MECHANICAL ENERGY GENERATION, ABSORPTION AND TRANSFER AMONGST SEGMENTS DURING WALKING*

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Abstract – The purpose of this paper was twofold: firstly to measure and partially validate the rates of work done (powers) by the joint reaction forces and moments on the leg segments and secondly to explain the changes in mechanical energy of the segments by the transfer, generation or absorption of energy by the muscles and/or the transfer of energy through the joints.

Measurement of the powers required the calculation of segmental kinematic information and joint reaction forces and moments. Force plate and cinefilm data were collected on two subjects walking at several walking speeds using a sagittal plane, linked, rigid body model of the human form.

The total powers delivered to or taken from the segments ($\dot{W}$t) were compared with the corresponding segmental rates of change of mechanical energy ($\dot{E}$). The work–energy theorem holds that these two measures are equal, however, modelling assumptions and approximations made to simplify the structure of the human body may cause considerable discrepancy. Thus, a comparison of these two measures can assess whether the human model is valid and hence whether the two measures are accurate.

Results indicate that the model and therefore the power measures were valid excepting the ankle powers during weight acceptance and late push-off. The rates of transfer of energy through the joints and muscles were found to be comparable in magnitude to the rates of energy generation and absorption by the muscles. Thus, the joint energy transfers perform a significant role in the mechanical energy variations of the segments during walking.

INTRODUCTION

The study of complex human movements, such as walking, often leads to the calculation of segmental kinematics from which mechanical energies are derived. These measures are an excellent means of quantifying and describing human movements but, unfortunately, yield no information as to which muscle groups control the movement or how much they contribute to the segments' motions. Similarly, resultant joint moment information quantifies which muscles are active but does not indicate where mechanical energy generated by muscles goes, where energy absorbed by muscles comes from or where energy is transferred between segments. The patterns of energy generation, absorption and transfer by muscles and energy transfer through the joints can be calculated by combining joint reaction forces and moments with segmental and joint kinematics.

Elftman (1939a, b) in his classic studies of human locomotion presented methods for the calculation of (1) the rate of change of energy (potential plus kinetic) of the legs, (2) 'the rate of energy transfer due to the joint forces' and (3) 'the rate at which the muscles do work on, or receive energy from, each part of the leg' including the 'energy transmitted by the muscle from one point of attachment to another.' He noted that

when the rate of change of energy of a segment is positive, that is its energy level is increasing, the increase is due to a net inflow of energy from work done by forces acting at the segment's joints or by muscle moments. The rate of work done (power), positively or negatively, by the joint forces (which will be called the joint power) can be calculated from:

$$\dot{W}j(j,s) = \mathbf{F}(j,s) \cdot \mathbf{V}(j), \qquad (1)$$

where $\dot{W}j(j,s)$ is the power delivered to or if negative taken from segment s at its joint j due to the work done by the joint reaction forces, $\mathbf{F}(j,s)$ is the joint reaction force vector acting on segment s at joint j and $\mathbf{V}(j)$ is the linear velocity vector of that joint.

A situation is depicted in Fig. 1 which shows the velocity and reaction force vectors between segment 1 and 2. A positive power indicates the rate of flow of energy into the segment at j, whereas, a negative power shows the rate of outflow of energy. The other segment connected at j has the same velocity vector $\mathbf{V}(j)$ but its joint reaction force vector is equal in magnitude and opposite in direction to $\mathbf{F}(j,s)$. Consequently, the other segment will always have a joint power equal in magnitude to $\dot{W}j(j,s)$ but opposite in sign. Thus, in Fig. 1, a flow of energy to segment 1 implies an equal outflow of energy from segment 2 connected at j. Joint powers therefore show only rates of *transfer* of energy between segments.

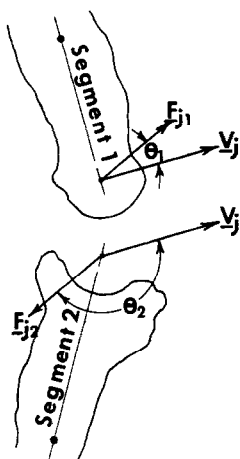The segments can also receive mechanical energy from work being done on them by muscles that are

Fig. 1. Calculation of joint powers for two adjacent segments from the joint reaction force vectors ($Fj_1 = -Fj_2$) and the joint velocity vector (Vj).

attached to them at both their proximal and distal ends. In the following analysis it will be assumed that the joint reaction moments acting on each segment are caused by muscle involvement alone. The contributions to the joint reaction moments by such structures as the ligaments being very small for such moderate activities as walking.

