidence that transfer does occur from an examination of the muscular activity (EMG) present in the lower extremities during this time. If muscular work was the primary cause of the increase in energy then there should be substantial EMG activity present in the appropriate muscles. Though EMG's were not collected in this study, some preliminary

![Fig. 6. When total between segment energy transfer (\(\text{TOTTR}\)) is assumed, expected trends are seen when values are compared across physiological efficiency groups, with the lowest mechanical power found for the most physiologically efficient group. The opposite trends are shown when no between segment energy transfer (\(\text{NOTR}\)) is assumed, indicating that the amount of energy transferred between segments (\(\text{ETR}\)) is an important aspect of efficient running.](image1)

![Fig. 7. The large increase in energy of the left leg coincident with the large decrease in energy of the right leg during the time from just before toe off (LTO) to the following foot strike (RFS) indicates that this is a period where a large amount of energy transfer between segments is likely to occur.](image2)
EMG data from other work (Unpublished data, P. R. Cavanagh), indicates that there is no EMG activity present that would account for these increases. Activity was, however, present in the muscles which would tend to decrease the swing leg's energy, providing the necessary prerequisites for energy transfer.

The trends seen in PTOT values across physiological efficiency groups also support the assumption that a great deal of between segment energy transfer occurs. Further indirect support comes from the efficiency ratios in Table 3 where methods assuming total transfer give ER values closer to the theoretical maximal efficiency of 0.30 (Whipp and Wasserman, 1969). While complete transfer seems unrealistic for reasons discussed previously, it is likely that marked transfer does occur. The shaded region in the column for ETR in Fig. 5 is suggested as a realistic range for assumptions of energy transfer.

One of the areas where previous methods (Pierrynowski et al., 1980; Winter, 1979b) differ markedly from that suggested by condition A in the present model is in the treatment of negative power. As discussed earlier, the computational methods which allow the positive power resulting from energy transfer to cancel out the associated negative power result in zero net power even though negative muscular work was done. The mechanical power attributed to negative muscular work when this was done, reflected by low values for coefficient c1, was much lower than that calculated in condition A where no negative work was allowed to be cancelled out. There would seem to be no justification for omitting the negative work associated with energy transfer for reasons discussed earlier. Completely ignoring negative work by assuming its metabolic cost is zero (Zarrugh, 1980), is also unrealistic. The present model, which has the means to account for all the negative energy changes, from both muscular and non-muscular sources, would appear more reasonable.

Though 15% of the total negative power was assumed in condition A to come from non-muscular sources, this value is speculative with little research available to suggest a more appropriate value. Joint range of motion restrictions would only be important at extreme segmental positions and would probably not be a substantial influence. The influence of factors related to internal musculoskeletal friction or viscosity are also uncertain as well (Pierrynowski et al. 1980). The shaded area for the column dealing with non-muscular sources in Fig. 5 suggests a likely range of reasonable values for coefficient c1.

It would also seem that assumptions that the relative efficiency of negative work is greater than that for positive work, such as those in conditions P and A, are more reasonable than the assumption of equal efficiencies, as in condition Q. Pierrynowski et al. (1980) came to similar conclusions for walking data, and the body of data documenting the lower metabolic cost of eccentric muscular work adds further support for this view (Abbott and Bigland, 1953; Nagle et al. 1965). The need for further research to provide a more valid estimate for coefficient d1 is obvious.

Elastic storage of energy continues to be one of the least understood factors in running mechanics. While its contribution has been shown to be substantial in an activity such as knee bends (Asmussen and Bonde-Peterson, 1974; Thya et al., 1972), and though its contribution to mechanical work in running has been theorized as being substantial (Cavagna and Kaneko, 1977; Luhtanen and Komi, 1980), there remain no direct experimental measures of elastic storage contributions during either running or walking. The best that can be done at present is to estimate elastic contributions as was done in the present model, or use estimates from related activities, such as knee bends. The mean 24% savings in $V_O_2$ during the knee bend experiment in this study attributed to elastic energy sources provides a useful reference for expected contributions during running, and the standard deviation of 69% suggests that there may be marked individual variability. In comparing vertical ground reaction forces during distance running to those involved in knee bends, forces are on the order of two to three times larger in running with a time duration approximately half as long. In light of some of the previous research on elastic storage of energy (Cavagna et al., 1965, 1968) this would suggest that there is likely to be greater than a 24% contribution during running, perhaps up to as high as the 47–62% figure suggested by Cavagna et al. (1964).

