The Difference Between Countermovement and Squat Jump Performances

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THE DIFFERENCE BETWEEN COUNTERMOVEMENT AND SQUAT JUMP PERFORMANCES: A REVIEW OF UNDERLYING MECHANISMS WITH PRACTICAL APPLICATIONS

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ABSTRACT

Van Hooren, B and Zolotarjova, J. The difference between countermovement and squat jump performances: a review of underlying mechanisms with practical applications. *J Strength Cond Res* 31(7): 2011–2020, 2017—Two movements that are widely used to monitor athletic performance are the countermovement jump (CMJ) and squat jump (SJ). Countermovement jump performance is almost always better than SJ performance, and the difference in performance is thought to reflect an effective utilization of the stretch-shortening cycle. However, the mechanisms responsible for the performance-enhancing effect of the stretch-shortening cycle are frequently undefined. Uncovering and understanding these mechanisms is essential to make an inference regarding the difference between the jumps. Therefore, we will review the potential mechanisms that explain the better performance in a CMJ as compared with a SJ. It is concluded that the difference in performance may primarily be related to the greater uptake of muscle slack and the buildup of stimulation during the countermovement in a CMJ. Elastic energy may also have a small contribution to an enhanced CMJ performance. Therefore, a larger difference between the jumps is not necessarily a better indicator of high-intensity sports performance. Although a larger difference may reflect the utilization of elastic energy in a small-amplitude CMJ as a result of a well-developed capability to co-activate muscles and quickly build up stimulation, a larger difference may also reflect a poor capability to reduce the degree of muscle slack and build up stimulation in the SJ. Because the capability to reduce the degree of muscle slack and quickly build up stimulation in the SJ may be especially important to high-intensity sports performance, training protocols might concentrate on attaining a smaller difference between the jumps.

KEY WORDS eccentric utilization ratio, prestretch augmentation, stretch reflex, active state, residual force enhancement, explosive strength

INTRODUCTION

Monitoring and testing athletic performance are essential components of periodization. Two commonly used tests to monitor performance in the field of strength and conditioning are the countermovement jump (CMJ) and the squat jump (SJ). In the CMJ, the athlete starts from a standing position and initiates a downward movement, which is immediately followed by an upward movement leading to takeoff. In contrast, during the SJ, the athlete descends into a semi-squat position and holds this position for approximately 3 seconds before takeoff. The performance of a movement with countermovement is almost always better than a movement without countermovement when there is no time-pressure present (5,7,44,58,67,74). For example, the height achieved or power produced during a CMJ is higher than during an SJ, and ball speed is greater during an overhead throw with countermovement than without countermovement. The duration of the CMJ as measured from the initiation of the downward movement until takeoff ranges from 500 to 1,000 milliseconds, whereas the duration of the SJ is shorter, varying between 300 and 430 milliseconds, when measured from the initiation of the upward phase until takeoff (75). Because of the relatively short duration of execution, both jumps are frequently used to evaluate the capability to rapidly develop force during dynamic movements. It is believed that the CMJ provides an assessment of the capability to quickly produce force in stretch-shortening cycle movements, whereas the SJ provides an assessment of the capability to rapidly develop force solely during a purely concentric movement (58,86).

In this review, we will discuss the traditional and current views on the differences between the CMJ and SJ, the

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proposed mechanisms attributed to the better acute performance observed during the CMJ, and the differences between athletic populations. Lastly, we will provide practical applications for health clinicians and athletic trainers regarding training and how to integrate these tests into training programs.