The rate of work done (power) by the muscle moments for segment s at joint j (which will be called the muscle power) is calculated from:

$$\dot{W}m(j,s) = M(j,s) \cdot \omega(s), \qquad (2)$$

where $\dot{W}m(j, s)$ is the mechanical power delivered to or taken from segment s at its joint j due to the work done by the muscle moments, $M(j,s)$ is the joint moment vector acting on segment s at joint j and $\omega(s)$ is the angular velocity vector of segment s. A positive rate again indicates the rate of mechanical work done by the muscle on segment s, while a negative rate shows the rate of mechanical work done by segment s on the muscle. Contrary to the situation for the joint powers, the two segments connected at j do not necessarily have the same angular velocity, consequently, there can be more than simply a transfer of energy from segment to segment through the muscles. The muscles can also *generate* mechanical energy or *absorb* mechanical energy by concentrically or eccentrically contracting, respectively.

Table 1 shows all possible work functions that can occur between two segments connected by an active muscle. Note that the muscles referred to are not the actual anatomical muscles; these are equivalent one joint muscles which perform either flexion or extension (cf. Elftman, 1939b). No partitioning of the work done by the various muscles crossing a joint will be undertaken (cf. Morrison, 1970).

The work–energy theorem enables the calculation of the rate of change of segmental energy by: (1) determining the net power ($\dot{W}t$) supplied to the segment which is equal to the sum of the segment's

muscle and joint powers or (2) by taking the time derivative of the segment's total mechanical energy ($\dot{E}$). Theoretically, these two measures are equivalent, however, errors in the modelling of the human form or experimental errors in the measuring equipment may produce discrepancies. Modelling errors arise from both kinematic and anthropometric sources. The kinematic errors result from digitizing cinefilm and the movement of skin. The major anthropometric errors result from tabled values not agreeing with actual values and their variations during the stride cycle. Four anthropometric parameters of concern are segment masses, moments of inertia and the locations of joint and mass centres. It is partly the purpose of this paper to assess the magnitudes of these discrepancies.

Elftman (1939a) measured $\dot{E}$ but did not calculate $\dot{W}t$. Quanbury et al. (1975) have calculated both measures for the shank-foot segment during the swing phase of gait and have shown an excellent agreement between the two measures. Winter et al. (1976) have expanded this approach, measuring powers of both the thigh and shank-foot segments during swing, but report only a partial comparison between the two measures.
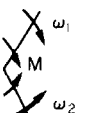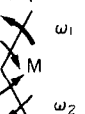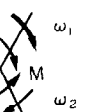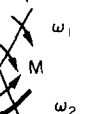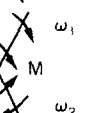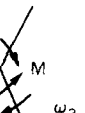
PURPOSE

The purpose of this paper is to report on the results of power analyses performed on eight walking trials over a range of walking speeds. These analyses include both the swing and stance phases of gait. Also, an attempt was made to validate the measures of joint power and muscle power by comparing the total power supplied to the segments with the segments' rates of change of mechanical energy. It will be assumed that the segmental rates of energy change are more accurate since these measures depend only upon cinefilm and anthropometric data, whereas, joint and muscle powers additionally require force platform information and the locations of the joint centers of rotation. Furthermore, the causes of energy in the lower limb segments will be discussed with emphasis placed on the role of energy transfers through the joints and muscles.

EXPERIMENTAL METHODS

To simplify the data collection and reduction procedures only a two dimensional sagittal plane analysis of walking was undertaken. The error caused by this simplification is rather small considering the relatively small magnitudes of linear and angular velocities and accelerations in the frontal and horizontal planes (Bresler and Berry, 1951).

Two male subjects were analyzed walking at four different cadences; these cadences ranged from slower to faster that normal walking cadences. Reflective markers were placed over the following anatomical landmarks on the right side of the subjects: metatarsalphalangeal joint, tip of the lateral malleolus (ankle),

Table 1.

