Mechanics of the Vertical Jump and Two-Joint Muscles: Implications for Training

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THE VERTICAL JUMP IS A MOVEment commonly performed in a number of sports. In certain sports such as basketball and volleyball, success largely depends on vertical jumping (VJ) ability. Due to the importance of VJ ability, the maximal vertical jump has been used as a test to monitor improvements in jumping ability following a strength and conditioning program.

The effect of strength and plyometric training on VJ ability has recently been reviewed (8). A maximal vertical jump may even give a rough estimate of lower extremity power output, although the validity and usefulness of such a measure of power has been questioned (7, 17).

Despite the prevalence of the vertical jump in sport performance, testing, and training, the mechanics of this movement are generally not well understood. Semenick and Adams (12) provided a general kinesiological analysis of the VJ but did not address the importance of specific muscle distributions and actions.

A brief review of the anatomy of the lower extremity reveals two facts that have strong implications for the performance of explosive leg movements.

First, many muscles of the lower extremity cross more than one joint. The most important examples are the rectus femoris, gastrocnemius, semimembranosus, semitendinosus, and the long head of biceps femoris. These last three muscles are typically considered together as the hamstrings group.

Second, the muscle mass of the legs is concentrated most heavily near the proximal joint (hip), with much less mass located near the distal joints (knee and ankle). This arrangement may seem odd, as the more distal muscles must support a greater proportion of total body mass in dynamic situations. But such an anatomical arrangement actually serves an important mechanical purpose, and the body has a unique mechanism for providing more power to the distal joints to compensate for the reduced muscle mass.

■ Biomechanical Research on the Vertical Jump

Biomechanists have generally used the techniques of high-speed cinematography and videography, muscle electrical activity detection, and ground reaction force measurement to explore the mechanical interactions of the musculoskeletal system during the vertical jump.

Using the laws of classical mechanics, it is possible to determine the net joint forces, net joint moments (torque), and joint powers generated during the vertical jump (1, 5). During the takeoff phase, the net joint moments about the hip, knee, and ankle are positive (2, 14), meaning that the net effect of all load-carrying structures (muscles, ligaments, joint capsules) will be to extend the hip, extend the knee, and plantarflex the ankle. During this phase the joint powers are generally positive, indicating predominately concentric activity of one-joint muscles (2, 11, 14).

The takeoff phase of the vertical jump begins with extension of the hip joint, followed sequentially by the knee and ankle joints. It ends when the feet lose contact with the floor. The takeoff phase is preceded by the preparatory phase, which involves flexion at the hip and knee joints and dorsiflexion at the ankle joint. Muscle activity is generally eccentric during the preparatory phase, with gravity providing the driving force (12). The preparatory and takeoff phases of the vertical jump are shown in Photos 1–3.

Interest in the actions of two-joint muscles during human movement is not new and dates back to at least 1867 (4). More recently, van Ingen Schenau reviewed the unique roles that two-joint muscles play in complex multijoint movements (13). One proposed function of two-joint muscles is to redistribute mechanical energy generated by concentric action of one-joint muscles, for optimal performance of explosive leg extension movements.

An early investigation by van Ingen Schenau and his colleagues (6) found a tremendously high power output at the ankle joint (approaching 3,500 watts) during the latter part of the jump takeoff. Further research revealed that maximal power output at the ankle during a max-effort vertical jump was up to six times as high as the maximal power that could be generated during isolated ankle plantar-flexion (14).

Although the storage and reutilization of mechanical energy in the elastic components of the muscles and tendons may have been the reason for enhanced jump performance, a considerable amount of the additional mechanical energy at the ankle seemed to have been transferred there from the hip and knee by two-joint muscles (3, 14).

