6

MECHANICAL WORK, ENERGY, AND POWER

6.0 INTRODUCTION

If we were to choose which biomechanical variable contains the most information, we would be forced to look at a variable that relates to the energetics. Without that knowledge, we would know nothing about the energy flows that *cause* the movement we are observing; and no movement would take place without those flows. Diagnostically, we have found joint mechanical powers to be the most discriminating in all our assessment of pathological gait. Without them, we could have made erroneous or incomplete assessments that would not have been detected by EMG or moment-of-force analyses alone. Also, valid mechanical work calculations are essential to any efficiency assessments that are made in sports and work-related tasks.

Before proceeding, the student should have clearly in mind certain terms and laws relating to mechanical energy, work, and power, and these will now be reviewed.

6.0.1 Mechanical Energy and Work

Mechanical energy and work have the same units (joules) but have different meanings. Mechanical energy is a measure of the state of a body *at an instant in time* as to its ability to do work. For example, a body which has 200 J of kinetic energy and 150 J of potential energy is capable of doing 350 J of work (on another body). Work, on the other hand, is the measure of energy flow from one body to another, and time must elapse for that work to be done. If

energy flows from body A to body B, we say that body A does work on body B; or muscle A can do work on segment B if energy flows from the muscle to the segment.

6.0.2   Law of Conservation of Energy

At all points in the body at all instants in time, the law of conservation of energy applies. For example, any body segment will change its energy only if there is a flow of energy or out of any adjacent structure (tendons, ligaments, or joint contact surfaces). Figure 6.1 depicts a segment that is in contact at the proximal and distal ends and has four muscle attachments. In this situation, there are six possible routes for energy flow. Figure 6.1a shows the work (in joules) done at each of these points over a short period of time Δt. The law of conservation of energy states that the algebraic sum of all the energy flows must equal the energy change of that segment. In the case shown, $\Delta E_s = 4 + 2.4 + 5.3 - 1.7 - 0.2 - 3.8 = 6.0\,\text{J}$. Thus, if we are able to calculate each of the individual energy flows at the six attachment points, we should be able to confirm ΔE_s through an independent analysis of mechanical energy of that segment. The balance will not be perfect because of measurement errors and because our link-segment model does not perfectly satisfy the assumptions inherent in link-segment analyses. A second way to look at the energy balance is through a *power balance*, which is shown in Figure 6.1b and effectively looks at the rate of flow of energy into and out of the segment and equates
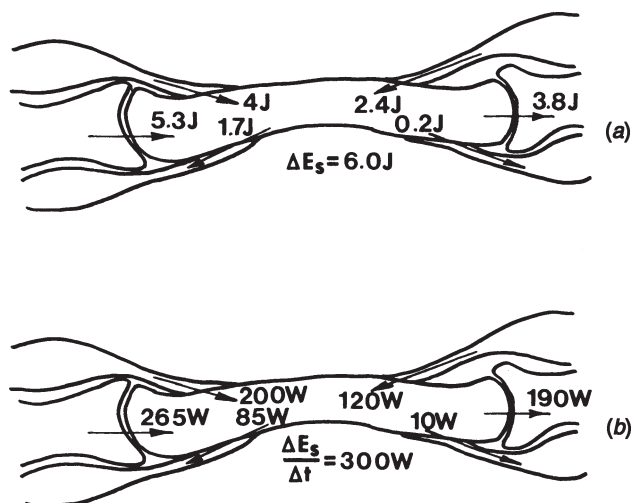

Figure 6.1   (a) Flow of energy into and out of a segment from the adjacent connective tissue and joint contacts over a period of time Δt. (b) Rate of flow of energy (power) for the same segment and same point in time as (a). A "power balance" can be calculated; see the text for discussion.

that to the rate of change of energy of the segment. Thus if, Δt is 20 ms, $\Delta E_s/\Delta t = 200 + 120 + 265 - 85 - 10 - 190 = 300$ W.

Another aspect of energy conservation takes place within each segment. Energy storage within each segment takes the form of potential and kinetic energy (translational and rotational). Thus, the segment energy E_s at any given point in time could be made up of any combination of potential and kinetic energies, quite independent of the energy flows into or out of the segment. In Section 6.3.1, the analysis of these components and the determination of the amount of conservation that occurs within a segment over any given period of time are demonstrated.

6.0.3 Internal versus External Work

The only source of mechanical energy generation in the human body is the muscles, and the major site of energy absorption is also the muscles. A very small fraction of energy is dissipated into heat as a result of joint friction and viscosity in the connective tissue. Thus, mechanical energy is continuously flowing into and out of muscles and from segment to segment. To reach an external load, there may be many energy changes in the intervening segments between the source and the external load. In a lifting task (see Figure 6.2), the
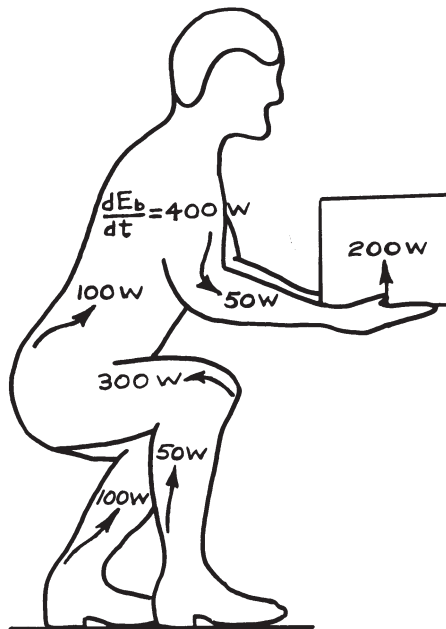

Figure 6.2 Lifting task showing the power generation from a number of muscles and the combined rate of change of energy of the body (internal work) and rate of energy flow to the load (external work).

work rate on the external load might be 200 W, but the work rate to increase the energy of the total body by the source muscles of the lower limb might be 400 W. Thus, the sum of the internal and external work rates would be 600 W, and this generation of energy might result from many source muscles, as shown. Or, during many movement tasks such as walking and running, there is no external load, and all the energy generation and absorption are required simply to move the body segments themselves. A distinction is made between the work done on the body segments (called *internal* work) and the work done on the load (called *external* work). Thus, lifting weights, pushing a car, or cycling an ergometer have well-defined external loads. One exception to external work definition includes lifting one's own body weight to a new height. Thus, running up a hill involves both internal and external work. External work can be negative if an external force is exerted on the body and the body gives way. Thus, in contact sports, external work is regularly done on players being pushed or tackled. A baseball does work on the catcher as his hand and arms give way.

In bicycle ergometry, the cyclist does internal work just to move his limbs through the cycle (freewheeling). Figure 6.3 shows a situation where the cyclist did both internal and external work. This complex experiment has one bicycle ergometer connected via the chain to a second bicycle. Thus, one cyclist can bicycle in the forward direction (positive work), while the other cycles backward (negative work). The assumption made by the researches who introduced this novel idea was that each cyclist was doing equal amounts of work (Abbot et al., 1952). This is not true because the positive-work
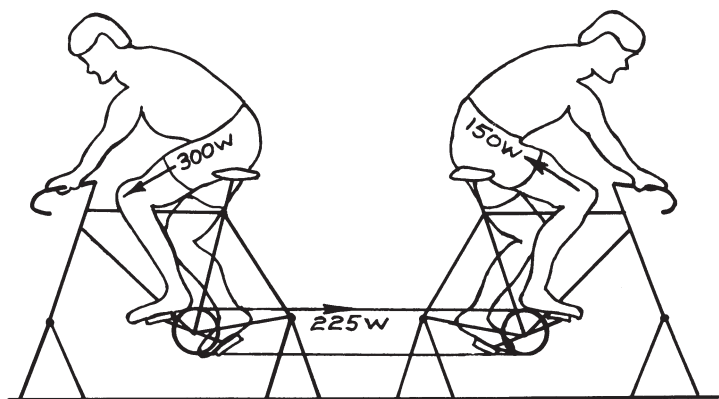

Figure 6.3 Bicycle ergometry situation in which one subject (left) cycles in a forward direction and does work on a second subject who cycles in the reverse direction. The positive-work cyclist not only does external work on the negative-work cyclist but also does the internal work to move the limbs of both cyclists. Contrary to common interpretation, both cyclists are not performing equal magnitudes of mechanical work.

cyclist must do his or her own internal work plus the internal work on the negative-work cyclist plus any additional negative work of that cyclist. Thus, if the internal work of each cyclist were 75 W, the positive-work cyclist would have to do mechanical work at 150-W rate just to "freewheel" both cyclists. Then as the negative-work cyclist contracted his or her muscles, an additional load would be added. Thus, if the negative-work cyclist worked at 150 W, the positive-work cyclists would be loaded to 300 W. It is no wonder that the negative-work cyclist can cycle with ease while the positive-work cyclist rapidly fatigues. They are simply not working at the same mechanical work rate, plus the metabolic demand of positive work far exceeds that of negative work.