Description of movement	Type of contraction	Directions of segmental ang. velocities	Muscle function	Amount, type and direction of power
Both segments rotating in opposite directions (a) joint angle decreasing	Concentric	ω_1 M ω_2	Mechanical energy generation	$M\omega_1$ generated to segment 1. $M\omega_2$ generated to segment 2.
(b) joint angle increasing	Eccentric	ω_1 M ω_2	Mechanical energy absorption	$M\omega_1$ absorbed from segment 1. $M\omega_2$ absorbed from segment 2.
Both segments rotating in same direction (a) joint angle decreasing (e.g. $\omega_1 > \omega_2$)	Concentric	ω_1 M ω_2	Mechanical energy generation and transfer	$M(\omega_1 - \omega_2)$ generated to segment 1. $M\omega_2$ transferred to segment 1 from 2.
(b) joint angle increasing (e.g. $\omega_2 > \omega_1$)	Eccentric	ω_1 M ω_2	Mechanical energy absorption and transfer	$M(\omega_2 - \omega_1)$ absorbed from segment 2. $M\omega_1$ transferred to segment 1 from 2.
(c) joint angle constant ($\omega_1 = \omega_2$)	Isometric (dynamic)	ω_1 M ω_2	Mechanical energy transfer	$M\omega_2$ transferred from segment 2 to 1.
One segment fixed (e.g. segment 1.) (a) joint angle decreasing ($\omega_1 = 0, \omega_2 > 0$)	Concentric	M ω_2	Mechanical energy generation	$M\omega_2$ generated to segment 2
(b) joint angle increasing ($\omega_1 = 0, \omega_2 > 0$)	Eccentric	M ω_2	Mechanical energy absorption	$M\omega_2$ absorbed from segment 2.
(c) joint angle constant ($\omega_1 = \omega_2 = 0$)	Isometric (static)	M	No mechanical energy function	Zero.

the posterior convexity of the femoral condyle (knee), tip of the greater trochanter (hip), and mid-way between the hip and shoulder axes of rotation (Dempster, 1955, see Fig. 2). The latter marker was used for descriptive purposes only and was not used in any of the calculations.

The subjects walked along a raised walkway across an inlaid force platform for approximately 10 steps. They were filmed by a cine camera at 60 frames/sec mounted on a cart which was guided along a track four metres from the walkway (cf. Winter et al., 1972). This procedure gave an image that filled the camera's field of view and provided data for several strides before and after the force plate.

The film was projected onto a table such that the projected image was approximately one-third life size. Anatomical and background reference markers were digitized and processed to yield coordinates in an absolute reference frame (Winter et al., 1972). The resolution of the digitization system was 1.4 mm and

the digitization error was less than 2.0 mm r.m.s. The coordinates were then digitally filtered by a zero lag, fourth order, low pass, Butterworth filter with a four hertz cut-off (Winter et al., 1974; Pezzack et al., 1977). The four hertz cut-off was chosen because it was the lowest frequency which did not cause significant attenuation of the accelerations during swing. A low cut-off was desirable to improve the signal-to-noise ratio during stance. Body segment parameters were determined using proportions collected by Dempster (1955) from cadaver dissections (Plagenhoef, 1971; Miller and Nelson, 1973).

Force platform signals were A/D converted, filtered and processed to yield the equivalent ground reaction force vector and its point of application on the foot. The cinefilm and force data were then synchronized to obtain the necessary segmental kinematics and reaction joint forces and moments. The joint forces and moments acting at the proximal end of the foot were calculated by imposing dynamic equilibrium knowing

the distal forces to be zero during swing and equal to the ground reaction forces during stance. The remaining joint forces were calculated using standard link segment mechanics (Elftman, 1939a; Bresler and Frankel, 1950).

POWER CALCULATIONS

The joint power of segment s at joint j was calculated by the following equation:

$$\dot{W}j(j,s) = F_x(j,s)V_x(j) + F_y(j,s)V_y(j) \qquad (3)$$

where $F_x(j,s)$ and $F_y(j,s)$ are the joint reaction force components acting on segment s at joint j and $V_x(j)$ and $V_y(j)$ are the linear velocity components of joint j. The subscript x refers to the antero-posterior axis, y the vertical axis and z the medio-lateral axis.

The muscle power of segment s at its end j was calculated from:

$$\dot{W}m(j,s) = M_z(j,s)\omega_z(s) \qquad (4)$$

where $M_z(j,s)$ is the joint reaction moment about the medio-lateral axis acting on segment s at joint j and $\omega_z(s)$ is the segment's angular velocity about the medio-lateral axis.

The total power for segment s was determined from:

$$\dot{W}t(s) = \sum_j [\dot{W}j(j,s) + \dot{W}m(j,s)] \qquad (5)$$

where the summation over j implies the sum for all of the segment's joints.

The segmental rate of change of energy was obtained by first calculating each segment's total mechanical energy. The segment's total mechanical energy at time t_1 was:

$$E(s,t_1) = m(s)gY(s,t_1) + \tfrac{1}{2}m(s)[V(s,t_1)]^2$$
$$+ \tfrac{1}{2}I\hat{z}(s)[\omega\hat{z}(s,t_1)]^2 \qquad (6)$$

where $m(s)$ is its mass, $I\hat{z}(s)$ is its moment of inertia about a medio-lateral axis through its centre of gravity, $Y(s,t_1)$ is the height of its centre of mass at time t_1 and $V(s,t_1)$, $\omega\hat{z}(s,t_1)$ are its linear and angular

velocities at time t_1. The segmental rate of change of energy was then calculated by the finite difference equation:

$$\dot{E}(s,t_1) = [E(s,t_2) - E(s,t_0)]/2\Delta t \qquad (7)$$

where t_0, t_1, t_2 represent times separated by an interval of Δt seconds (time between successive cine frames).