Additional studies have revealed that the sequence of muscle activation during VJ follows a proximal-to-distal pattern (2, 10, 15), with activation of the hip muscles followed by activity of the knee and ankle muscles. Mathematical and mechanical models of the human body have also been

Photo 1

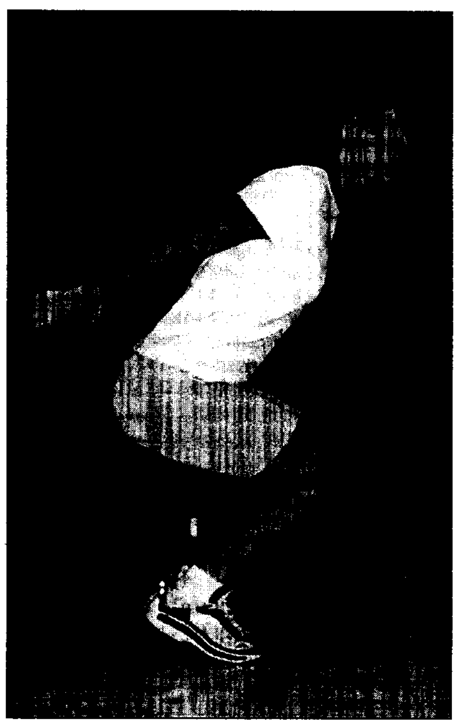

Photo 2

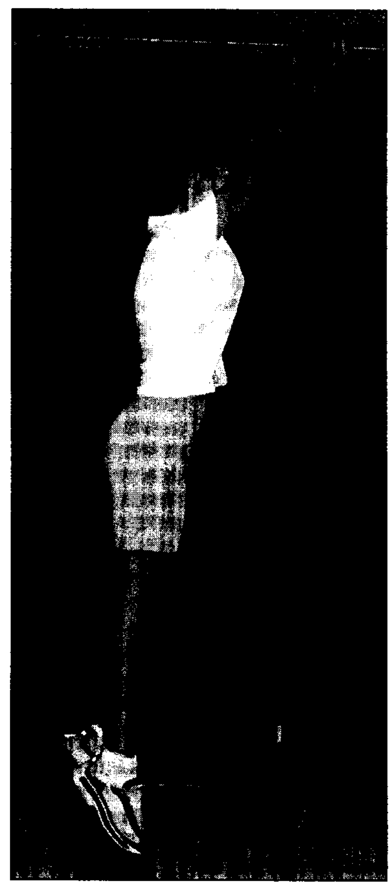

Photo 3

From the starting position (Photo 1), the preparatory phase involves flexion at the hip and knee, and dorsiflexion at the ankle; gravity provides the driving force. Activity of the one-joint muscles is primarily eccentric. The takeoff phase (Photo 2) of the VJ begins with hip extension, followed immediately by knee extension, then ankle plantar-flexion. Activity of the one-joint muscles is primarily concentric. The takeoff phase (Photo 3) ends when the jumper's toes lose contact with the floor.

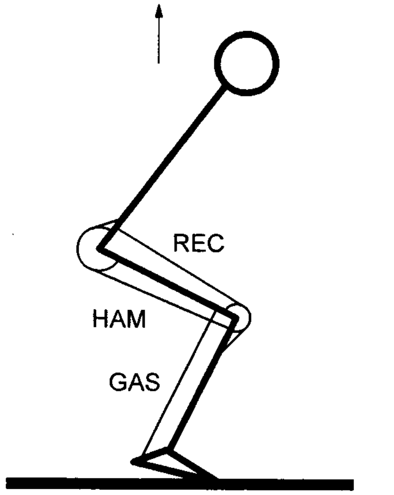

Figure 1 Simplified model of musculoskeletal system at beginning of takeoff phase of a VJ. Two-joint muscles include rectus femoris, gastrocnemius, and hamstrings (arrow indicates direction of motion of body's center of mass).