6.0.4 Positive Work of Muscles

Positive work is work done during a concentric contraction, when the muscle moment acts in the same direction as the angular velocity of the joint. If a flexor muscle is causing a shortening, we can consider the flexor moment to be positive and the angular velocity to be positive. The product of muscle moment and angular velocity is positive; thus, power is positive, as depicted in Figure 6.4a. Conversely, if an extensor muscle moment is negative and an extensor angular velocity is negative, the product is still positive, as shown in Figure 6.4b. The integral of the power over the time of the contraction is the net work done by the muscle and represents generated energy transferred from the muscles to the limbs.
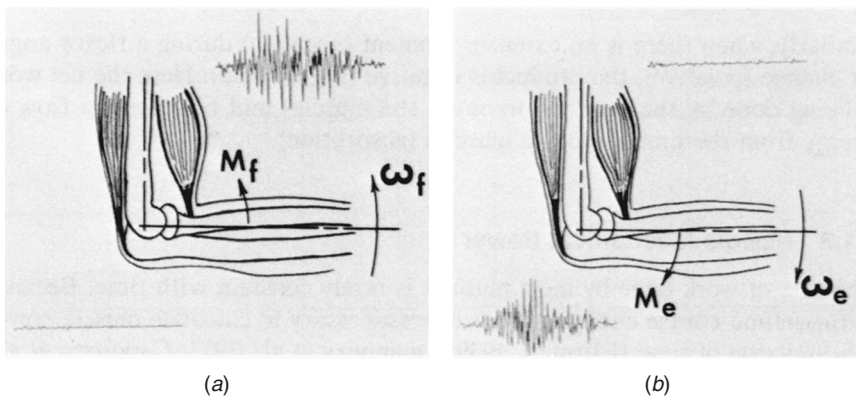

(a)   (b)

Figure 6.4 Positive power as defined by the net muscle moment and angular velocity. (*a*) A flexion moment acts while the forearm is flexing. (*b*) An extension moment acts during and extensor angular velocity. (Reproduced by permission of *Physiotherapy Canada*.)
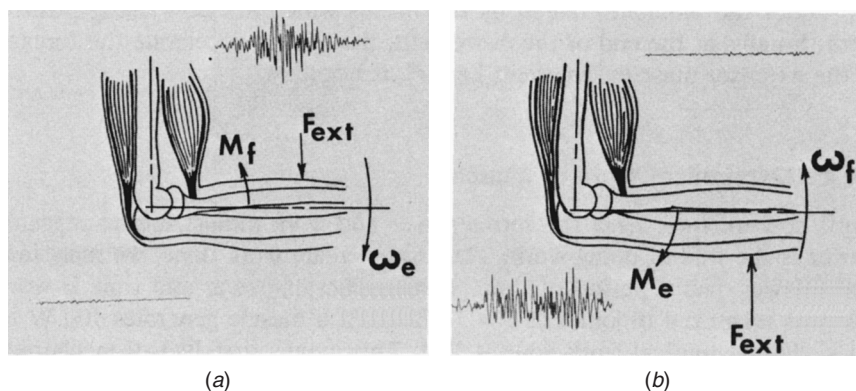
Figure 6.5 Negative power as defined by net muscle moment and angular velocity. (*a*) An external force causes extension when the flexors are active. (*b*) An external force causes flexion in the presence of an extensor muscle moment. (Reproduced by permission of *Physiotherapy Canada*.)

6.0.5   Negative Work of Muscles

Negative work is work done during an eccentric contraction when the muscle moment acts in the opposite direction to the movement of the joint. This usually happens when an external force, F_{ext}, acts on the segment and is such that it creates a joint moment greater than the muscle moment. The external force could include gravitational or ground reaction forces. Using the polarity convention as described, we can see in Figure 6.5*a* that we have a flexor moment (positive) with an extensor angular velocity (negative). The product yields a negative power, so that the work done during this angular change is negative. Similarly, when there is an extensor moment (negative) during a flexor angular change (positive), the product is negative (Figure 6.5*b*). Here, the net work is being done by the external force on the muscles and represents a flow of energy from the limbs into the muscles (absorption).

6.0.6   Muscle Mechanical Power

The rate of work done by most muscles is rarely constant with time. Because of rapid time-course changes, it has been necessary to calculate muscle power as a function of time (Elftman, 1939; Quanbury et al., 1975; Cappozzo et al., 1976; Winter and Robertson, 1978). At a given joint, muscle power is the product of the net muscle moment and angular velocity,

$$P_m = M_j \omega_j \quad \text{W} \tag{6.1}$$

where: $P_m =$ muscle power, watts
$\quad\quad M_j =$ net muscle moment, N · m
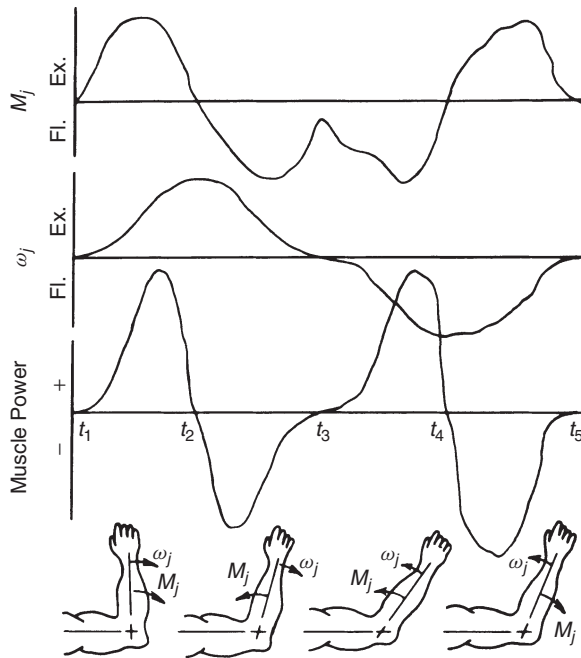$\quad\quad \omega_j =$ joint angular velocity, rad/s

Figure 6.6   Sequence of events during simple extension and flexion of forearm. Muscle power shows two positive bursts alternating with two negative bursts.

As has been described in the previous sections, P_m can be either positive or negative. During even the simplest movements, the power will reverse sign several times. Figure 6.6 depicts the muscle moment, angular velocities, and muscle power as a function of time during a simple extension and flexion of the forearm. As can be seen, the time courses of M_j and ω_j are roughly out of phase by $90°$. During the initial extension, there is an extensor moment and an extensor angular velocity as the triceps do positive work on the forearm. During the latter extension phase, the forearm is decelerated by the biceps (flexor moment). Here the biceps are doing negative work (absorbing mechanical energy). Once the forearm is stopped, it starts accelerating in a flexor direction still under the moment created by the biceps, which are now doing positive work. Finally, at the end of the movement, the triceps decelerate the forearm as the extensor muscles lengthen; here, P_m is negative.

6.0.7   Mechanical Work of Muscles

Until now we have used the terms *power* and *work* almost interchangeably. Power is the rate of doing work. Thus, to calculate work done, we must integrate power over a period of time. The product of power and time is work, and it is measured in joules ($1\,\text{J} = 1\,\text{W} \cdot \text{s}$). If a muscle generates 100 W for

0.1 s, the mechanical work done is 10 J. This means that 10 J of mechanical energy has been transferred from the muscle to the limb segments. As the example in Figure 6.6 shows, power is continuously changing with time. Thus, the mechanical work done must be calculated from the time integral of the power curve. The work done by a muscle during a period t_1 to t_2 is:

$$W_m = \int_{t_1}^{t_2} P_m \, dt \quad \text{J} \tag{6.2}$$

In the example described, the work done from t_1 to t_2 is positive, from t_2 to t_3 it is negative, from t_3 to t_4 it is positive again, and during t_4 to t_5 it is negative. If the forearm returns to the starting position, the net mechanical work done by the muscles is zero, meaning that the time integral of P_m from t_1 to t_5 is zero. It is therefore critical to know the exact times when P_m is reversing polarities in order to calculate the total negative and the total positive work done during the event.

6.0.8   Mechanical Work Done on an External Load

When any part of the body exerts a force on an adjacent segment or on an external body, it can only do work if there is movement. In this case, work is defined as the product of the force acting on a body and the displacement of the body in the direction of the applied force. The work, dW, done when a force causes an infinitesimal displacement, ds, is:

$$dW = F \, ds \tag{6.3}$$

Or the work done when F acts over a distance S_1 is:

$$W = \int_0^{S_1} F \, ds = FS_1 \tag{6.4}$$

If the force is not constant (which is most often the case), then we have two variables that change with time. Therefore, it is necessary to calculate the power as a function of time and integrate the power curve with respect to time to yield the work done. Power is the rate of doing work, or dW/dt.

$$P = \frac{dW}{dt} = F \frac{ds}{dt}$$
$$= \overline{F} \cdot \overline{V} \tag{6.5}$$

where: P = instantaneous power, watts
$\overline{F}$ = force, newtons
$\overline{V}$ = velocity, m/s

Since both force and velocity are vectors, we must take the dot product, or the product of the force and the component of the velocity that is in the same direction as the force. This will yield:

$$P = FV\cos\theta = F_x V_x + F_y V_y \tag{6.6}$$

where: θ = angle between force and velocity vectors in the plane defined by those vectors

F_x and F_y = forces in x and y directions

V_x and V_y = velocities in x and y directions

For the purpose of this initial discussion, let us assume that the force and the velocity are always in the same direction. Therefore, $\cos\theta = 1$ and:

$$P = FV \quad \text{W}$$

$$W = \int_0^t P \, dt = \int_0^t FV \, dt \quad \text{J} \tag{6.7}$$

Example 6.1. A baseball is thrown with a constant accelerating force of 100 N for a period of 180 ms. The mass of the baseball is 1.0 kg, and it starts from rest. Calculate the work done on the baseball during the time of force application.

Solution

$$S_1 = ut + \tfrac{1}{2}at^2$$

$$u = 0$$

$$a = F/m = 100/1.0 = 100 \text{ m/s}^2$$

$$S_1 = \tfrac{1}{2} \times 100(0.18)^2 = 1.62 \text{ m}$$

$$W = \int_0^{S_1} F \, ds = FS_1 = 100 \times 1.62 = 162 \text{ J}$$

Example 6.2. A baseball of mass 1 kg is thrown with a force that varies with time, as indicated in Figure 6.7. The velocity of the baseball in the direction of the force is also plotted on the same time base and was calculated from the time integral of the acceleration curve (which has the same numerical value as the force curve because the mass of the baseball is 1 kg). Calculate the instantaneous power to the baseball and the total work done on the baseball during the throwing period.

