arm can be assessed by evaluating the ability of patients to perform such tasks as touching the opposite knee, placing the hand on the chin, and raising the arm overhead (Gowland, deBruin, Basmajian, Plews, & Burcea, 1992). The inability of a patient to perform one of these tasks is due to the generation of an inadequate net muscle torque. Neurodevelopmental theory (Bobath, 1978) suggests that this inability is due to an inappropriate coactivation of muscle because of a failure to inhibit antagonist activity. It appears, however, that the problem has more to do with muscle weakness and insufficient motor unit activity rather than with heightened coactivation (Burke, 1988; Gowland et al., 1992; Tang & Rymer, 1981).

Stretch-Shorten Cycle. A common pattern of muscle activation, particularly during high-performance tasks, is to use *an eccentric-concentric sequence in which the active muscle is first lengthened and then shortened.* The advantage of this strategy is that a muscle can perform more positive work if it is actively stretched before being allowed to shorten (Cavagna & Citterio, 1974; Fenn, 1924). The result of this **stretch-shorten cycle** is that *a greater quantity of work is done during the concentric contraction than would be done if the muscle simply performed a concentric contraction by itself.* The experimental evidence for this conclusion is based on the work done by an isolated muscle (Figure 7.31). The experiment had two parts: The muscle was first stretched and then stimulated before it was allowed to shorten and perform positive work (Figure 7.31a); next the muscle was first stimulated and then stretched before it performed positive work (Figure 7.31b). The results for each part of the experiment are shown as length-time, force-time, and force-length graphs. The critical comparison is contained in the force-length graphs. Phase c shows the change in force and length as the muscle performs work. Because work is defined as the product of force and displacement, the area under the force-length graph during the c phase represents the work done during each part of the experiment. Clearly, the area under the curve is greater for the second part of this experiment, which consisted of the stretch (lengthening) of an active muscle; this corresponds to the stretch-shorten cycle.

The work-energy relationship (chapter 3) states that an increase in the work done by a muscle requires an increased expenditure of energy. Where might this additional energy come from? The typical two-part rationale (e.g., Cavagna, 1977) is as follows. First, the eccentric contraction loads the series-elastic element by stretching it (three-element model of muscle in chapter 6), which can be envisaged as a transfer of energy from the load to the series elastic element; this represents the *storage* of elastic energy. For example, if an elastic band is held with one end in each hand and then stretched, some of the arm-hand muscle activity involved in stretching the band is stored in the band as elastic energy. And second, once released, the molecular structure of the elastic band will use this elastic energy to return to its original shape. Similarly, as the ratio of muscle force to load force changes and the muscle

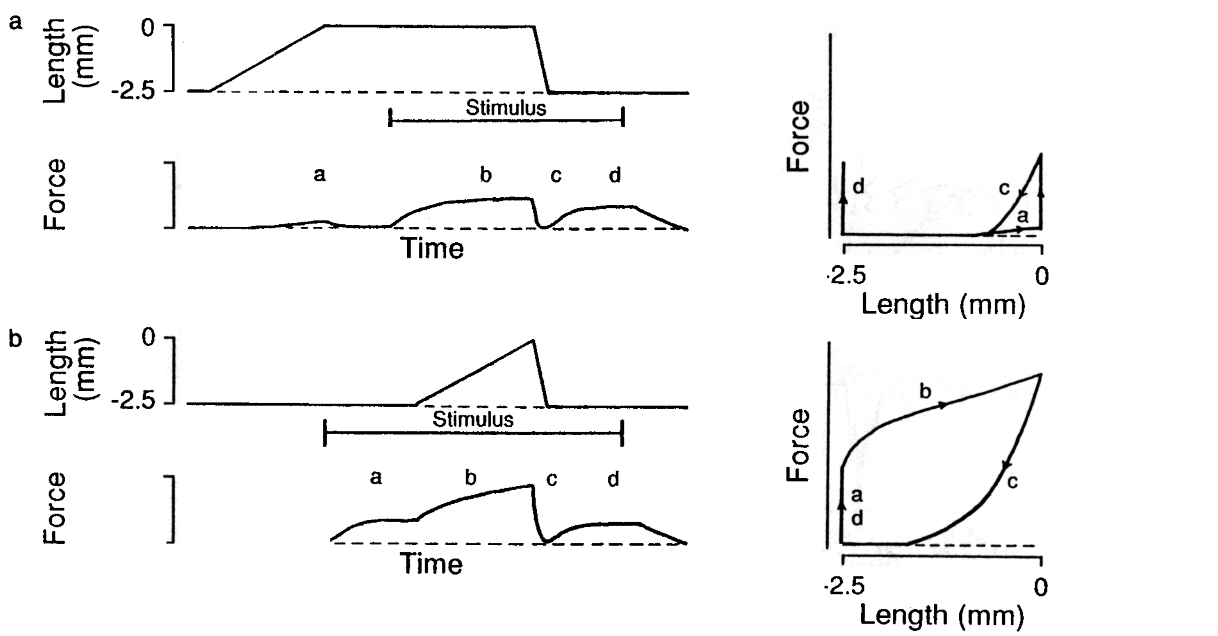

Figure 7.31 Positive work done by an isolated muscle during (a) isometric-concentric and (b) eccentric-concentric activation sequences. The work done by the muscle (area under phase c of the force-length curve) is greater for the eccentric-concentric (stretch-shorten) contraction.

