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 (Wt) were compared with the corresponding
segmental rates of change of mechanical energy (ΔE). 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 de-

erived. 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, re-

sultant 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:

\[ \dot{W}_j(s) = \mathbf{F}(j, s) \cdot \mathbf{V}(j), \]

where \( \dot{W}_j(s) \) 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 \( \dot{W}_j(s) \) 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

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Fig. 1. Calculation of joint powers for two adjacent segments from the joint reaction force vectors \((F_j = -F_j^j)\) and the joint velocity vector \((V_j)\). 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:

\[
\dot{W}_m(j, s) = M(j, s) \cdot \omega(s),
\]

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 \textit{generate} mechanical energy or \textit{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 \textit{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 \textit{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: metatarsal-phalangeal joint, tip of the lateral malleolus (ankle),
Table 1.

<table>
<thead>
<tr>
<th>Description of movement</th>
<th>Type of contraction</th>
<th>Directions of segmental angular velocities</th>
<th>Muscle function</th>
<th>Amount, type and direction of power</th>
</tr>
</thead>
<tbody>
<tr>
<td>Both segments rotating in opposite directions</td>
<td>Concentric</td>
<td>$\omega_1$, $\omega_2$</td>
<td>Mechanical energy generation</td>
<td>$M_{w1}$ generated to segment 1. $M_{w2}$ generated to segment 2.</td>
</tr>
<tr>
<td>(a) joint angle decreasing</td>
<td>Eccentric</td>
<td>$\omega_1$, $\omega_2$</td>
<td>Mechanical energy absorption</td>
<td>$M_{w1}$ absorbed from segment 1. $M_{w2}$ absorbed from segment 2.</td>
</tr>
<tr>
<td>Both segments rotating in some direction</td>
<td>Concentric</td>
<td>$\omega_1$, $\omega_2$</td>
<td>Mechanical energy generation and transfer</td>
<td>$M_{w1}$ transferred to segment 1 from 2. $M_{w2}$ transferred to segment 1 from 2.</td>
</tr>
<tr>
<td>(a) joint angle decreasing (e.g. $\omega_1 &lt; \omega_2$)</td>
<td>Eccentric</td>
<td>$\omega_1$, $\omega_2$</td>
<td>Mechanical energy absorption and transfer</td>
<td>$M_{w1}$ transferred to segment 2 from 1. $M_{w2}$ transferred to segment 2 from 1.</td>
</tr>
<tr>
<td>(c) joint angle constant ($\omega_1$ = $\omega_2$)</td>
<td>Isometric (dynamic)</td>
<td>$\omega_1$, $\omega_2$</td>
<td>Mechanical energy transfer</td>
<td></td>
</tr>
<tr>
<td>One segment fixed (e.g. segment 1.)</td>
<td>Concentric</td>
<td>$\omega_1$, $\omega_2$</td>
<td>Mechanical energy generation</td>
<td>$M_{w1}$ generated to segment 2.</td>
</tr>
<tr>
<td>(a) joint angle decreasing ($\omega_1 &lt; \omega_2$)</td>
<td>Eccentric</td>
<td>$\omega_1$, $\omega_2$</td>
<td>Mechanical energy absorption</td>
<td>$M_{w1}$ absorbed from segment 2.</td>
</tr>
<tr>
<td>(c) joint angle constant ($\omega_1$ = $\omega_2$)</td>
<td>Isometric (static)</td>
<td>$\omega_1$, $\omega_2$</td>
<td>No mechanical energy function</td>
<td>$M_{w1}$ absorbed from segment 2.</td>
</tr>
</tbody>
</table>

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 on 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 remain-
ing 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:

\[ W_j(s) = F_x(j,s)\dot{X}(j) + F_y(j,s)\dot{Y}(j) \]  

where \( F_x(j,s) \) and \( F_y(j,s) \) are the joint reaction force
components acting on segment s at joint j and \( \dot{X}(j) \) and
\( \dot{Y}(j) \) 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:

\[ W_m(j,s) = M'(j,s)\dot{\theta}(s) \]

where \( M'(j,s) \) is the joint reaction moment about the
medio-lateral axis acting on segment s at joint j and
\( \dot{\theta}(s) \) is the segment's angular velocity about the
medio-lateral axis.