The mechanical power calculated was also dependent on the cutoff frequency used during digital filtering of the kinematic data. A cutoff value of 5 Hz was chosen as the most appropriate based upon the effects of various cutoff frequencies on kinematic derivatives, but it should be noted that other choices for a cutoff frequency would result in different PTOT values. For example, using net positive power assuming total energy transfer ($a = 0.63$) for comparison, cutoffs of 4, 5, 6, 7 and 10 Hz would result in NETPTR values of 251.2 W, 280.9 W, 311.4 W, 348.7 W and 495.6 W respectively. Any study involving a kinematic analysis of motion should carefully examine the changes to the data brought about by digital filtering to determine the most appropriate cutoff frequency.

Several approaches may be used to assess the appropriateness of the model presented in equation (1) for the calculation of the mechanical power output during running. A qualitative assessment of the assumptions involved, as has just been done, helps to justify the values used for coefficients in the model based on research findings from the available literature. The data presented showing trends in mechanical power measures across groups based on oxygen consumption provides additional support, particularly for energy transfer. It would be expected that the most efficient runners metabolically would also be the most efficient mechanically. From the results comparing the TOTTR and NOTR energy transfer methods across
physiological efficiency groups, it would appear that between segment energy transfer is an important contributor to efficient running. It remains to be determined which specific kinematic and kinetic factors are responsible for efficient energy transfer.

The mean net efficiency ratio found in this study for condition A (ER = 0.44) is higher than the traditional theoretical maximum efficiency derived from thermodynamics of 0.30 (Whipp and Wasserman, 1969), but is the same order of magnitude as values found by some investigators for running or walking (Cavagna and Kaneko, 1977; Pierrynowski et al., 1980). Since the 0.44 value determined reflects estimated positive efficiency, this would predict a negative efficiency of 1.32 based on the assumption of negative work being three times more efficient than positive work. This is an unrealistic value, and suggests that refinements of the model are necessary. Since the values used for the various coefficients were based upon a number of assumptions, more direct experimental evaluations relevant to these factors may aid in the development of more accurate values.

Another possible approach for evaluating various assumptions would be to use the model in reverse and predict a given coefficient value subject to various constraints. For example, assume that coefficients a, b and d were the same as in condition A, but the efficiency ratio for positive power was constrained to be 0.3. This would predict a value of 0.37 for coefficient c, the percentage of negative power due to muscular sources. If a and d were the same, b was changed to 0.50, and the positive ER was set at 0.3, a value of 0.5 would be attributed to coefficient c. It may be possible that through manipulations of this type, coupled with further research into the determination of the coefficients, that more accurate estimates of the mechanical power involved in distance running can be made.

REFERENCES


Fenn, W. O. (1930a) Frictional and kinetic factors in the work of sprint running. Am. J. Physiol. 92, 583-611.

Fenn, W. O. (1930b) Work against gravity and work due to velocity changes in running. Am. J. Physiol. 93, 433-462.


NOMENCLATURE

(All Units MKS)

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>M</td>
<td>total number of segments</td>
</tr>
<tr>
<td>N</td>
<td>total number of frames or time intervals</td>
</tr>
<tr>
<td>K</td>
<td>number of segments adjacent to a given segment (head, forearm, foot; K = 1; upper arm, thigh, calf; K = 2; trunk; K = 5)</td>
</tr>
<tr>
<td>L</td>
<td>number of appendages from trunk (L = 5: head, right arm, left arm, right leg, left leg)</td>
</tr>
</tbody>
</table>
number of segments per appendage (head, L = 1; arms, L = 2; legs L = 3)

mass of a segment

acceleration due to gravity

segmental moment of inertia about mass center

vertical position of segment mass center

resultant translational velocity of segment mass center

instantaneous segmental energy

total cycle work done by a segment assuming total within segment energy transfer

total cycle work done by a segment assuming no within segment energy transfer

total body work for a given time interval assuming both total within and between segment energy transfer

total cycle work done by the body assuming both total within and between segment energy transfer

total cycle work done by the body assuming no between segment energy transfer and no within segment energy transfer

total cycle positive power assuming complete within segment energy transfer and no between segment energy transfer

total cycle negative power assuming complete within segment energy transfer

total segmental power calculated using changes in the energy of the center of mass alone