Note. From "Effect of Stretching on the Elastic Characteristics and the Contractile Component of Frog Striated Muscle" by G.A. Cavagna and G. Citterio, 1974, *Journal of Physiology (London)*, **239**, p. 4. Copyright 1974 by Cambridge University Press. Adapted by permission.

undergoes a concentric contraction, the elastic energy stored in the series elastic element can be recovered and used to contribute to the shortening contraction (positive work).

This phenomenon can be stated algebraically by using the first law of thermodynamics (chapter 3):

$$U = \Delta E_h + \Delta E_m + \Delta E_{p,s}$$

where U = work, ΔE_h= change in heat or thermal energy, ΔE_m = change in chemical energy, and $\Delta E_{p,s}$ = change in elastic energy. The eccentric-concentric sequence in Figure 7.31 resulted in an increase in the work (U) done during the concentric activity. When muscle is activated, ATP is supplied by a variety of metabolic processes as the essential unit of chemical energy (E_m). In both the generation and use of ATP, some of the energy is degraded as heat (E_h). As the above equation states, if both the chemical energy used and the heat given off remain constant (let $E_{p,s}$ = 0 for now), the amount of work done will remain the same. But the point of Figure 7.31 is that the work done increased with an eccentric-concentric (stretch-shorten) sequence. One explanation for this is that either E_m or E_h changed. The explanation based on the phenomenon of storage and utilization of elastic energy, however, is that *additional energy ($E_{p,s}$) beyond that provided by chemical means is made available for the performance of work.* According to this point of view, E_m and E_h may vary little between the isometric-concentric and eccentric-concentric modes, but most of the extra work can be done because of the elastic energy ($E_{p,s}$) contribution.

This ability to use stored elastic energy is affected by three variables: time, magnitude of stretch, and velocity of stretch. Cavagna (1977) has demonstrated that there should be no time delay between the eccentric and concentric contractions; otherwise, some of the stored elastic energy is lost (dissipated). Presumably the energy loss is due to the detachment and reattachment of crossbridges during the delay such that, following reattachment, the myofilaments are under less stretch. Similarly, if the magnitude of the lengthening contraction is too great, fewer crossbridges remain attached following the stretch, and hence less elastic energy is stored (Edman, Elzinga, & Noble, 1978). Provided the crossbridges remain attached, however, the greater the velocity of stretch, the greater the storage of elastic energy (e.g., Rack & Westbury, 1974).

Despite the widespread use of the phenomenon of the storage and utilization of elastic energy to account for the increased positive work associated with eccentric-concentric contractions, the enhanced positive work is probably also due to a substantial increase in the amount of available chemical (E_m) energy (Jaric, Gavrilovic, & Ivancevic, 1985). This increase in the available chemical energy is called the **preload effect**. For example, note that the force at the beginning of phase c on the force-length graph in Figure 7.31 is greater during the eccentric-concentric condition than during the isometric-concentric condition; this corresponds to the right-most peak in the force-length graphs. Clearly, the force at the beginning of the concentric phase in the eccentric-concentric condition is greater.

An estimate of the relative contributions of the elastic energy and the preload effects can be obtained by considering the height that subjects can jump using two types of vertical jumps (Komi & Bosco, 1978). The *squat jump* begins from a squat position (knee angle about 2 rad) and simply involves an extension of the knee and ankle joints; the arms are kept stretched overhead to minimize their contribution to the jump. The *countermovement jump* begins from an upright posture and involves, in one continuous movement, squatting down to a knee angle of about 2 rad and then extending the knee and ankle joints as in the squat jump. The major difference between these two techniques is the manner in which the powerful knee extensors are used (they perform about 50% of the work during the maximum vertical jump) (Hubley & Wells, 1983); namely, the squat jump involves only an isometric-concentric contraction of the knee extensors, whereas a countermovement jump requires an eccentric-concentric sequence.

Whether these jumps are performed on one or two legs also alters the magnitude of the initial concentric knee extensor torque. The *one-legged jumps generate a preload effect* compared with the two-legged jumps. This point is illustrated in Figure 7.32, which shows the torque-angle relationship for a one-legged and a two-legged squat jump. The torque represents the resultant muscle torque about the knee joint for a single leg. The knee angle changes from 2.0 rad to complete extension (3.14 rad) during the takeoff phase. The main point shown in Figure 7.32 is that the initial torque (at 2.0 rad) during the one-legged jump is about twice that for the two-legged jump. In the one-legged jump, the single leg must support the whole body weight, whereas in the two-legged jump, a single leg need support only half of that weight. Because of this difference, the initial load supported by the single leg is much greater in the one-legged jump, and hence we say the limb (particularly the muscles about the knee joint) has been preloaded. Also, the greater initial torque exerted by the knee extensors requires a greater supply of chemical energy (E_m).