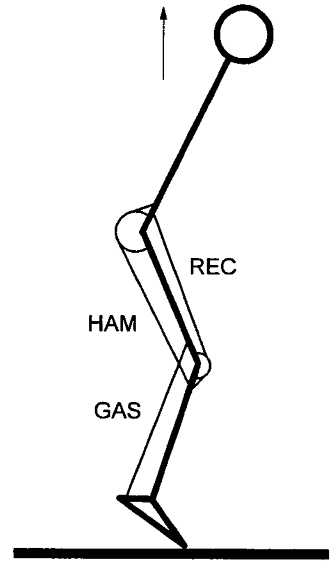

Figure 2 Simple model of musculoskeletal system near end of VJ takeoff phase. REC and GAS transport mechanical energy generated by proximal one-joint muscles (not shown) to more distal joints. Hamstrings transport some mechanical energy back to the hip.

used to show that VJ height is maximized by the presence of the two-joint gastrocnemius (GAS). Jump height was found to decrease when the GAS was modeled as a one-joint muscle that only crossed the ankle joint (10, 16).

From the results of the preceding studies has evolved a theory to explain the role of two-joint muscles in the transfer of mechanical energy during jumping.

Transfer of Mechanical Energy by Two-Joint Muscles

During many lower body movements including the vertical jump, the two-joint muscles are placed in a unique situation. The rectus femoris (REC), for example, acts to flex the hip and extend the knee. If the REC is activated, it will attempt to perform both of these actions simultaneously.

During the takeoff phase of the VJ, however, the hip and knee are both extending at the same time, causing antagonistic actions of the REC by lengthening at one end and shortening at the other. The result of these antagonistic effects during the entire takeoff phase of the jump is that the net length of the two-joint muscles may not change substantially. The contraction velocity of the two-joint muscles will be very low and perhaps nearly isometric (6, 11).

Based on the force-velocity relationship for muscle, this allows the two-joint muscles to exert high forces during the period of contraction. Despite the high forces that can be generated by these muscles during a jump, very little work is done at the joints, due to the small change in muscle length. Instead, energy generated by the proximal one-joint muscles can be transferred by the two-joint muscles and appears as work at a distal joint.

The transfer of mechanical energy by two-joint muscles during the VJ can be explained as follows: If the REC and GAS are nearly isometric during the takeoff phase, we can consider them to act as stiff cables connecting the anterior portion of the pelvis to the tibial tuberosity (REC), and the posterior portion of the distal femur to the calcaneus (GAS). Figures 1 and 2 show this anatomical arrangement.

Contraction of the hip extensors will cause a tendency not only for extension about the hip but also for extension about the knee, due to the pull on the stiff cable (the REC). A portion of the mechanical energy generated by the hip extensors during the takeoff phase will be transferred through the REC and appear as work at the knee joint.

A similar situation occurs with the GAS at the knee and ankle joints. Work done by the one-joint knee extensors (vasti group) will act to extend the knee joint, but a portion of the energy generated will be transferred through the stiff cable connecting the femur and calcaneus (the GAS). The energy transferred through the GAS will appear as work at the ankle joint (2, 6, 9, 11).

Approximately half the total mechanical energy generated by the hip extensors is transferred distally to help extend the knee and ankle (11). Due to the design of the musculoskeletal system, the large muscles of the hip are able to compensate for the lower force production of the smaller muscles of the knee and ankle, providing the mechanical energy needed for an optimal VJ.

Another way this mechanism can be understood is to consider that the REC causes a tendency to extend the knee when it contracts, due to the pull on the distal tendon which attaches to the tibial tuberosity. If a pull were applied to the proximal end of the REC, with the muscle contracting isometrically, the pull would be transferred through the muscle to the distal tendon. The pull on the distal tendon would cause a similar tendency to extend the knee.