TRADITIONAL AND CURRENT VIEWS ON THE DIFFERENCE BETWEEN THE COUNTERMOVEMENT JUMP AND SQUAT JUMP

It has been proposed that the difference between movements with and without countermovement is caused by the performance-enhancing effect of the stretch-shortening cycle during the countermovement (58). As a result, the difference in performance can be used to measure the contribution of the stretch-shortening cycle, with a larger difference between the movements with and without countermovement being indicative of a better utilization of the stretch-shortening cycle. In particular, Komi and Bosco (44) attributed the difference between the CMJ and SJ to the storage and utilization of elastic energy during the countermovement and concluded that a greater difference between the CMJ and SJ would be suggestive of a better capability to store and use elastic energy. In a later study, it was suggested that the difference between the SJ and CMJ may also serve as an indicator of fiber type distribution after the researchers found a significant correlation between fiber type of the vastus lateralis and the difference in average force between the CMJ and SJ (13). Other researchers proposed that the difference between the CMJ and SJ provides an assessment of prestretch augmentation (calculated as $[\text{CMJ} - \text{SJ}]/\text{SJ} \times 100$) (83) or reactive strength under slow stretch-shortening cycle conditions (calculated as $\text{CMJ} - \text{SJ}$) (86). Although different equations were used to calculate the prestretch augmentation and reactive strength, in both studies, a larger difference between the jumps was suggestive of a superior capability to use the stretch-shortening cycle. Lastly, McGuigan et al. (58) recognized that the performance difference between the CMJ and SJ is likely not primarily the result of storage and utilization of elastic energy and suggested that the eccentric utilization ratio (calculated as CMJ/SJ) would be a more suitable term as this reflects the effective utilization of the eccentric phase during the CMJ. Similar to previous researchers, they also suggested that a larger difference between the jumps, as indicated by a higher eccentric utilization ratio, would be indicative of a better capability to use the eccentric phase.

Overall, these studies imply that the difference in height achieved or power produced during a CMJ and an SJ is due to an effective use of the stretch-shortening cycle and a larger difference between the jumps would be indicative of a better capability to use the stretch-shortening cycle. However, it is frequently not specified which mechanisms are responsible for the performance-enhancing effect of the stretch-shortening cycle. Therefore, it is important to uncover and understand these mechanisms to make an inference regarding the difference between the jumps. For example, if the storage and utilization of elastic energy would primarily be responsible for the greater acute performance during a CMJ, a larger difference between the SJ and CMJ would indeed be beneficial as this reflects a greater capability to store and use elastic energy. On the other hand, if the uptake of muscle slack (i.e., the uptake of slack in the fascicles and tendinous tissues, alignment of the dangling position of the muscle-tendon unit, and stretch of the tendinous tissues) would be primarily responsible for the better acute performance during a CMJ, a larger difference between the SJ and CMJ is not preferred as this may reflect more muscle slack because of a poor capability to develop pretension by co-activation of the muscles (75). Therefore, we will critically review the mechanisms that may explain the superior acute performance observed during the CMJ. Because most studies did not apply an arm swing during the jumps, the mechanisms will be compared between the CMJ and SJ without arm swing.

MECHANISMS THAT POTENTIALLY EXPLAIN THE ENHANCED COUNTERMOVEMENT JUMP PERFORMANCE

Muscle-Tendon Interaction During the Countermovement Jump and Squat Jump

It is important to take note of the muscle-tendon interaction to better understand the mechanisms that may explain the enhanced CMJ performance. Commonly, the stretch-shortening cycle is ambiguously described as a stretch of the muscle followed by a phase of shortening. However, the elements of the muscle that stretch and shorten are not distinguished, and this can lead to incorrect interpretations. For example, it is often assumed that there is an eccentric action (i.e., active lengthening) of the fascicles of the leg muscles during the downward movement of the CMJ. Although some studies indeed show that the fascicles lengthen during the downward phase of a CMJ, this lengthening is mostly passive and occurs primarily, but not exclusively in monoarticular muscles (28–30). Furthermore, studies also show a shortening of fascicles (28,50) or suggest an isometric action of the contractile element during the downward phase of a CMJ (45,46). Therefore, there is usually no active lengthening (i.e., eccentric action) of the fascicles during the downward movement of the CMJ. The fascicles may passively lengthen only during slowly executed, submaximal, and large-amplitude (i.e., deep countermovement) CMJs, thereby dissipating energy, whereas they remain isometrically or concentrically contracted during faster, maximum effort, and small-amplitude jumps (45,46,68). Hence, it can be recommended that future research refers to the downward and upward phases rather than to the eccentric and concentric phases of a CMJ and avoids the use of terminology that refers to an eccentric phase (e.g., eccentric utilization ratio). Furthermore, attributing the difference between the CMJ and SJ to an effective utilization of the eccentric phase and mechanisms occurring during eccentric muscle actions is problematic because there may be no eccentric phase during the CMJ. Instead, the better acute performance in the CMJ may be the result of other mechanisms.