By comparing the height reached in the vertical jumps (Table 7.4), we can examine the contribution of elastic energy (storage and utilization) and chemical energy (preload effect) to the performance. Where does the energy come from (elastic or chemical) for the greater work done (height achieved) in the countermovement jumps? A comparison of the one- versus two-legged jumps illustrates the preload effect (chemical energy), whereas differences between squat and countermovement jumps include both effects (chemical and elastic). The differences in height jumped with the four combinations illustrate three features of mus-

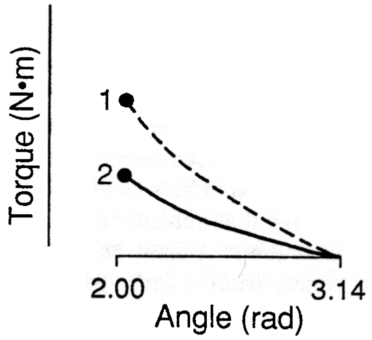

Figure 7.32 Idealized resultant muscle torque-angle relationship about one knee joint during one-legged (dashed line) and two-legged (solid line) squat jumps.

cle use in this type of task. First, for both the one- and two-legged jumps, the subjects reached a greater height with the countermovement jump than with the squat jump; this observation supports the superiority of the eccentric-concentric contraction over the isometric-concentric contraction. Second, the heights attained with the two-legged jumps were greater than those attained with the one-legged jumps due to the greater muscle mass (and hence chemical energy) available to the former. Third, the height jumped in the two-legged situations was not twice that achieved in the one-legged jumps despite the fact that twice the muscle mass was available. That is, the heights attained in the two-legged squat jump were on average 147% of those attained in the one-legged squat jump. If the difference between the two jumps were simply the quantity of muscle mass involved, we would expect the height reached in the two-legged jump to be 200% of the one-legged height. However, because the height reached in the one-legged jump was greater than 50% of the two-legged height, the increased performance of the single leg in the one-legged jump is due to the greater amount of chemical energy (preload effect). Such analyses suggest that the storage and utilization of elastic energy is of lesser importance than the preload effect (increased chemical energy) in such tasks as the vertical jump but may be more important in such activities as hopping (Fukashiro & Komi, 1987; van Ingen Schenau, 1984).

Table 7.4 The Vertical Heights Attained With One- and Two-Legged Squat and Countermovement Jumps

	Squat	Countermovement
One-legged	22.1 ± 5.9[a]	24.0 ± 6.6
Two-legged	32.4 ± 9.1	36.4 ± 8.5

Note. [a]The values are mean ± *SD* in centimeters for 44 subjects.

Many human movements have evolved to capitalize on the stretch-shorten effect. For example, the normal mode of performing the vertical jump (e.g., basketball, net ball, volleyball) is the countermovement style, which, as discussed above, maximizes the height that can be reached. The stretch-shorten cycle is also used in kicking and running. The foot is first placed on the ground in running, and the knee flexes and extends (Figures 1.14 and 1.15) as the total-body center of gravity passes over the foot. This pattern of knee flexion-extension is accomplished by an eccentric-concentric sequence of knee extensor activity. However, this mode of activation does not always enhance the ensuing positive work; Cavagna (1977) has estimated that the elastic energy recovered in running makes significant contributions to the power generated by the muscles only at running speeds greater than about 6.5 m/s. A similar observation has been reported for the takeoff in the long and triple jumps (Luthanen & Komi, 1980).

Our final example of the stretch-shorten cycle concerns the experimental situation in which a barbell is suspended from the ceiling so that it is horizontal and located at shoulder height. The subject is asked to stand under the barbell so that it touches the shoulders, but not to support the weight of the barbell, and to grasp the ends of the barbell, one with each hand. Once in this position, the subject is given a signal to rotate the barbell in the horizontal plane by approximately 1.57 rad as rapidly as possible. How might the subject accomplish this task? Grieve (1969) performed this experiment and found that subjects first rotated the hips in the desired direction while the shoulders and barbell were briefly rotated in the opposite direction. This action had the effect of actively stretching (eccentric contraction) the trunk muscles, which were subsequently used concentrically to rotate the shoulders and barbell. The peak torque exerted during this movement occurred during the eccentric phase. This observation provides support for the notion of leading with the hips in a golf drive; the torque applied to the golf club will be greater if the muscle activity comprises an eccentric-concentric sequence rather than just a concentric contraction.

Manipulation. In our discussion of movement strategies, we have focused on activities such as walking, running, throwing, kicking, reaching, and stabilizing. In the spectrum of movement capabilities, however, a qualitatively different type of movement involves the exploration of our environment. This distinction is typified by the different functions performed by the hands compared with those of the arms and legs. The hand and brain are close partners in the human's ability to explore the physical world and to reshape it (Lemon, 1993). Both exploring and reshaping an environment depend on accurate descriptions of mechanical events when objects are bought in close contact with the hand. Much of this information is provided by the mechanore-