Role of the Stretch–Shortening Cycle in Jumping

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There is ample evidence that power output is enhanced by the stretch–shortening cycle in explosive movements. Ingen Schenau et al. argue that the improved jumping performance with a countermovement is not due to the storage and release of elastic energy or muscle potentiation. Indeed, both experimental data and modeling results seem to support this view. I disagree with broadly interpreting this finding to mean that the stretch–shortening cycle never plays an important role in enhancing muscle force and power output in explosive movements. In the most obvious examples in which the stretch–shortening cycle plays an important role, muscle force or power output exceeds what would be possible without a prestretch. I will discuss three examples of this type: countermovement jumps in humans, frog jumping, and kangaroo rat jumping. Animal models hold promise for elucidating the role of the stretch–shortening cycle because it is possible to actually measure in vivo muscle forces and in vitro muscle properties.

Countermovement Jumps in Humans

The peak power output by the muscles acting about the ankle is substantially higher during countermovement jumps than during isokinetic contractions. The peak power output at each ankle is 1,800 W during a one-legged countermovement jump and 1,200 W during a two-legged countermovement jump (Soest, Roebroeck, Bobbert, Huijing, & Ingen Schenau, 1985). The maximum power output at the ankle during isokinetic testing is less than 200 W (Fugl-Meyer, Mild, & Hornsten, 1982). Thus, compared to the maximum isokinetic power output, the power output at the ankle is approximately nine times greater in a one-legged jump and six times greater in a two-legged jump. The most important reason for these exceptionally high power outputs is that elastic energy stored in tendons during the countermovement is released during the push-off (Bobbert, Huijing, & Ingen Schenau, 1986). Models of ankle extensor muscle behavior during a jump indicate that substantial energy is stored and released by tendinous structures during a countermovement jump, contributing 50–70% of the power output at the ankle (Anderson & Pandy, 1993; Bobbert et al., 1986). In addition, some power is transferred from the knee to the ankle via the biarticular gastrocnemius muscle, but it only accounts for approximately 20% of the power output at the ankle (Bobbert et al., 1986). Thus, elastic energy storage and release seem to be the primary reason for the exceptionally high power output at the ankle during jumping.

It is interesting to note that the power output at the ankle is about 50% higher during a one-legged jump than during a two-legged jump. It seems likely that this difference can be explained, at least in part, by a difference in elastic energy storage. Muscle activa-
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tion levels are higher during a one-legged jump than a two-legged jump, but the difference is not large enough to fully explain the 50% higher power output at the ankle in a one-legged jump (Soest et al., 1985). The medial and lateral gastrocnemius muscles only show 25% and 12% increases, respectively, in mean EMG level in a one-legged jump compared to a two-legged jump. There is no significant difference in soleus muscle mean EMG level (Soest et al., 1985). Thus, changes in muscle activation do not fully explain the 50% difference in peak power output. However, some data do suggest a substantial difference in elastic energy stored during the countermovement in a one-legged jump compared to a two-legged jump. Elastic energy storage increases as muscle force increases (Ingen Schenau et al., 1997). The ankle net muscle moment at the end of the countermovement is 60% higher for a one-legged jump than for a two-legged jump (Soest et al., 1985). As a result, it is likely that the amount of elastic energy stored in the Achilles tendon is substantially higher at the end of the countermovement for a one-legged jump than a two-legged jump, leading to enhanced power output at the ankle in a one-legged jump.

Evidence for an Important Role of Elastic Energy Storage in Jumping Frogs

Some frogs are incredible jumpers; for example, a frog with a body mass of less than 1 g (Pseudacris crucifer, spring peeper) can jump a horizontal distance of 0.6 m (Marsh & John-Alder, 1994). Surprisingly, the total power output during a maximal jump is higher than the muscles are capable of producing during isotonic shortening. For example, in a maximal jump by a spring peeper, the average power output is 535 W per kg of muscle mass, and the peak power output is greater than 1,000 W per kg of muscle mass (Marsh & John-Alder, 1994). These values are substantially higher than the maximum power output of 350 W/kg of frog muscle during isotonic shortening at the same temperature as used for the jumping experiments (20 °C) (Cecchi, Colomo, & Lombardi, 1978; Lannergren, Lindblom, & Johansson, 1982). In interpreting these results, it is important to realize that the estimate of power output per unit muscle mass during a jump is actually most likely to be an underestimate! The reason is that all of the muscles that could have conceivably contributed power to the jump were included in the calculation. Thus, the actual mass of active muscle is likely to be lower than the value used in the calculations, leading to an underestimate of the power output per unit active muscle mass.

These findings point to an important role of elastic energy storage in frog jumping. Surprisingly, these extraordinary jumps are achieved without a visually obvious countermovement phase. It has been suggested that the muscles may perform work on the tendons before the frog begins to move and early in the push-off phase (Marsh, 1994; Marsh & John-Alder, 1994). Subsequently, the tendons can release the elastic energy during the late push-off phase at the time when peak power output is achieved. This mechanism for temporal redistribution of muscle work is used by some insects. In these insects, anatomical “catch” mechanisms allow the muscles to perform work on elastic structures before body movement begins (Bennet-Clark, 1977). Anatomical catch mechanisms have not been identified in frogs, but it has been speculated that the poor mechanical advantage of the muscles early in the push-off phase or coactivation of antagonists provides a functional catch mechanism (Marsh & John-Alder, 1994). Regardless of the mechanism, the extremely high peak power outputs during a jump indicate that elastic energy storage must play an important role in frog jumping.