Residual Force Enhancement

When an activated muscle is lengthened, the steady-state isometric force production following lengthening is greater than the corresponding force in an isometric action at a similar length. This effect has been termed residual force enhancement (25,39) or potentiation (15,26). Residual force enhancement has been observed in a variety of experiments examining single-muscle fibers (24,25,66) and in situ rat and cat muscles (27,40). It is thought that residual force enhancement also occurs during a CMJ, and it could therefore partially explain the superior acute performance during a CMJ. However, the contribution of residual force enhancement to an enhanced force production during a CMJ is likely minimal because the muscle fibers may only lengthen during slow large-amplitude CMJs (45,46,68) while remaining isometric (45,46) or contracting concentrically (50) during fast and small-amplitude CMJs. In addition, when muscle fibers lengthen during the downward phase, it is usually passive lengthening (28–30). Therefore, there may be no active lengthening and residual force enhancement may not be present during a CMJ. Furthermore, residual force enhancement increases with a greater magnitude of muscle fiber lengthening and is largely independent of lengthening speed and decreases with the amount of time elapsed after lengthening, with a large proportion of the force enhancement being decayed within approximately 1 second (24,25,31,38). Therefore, if there is active muscle fiber lengthening during a slow large-amplitude CMJ, this will evoke a relatively slow stretch and considerable time will elapse between the stretch and the subsequent contraction (7), thereby reducing the effect of residual force enhancement.

In support of this, based on in situ experiments in rats (27) and in vivo experiments in humans (7,20,28,79), several authors have concluded that the effects of residual force enhancement in in vivo movements are essentially small. This is most likely because of the delay between possible active lengthening and maximum force production, which is relatively long (7). Additionally, slack in the fascicles, tendinous tissues, and total muscle-tendon unit, an increase in pennation angle, and compliance of the tendinous tissues may reduce the stretch applied to the muscle fibers (76) and hence diminish the effects of residual force enhancement. In parallel, in a computational modelling study, CMJ height was higher than SJ height even though the effects of residual force enhancement were not incorporated (5), suggesting that residual force enhancement may have no or a minimum contribution to the better acute performance during a CMJ. Taken together, these findings suggest that there usually is no residual force enhancement because there is no active lengthening of the muscle fibers during a CMJ. Moreover, if muscle fibers actively lengthen and residual force enhancement occurs, the contribution to the better acute performance during a CMJ is likely small.

Stretch Reflex

Another mechanism commonly believed to be responsible for the greater acute effect observed during the CMJ is increased muscle activation because of an activated stretch reflex. Specifically, when muscle fibers are lengthened or when vibration waves travel through the muscle, the muscle spindle can initiate both short- and longer latency reflexes by which additional motor units are recruited or the firing rate of the recruited motor units increases (17,19,52,61). These mechanisms are thought to increase force production during the downward and upward phases of a countermovement, thereby enhancing CMJ performance. Muscle spindles are, however, not only sensitive to the amplitude of lengthening but also to the velocity of lengthening (52), with higher velocities inducing a greater magnitude stretch reflex (51). Notably, a reflex is only evoked once the threshold velocity is reached. This threshold velocity varies depending on athletic training background, the assessed muscle, and individual differences within the muscle, such as motor unit composition or muscle spindle density (51,64).

During the downward movement in the CMJ, the average angular velocities of the ankle, knee, and hip joint are approximately 0°, 133–199°, and 216° per second (7,28,50), respectively. For the knee and hip joint, these average angular velocities are higher than the angular velocities at which the stretch reflex is evoked during a passive ankle dorsiflexion (i.e., 69° per second), (63) but lower than the angular velocities at which the stretch reflex is evoked during a passive elbow extension, where angular velocities up to 300° per second did not evoke a stretch reflex in the elbow flexors (54,84). The angular velocity of the ankle joint is lower than the angular velocity at which the stretch reflex is evoked in the plantar flexors during a passive ankle dorsiflexion (63). Therefore, based on the angular joint velocities, it remains unclear whether a stretch reflex is evoked in the muscles spanning the hip and knee joint during the downward phase of the CMJ. Prominently, it seems unlikely that a stretch reflex is evoked for the plantar flexors based on the average angular velocity of the ankle joint.