The peak power calculated here may be considered quite high, but it should be noted that this peak has a short duration. The average power for the throwing period is less than 500 W. In real-life situations, it is highly unlikely that the force will ever be constant; thus, instantaneous power must always be
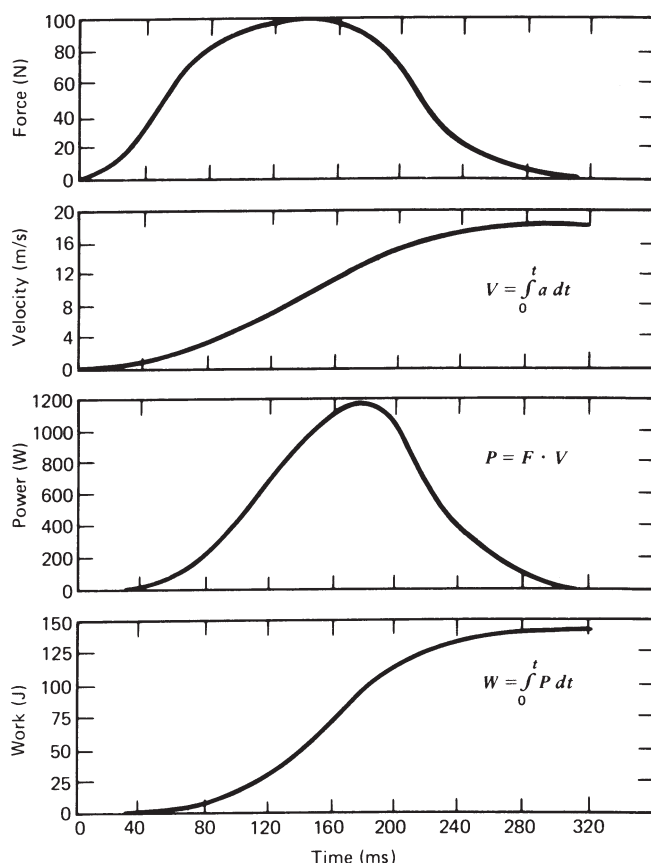
Figure 6.7 Forces, velocity, mechanical power, and work done on a baseball while being thrown. See the text for details.

calculated. When the baseball is caught, the force of the hand still acts against the baseball, but the velocity is reversed. The force and velocity vectors are now in opposite directions. Thus, the power is negative and the work done is also negative, indicating that the baseball is doing work on the body.

6.0.9 Mechanical Energy Transfer between Segments

Each body segment exerts forces on its neighboring segments, and if there is a translational movement of the joints, there is a mechanical energy transfer between segments. In other words, one segment can do work on an adjacent segment by a force displacement through the joint center (Quanbury et al., 1975). This work is in addition to the muscular work described in Sections 6.0.4 to 6.0.7. Equations (6.5) and (6.6) can be used to calculate the rate of energy transfer (i.e., power) across the joint center. Consider the
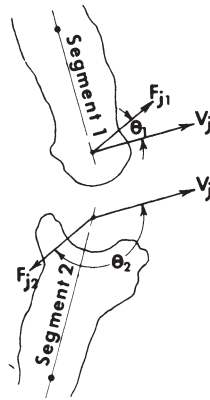
Figure 6.8   Reaction forces and velocities at a joint center during dynamic activity. The dot product of the force and velocity vectors is the mechanical power (rate of mechanical energy transfer) across the joint.

situation in Figure 6.8 at the joint between two adjacent segments. F_{j1}, the reaction force of segment 2 on segment 1, acts at an angle θ_1 from the velocity vector V_j. The product of $F_{j1}V_j \cos \theta_1$ is positive, indicating that energy is being transferred into segment 1. Conversely, $F_{j2}V_j \cos \theta_2$ is negative, denoting a rate of energy outflow from segment 2. Since $P_{j1} = -P_{j2}$, the outflow from segment 2 equals the inflow to segment 1. In an n-joint system, there will be n power flows, but the algebraic sum of all those power flows will be zero, reinforcing the fact that these flows are passive and, therefore, do not add to or subtract from the total body energy.

This mechanism of energy transfer between adjacent segments is quite important in the conservation of energy of any movement because it is a passive process and does not require muscle activity. In walking, this has been analyzed in detail (Winter and Robertson, 1978). At the end of swing, for example, the swinging foot and leg lose much of their energy by transfer upward through the thigh to the trunk, where it is conserved and converted to kinetic energy to accelerate the upper body in the forward direction.

6.1   EFFICIENCY

The term *efficiency* is probably the most abused and misunderstood term in human movement energetics. Confusion and error result from an improper definition of both the numerator and the denominator of the efficiency equation (Gaesser and Brooks, 1975; Whipp and Wasserman, 1969). In the next section, four causes of inefficiency are discussed in detail, and these mechanisms must be recognized in whatever formula evolves. Overlaid on these four mechanisms are two fundamental reasons for inefficiency: inefficiency in the conversion of metabolic energy to mechanical energy, and

neurological inefficiency in the control of that energy. Metabolic energy is converted to mechanical energy at the tendon, and the metabolic efficiency depends on the conditioning of each muscle, the metabolic (fatigue) state of muscle, the subject's diet, and any possible metabolic disorder. This conversion of energy would be called *metabolic* or *muscle efficiency* and would be defined as follows:

$$\text{metabolic (muscle) efficiency} = \frac{\Sigma \text{ mechanical work done by all muscles}}{\text{metabolic work of muscles}}$$

$$(6.8)$$

Such an efficiency is impossible to calculate at this time because it is currently impossible to calculate the work of each muscle (which would require force and velocity time histories of every muscle involved in the movement) and to isolate the metabolic energy of those muscles. Thus, we are forced to compromise and calculate an efficiency based on segmental work and to correct the metabolic cost by subtracting estimates of overhead costs not associated with the actual mechanical work involved. Thus, an efficiency would be defined as:

$$\text{mechanical efficiency} = \frac{\text{mechanical work (internal + external)}}{\text{metabolic cost} - \text{resting metabolic cost}} \quad (6.9)$$

The resting metabolic cost in bicycling, for example, could be the cost associated with sitting still on the bicycle.

A further modification is *work efficiency*, which is defined as:

$$\text{work efficiency} = \frac{\text{external mechanical work}}{\text{metabolic cost} - \text{zero-work metabolic cost}} \quad (6.10)$$

The zero-work cost would be the cost measured with the cyclist freewheeling.

In all of the efficiency calculations described, there are varying amounts of positive and negative work. The metabolic cost of positive work exceeds that of equal levels of negative work. However, negative work is not negligible in most activities. Level gait has equal amounts of positive and negative work. Running uphill has more positive work than negative work, and vice versa for downhill locomotion. Thus, all of the efficiency calculations yield numbers that are strongly influenced by the relative percentages of positive and negative work. An equation that gets around this problem is:

$$\text{metabolic cost (positive work)}$$

$$+ \text{metabolic cost (negative work)} = \text{metabolic cost}$$

or $$\frac{\text{positive work}}{\eta_+} + \frac{\text{negative work}}{\eta_-} = \text{metabolic cost} \quad (6.11)$$

where η_+ and η_- are the positive and negative work efficiencies, respectively.

The interpretation of efficiency is faulty if it is assumed to be simply a measure of how well the metabolic system converts biochemical energy into mechanical energy, rather than a measure of how well the neural system is performing to control the conversion of that energy. An example will demonstrate the anomaly that results. A normal healthy adult walks with 100 J mechanical work per stride (half positive, half negative). The metabolic cost is 300 J per stride, and this yields an efficiency of 33%. A neurologically disabled adult would do considerably more mechanical work because of his or her jerky gait pattern, say 200 J per stride. Metabolically, the cost might be 500 J per stride, which would give an efficiency of 40%. Obviously, the healthy adult is a more efficient walker, but our efficiency calculation does not reflect that fact. Neurologically, the disabled person is quite inefficient because he or she is not generating an effective and smooth neural pattern. However, the disabled person is quite efficient in the actual conversion of metabolic energy to mechanical energy (at the tendon), and that is all that is reflected in the higher efficiency score.

6.1.1 Causes of Inefficient Movement

It is often difficult for a therapist or coach to concentrate directly on efficiency. Rather, it is more reasonable to focus on the individual causes of inefficiency and thereby automatically improve the efficiency of the movement. The four major causes of mechanical inefficiency (Winter, 1978) will now be described.

6.1.1.1 Cocontractions.   Obviously, it is inefficient to have muscles cocontract because they fight against each other without producing a net movement. Suppose that a certain movement can be accomplished with a flexor moment of 30 N · m. The most efficient way to do this is with flexor activity only. However, the same movement can be achieved with 40 N · m flexion and 10 N · m extension, or with 50 N · m flexion and 20 N · m extension. In the latter case, there is an unnecessary 20 N · m moment in both the extensors and the flexors. Another way to look at this situation is that the flexors are doing unnecessary positive work to overcome the negative work of the extensors.

Cocontractions occur in many pathologies, notably hemiplegia and spastic cerebral palsy. They also occur to a limited extent during normal movement when it is necessary to stabilize a joint, especially if heavy weights are being lifted or at the ankle joint during walking or running. At present, the measurement of unnecessary cocontractions is only possible by monitoring the EMG activity of the antagonistic muscles. Without an exact EMG calibration versus tension for each muscle, it is impossible to arrive at a quantitative measure of cocontraction. Falconer and Winter (1985) presented a formula by which cocontraction can be quantified,

$$\%\text{COCON} = 2 \times \frac{M_{\text{antag}}}{M_{\text{agon}} + M_{\text{antag}}} \times 100\% \qquad (6.12)$$
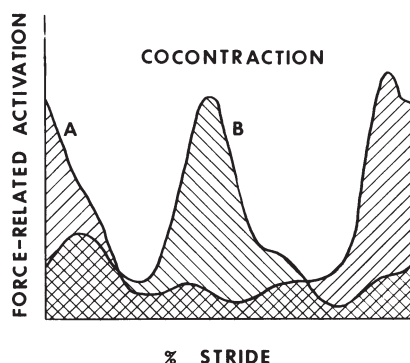
Figure 6.9 Profiles of activity of two antagonist muscles, with cross-hatched area representing the cocontraction. See the text for detailed discussion and analysis.

where M_{antag} and M_{agon} are the moments of force of antagonists and agonists, respectively.