This approximates what happens during the takeoff phase of the vertical jump, with the "pull" on the proximal end of the REC being provided by the hip extensors rotating the pelvis relative to the femur. The pull on the proximal end of the GAS is provided by the extension of the femur relative to the tibia, and is transferred to the ankle, where the effect is the same as a powerful contraction of the plantar-flexors. The transfer, or redistribution, of mechanical energy throughout the lower extremity is thought to be critical to the optimal use of the total mechanical energy generated by the muscles, and the optimal performance of the VJ (2, 13).

Although not directly related to VJ performance, the above process appears to happen in reverse when landing from a jump, with the proximal one-joint muscles absorbing energy transferred in a distal-to-proximal manner by the two-joint muscles (11).

■ Significance of Energy Transfer

The extent to which the energy transfer mechanisms contribute to VJ performance has been estimated recently in 7 elite athletes (9). Through a biomechanical analysis similar to that used in the studies cited above (2, 6, 11, 14), 21% of the work done in extending the knee was found to come from the hip extensors via transfer through the REC. At the ankle, 25% of the work done in plantarflexion was derived from the knee via the GAS.

Interestingly, the hamstrings acted to transfer energy back to the hip from the knee during the takeoff phase of the jump, but the effect was small compared to the proximal-to-distal transfer of energy by the REC.

Not all researchers are in complete agreement with the findings stated in this review (10). However, Prilutsky and Zatsiorsky (11) feel that the differences of opinion regarding transfer of mechanical energy by two-joint muscles are primarily semantic ones and not basic theoretical differences.

The potential for energy transfer by two-joint muscles provides a distinct mechanical design advantage, by allowing the bulk of the lower extremity muscle mass to be located near the proximal end of the leg. With more of the mass of the leg located proximally, its moment of inertia is reduced, decreasing the resistance to rotation about the hip joint (11). The leg's decreased moment of inertia allows more efficient movement by increasing angular velocity of the leg about the hip.

The problem associated with the bulk of the muscle mass being located more proximally, with much smaller muscles located distally, is avoided by the potential for mechanical energy generated by the proximal muscles to be transferred to the distal joints by the two-joint muscles as needed.

■ Implications

The strength and conditioning professional will certainly benefit from a better understanding of the mechanics of any sports related motor pattern. Moreover, the knowledge gained from mechanical analyses of the vertical jump has direct implications for appropriate exercise selection when designing a training program.

The concept that the power measured at a particular joint may not be the result of discrete contractions of the muscles normally associated with that joint adds further credence to the idea that the mode of training should mimic closely the activity to be performed.

If the vertical jump involves a highly orchestrated sequence of events that involve all parts of the lower extremity, then exercises that stress the body in a similar fashion, such as the power clean and snatch, hang clean, or plyometrics, should be chosen. In the power clean and snatch, care should be taken to emphasize the second pull, as this is the portion that most closely replicates the jumping motion.

Although isometric movements are generally not a major portion of the strength program for competitive athletes, exercises that stress the REC and GAS at a low or zero-contraction velocity may be indicated for athletes who perform many max intensity jumps, as these muscles must transmit very high loads at a low contraction velocity during such jumps.

Activities for the REC could include slow, heavy squats, or isometric squats in a safety cage. Appropriate exercises for the GAS might include slow, heavy heel raises, with the knees near full extension.

Although one must be careful about assuming cause-and-effect, it is interesting to note that Hedrick and Anderson (8) found that VJ improvement was closely related to the degree of improvement in 1-RM for both the clean, an explosive movement, and the squat, a slow movement.

In conclusion, much information has been gained about the mechanical function of the musculoskeletal system during vertical jumping. Further research in this area should reveal even more details that would be of interest to the strength and conditioning professional. ▲

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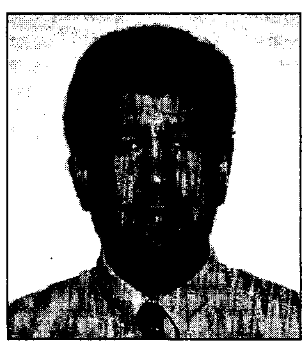

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