As discussed previously, muscle fibers do not necessarily lengthen during the downward phase of the countermovement (46,50). Therefore, even if the angular joint velocities are high enough to evoke a stretch reflex, the reflex may not be evoked if there is no lengthening of the muscle fibers. Furthermore, by relaxation of the intrafusal muscle fibers, the muscle spindle can be set to fire only when a specific muscle length is reached. When this muscle length is set to correspond to a length that is greater than the length reached during the countermovement, the reflex may not be initiated at all. Therefore, angular joint velocities, muscle fiber lengthening, and stretch of the muscle spindle do not necessarily correspond. These concepts may explain why some studies reported higher surface electromyographic activity of the plantar flexors during the concentric phase of the CMJ (49), whereas others reported similar electromyographic activity of the plantar flexors in the SJ and CMJ (33) or found no significant difference in electromyographic activity of the lower and upper leg muscles between the SJ and CMJ (7). These findings suggest that the stretch reflex may not be evoked in small-amplitude CMJs when there is no muscle fiber lengthening present, whereas it may be evoked in large-amplitude submaximal CMJs if the muscle fibers lengthen and the threshold velocity is reached. It should be noted, however, that the short-latency stretch reflex has recently been found to be poorly correlated to fascicle length changes and velocities, suggesting that the vibration of the muscle may also have an important role in evoking a stretch reflex (17). Nevertheless, it has been established that ballistic movements such as vertical jumping already require a maximal activation of motor units, irrespective of muscle shortening speed during the concentric phase (49,57). Because it has been shown that the contribution of the stretch reflex in the lower extremities decreases with an increase in force production and muscle activation (59,62,71), it can be questioned whether the stretch reflex can still recruit additional motor units or increase the firing rate of the recruited motor units during the CMJ.

Overall, because of the multitude of individual factors affecting stretch reflex activation such as jump amplitude, muscle fiber lengthening, and the threshold velocity, the stretch reflex may or may not be activated during the CMJ. Therefore, evidence about the contribution of the stretch reflex during the CMJ is inconsistent, and consequently, the stretch reflex cannot be regarded as the prime mechanism related to the better acute performance during the CMJ. In support of this, Bobbert and Casius (5) did not incorporate a stretch reflex in their computational model and found that CMJ height was higher than SJ height, signifying that the stretch reflex has a negligible or no contribution to the better acute performance during the CMJ.

Differences in Kinematics

When examining jump kinematics, researchers have suggested that the SJ is an unnatural movement because almost all forceful movements are performed with some degree of a countermovement present (34). Indeed, a large body of evidence has supported that individuals often unconsciously perform a small-amplitude countermovement during an SJ (6,7,34,60,70,82). As a result, it can be deduced that the total elimination of a countermovement is difficult and would require great practice.

Studies that have investigated coordination aspects between the SJ and CMJ have found no clear differences in jump kinematics. For example, Bobbert et al. (7) found no indication of movement disintegration during the SJs performed by well-trained male volleyball players. Notably, there is always some interindividual variation in body configuration during the propulsion phase of a jump. However, individuals will display a comparable kinematic pattern by the end of the propulsion phase (5,9). Altogether, these findings suggest that there are no or minimal differences in kinematic patterns between the CMJ and SJ. Individual variations in movement patterns are therefore unlikely to explain the better acute performance during the CMJ.

Range of Motion Over Which Force Can Be Produced

When the starting jump position is not controlled, most individuals tend to lower their center of mass less in an SJ than in a CMJ (7,32,42,56,82). As a result, the range of motion over which one can produce force is smaller and this may explain the lower performance during an SJ. However, even when the starting positions are similar or when participants initiate the SJ from a deeper position than the CMJ, jump performance is still higher during the CMJ (1,7,32,42,60). Therefore, the range of motion over which force can be produced does not explain the difference between the jumps.