In the example reported, the antagonist activity results in an equal increase in agonist activity; thus, the unnecessary activity must be twice that of the antagonist alone. If the antagonists created a $20\,N \cdot m$ extensor moment and the agonists generated a $50\,N \cdot m$ flexor moment, %COCON would be $40/70 \times 100\% = 57\%$. However, most movements involve continuously changing muscle forces; thus, an agonist muscle at the beginning of the movement will likely reverse its role and become an antagonist later on in the movement. Joint moments of force, as seen in many graphs in Chapter 4, reverse their polarities many times; thus, a modification of Equation (5.12) is needed to cope with these time-varying changes. Figure 6.9 demonstrates the profile of activity of two antagonistic muscles during a given movement. The cross-hatching of muscles A and B shows a common area of activity that indicates the cocontraction area. Thus, the percent cocontraction is defined as:

$$\%COCON = 2 \times \frac{\text{common area } A\& B}{\text{area } A + \text{area } B} \times 100\% \qquad (6.13)$$

If EMG is the primary measure of relative tension in the muscle, we can suitably process the raw EMG to yield a tension-related activation profile (Milner-Brown et al., 1973; Winter, 1976). The activity profiles of many common muscles look very much like those portrayed in Figure 6.9. In this case, muscle A is the tibialis anterior and muscle B is the soleus as seen over one walking stride. Using Equation (6.13) for the profiles in Figure 5.9, %COCON was calculated to be 24%.

6.1.1.2 Isometric Contractions against Gravity. In normal dynamic movement, there is minimal muscle activity that can be attributed to holding limb segments against the forces of gravity. This is because the momentum

of the body and limb segments allows for a smooth interchange of energy. However, in many pathologies the movement is so slow that there are extended periods of time when limb segments or the trunk are being held in near-isometric contractions. Spastic cerebral palsy patients often crouch with their knee flexed, requiring excessive quadriceps activity to keep them from falling down. Or, as seen in Figure 6.10, the crutch-walking cerebral palsy child holds her leg off the ground for a period of time prior to swing-through.

At the present time, it is impossible to quantify work against gravity because there is no movement involved. The only possible technique that might be used is the EMG, and each muscle's EMG would have to be calibrated against the extra metabolism required to contract that muscle. At present, no valid technique has been developed to separate the metabolic cost of this inefficiency.

6.1.1.3 *Generation of Energy at One Joint and Absorption at Another.*
The least known and understood cause of inefficiency occurs when one muscle group at one joint does positive work at the same time as negative work is being done at others. Such an occurrence is really an extension of what occurs during a cocontraction (e.g., positive work being canceled out by negative work of the antagonistic muscles). It is quite difficult to visualize when this happens. During normal walking, it occurs during double support when the energy increase of the pushoff leg takes place at the same time as the weight-accepting leg absorbs energy. Figure 6.11 shows this point in gait: the left leg's pushoff (positive work) is due primarily to plantarflexors; the right leg's energy absorption (negative work) takes place in the quadriceps and tibialis anterior. There is no doubt that the instability of pathological gait
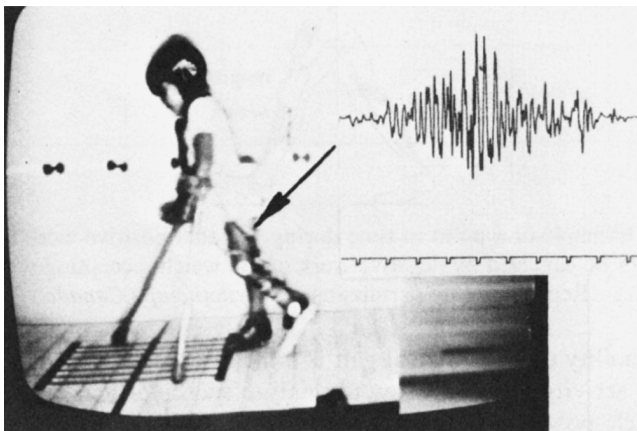

Figure 6.10 Example of "work" against gravity, one of the causes of inefficient movement. Here a cerebral palsy child holds her leg against gravity for an extended period prior to swinging through. (Reproduced by permission of *Physiotherapy Canada*.)
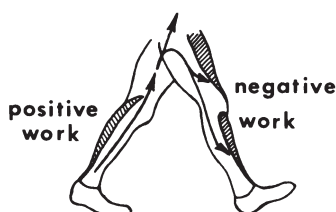
Figure 6.11   Example of a point in time during gait that positive work by the pushoff muscles can be canceled by negative work of the weight-accepting muscles of the contralateral leg. (Reproduced by permission of *Physiotherapy Canada*.)

is a major cause of this type of inefficient muscle activity. The only way to analyze such inefficiencies is to calculate the muscle power at each joint separately and to quantify the overlap of simultaneous phases of positive and negative work.

In spite of the inefficiencies inferred by such events, it must be remembered that many complex movements such as walking or running require that several functional tasks be performed at the same time. The example in Figure 6.11 illustrates such a situation: the plantarflexors are completing pushoff while the contralateral muscles are involved in weight acceptance. Both these events are essential to a safe walking pattern.

6.1.1.4 Jerky Movements.   Efficient energy exchanges are characterized by smooth-looking movements. A ballet dancer and a high jumper execute smooth movements for different reasons, one for artistic purposes, the other for efficient performance. Energy added to the body by positive work at one point in time is conserved, and very little of this energy is lost by muscles doing negative work. The jerky gait of a cerebral palsy child is quite the opposite. Energy added at one time is removed a fraction of a second later. The movement has a steady succession of stops and starts, and each of these bursts of positive and negative work has a metabolic cost. The energy cost from jerky movements can be assessed in two ways: by work analysis based on a segment-by-segment energy analysis or by a joint-by-joint power analysis. Both of these techniques are described later.

6.1.2 Summary of Energy Flows

It is valuable to summarize the flows of energy from the metabolic level through to an external load. Figure 6.12 depicts this process schematically. Metabolic energy cannot be measured directly but can be calculated indirectly from the amount of O_2 required or by the CO_2 expired. The details of these calculations and their interpretation are the subject of many textbooks and are beyond the scope of this book.
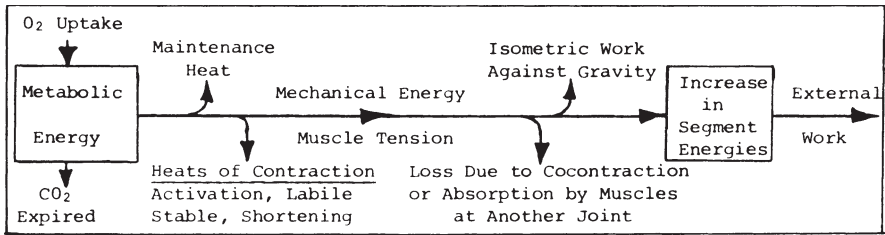
Figure 6.12 Flow of energy from metabolic level of external mechanical work. Energy is lost as heat associated with the contractile process or by inefficiencies after energy has been converted to mechanical energy.

At the basal level (resting, lying down), the muscles are relaxed, but they still require metabolic energy to keep them alive. The measure of this energy level is called *maintenance heat*. Then as a muscle contracts, it requires energy, which shows up as additional heat called *activation heat*. It has been shown to be associated with the rate of build-up of tension within the muscle and is accompanied by an internal shortening of the muscle contractile elements. Stable heat is the heat that measures the energy required to maintain tension within accounted for the muscle. *Labile heat* is a third type of heat seen in isometric contractions and is the heat not generated by either tension or rate of tension generation. The final type of heat loss is *shortening heat*, which is associated with the actual shortening of the muscle under load. Students are referred to the excellent review by Hill (1960).

Finally, at the tendon we see the energy in mechanical form. The muscle tension can contribute to four types of mechanical loads. It can be involved with a cocontraction, isometric "work" against gravity, or a simultaneous absorption by another muscle, or it can cause a net change in the body energy. In the latter case, if positive work is done, the net body energy will increase; if negative work is done, there will be a decrease in total body energy. Finally, if the body exerts forces on an external body, some of the energy may be transferred as the body performs external work.

6.2   FORMS OF ENERGY STORAGE

1. Potential Energy. Potential energy (PE) is the energy due to gravity and, therefore, increases with the height of the body above ground or above some other suitable reference datum,

$$PE = mgh \quad \mathbf{J} \tag{6.14}$$

where m = mass, kg
$\quad g$ = gravitational acceleration, = 9.8 m/s^2
$\quad h$ = height of center of mass, meters

With $h = 0$, the potential energy decreases to zero. However, the ground reference datum should be carefully chosen to fit the problem in question. Normally, it is considered to be the lowest point that the body takes during the given movement. For a diver, it could be the water level; for a person walking, it would be the lowest point in the pathway.

2. Kinetic Energy. There are two forms of kinetic energy (KE), that due to translational velocity and that due to rotational velocity,

$$\text{translational KE} = \tfrac{1}{2}mv^2 \quad \textbf{J} \tag{6.15}$$

where $v =$ velocity of center of mass, m/s

$$\text{rotational KE} = \tfrac{1}{2}I\omega^2 \quad \textbf{J} \tag{6.16}$$

where $I =$ rotational moment of inertia, kg · m^2
$\omega =$ rotational velocity of segment, rad/s

Note that these two energies increase as the velocity squared. The polarity of direction of the velocity is unimportant because velocity squared is always positive. The lowest level of kinetic energy is therefore zero when a body is at rest.