RESULTS

Characteristics of the subjects and the walking trials are summarized in Table 2. Trials WN21B, WN21F, WN22A and WN22F were the subjects normal walking speeds, trials WN21C and WN21H were slower than normal and trials WN22E and WN22I were faster than normal. Figure 2 shows stick figure representations of the data from trial WN21F; every third figure has been plotted (0.06 s between figures). The various phases and events of gait and temporal characteristics for trial WN21F are presented in Table 3.

Typical patterns of the total mechanical energy variations for the three leg segments are plotted in Fig. 3. The graph's zero potential energy level is at ground level and a broken scale was used because of the high potential energy bias of the thigh segment. Later, in Fig. 7, the rates of change of these energies are plotted.

The foot's energy (Fig. 3) has a total change of 11 J from its base level of 1 J. The increase, mainly in its forward translational kinetic energy (90%), begins after heel off reaching a maximum by mid-swing. At the end of swing the foot's energy has almost returned to its base level. It is now possible, by knowing the joint force and muscle powers, to determine the sources of the energy influx or to determine where the foot's energy outflow went. These energy changes can be caused by either energy transfers across the ankle joint or by energy generation, absorption or transfer by the ankle muscles (see Discussion).

The shank shows an energy change similar to that of the foot, excepting it has a total energy change of 16 J. The thigh is slightly different having a peak change of 12 J during swing and a secondary peak during weight
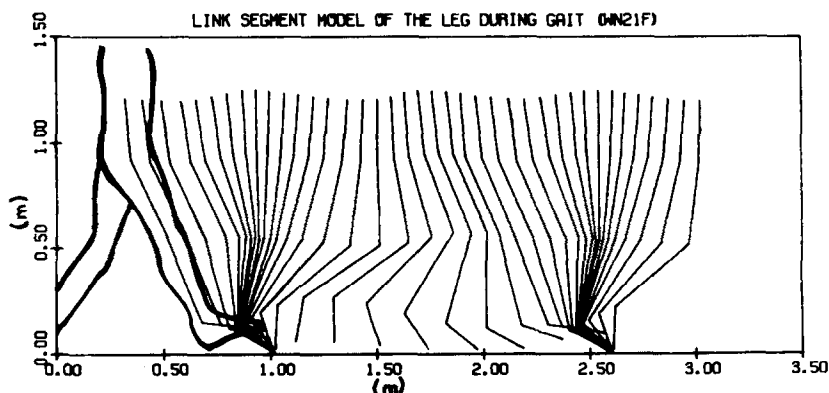

Fig. 2. Stick figure representations of the coordinate data, plotted every third digitized frame (i.e. 0.06 sec interval). Only data from the right side of the body were collected.

Table 2. Characteristics of the subjects and walking trials

Subject Information	Trial code	Stride rate* (/sec)	Stride length* (m)	Stride velocity* (m/sec)
Code: WN21	B	0.82	1.57	1.29
Height: 1.79 m	C	0.71	1.41	1.00
Weight: 80.0 kg	F	0.88	1.58	1.39
Age: 26	H	0.70	1.59	1.11
Code: WN22	A	0.90	1.57	1.41
Height: 1.87 m	E	1.02	1.59	1.62
Weight: 76.8 kg	F	0.94	1.63	1.53
Age: 26	I	1.05	1.74	1.83

*Calculations from right heel contact to right heel contact.

Table 3. Temporal and phasic characteristics of walking trial WN21F

Phase	Start* event	End* event	Time interval (sec)	Percentage of stride
One stride	HCR	HCR	1.13	100
(a) Stance	HCR	TOR	0.73	65
(i) Weight acceptance	HCR	TOL	0.15	13
(ii) Mid-stance	TOL	HOR	0.10	9
(iii) Push off	HOR	TOR	0.48	42
(b) Swing	TOR	HCR	0.40	35
(i) Acceleration	HCR	MSR	0.17	15
(ii) Deceleration	MSR	HCR	0.23	20