The segmental rate of change of energy was ob-
tained by first calculating each segment's total
mechanical energy. The segment's total mechanical
energy at time \( t_1 \) was:

\[ E(s, t_1) = m(s)gY(s, t_1) + \frac{1}{2}m(s)[V(s, t_1)]^2 \]

where \( m(s) \) is its mass, \( g \) is the acceleration due to
gravity, \( Y(s, t_1) \) is the height of its centre of mass at time
\( t_1 \) and \( V(s, t_1) \) is its linear and angular
velocities at time \( t_1 \). The segmental rate of change of
energy was then calculated by the finite difference
equation:

\[ \dot{E}(s, t_1) = [E(s, t_1) - E(s, t_2)]/\Delta t \]

where \( t_0, t_1, t_2 \) represent times separated by an interval of
\( \Delta t \) 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
to faster than normal. Figure 2 shows stick figure rep-esentations 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
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Table 2. Characteristics of the subjects and walking trials

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

*Calculations from right heel contact to right heel contact.

Table 3. Temporal and phasic characteristics of walking trial WN21F

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

*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.
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. 4. Muscle and joint powers and the total power supplied to the foot.

Fig. 5. Muscle and joint powers and the total power supplied to the shank.
Fig. 6. Muscle and joint powers and the total power supplied to the thigh.

Fig. 7. Powers supplied to the three lower limb segments (Wt) and their rates of change of mechanical energy (E).
total powers are in close agreement with the segment's rates of change of mechanical energy during midstance 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 $E(s)$ and $\dot{W}(s)$ 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 $\dot{W}(ankle, foot)$ or $\dot{W}(foot)$ 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 $E(foot)$ (see Figs. 4 and 7).

**DISCUSSION**

**Errors in the joint and muscle powers**

Figure 7 shows that the two measures, $E(s)$ and $\dot{W}(s)$ 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 $E(s)$ can be accounted for by variance in $\dot{W}(s)$. 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 $E(s)$ and $\dot{W}(s)$ 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 foot, 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 $E(foot)$ and $\dot{W}(foot)$ 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 $\dot{W}$, whereas, $E$ 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 $\dot{W}(ankle, foot)$ but has little effect on the $\dot{W}(ankle, foot)$. 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 11J 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 ($\dot{W}(ankle, foot)$ in Fig. 4). During the acceleration phase of swing, there is a transfer of energy from the

<table>
<thead>
<tr>
<th>Trial</th>
<th>Stance</th>
<th>Swing</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Foot</td>
<td>Shank</td>
</tr>
<tr>
<td>WN21B</td>
<td>-0.286</td>
<td>0.965</td>
</tr>
<tr>
<td>WN21C</td>
<td>-0.489</td>
<td>0.815</td>
</tr>
<tr>
<td>WN21F</td>
<td>-0.069</td>
<td>0.978</td>
</tr>
<tr>
<td>WN21H</td>
<td>-0.014</td>
<td>0.847</td>
</tr>
<tr>
<td>WN22A</td>
<td>-0.312</td>
<td>0.923</td>
</tr>
<tr>
<td>WN22E</td>
<td>-0.168</td>
<td>0.977</td>
</tr>
<tr>
<td>WN22F</td>
<td>0.001</td>
<td>0.971</td>
</tr>
<tr>
<td>WN22F</td>
<td>0.039</td>
<td>0.970</td>
</tr>
</tbody>
</table>
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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 $W_{\text{f}}(\text{ankle, shank})$ and out through the knee to the thigh $W_{\text{k}}(\text{knee, shank})$. 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 $W_{\text{j}}(\text{hip, thigh})$. 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 ($W_{\text{r}}(\text{hip, thigh})$). 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 $W_{\text{j}}(\text{hip, thigh})$ 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 $W_{\text{f}}(\text{knee, thigh})$ 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 thigh 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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