3. Total Energy and Exchange within a Segment. As mentioned previously, the energy of a body exists in three forms so that the total energy of a body is

$$E_s = \text{PE} + \text{translational KE} + \text{rotational KE} \tag{6.17}$$
$$= mgh + \tfrac{1}{2}mv^2 + \tfrac{1}{2}I\omega^2 \quad \textbf{J}$$

It is possible for a body to exchange energy within itself and still maintain a constant total energy.

Example 6.3. Suppose that the baseball in Example 6.1 is thrown vertically. Calculate the potential and kinetic energies at the time of release, at maximum height, and when its reaches the ground. Assume that it is released at a height of 2 m above the ground and that the vertical accelerating force of 100 N is in excess of gravitational force. At release,

$$a = 100 \text{ m/s}^2 \quad \text{(as calculated previously)}$$

$$v = \int_0^{t_1} a\, dt = at_1 = 100t_1$$

$$t_1 = 180 \, \text{ms}$$

$$v = 18 \text{ m/s}$$

$$\text{translational KE} = \tfrac{1}{2}mv^2 = \tfrac{1}{2} \times 1 \times 18^2 = 162 \, \textbf{J}$$

Note that this 162 **J** is equal to the work done on the baseball prior to release.

$$\text{total energy} = \text{PE}(t_1) + \text{translational KE}(t_1)$$

$$= 19.6 + 162 = 181.6 \, \textbf{J}$$

If we ignore air resistance, the total energy remains constant during the flight of the baseball, such that at t_2, when the maximum height is reached, all the energy is potential energy and KE $= 0$. Therefore, PE$(t_2) = 181.6$ J. This means that the baseball reaches a height such that $mgh_2 = 181.6$ J, and:

$$h_2 = \frac{181.6}{1.0 \times 9.8} = 18.5 \text{ m}$$

At t_3 the baseball strikes the ground, and $h = 0$. Thus, PE$(t_3) = 0$ and KE$(t_3) = 181.6$ J. This means that the velocity of the baseball is such that $\frac{1}{2}mv^2 = 181.6$ J, or:

$$v = 19.1 \, \text{m/s}$$

This velocity is slightly higher than the release velocity of 18 m/s because the ball was released from 2 m above ground level.

6.2.1 Energy of a Body Segment and Exchanges of Energy Within the Segment

Most body segments contain all three energies in various combinations at any point in time during a given movement. A diver at the top of a dive has considerable potential energy, and during the dive, converts it to kinetic energy. Similarly, a boomerang when released has rotational and translational kinetic energy, and at peak height some of the translational kinetic energy has been converted to potential energy. At the end of its travel, the boomerang will have regained most of its translational kinetic energy.

In a multisegment system, such as the human body, the exchange of energy can be considerably more complex. There can be exchanges within a segment or between adjacent segments. A good example of energy exchange within a segment is during normal gait. The upper part of the body [head, arms, and trunk (HAT)] has two peaks of potential energy each stride—during midstance of each leg. At this time, HAT has slowed its forward velocity to a minimum. Then, as the body falls forward to the double-support
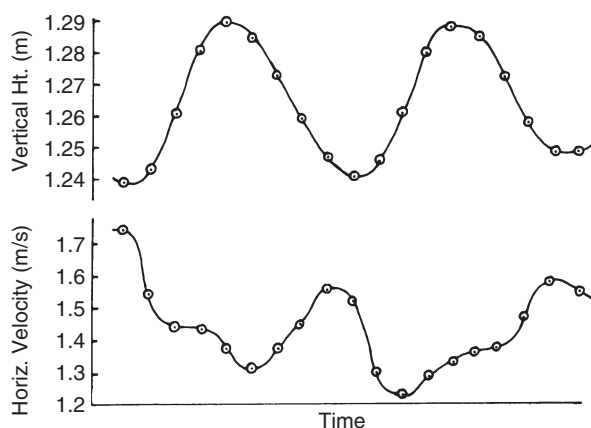
Figure 6.13   Plot of vertical displacement and horizontal velocity of HAT shows evidence of energy exchange within the upper part of the body during gait.

position, HAT picks up velocity at the expense of a loss in height. Evidence of energy exchange should be seen from a plot of the horizontal velocity and the vertical displacement of the center of gravity of HAT (see Figure 6.13). The potential energy, which varies with height, changes roughly as a sinusoidal wave, with a minimum during double support and reaching a maximum during midstance. The forward velocity is almost completely out of phase, with peaks approximately during double support and minima during midstance.

Exchanges of energy within a segment are characterized by opposite changes of the potential and kinetic energy components. Figure 6.14 shows what would happen if a perfect exchange took place, as in a swinging frictionless pendulum. The total energy would remain constant over time in the presence of large changes of potential and kinetic energy.
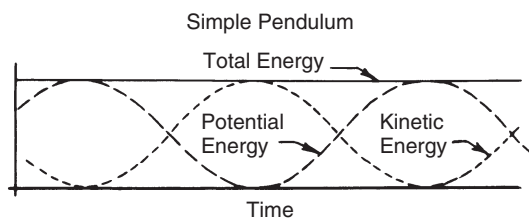

Figure 6.14   Exchange of kinetic and potential energies in a swinging frictionless pendulum. Total energy of the system is constant, indicating that no energy is being added or lost. (Reproduced by permission of *Physiotherapy Canada*.)
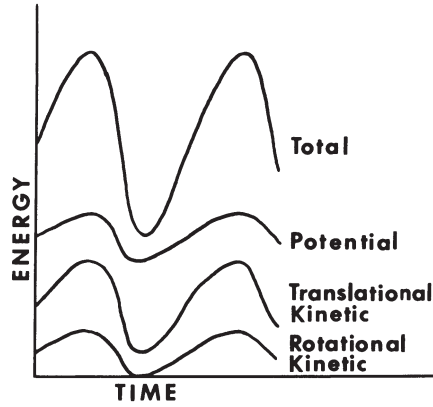
Figure 6.15   Energy patterns for a segment in which no exchanges are taking place. All energy components are perfectly in phase.

Consider the other extreme, in which no energy exchange takes place. Such a situation would be characterized by totally in-phase energy components, not necessarily of equal magnitude, as depicted in Figure 6.15.

6.2.1.1 *Approximate Formula for Energy Exchanges within a Segment.*
An approximation of energy exchange can be calculated if we know the peak-to-peak change in each of the energy components over a period of time:

$$E_{ex} = \Delta E_p + \Delta E_{kt} + \Delta E_{kr} - \Delta E_s \tag{6.18}$$

If there is no exchange, $\Delta E_p + \Delta E_{kt} + \Delta E_{kr} = \Delta E_s$. If there is 100% exchange, $\Delta E_s = 0$.

Example 6.4.   A visual scan of the energies of the leg segment during walking yields the following maximum and minimum energies on the stride period: $E_s(\text{max}) = 29.30\,\text{J}, E_s(\text{min}) = 13.14\,\text{J}, E_p(\text{max}) = 15.18\,\text{J}, E_p(\text{min}) = 13.02\,\text{J}, E_{kt}(\text{max}) = 13.63\,\text{J}, E_{kt}(\text{min}) = 0.09\,\text{J}, E_{kr}(\text{max}) = 0.95\,\text{J}, E_{kr}(\text{min}) = 0\,\text{J}.$ Thus, $\Delta E_s = 29.30 - 13.14 = 16.16\,\text{J}, \Delta E_p = 15.18 - 13.02 = 2.16\,\text{J}, \Delta E_{kt} = 13.63 - 0.09 = 13.54\,\text{J}, \Delta E_{kr} = 0.95 - 0 = 0.95\,\text{J}.$
Since $\Delta E_p + \Delta E_{kt} + \Delta E_{kr} = 16.65\,\text{J}$, it can be said that $16.65 - 16.16 = 0.49\,\text{J}$ exchanged during the stride. Thus, the leg is a highly nonconservative system.

6.2.1.2 *Exact Formula for Energy Exchange within Segments.* The example just discussed illustrates a simple situation in which only one minimum and maximum occur over the period of interest. If individual energy components have several maxima and minima, we must calculate the sum of the absolute energy changes over the time period. The work, W_s, done on and by a segment during N sample periods is:

$$W_s = \sum_{i=1}^{N} |\Delta E_s| \quad \mathbf{J} \tag{6.19}$$

Assuming that there are no energy exchanges between any of the three components (Norman et al., 1976), the work done by the segment during the N sample periods is:

$$W_s' = \sum_{i=1}^{N} \left(|\Delta E_p| + |\Delta E_{kt}| + |\Delta E_{kr}| \right) \quad \mathbf{J} \tag{6.20}$$

Therefore, the energy W_c conserved within the segment during the time is

$$W_c = W_s' - W_s \quad \mathbf{J} \tag{6.21}$$

The percentage energy conservation, C_s, during the time of this event is:

$$C_s = \frac{W_c}{W_s'} \times 100\% \tag{6.22}$$

If $W_s' - W_s$, all three energy components are in phase (they have exactly the same shape and have their minima and maxima at the same time), and there is no energy conservation. Conversely, as demonstrated by an ideal pendulum, if $W_s = 0$, then 100% of the energy is being conserved.

6.2.2 Total Energy of a Multisegment System

As we proceed with the calculation of the total energy of the body, we merely sum the energies of each of the body segments at each point in time (Bresler and Berry, 1951; Ralston and Lukin, 1969; Winter et al., 1976). Thus, the total body energy E_b at a given time is:

$$E_b = \sum_{i=1}^{B} E_{si} \quad \mathbf{J} \tag{6.23}$$

where: E_{si} = total energy of ith segment at that point in time
B = number of body segments

The individual segment energies continuously change with time, so it is not surprising that the sum of these energies will also change with time. However, the interpretation of changes in E_b must be done with caution when one considers the potential for transfer of energy between segments and the number of possible generators and absorbers of energy at each joint. For example, transfers of energy between segments (see Section 6.0.9) will not result in either an increase or a loss in total body energy. However, in other than the simplest movements, there may be several simultaneous concentric and eccentric contractions. Thus, over a period of time, two muscle groups may generate 30 J, while one other muscle group may absorb 20 J. The net change in body energy over that time would be an increase of 10 J. Only through a detailed analysis of mechanical power at the joints (see Section 6.3.1.4) are we able to assess the extent of such a cancellation. Such events are obviously inefficient but are necessary to accomplish many desired movement patterns.