*The following codes were used for events: HCR — heel contact, right; TOR — toe off, right; TOL — toe off, left; HOR — heel off, right; and MSR — mid-swing, right. MSR was at the time when the foot shank energies were at a maximum.
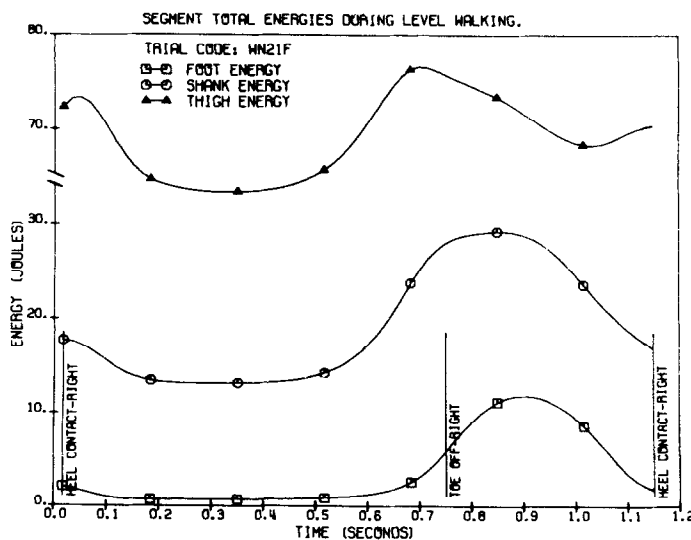

Fig. 3. Instantaneous energies (potential plus kinetic) of the thigh, shank and foot for one stride.
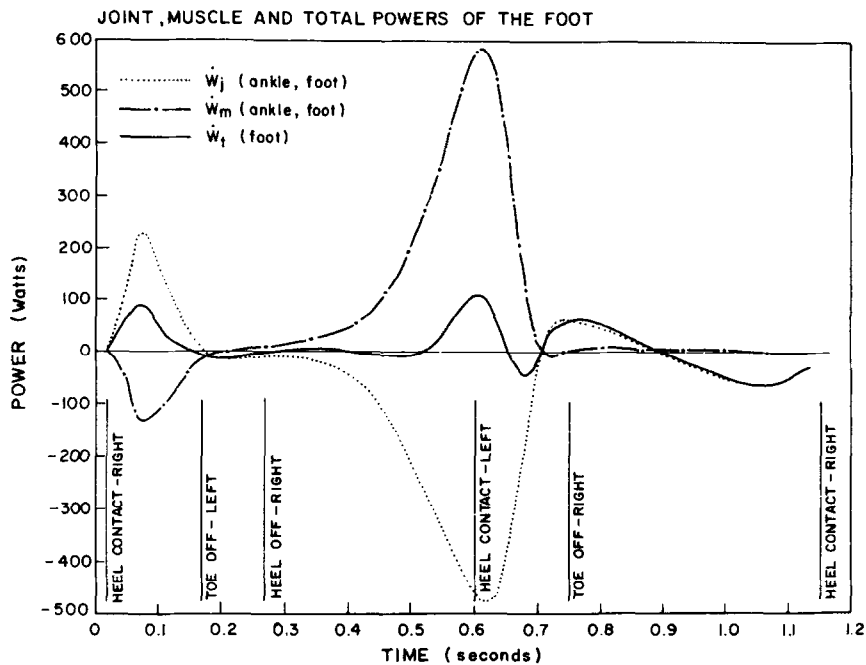
Fig. 4. Muscle and joint powers and the total power supplied to the foot.

acceptance of 9 J. Again, the changes in the energy levels of the shank and thigh are due mainly to changes in their forward translational kinetic energies.

Figures 4, 5 and 6 show the joint and muscle powers of the three leg segments. A positive power indicates the rate of inflow of energy from the particular source plotted; negative powers show the rates of energy outflow. Also plotted is the total power supplied to the segment ($\dot{W}t$). When this sum is positive it signifies that

the segment is gaining mechanical energy implying a net increase in potential and/or kinetic energies. Conversely, a negative power tells the rate of loss in the segment's total mechanical energy.