Storage and Utilization of Elastic Energy

Another mechanism that is held responsible for the enhanced acute effects during the CMJ is the storage and utilization of elastic energy. This belief is based on earlier studies in which it was suggested that elastic energy could be stored in the tendinous tissues during the downward phase and used during the upward phase to increase force production (12,44). More recently, several researchers have, however, argued that the storage and utilization of elastic energy does not explain the difference in jump height between the CMJ and SJ (1,2,5,7,50,77–79), even though elastic energy enhances force production in both SJ and CMJ performances (30,68,90). More specifically, during the initial upward phase of the SJ and CMJ, a concentric contraction of the muscle fibers stretches the tendinous tissues, which later in the upward phase will recoil in a catapult-like manner to enhance force production. These findings indicate that the storage and utilization of elastic energy plays a role in both the SJ and CMJ. However, as previously stated, the results from computational modelling and experimental studies suggest that it cannot explain the difference between the jumps because only a small amount of extra energy is stored in the tendinous tissues during the countermovement in the CMJ (2,7,50), whereas a significant portion of energy is lost as heat during the execution of a CMJ as compared with the SJ (1,7,45,77,78). Nonetheless, it is important to distinguish between slowly executed, submaximal, and large-amplitude CMJs and faster, maximum effort, and small-amplitude CMJs. In the former CMJs, elastic energy is unlikely to enhance the performance because the chemical and kinetic energies are dissipated into heat, whereas elastic energy may be used to enhance CMJ performance in the latter CMJs (45,46,68). Specifically, the findings of Kopper et al. (45) and Kopper et al. (46) suggest that the contractile element remains isometric during small-amplitude CMJs, thereby allowing storage and reutilization of elastic energy in the series elastic element, whereas the contractile element passively lengthens during large-amplitude CMJs, thereby storing no to minimal elastic energy and dissipating chemical and kinetic energies into heat (45,46,68). Therefore, whether elastic energy enhances CMJ performance as compared with SJ performance may depend on the amplitude of the countermovement and the effort used during the movement. Additionally, whether elastic energy enhances CMJ performance during these faster, maximum effort, and small-amplitude CMJs may also depend on the capability to quickly increase muscle stimulation and reduce muscle slack (see Interaction Between the Mechanisms), with elastic energy only being used when individuals can quickly increase muscle stimulation and reduce muscle slack. Altogether, these findings suggest that the storage and utilization of elastic energy has only minor effects on the increased acute performance during slowly executed, submaximal, and large-amplitude CMJs, whereas it may have a larger, albeit probably still relatively smaller, effect during faster, maximum effort, and small-amplitude CMJs. The enhanced performance and underlying mechanisms of a fast and large-amplitude CMJ as compared with an SJ requires further investigation.

Reduction of Muscle Slack and Buildup of Stimulation

All mechanisms reviewed thus far are unlikely to have a major contribution to the better acute performance in the CMJ as compared with the SJ. Other closely related mechanisms that may explain the difference between the jumps are stimulation, excitation, and contraction dynamics.

Specifically, stimulation dynamics refers to the buildup of muscle stimulation (as measured by the rate of increase in electromyographic activity, although this does strictly speaking not reflect the input to the muscle); excitation dynamics refers to the development of active state (i.e., the fraction of actin binding sites available for crossbridge formation) in response to the stimulation; and contraction dynamics refers to the development of force in response to the active state (5,7,10). With regard to stimulation dynamics, muscle stimulation may not reach a maximum level instantaneously, but rather, it will take time to develop maximum stimulation because of the dynamics of motor neuron pool excitation and the central commands (10). In addition, when a muscle is stimulated, it does not instantaneously contract because of electrochemical delays associated with the propagation of the action potential across the muscle membrane and excitation-contraction coupling (75,81,88). Finally, in relaxed muscles, the fascicles, tendinous tissues, and the total muscle-tendon unit may be slack (36,37,75), which indicates that there is no production of passive elastic force (41). This slack has to be taken up, and the tendinous tissues have to be stretched before force can be transmitted to the bones to initiate joint movement. The processes associated with the uptake of slack and stretching of the tendinous tissues have collectively been termed muscle slack (75).

Because the duration of the electrochemical processes is relatively short (approximately 3–6 ms, 75), it is unlikely that they have a large contribution to the difference between the jumps. In contrast, the uptake of muscle slack can take more than 100 milliseconds (75). Therefore, performance may significantly be improved by a reduction of muscle slack during the countermovement. Specifically, a countermovement moves the attachment points of the muscle-tendon unit further apart, thereby taking up slack in the fascicles and tendinous tissues, aligning the muscle-tendon unit, stretching the tendinous tissues, and allowing a quicker force transmission (30,75). However, when an individual descends into the starting position of an SJ, the attachment points of the muscle-tendon unit are also moved further apart, thereby reducing the effect of muscle slack (75). In the starting position of the SJ, the forces should, however, only be high enough to counteract the forces of gravity. In contrast, when the upward movement of the CMJ is initiated, the forces are high enough to counteract the forces of gravity and the downward acceleration of the center of mass. As a result, the ground reaction forces and forces acting on the muscle-tendon unit are higher during the initiation of the upward movement in the CMJ as compared with the forces acting on the muscle-tendon unit in the starting position of the SJ. The tendinous tissues are stretched more during the countermovement as a result of these higher forces (3,4,23,45), resulting in a higher stiffness of the tendinous tissues. This higher stiffness may allow the muscle fibers to shorten at a slower velocity, thereby increasing their force-producing capability and CMJ performance (30).