Consider now a simple muscular system that can be represented by a pendulum mass with a pair of antagonistic muscle groups, m_1 and m_2, crossing a simple hinge joint. Figure 6.16 shows such an arrangement along with a time history of the total energy of the system. At t_1, the segment is rotating counterclockwise at ω_1 rad/s. No muscle activity occurs until t_2 when m_2 contracts. Between t_1, and t_2, the normal pendulum energy exchange takes place and the total energy remains constant. However, between t_2 and t_3, muscle m_2 causes an increase in both kinetic and potential energies of the segment. The muscle moment has been in the same direction as the direction of rotation, so positive work has been done by the muscle on the limb segment, and the total energy of the limb has increased. Between t_3 and t_4, both muscles are inactive, and the total energy remains at the higher but constant level. At t_4, muscle m_1 contracts to slow down the segment. Energy is lost by the segment and is absorbed by m_1. This is negative work being done by the muscle because it is lengthening during its contraction. Thus, at t_5 the segment has a lower total energy than at t_4.
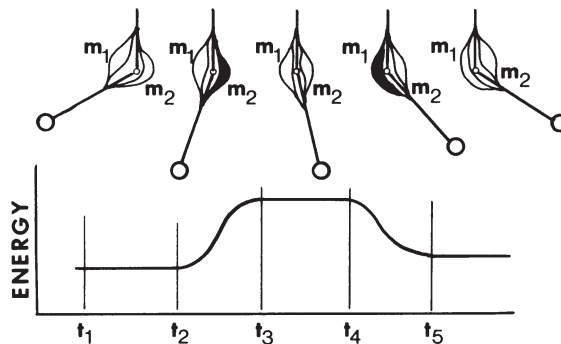

Figure 6.16 Pendulum system with muscles. When positive work is done, the total energy increases; when negative work is done, the total energy decreases.

The following major conclusions can be drawn from this example.

1. When muscles do positive work, they increase the total body energy.
2. When muscles do negative work, they decrease the total body energy.
3. During cyclical activity, such as constant velocity level running, the net energy change per stride equals zero (neglecting the small air friction and shoe friction losses). Thus, the internal positive work done per stride should equal the internal negative work done per stride.

6.3   CALCULATION OF INTERNAL AND EXTERNAL WORK

Internal and external work has been calculated in a multitude of ways by different researchers. Some assume that the energy changes in the body center of mass yield the total internal work done by all the muscles. Others look only at the "vertical work" resulting from potential energy increases of the body center of gravity, while others (especially in the exercise physiology area) even ignore internal work completely. It is, therefore, important to look at all possible sources of muscle activity that have a metabolic cost and keep those readily available on a "checklist" to see how complete any analysis really is. This same list serves a useful purpose in focusing our attention on possible causes of inefficient movement (see Section 6.1.1).

6.3.1   Internal Work Calculation

The various techniques for calculating the internal work have undergone a general improvement over the years. The vast majority of the research has been done in the area of human gait, and because gait is a complex movement, it will serve well as an example of the dos and don'ts.

6.3.1.1   Energy Increases in Segments.   A number of early researchers attempted a calculation of work based on increases in potential or kinetic energies of the body or of individual segments. Fenn (1929), in his accounting of the flow of energy from metabolic to mechanical, calculated the kinetic and potential energies of each major segment of a sprinter. He then summed the increases in each of these segment energies over the stride period to yield the net mechanical work. Unfortunately, Fenn's calculations ignored two important energy-conserving mechanisms: energy exchanges within segments and passive transfers between segments. Thus, his mechanical work calculations were predictably high: the average power of his sprinters was computed to be 3 horsepower. Conversely, Saunders et al. (1953), Cotes and Meade (1960), and Liberson (1965) calculated the "vertical work" of the trunk as representing the total work done by the body. These calculations ignored the major energy exchange that takes place within the HAT and also the major work done by the lower limbs.

6.3.1.2   Center-of-Mass Approach.

Cavagna and Margaria proposed in (1966) and in many subsequent papers a technique that is based on the potential and kinetic energies of the body's center of mass. Their data were based on force platform records during walking and running, from which the translational kinetic and potential energies were calculated. Such a model makes the erroneous assumption that the body's center of mass reflects the energy changes in all segments. The body's center of mass is a *vector* sum of all segment mass-acceleration products, and, as such, opposite-polarity accelerations will cancel out. But energies are scalars, not vectors, and, therefore, the reciprocal movements that dominate walking and running will be largely canceled. Thus, simultaneous increases and decreases in oppositely moving segments will go unnoticed. Also, Cavagna's technique is tied to force platform data, and nothing is known about the body's center of gravity during non-weight-bearing phases of running. Thus, this technique has underestimation errors and limitations that have been documented (Winter, 1979). Also, the center-of-mass approach does not account for the energy losses from the simultaneous generation and absorption of energy at different joints.

6.3.1.3   Sum of Segment Energies.

A major improvement on the previous techniques was made by Ralston and Lukin (1969) and Winter et al. (1976). Using displacement transducers and TV imaging techniques, the kinetic and potential energies of the major segments were calculated. A sum of the energy components within each segment recognized the conservation of energy within each segment (see Section 6.2.1) and a second summation across all segments recognized energy transfers between adjacent segments (see Section 6.0.9). The total body work is calculated (Winter, 1979) to be:

$$W_b = \sum_{i=1}^{N} |\Delta E_b| \quad \mathbf{J} \tag{6.24}$$

However, this calculation underestimates the simultaneous energy generation and absorption at different joints. Thus, W_b will reflect a low estimate of the positive and negative work done by the human motor system. Williams and Cavanagh (1983) made empirical estimates to correct for these underestimates in running.

6.3.1.4   Joint Power and Work.

In Sections 6.0.6 and 6.0.7, techniques for the calculation of the positive and negative work at each joint were presented. Using the time integral of the power curve [Equation (6.6)], we are able to get at the "sources" and "sinks" of all the mechanical energy. Figure 6.17 is an example to show the work phases at the knee during slow running. The power bursts are labeled $K_1, \cdots, K_5$, and the energy generation/absorption resulting from the time integral of each phase is shown (Winter, 1983). In

this runner, it is evident that the energies absorbed early in stance (53 J) by the knee extensors and by the knee flexors in later swing (24 J) dominate the profile; only 31 J are generated by the knee extensors in middle and late stance.

It should be noted that this technique automatically calculates any external work that is done. The external power will be reflected in increased joint moments, which, when multiplied by the joint angular velocity, will show an increased power equal to that done externally.

6.3.1.5 *Muscle Power and Work.*

Even with the detailed analysis described in the previous section, we have underestimated the work done by cocontracting muscles. Joint power, as calculated, is the product of the joint moment of force M_j and the angular velocity ω_j. M_j is the net moment resulting from all agonist and antagonist activity, and therefore, cannot account for simultaneous generation by one muscle group and absorption by the antagonist group, or vice versa. For example, if $M_j = 40\,\text{N} \cdot \text{m}$ and $\omega_j = 3\,\text{rad/s}$, the joint power would be calculated to be 120 W. However, if there were a cocontraction, the antagonists might be producing a resisting moment of $10\,\text{N} \cdot \text{m}$. Thus, in this case, the agonists would be generating energy at the rate of $50 \times 3 = 150\,\text{W}$. while the antagonists would be absorbing energy at a rate of $10 \times 3 = 30\,\text{W}$. Thus, the net power and work calculations as described in Section 6.3.1.4 will underestimate both the positive and the negative work done by the muscle groups at each joint. To date, there has been very limited progress to calculate the power and work associated with each muscle's action. The major problem is to partition the contribution of each muscle to the net moment, and this issue has been addressed in Section 5.5.1. However, if the muscle force F_m and the muscle velocity V_m were known, the muscle work W_m would be calculated as:

$$W_m = \int_{t_1}^{t_2} F_m \cdot V_m \, dt \tag{6.25}$$

Morrison (1970) analyzed the power and work in four muscles in normal walking, and some later work (Yack, 1986) analyzed the muscles forces and powers in the three major biarticulate muscle groups during walking.