A comparison of $\dot{W}t(s)$ with $\dot{E}(s)$ for the three segments is presented in Fig. 7. These curves are intended to show the accuracy of the joint and muscle powers since their sum for a given segment should be equal to the segment's rate of change of energy. The
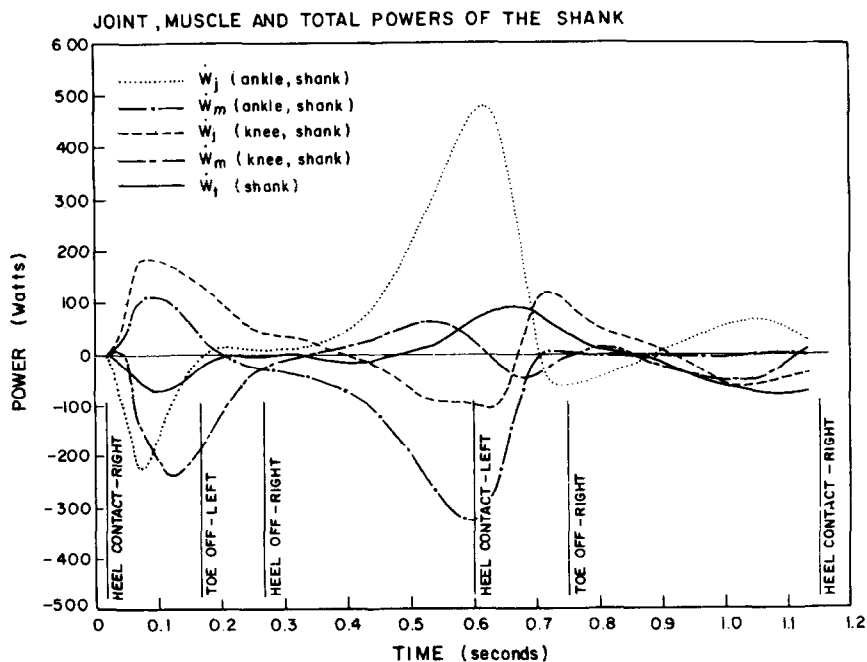

Fig. 5. Muscle and joint powers and the total power supplied to the shank.

JOINT, MUSCLE AND TOTAL POWERS OF THE THIGH
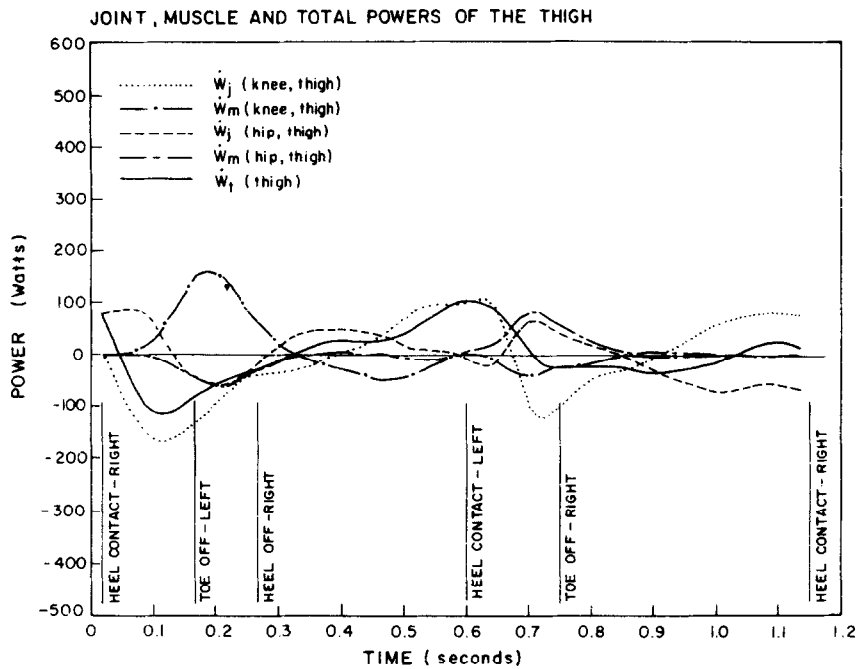
Fig. 6. Muscle and joint powers and the total power supplied to the thigh.

TOTAL POWER DELIVERED TO THE SEGMENT
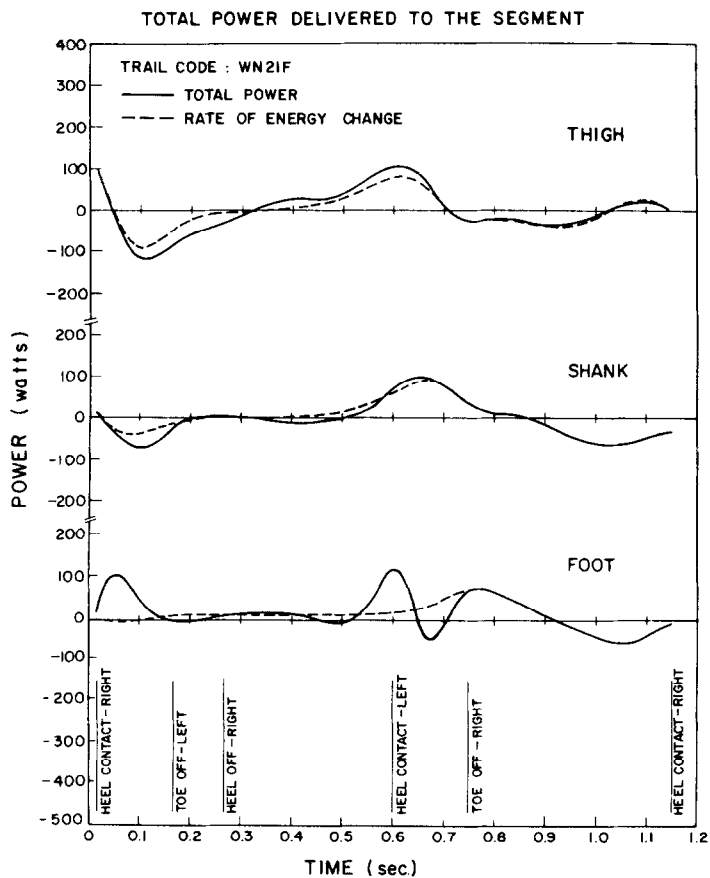
Fig. 7. Powers supplied to the three lower limb segments ($\dot{W}t$) and their rates of change of mechanical energy
($\dot{E}$).