In parallel, it has been shown that individuals with stiffer tendinous tissues show smaller differences between the CMJ and SJ than individuals with more compliant tendinous tissues (47,48). Previously, these findings have been interpreted as evidence that individuals with more compliant tendinous tissues can store and use more elastic energy during the countermovement and hence show a larger difference between the SJ and CMJ. However, these findings may actually indicate that those with compliant tendinous tissues benefit more from the stiffening effect of the countermovement, whereas this effect is less pronounced in individuals who already have a higher tendon stiffness. Furthermore, although it has previously been suggested that muscle fiber type may also partially explain the difference between the CMJ and SJ (13,77), Kubo et al. (48) speculated that the stiffness of the tendinous tissues rather than muscle fiber type mostly influences the difference between the CMJ and SJ. Specifically, in their study, the participants were divided into a stiff and compliant group, and it was detected that the stiffness of the tendinous tissues considerably affected the difference in CMJ and SJ performances, even though both groups included sprinters, which were expected to have a higher percentage of fast-twitch fibers.

Although the stiffness of the tendinous tissues may partially explain the difference between the CMJ and SJ, using computational modelling, Bobbert et al. (7) found that the countermovement also allowed muscles to build up a high stimulation before shortening. In a later study, the researchers showed that the difference between the CMJ and SJ decreases with a faster stimulation because the muscle shortening distance covered at a submaximal active state in the SJ decreased (5). Taken together, these findings indicate that the difference between a CMJ and an SJ is also partially related to the buildup of a high muscle stimulation during the countermovement, which allows for a larger distance to be covered at maximal active state during the upward phase in the CMJ as compared with the SJ (2,77,79). It should be noted that the buildup of stimulation and a reduction of muscle slack are interrelated, as a faster buildup in stimulation would likely also lead to a faster reduction in muscle slack. For example, the rate at which stimulation increases explains a large proportion (approximately 50%) of the force dynamics across individuals during an SJ (10). It has been suggested that some individuals build up this stimulation slower than others because this may reduce the sensitivity of jump height to noise or errors in the timing of muscle activation (10,11). Several studies have shown the timing of muscle activation to be of major importance to vertical jump performance (8,11,65). For example, using computational modelling, it has been shown that less than a 10-millisecond difference in the timing of the plantar flexor activation during an SJ resulted in more than a 10-cm decrease in jump height (11). These findings suggest that individuals with poor coordination (i.e., poor capability to correctly time muscle activation) perform worse in an SJ, whereas they may still perform relatively well on a CMJ because they can build up stimulation during the countermovement. Training specifically on coordination may therefore be important to improve performance in high-intensity sports situations, in which it is important to quickly increase stimulation and in which there may be almost no time to perform a countermovement (e.g., start of swimming and athletics, block jump in volleyball).

In summary, these findings indicate that the difference between CMJ and SJ height is primarily related to the uptake of muscle slack and the buildup of stimulation and the corresponding active state during the countermovement in the CMJ.

Interaction Between the Mechanisms

Notably, the mechanisms discussed thus far have usually solely been investigated in isolation. However, there is likely a complex interaction between the mechanisms in in vivo human movements. To date, only one study has specifically investigated the interaction between two of these mechanisms. Arakawa et al. (2) used a Hill-type muscle model to simulate the effects of an increase or a decrease in the duration of active state on the storage and utilization of elastic energy during movements with and without a countermovement. They found that a decrease in the duration of active state led to an increase in the utilization of elastic energy during the countermovement. These findings may imply that individuals who lack the capability to quickly increase stimulation and reduce the degree of muscle slack through co-contractions use the countermovement to reduce the degree of muscle slack and build up stimulation, whereas individuals who can quickly increase stimulation and reduce the degree of muscle slack through co-contractions may partially use the countermovement to store elastic energy. However, the authors suggested that the contribution of elastic energy would likely be most relevant in movements actuated primarily by the ankle joint, whereas it would be less relevant in whole-body movements such as a CMJ and an SJ. Because the modelling study used a very simplified model (2), more research is warranted in more realistic models or humans to determine how much extra elastic energy can be stored if one possesses the skill to quickly build up stimulation and reduce the degree of muscle slack by means of co-contractions.