6.3.1.6 *Summary of Work Calculation Techniques.*

Table 6.1 summarizes the various approaches described over the past few decades and the different energy components that are not accounted for by each technique.
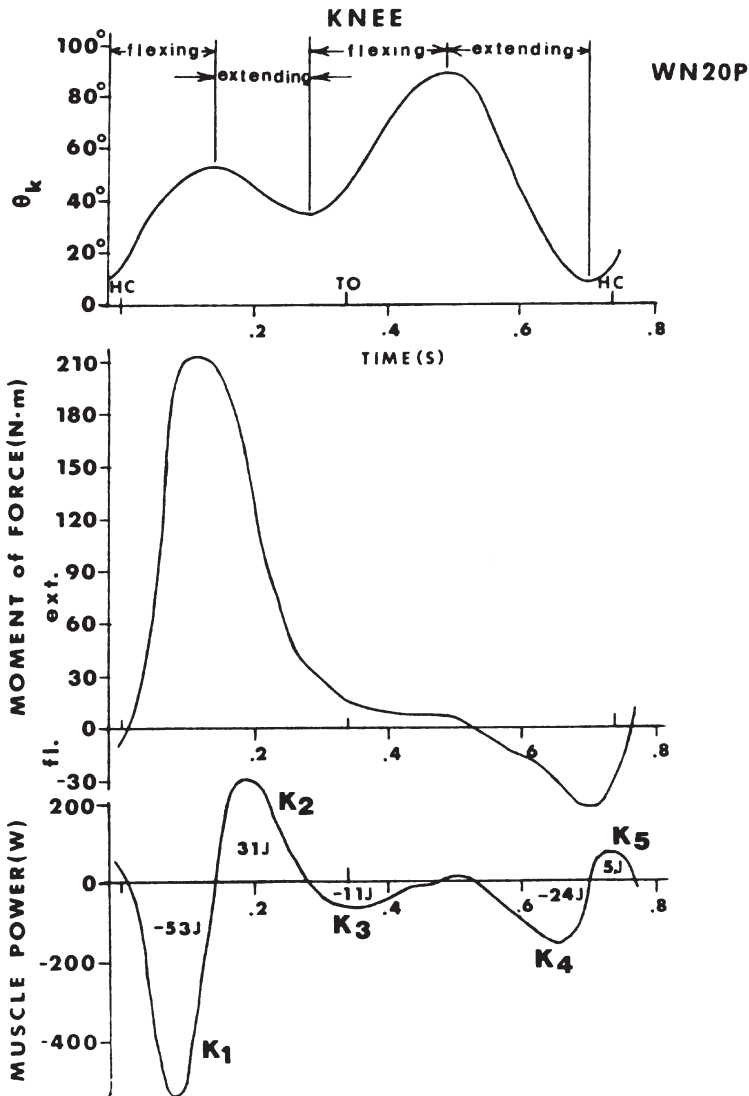
Figure 6.17 Plots of knee angle, moment of force, and power in a slow runner. Five power phases are evident: K_1, energy absorption by knee extensors; K_2, positive work as extensors shorten under tension; K_3, deceleration of backward rotation of leg and foot as thigh drives forward during late stance and early swing; K_4, deceleration of swinging leg and foot by knee flexors prior to heel contact; and K_5, small positive burst to flex the leg slightly and slow down its forward motion to near zero velocity prior to heel contact. (From Winter, 1983. Reproduced by permission of *J. Biomechanics*.)

TABLE 6.1 Techniques to Calculate Internal Work in Movement

Technique	Work Components Not Accounted for by Technique				
Increase PE or KE Fenn (1929) Saunders et al. (1953) Liberson (1965)	Energy exchange within segments and transfers between segments	Simultaneous increases or decreases in reciprocally moving segments	Simultaneous generation and absorption at different joints	Cocontractions	Work against g
Center of mass Cavagna and Margaria (1966)		Simultaneous increases or decreases in reciprocally moving segments	Simultaneous generation and absorption at different joints	Cocontractions	Work against g
Σ Segment energies Winter (1979)			Simultaneous generation and absorption at different joints	Cocontractions	Work against g
Joint power* $\int M_j \omega_j\, dt$ Winter (1983)				Cocontractions	Work against g
Muscle power* $\int F_m V_m\, dt$ Yack (1986)					Work against g

*Also accounts for external work if it is present.

6.3.2 External Work Calculation

It was noted in Sections 6.3.1.4 and 6.3.1.5 that the work calculations done using Equations (6.6) and (6.25) automatically take into account all work done by the muscles independent of whether that work was internal or external. There is no way to partition the external work except by taking measurements at the interface between human and external load. A cyclist, for example, would require a force transducer on both pedals plus a measure of the velocity of the pedal. Similarly, to analyze a person lifting or lowering a load would need a force transducer between the hands and the load, or an imaging record of the load and the body (from which an inverse solution would calculate the reaction forces and velocity). The external work W_e is calculated as:

$$W_e = \int_{t_1}^{t_2} \overline{F}_r \cdot \overline{V}_c \, dt \qquad (6.26)$$

where $\overline{F}_r$ = reaction force vector, newtons
$\overline{V}_c$ = velocity of contact point, m/s
t_1, t_2 = times of beginning and end of each power phase

6.4 POWER BALANCES AT JOINTS AND WITHIN SEGMENTS

In Section 6.0.2, examples were presented to demonstrate the law of conservation of mechanical energy within a segment. Also, in Section 6.0.6, muscle mechanical power was introduced, and in Section 6.0.9, the concept of passive energy transfers across joints was noted. We can now look at one other aspect of muscle energetics that is necessary before we can achieve a complete power balance segment by segment: the fact that active muscles can transfer energy from segment to segment in addition to their normal role of generation and absorption of energy.

6.4.1 Energy Transfer via Muscles

Muscles can function to transfer energy from one segment to the other if the two segments are rotating in the same direction. In Figure 6.18, we have two segments rotating in the same direction but with different angular velocities. The product of $M\omega_2$ is positive (both M and ω_2 have the same polarity), and this means that energy is flowing into segment 2 from the muscles responsible for moment M. The reverse is true as far as segment 1 is concerned, $M\omega_1$ is negative, showing that energy is leaving that segment and entering the muscle. If $\omega_1 = \omega_2$ (i.e., an isometric contraction), the same energy rate occurs and a transfer of energy from segment 1 to segment 2 via the isometrically acting muscles. If $\omega_1 > \omega_2$, the muscles are lengthening, and thus, absorption
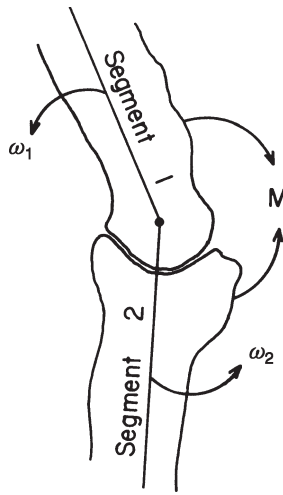
Figure 6.18   Energy transfer between segments occurs when both segments are rotating in the same direction and when there is a net moment of force acting across the joint. See the text for a detailed discussion.

plus a transfer take place, while if $\omega_1 < \omega_2$, the muscles are shortening and a generation as well as a transfer occur. Table 6.2, from Robertson and Winter (1980), summarizes all possible power functions that can occur at a given joint, and if we do not account for these energy transfers through the muscles, we will not be able to account for the total power balance within each segment. Thus, we must modify Equation (6.5) to include the angular velocities of the adjacent segments in order to partition the transfer component. Therefore, ω_j is replaced by $(\omega_1 - \omega_2)$,
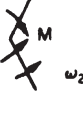
$$P_m = M_j(\omega_1 - \omega_2) \quad \text{W} \tag{6.27}$$

Thus, if ω_1 and ω_2 have the same polarity, the rate of transfer will be the lesser of the two power components. Examples are presented in Section 6.4.2 to demonstrate the calculation and to reinforce the sign convention used.

6.4.2   Power Balance Within Segments

Energy can enter or leave a segment at muscles and across joints at the proximal and distal ends. Passive transfer across the joint [Equation (6.9)] and active transfer plus absorption or generation [Equation (6.27)] must be calculated. Consider Figure 6.19a as the state of a given segment at any given point in time. The reaction forces and the velocities at the joint centers at the proximal and distal ends are shown plus the moments of force acting at the proximal and distal ends along with the segment angular velocity. The total energy of the segment E_s as calculated by Equation (6.17) must also

TABLE 6.2 Power Generation, Transfer, and Absorption Functions

Description of Movement	Type of Contraction	Directions of Segmental Angular Velocities	Muscle Function	Amount, Type, and Direction of Power
Both segments rotating in opposite directions	Concentric	ω_1 / ω_2	Mechanical energy generation	$M\omega_1$ generated to segment 1
(a) joint angle decreasing				$M\omega_2$ generated to segment 2
(b) joint angle increasing	Eccentric	ω_1 / ω_2	Mechanical energy absorption	$M\omega$ absorbed from segment 1
				$M\omega_2$ absorbed from segment 2
Both segments rotating in some direction	Concentric	ω_1 / ω_2	Mechanical energy generation and transfer	$M(\omega_1 - \omega_2)$ generated to segment 1
(a) joint angle decreasing (e.g. $\omega_1 > \omega_2$)				$M\omega_2$ transferred to segment 1 from 2
(b) joint angle increasing (e.g. $\omega_2 > \omega_1$)	Eccentric	ω_1 / 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 / ω_2	Mechanical energy transfer	$M\omega_2$ transferred from segment 2 to 1
One segment fixed (e g segment 1)	Concentric	ω_2	Mechanical energy generation	$M\omega_2$ generated to segment 2
(a) joint angle decreasing $(\omega_1 = O_1$ $\omega_2 > O)$				
(b) joint angle increasing $(\omega_1 = O_1$ $\omega_2 > O)$	Eccentric	ω_2	Mechanical energy absorption	$M\omega_2$ absorbed from segment 2
(c) joint angle constant $(\omega_1 = \omega_2 = O)$	Isometric (static)		No mechanical energy function	Zero

From Roberston and Winter (1980). (Reproduced by permission from *J. Biomechanics*.)
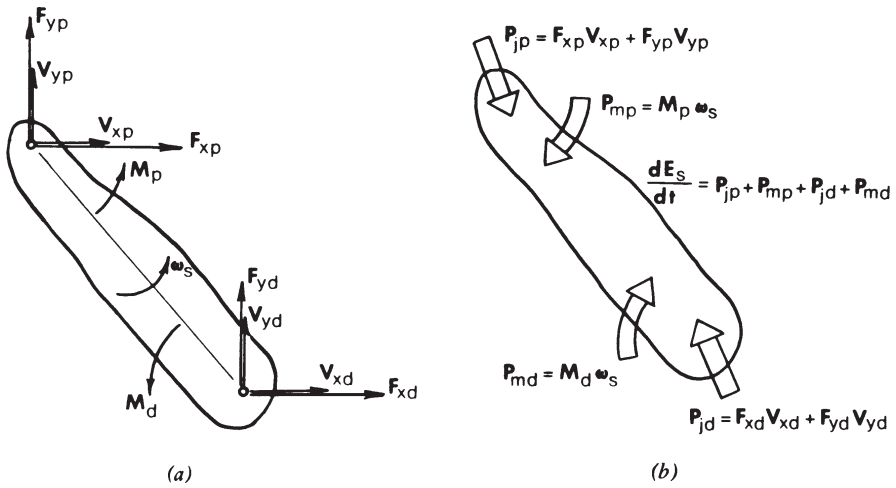
Figure 6.19   (a) Biomechanical variables describing the instantaneous state of a given segment in which passive energy transfers may occur at the proximal and distal joint centers and active transfers through the muscles at the proximal and distal ends. (b) Power balance as calculated using the variables shown in (a). The passive power flow at the proximal end P_{jp}, and the distal end P_{jd}, combined with the active (muscle) power at the proximal end P_{mp} and the distal end P_{md}, must equal the rate of change of energy of the segment dE_s / dt.

be known. Figure 6.19b is the power balance for that segment, the arrows showing the directions where the powers are positive (energy entering the segment across the joint or through the tendons of the dominant muscles). If the force—velocity or moment—ω product turns out to be negative, this means that energy flow is leaving the segment. According to the law of conservation of energy, the rate of change of energy of the segment should equal the four power terms,

$$\frac{dE_s}{dt} = P_{jp} + P_{mp} + P_{jd} + P_{md} \tag{6.28}$$

A sample calculation for two adjacent segments is necessary to demonstrate the use of such power balances and also to demonstrate the importance of passive transfers across joints and across muscles as major mechanisms in the energetics of human movement.