total powers are in close agreement with the segment's rates of change of mechanical energy during mid-stance and during the entire swing period. Differences are in evidence, however, during weight acceptance and late push off, but these differences are only significant for the foot segment where the joint and muscle powers are highest. These results are typical of all the walking trials excepting the faster walking trials which have correspondingly higher powers.

Correlation coefficients over time between $\dot{E}(s)$ and $\dot{W}t(s)$ for each segment appear in Table 4. Correlations were made for all trials, with separate coefficients being calculated for the swing and stance phases. The swing phase correlations for all segments and trials are very high ranging from 0.989 to 1.000, being higher for the foot and shank which have larger kinematic signals (i.e. higher signal to noise ratio). During stance, the correlations are lower but still quite high with the exception of the foot which showed no correlation between the two measures. The lack of correlation for the foot is due to errors in either $\dot{W}j$(ankle, foot) or $\dot{W}m$(ankle, foot) during weight acceptance and push off when these variables are high in magnitude and opposite in polarity. Consequently, a small percentage error in one of the measures is quite large in comparison to the near zero $\dot{E}$(foot) (see Figs. 4 and 7).

DISCUSSION

Errors in the joint and muscle powers

Figure 7 shows that the two measures, $\dot{E}(s)$ and $\dot{W}t(s)$ during swing are in very close agreement for all segments and trials (on the scale plotted these two curves appear as one line). Further confirmation is offered in Table 4 where correlations between the two measures are all greater than 0.989. Thus, at least 94 % of the variance in $\dot{E}(s)$ can be accounted for by variance in $\dot{W}t(s)$. This indicates that there is a strong phasic relationship between the two measures. It is possible, however, that an error in one of the segment's joint or muscle powers can be masked by errors in some or all of the segment's other joint or muscle powers but this is unlikely to occur over an entire swing phase. Furthermore, the results are reinforced by the repeatable patterns in all of the trials and because they are similar to results reported by other investigators (Elftman,

1939a; Quanbury *et al.*, 1975; Cappozzo *et al.*, 1976; Winter *et al.*, 1976).

The patterns of $\dot{E}(s)$ and $\dot{W}t(s)$ for the shank and thigh segments during stance are very similar; their correlation coefficients ranging between 0.815 and 0.978. The curves plotted in Fig. 7 confirm these results for trial WN21F but show that there are slight differences in the magnitudes of the two measures. The feet, on the other hand, show no correlation between the two power measures during stance, making the magnitudes of the joint or muscle powers doubtful. Figure 7 shows that the $\dot{E}$(foot) and $\dot{W}t$(foot) are in agreement during mid-stance and early push off. They are not in agreement during weight acceptance and late push off when the muscle and joint powers at the foot are large and nearly equal in magnitude but opposite in sign (see Fig. 4). In consequence, a relatively small error in one of the powers appears as a large change in the foot's $\dot{W}t$, whereas, $\dot{E}$ is very small since the foot is moving slowly. Further analysis of the errors during these periods has shown that the location of the ankle centre of rotation is important for the calculation of the $\dot{W}m$(ankle, foot) but has little effect on the $\dot{W}j$(ankle, foot). Dempster (1955) has shown that the ankle centre of rotation moves relative to the bones, whereas, the present model assumes that it has a fixed location with respect to the skeletal system. Unfortunately, the authors have found no suitable means of obtaining the locations of the instantaneous centres of rotation throughout the entire walking cycle. Care must therefore be taken when interpreting the results of the foot's joint and muscle powers during the periods of weight acceptance and late push off.