Implications for the Difference Between Countermovement Jump and Squat Jump Performances

As discussed previously, the traditional view on the difference between CMJ and SJ performances is that a larger difference is better as this reflects a better utilization of the stretch-shortening cycle (44,58,83,86). However, the findings of this review suggest that a larger difference is not necessarily better. Although a larger difference may reflect an effective utilization of elastic energy in a fast and small-amplitude CMJ as a result of a well-developed capability to co-activate muscles and quickly build up muscle stimulation, a larger difference may also reflect a poor capability to reduce the degree of muscle slack and build up stimulation in the SJ.

Differences Between Athletic Populations

The findings of cross-sectional studies among different athletic populations also suggest that a larger difference between CMJ and SJ performances is not always better. For example, better trained athletes do not consistently show a larger difference between CMJ and SJ performances than lesser trained athletes (14,35,44,47,72), which would be expected if the difference only reflected better utilization of the stretch-shortening cycle. For example, national-level male volleyball players have shown a larger difference between the SJ and CMJ as compared with male physical education students (44). In addition, sprinters showed a larger difference between SJ and CMJ performances in comparison with endurance athletes, who in turn demonstrated a larger difference relative to untrained individuals (72). Furthermore, national-level female soccer players showed a greater difference as compared with under-19 and under-17-year-old players, whereas this trend was not reflected among male teams (14). However, endurance athletes actually showed a smaller difference when compared with untrained individuals (47). These conflicting results suggest that a larger difference is not necessarily better.

Implications for Training

Especially, the capability to reduce the degree of muscle slack and quickly build up stimulation in the SJ may be crucial to high-intensity sports performance because there is usually not enough time to perform a large countermovement during most high-intensity sports situations (75). Training might therefore attempt to minimize the difference between CMJ and SJ performances by training specifically on these two capabilities.

As stated previously, the capability to quickly build up stimulation may be related to coordination. To optimize coordination, it is important to specifically mimic the intermuscular coordination patterns of vertical jumping during training. For example, Dalen et al. (18) divided sport science students in a multijoint group that performed a ballistic squat with plantar flexion and a single-joint group that performed a ballistic squat without plantar flexion and a plantar flexion exercise separately. Although both groups increased their 1 repetition maximum back squat, vertical jump performance decreased slightly for the single-joint group, whereas it significantly increased for the multijoint group. The decrease in the single-joint group was probably related to an altered intermuscular coordination of the biarticular gastrocnemius (8,53). Specifically, the timing of muscle activation was likely not trained in the single-joint group, although this is of paramount importance for energy transport from the knee to the ankle joint. These findings emphasize the importance of specificity to enhance intermuscular coordination.

It has previously been suggested that creating pretension by co-contractions is the only effective acute strategy to reduce muscle slack, and training should therefore aim to augment the capability to effectively create pretension (75). This may be accomplished by performing movements under time-pressure and applying unstable loads and surfaces during training. Specifically, the athlete does not have time to perform a large countermovement when there is time-pressure, and pretension is therefore the only effective solution to minimize muscle slack and to successfully complete the movement under time-pressure. Unstable loads and surfaces may cause perturbations in the movement, and when there is very little time for correction of these perturbations, reflexes may be too slow, and pretension is then the only adequate solution to minimize these perturbations because of the preflex effect (21,80). It should be therefore noted that unstable load and surface training is likely not effective when there is plenty of time to correct the perturbations such as during traditional balance training. However, more research is needed to determine the effectiveness of these methods.

The CMJ is usually incorporated in training with the rationale of optimizing the stretch-shortening cycle or, more specifically, to improve the storage and utilization of elastic energy. However, the findings of this review suggest that elastic energy has only a small contribution to the enhanced CMJ performance. It can therefore be questioned whether the capability to store and use elastic energy is effectively trained during a CMJ. Instead, CMJ training may decrease the capability to effectively create pretension and quickly build up stimulation because the athlete is not forced to create pretension and quickly build up stimulation as the countermovement reduces the degree of muscle slack and allows more time to build up stimulation. CMJ training may therefore be detrimental to high-intensity sports performance, especially when performed without time-pressure.