Component energies of a segment

\[ PE = mgh \]

\[ TKE = \frac{1}{2} I \omega^2 \]

\[ RKE = \frac{1}{2} I \omega^2 \]

Total instantaneous energy of a segment

\[ ES = PE + TKE + RKE. \]

Psuedowork (Norman et al. 1976)

\[ TPW = \sum_{i=1}^{M} \sum_{j=1}^{L} (|\Delta PE| + |\Delta TKE| + |\Delta RKE|). \]

APPENDIX

(a) Segmental work:

\[ Ws = \sum_{i=1}^{M} \Delta ES \]

\[ Ws' = \sum_{i=1}^{M} (|\Delta PE| + |\Delta TKE| + |\Delta RKE|). \]

(b) Total body work:

\[ Eb = \sum_{i=1}^{M} \Delta ES \]

\[ Wb = \sum_{i=1}^{M} \Delta Eb \]

\[ Wb' = \sum_{i=1}^{M} |\Delta ES|. \]

(5) Segmental energy analysis (this study)

\[ TNEG = \sum_{i=1}^{M} \Delta ES \text{ if } \Delta ES < 0 \]

\[ TPOS = \sum_{i=1}^{M} \Delta ES \text{ if } \Delta ES > 0 \]

\[ TOTTR = \sum_{i=1}^{M} \Delta Eb \text{ if } \Delta Es > 0 \]

\[ NOTR = TPOS \]

\[ LIMBTR = \sum_{i=1}^{M} \Delta Eb' \text{ where:} \]

(1) If \( \Delta ES \) (trunk) < 0, then:

\[ \Delta EI = \sum_{i=1}^{L} \Delta ES \text{ unless } \Delta EI < 0; \text{ then } \Delta EI = 0 \]

\[ \Delta EB' = \sum_{i=1}^{L} \Delta ES \text{ (trunk) unless } \Delta EB' < 0, \text{ then } \Delta EB' = 0 \]

(2) If \( \Delta ES \) (trunk) > 0, then:

\[ \Delta EI = \sum_{i=1}^{L} \Delta ES \]

\[ \Delta EB' = \Delta ES \text{ (trunk)} + \sum_{i=1}^{L} \Delta EI \text{ (if } \Delta EI < 0) \]

\[ \text{unless } \Delta EI < 0; \text{ then } \Delta EI = 0 \]

\[ \Delta EB' = \Delta Ei + \sum_{i=1}^{L} \Delta Ei \text{ (if } \Delta Ei > 0) \]

\[ \text{SEGTR} = \sum_{i=1}^{M} \Delta Eb' \text{ where } \Delta Eb' \text{ is defined by the following computer algorithm:} \]

Let \( A = \Delta ES \) for segment \( i \) (\( i = 1, M \))

Let \( B = \Delta ES \) for segment \( k \) adjacent to \( i \) (\( k = 1, K \))

DO \( i = 1, M \)

\( A = \Delta ES \) (\( i \))

DO \( j = 1, K \)

\( B = \Delta ES \) (\( j \))

IF (\( A > 0 \) or \( B < 0 \)) GO TO 10

\( X = A + B \)

IF (\( X > 0 \)) \( \Delta ES \) (\( i \)) = 0 and \( \Delta ES \) (\( j \)) = \( X \)

IF (\( X < 0 \)) \( \Delta ES \) (\( i \)) = \( X \) and \( \Delta ES \) (\( j \)) = 0

10 CONTINUE

Then:

\[ \Delta EB' = \sum_{i=1}^{M} \Delta ES. \]