Causes of segmental energy changes in walking

Figure 3 shows the mechanical energy patterns of the three leg segments. Questions that arise from these curves are: how are the segments supplied with energy?; where and when is energy generated or absorbed? and; how are the segments' energies reduced? The foot shows an 11 J increase and decrease during swing which is almost totally accounted for by the transfer of energy to and from the shank through the ankle joint ($\dot{W}j$(ankle, foot) in Fig. 4). During the acceleration phase of swing, there is a transfer of energy from the

Table 4. Correlation of the rates of change of energy ($\dot{E}$) with the total powers ($\dot{W}t$)

Trial	Stance			Swing		
	Foot	Shank	Thigh	Foot	Shank	Thigh
WN21B	−0.286	0.965	0.933	1.000	0.998	0.997
WN21C	−0.489	0.815	0.882	0.998	0.997	0.990
WN21F	−0.069	0.978	0.907	1.000	1.000	0.998
WN21H	−0.014	0.847	0.907	1.000	0.998	0.989
WN22A	−0.312	0.923	0.977	1.000	1.000	0.999
WN22E	−0.168	0.977	0.968	1.000	1.000	0.999
WN22F	0.001	0.971	0.964	1.000	1.000	0.998
WN22I	0.039	0.970	0.969	1.000	1.000	0.999

shank; energy which was originally generated by the hip flexors. The shank at this time merely acts as a means for transferring the energy. The deceleration phase of swing is characterized by the transfer of energy out of the foot to the shank with little or no muscle involvement. The ankle dorsiflexors act only to generate enough energy to dorsiflex the foot preventing stubbing of the toes on the ground; this activity amounts to only 0.5 J of work.

The shank energy increase shown in Fig. 3 is approximately 16 J. The initial part of this energy surge is supplied by the transferring of foot energy; energy which was originally generated by the ankle plantar flexors. The latter portion, beginning shortly after heel contact of the contralateral leg, is due to the transferring of energy from the thigh through the hip and knee. This energy originates with hip flexor concentric contractions and amounts to 12 J. During the deceleration phase of swing, energy flows into the shank from the foot $\dot{W}j$(ankle, shank) and out through the knee to the thigh $\dot{W}j$(knee, shank). The knee flexors during this period contract eccentrically, absorbing 9 J of excess energy. The remainder of the energy losses of the shank and foot during deceleration is seen as an increase in the energy level of the thigh with a considerable amount passing onto the rest of the body. This energy transfer to the body is indicated by the high negative rate of energy transfer through the hip ($\dot{W}j$(hip, thigh)). The body thus attempts to conserve energy by transferring it into and out of the shank and foot as it is required.

The thigh's energy increase at the end of the swing, as previously mentioned, is due to the transferring of energy through the knee's joint connective tissues from the shank and foot. After heel contact, the thigh's energy continues to increase by energy transfers from the rest of the body ($\dot{W}j$(hip, thigh)). The thigh's energy level (73 J) is then reduced (to 64 J) by the absorption of energy by the hip flexors (8 J) and the transfer of energy to the shank and foot for absorption by knee extensors (16 J) and ankle plantar flexors (5 J). Some of the energy absorbed by these muscles comes from the rest of the body and not simply from the thigh. This is indicated by $\dot{W}j$ (hip, thigh) being positive while the thigh's energy level is dropping, thus, energy flowing into the thigh at the hip must also be leaving through the knee (shown by a negative joint power).

The thigh's next major energy increase occurs prior to swing reaching a maximum of 77 J. This surge comes from an energy transfer from the shank $\dot{W}j$(knee, thigh) of energy generated by ankle plantar flexors. During the entire period of push off, the ankle plantar flexors supply the majority of the energy necessary for moving the legs and the body. For trial WN21F, the plantar flexors generated 29 J compared to 9 J of work output by the hip flexors. The range of plantar flexor work output for the other walking trials was between 23 J and 38 J. Interestingly, the maximum values were not recorded from the faster walking trials. It would seem the faster speeds are not obtained by simply

increasing the work output of the plantar flexors but by some more complex strategy. After the thigh's peak energy level is attained, prior to swing, it is then reduced to a level of 68 J by the transferring of energy through the knee to the shank and foot. The shank and foot during the remainder of swing act much like a pendulum with the exception of slight ankle dorsiflexor activity and knee flexor absorption. A more detailed analysis of the energy flows among the segments can be found in Winter and Robertson (1978).

CONCLUSIONS

1. The measurements of joint and muscle powers were found to be valid throughout the walking cycle for all trials for the three leg segments studied, excepting the ankle powers during weight acceptance and late push off.

2. The role of joint energy transfers (joint powers) was found to be as important as the muscle's role of generating and absorbing energy for assessing the causes of energy change in the individual leg segments.

3. The assumption that the joints act as ideal hinge connections was found to be valid for this type of analysis since the calculation of the segments' rates of change of energy and total powers were very much in agreement (especially during the larger and more rapid changes seen in swing).

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