Practical Applications

Several equations have been proposed to express the difference between the CMJ and SJ (73). In a recent study, it was shown that the equations used to determine the eccentric utilization ratio (CMJ/SJ) and prestretch augmentation ($[\text{CMJ} - \text{SJ}]/\text{SJ} \times 100$) provide exactly the same information, although they are expressed in two different forms (i.e., ratio vs. percentage) (73). Therefore, both equations can be used to express the difference between the jumps and the choice of which equation is used depends on whether ratios or percentages are better understood by the practitioner. However, as mentioned previously, we suggest that future research evades the use of eccentric terminology, such as in the eccentric utilization ratio, and replace this by, for example, the countermovement utilization ratio.

Although it is common practice to measure several mechanical variables such as power in addition to jump height, using principal component analysis, Markovic and Jaric (55) determined that when power is appropriately normalized for body mass, it actually measures the same construct as vertical jump height. Moreover, it has been suggested that power is merely a variable that happens to be correlated with the net vertical impulse, which exactly determines jump height (43,69). Therefore, we suggest that vertical jump height rather than power is measured and used to express the difference between the jumps. Additionally, the average height of multiple jumps rather than the maximum jump height may be most appropriate to express this difference (16). However, the effects of increasing fatigue and a decrease in motivation on the performance in multiple jumps should also be considered.

Although a force platform is not necessarily needed to determine jump height, testing should preferably be done using a force platform, a linear position transducer, or a combination of both because field measurements are not sensitive enough to detect small-amplitude countermovements, which can significantly influence performance (34,70). For example, it has been shown that small-amplitude countermovements may enhance SJ height up to 6 cm in elite athletes (70), and this could incorrectly suggest that the difference between the CMJ and SJ is small. Additionally, a force platform or linear position transducer can measure rapid force development, which may be a more sensitive measure than jump height. For example, the average duration of the CMJ and SJ ranges from 500 to 1,000 and 300 to 430 milliseconds, respectively (75), whereas the time available for force development in many athletic movements is shorter, with durations up to 300 milliseconds (89). Therefore, measures of rapid force development, such as the slope of the force-time curve, may provide more detailed information than vertical jump height. Furthermore, an external load is sometimes used during jumping (85,87). However, the external load may have a similar effect as a countermovement in that it also reduces the degree of muscle slack (75). More specifically, the external load may take up slack in the fascicles and tendinous tissues, align the muscle-tendon unit, and stretch the tendinous tissues. Additionally, the external load may provide more time to build up stimulation Therefore, an external load should not be used during the tests. In addition, an arm swing may also allow more time to build up stimulation and reduce the degree of muscle slack because of the generation of extra gravitational forces that apply a stretching force to the muscle-tendon unit (22). Therefore, the hands of the individual tested should be kept on the hip.

CONCLUSION

The findings of the reviewed literature suggest that residual force enhancement, stretch reflexes, and differences in kinematics have likely no or a small contribution to the superior acute performance of the CMJ as compared with the SJ. Rather, the difference in performance may primarily be related to the greater uptake of muscle slack and the buildup of high stimulation during the countermovement in a CMJ. The storage and utilization of elastic energy may also have a small contribution to the enhanced CMJ performance, although this depends on several factors such as the amplitude of the countermovement and the capability of the individual to reduce muscle slack and quickly increase stimulation. It can be concluded that a larger difference between CMJ and SJ performances is not necessarily better because it may not only reflect the utilization of elastic energy in a small-amplitude CMJ as a result of a well-developed capability to co-activate muscles and quickly build up muscle stimulation, but may also reflect a poor capability to reduce the degree of muscle slack and quickly build up stimulation in the SJ. Especially, the capability to reduce the degree of muscle slack and quickly build up stimulation in the SJ may be crucial to high-intensity sports performance and training might therefore attempt to minimize the difference between the jumps.

It should be noted that the mechanisms that explain the difference between the jumps have usually solely been investigated in isolation, and future research should also investigate the interaction of these mechanisms. Finally, it should be distinguished that the findings discussed in this review are only applicable to the CMJ and SJ because there may be a different interaction of the mechanisms in other movements.

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