Example 6.5.   Carry out a power balance for the leg and thigh segments for frame 5, that is, deduce the dynamics of energy flow for each segment separately and determine the power dynamics of the knee muscles (generation, absorption, transfer):

Table A.2a, hip velocities,

$$V_{xh} = 1.36 \, \text{m/s} \quad V_{yh} = 0.27 \, \text{m/s}$$

Table A.2b, knee velocities,

$$V_{xk} = 2.61 \, \text{m/s} \quad V_{yk} = 0.37 \, \text{m/s}$$

Table A.2c, ankle velocities,

$$V_{xa} = 3.02 \, \text{m/s} \quad V_{ya} = 0.07 \, \text{m/s}$$

Table A.3b, leg angular velocity,

$$\omega_{lg} = 1.24 \, \text{rad/s}$$

Table A.3c, thigh angular velocity,

$$\omega_{th} = 3.98 \, \text{rad/s}$$

Table A.5a, leg segment reaction forces and moments,

$$F_{xk} = 15.1 \, \text{N}, \quad F_{yk} = 14.6 \, \text{N}, \quad F_{xa} = -12.3 \, \text{N}, \quad F_{ya} = 5.5 \, \text{N},$$
$$M_a = -1.1 \, \text{N} \cdot \text{m} \quad M_k = 5.8 \, \text{N} \cdot \text{m}$$

Table A.5b, thigh segment reaction forces and moments,

$$F_{xk} = -15.1 \, \text{N}, \quad F_{yk} = -14.6 \, \text{N}, \quad F_{xh} = -9.4 \, \text{N}, \quad F_{yk} = 102.8 \, \text{N},$$
$$M_k = -5.8 \, \text{N} \cdot \text{m}, \quad M_h = 8.5 \, \text{N} \cdot \text{m}$$

Table A.6, leg energy,

$$E_{lg} \, (\text{frame } 6) = 20.5 \, \text{J}, \quad E_{lg} \, (\text{frame } 4) = 20.0 \, \textbf{J}$$

Table A.6, thigh energy,

$$E_{th} \, (\text{frame } 6) = 47.4 \, \text{J}, \quad E_{th} \, (\text{frame } 4) = 47.9 \, \textbf{J}$$

1. Leg Power Balance

$$\begin{aligned}
\Sigma \, \text{powers} &= F_{xk} V_{xk} + F_{yk} V_{yk} + M_k \omega_{lg} + F_{xa} V_{xa} + F_{ya} V_{ya} + M_a \omega_{lg} \\
&= 15.1 \times 2.61 + 14.6 \times 0.37 + 5.8 \times 1.24 - 12.3 \\
&\quad \times 3.02 + 5.5 \times 0.7 - 1.1 \times 1.24 \\
&= 44.81 + 7.19 - 33.3 - 1.36 \\
&= 17.34 \, \text{W}
\end{aligned}$$

$$\frac{\Delta E_{lg}}{\Delta t} = \frac{20.5 - 20.0}{0.0286} = 17.5 \, \text{W}$$

$$\text{balance} = 17.5 - 17.34 = 0.16 \, \text{W}$$

2. Thigh Power Balance

$$\Sigma \, \text{powers} = F_{xh}V_{xh} + F_{yh}V_{yh} + M_h\omega_{th} + F_{xk}V_{xk} + F_{yk}V_{yk} + M_k\omega_{th}$$

$$= -9.4 \times 1.36 + 102.8 \times 0.27 + 8.5 \times 3.98$$

$$- 15.1 \times 2.61 - 14.6 \times 0.37 - 5.8 \times 3.98$$

$$= 14.97 + 33.83 - 44.81 - 23.08$$

$$= -19.09 \, \text{W}$$

$$\frac{\Delta E_{th}}{\Delta t} = \frac{47.4 - 47.9}{0.0286} = -17.5 \, \text{W}$$

$$\text{balance} = -17.5 - (-19.09) = 1.59 \, \text{W}$$

3. *Summary of Power Flows*. The power flows are summarized in Figure 6.20 as follows: 23.08 W leave the thigh into the knee extensors, and 7.19 W enter the leg from the same extensors. Thus, the knee extensors are actively transferring 7.19 W from the thigh to the leg and are simultaneously absorbing 15.89 W.
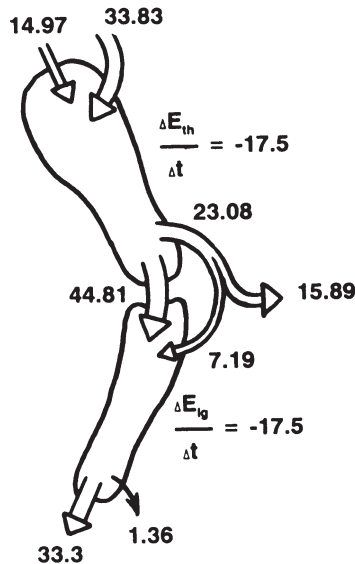

Figure 6.20   Summary of thigh and leg power flows as calculated in Example 6.5. There is power transfer from the thigh to the leg at a rate of 7.19 W through the quadriceps muscles plus passive flow across the knee of 44.81 W.

6.5   PROBLEMS BASED ON KINETIC AND KINEMATIC DATA

1. (a) Calculate the potential, translational, and rotational kinetic energies of the leg segment for frame 20 using appropriate kinematic data, and check your answer with Table A.6 in Appendix A.

   (b) Repeat Problem 1*a* for the thigh segment for frame 70.

2. (a) Plot (every second frame) the three components of energy plus total energy of the leg over the stride period and discuss whether this segment conserves or does not conserve energy over the stride period (frames 28 to 97).

   (b) Repeat Problem 2*a* for the thigh segment.

   (c) Repeat Problem 2*a* for the HAT segment. Using Equation (6.18), calculate the approximate percentage of energy conservation in the HAT segment over the stride period. Compare this percentage with that calculated using the exact Equations (6.19) to (6.22).

3. (a) Assuming symmetrical gait, calculate the total energy of the body for frame 28. [*Hint:* For a stride period of 68 frames, data for the left side of the body can be estimated using right side data half a stride (34 frames) later.]

   (b) Scan the total energy of all segments, and note the energy changes over the stride period in the lower limb compared with that of the HAT. From your observations, deduce whether the movement of the lower limbs or that of HAT makes the major demands on the metabolic system.

4. (a) Using segment angular velocity data in Table A.7 in the Appendix plus appropriate data from other tables, calculate the power generation or absorption of the muscles at the following joints. Identify in each case the muscle groups involved that are responsible for the generation or absorption. Check your numerical answers with Table A.7.

   (i)   Ankle joint for frame 30.
   (ii)   Ankle joint for frame 50.
   (iii)   Ankle joint for frame 65.
   (iv)   Knee joint for frame 35.
   (v)   Knee joint for frame 40.
   (vi)   Knee joint for frame 65.
   (vii)   Knee joint for frame 20.
   (viii) Hip joint for frame 50
   (ix)   Hip joint for frame 70
   (x)   Hip joint for frame 4.

   (b) (i)   Scan the listings for muscle power in Table A.7 and identify where the major energy generation occurs during walking. When in the gait cycle does this occur and by what muscles?

   (ii)   Do the knee extensors generate any significant energy during walking? If so, when during the walking cycle?

(iii)   What hip muscle group generates energy to assist the swinging of the lower limb? When is this energy generated?

5. Using Equation (6.10) (see Figure 6.8), calculate the passive rate of energy transfer across the following joints, and check your answers with Table A.7. From what segment to what segment is the energy flowing?
(i)   Ankle for frame 20.
(ii)   Ankle for frame 33.
(iii)   Ankle for frame 65.
(iv)   Knee for frame 2.
(v)   Knee for frame 20.
(vi)   Knee for frame 65.
(vii)   Hip for frame 2.
(viii)   Hip for frame 20.
(ix)   Hip for frame 67.

6. (a) Using equations in Figure 6.19*b*, carry out a power balance for the foot segment for frame 20.
(b) Repeat Problem 6*(a)* for the leg segment for frame 20.
(c) Repeat Problem 6*(a)* for the leg segment for frame 65.
(d) Repeat Problem 6*(a)* for the thigh segment for frame 63.

7. Muscles can transfer energy between adjacent segments when they are rotating in the same direction in space. Calculate the power transfer between the following segments, and indicate the direction of energy flow. Compare your answers with those listed in Table A.7.
(a) Leg/foot for frame 60.
(b) Thigh/leg for frame 7.
(c) Thigh/leg for frame 35.

6.6   REFERENCES

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