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absorbing the landing forces by flexing at the hip, knee, and ankles, rather than halting motion abruptly, often is termed giving.

Giving decreases the peak GRF on the body by increasing the time over which the force is imparted (when viewed in the impulse-momentum relationship where the change in momentum is the same, based on the initial and final conditions, regardless of how slowly or quickly the landing is completed between these points in time). Giving also decreases the GRF by increasing the displacement while bringing the \( V_{\text{COM}} \) to zero at the bottom of the landing (when viewed in the work-energy relationship where the change in energy is the same, regardless of the technique used). Giving is common in sport, serving to reduce the risk of injury to which higher forces might expose an athlete. It is the same concept that encourages a slight give when catching and follow-through when kicking and throwing.

Even with the standard giving motion incorporated into a landing, the GRF generally reaches levels much higher than those attained earlier in the jump. This is due to the eccentric muscle contractions required of the hip, knee, and ankle extensor muscles to halt the downward movement of the COM, which can be more forceful than the concentric contractions. Although the technique favored usually produces forces higher than those in the propulsion phase, it could be performed with peak forces of the same or reduced levels, depending on the amount of give.

The same mechanisms are in place in the landing as in the countermovement phase. However, because the landing phase begins with a large downward velocity and the countermovement phase begins with zero velocity, the level of forces generated by the muscles easily become much greater. Because the muscle stretch and GRF are much greater when landing than during the countermovement phase, the contribution of the stretch-reflex and extensor thrust reflex are probably significant in the landing. This is one of the reasons why plyometric training is included in many strength and conditioning programs: it can train neural mechanisms that are not incorporated in slower, more controlled movements (20).

During the “giving” portion of the landing, power generally will be both high in magnitude and negative in direction (Figure 6). It is high in magnitude because both \( V_{\text{COM}} \) and GRF are usually quite large, and negative because \( V_{\text{COM}} \) is downward while the GRF is acting upward. Because displacement is also downward at this time, work is negative as well. A negative value in these terms is indicative of a reduction of energy in the body of interest. This giving portion reduces the PE\(_{\text{L}}\) of the system, because the COM moves downward. It also reduces the KE\(_{\text{L}}\), because the magnitude of \( V_{\text{COM}} \) is being reduced. Therefore, the energy that was added to the body during the propulsion phase with positive values for work and power is being removed now, leaving the person at the end of the landing phase with the same amount of energy as at the start in the CMJ. Due to the SI starting in the squat/semisquat position, a person will have more energy at the end of the jump, because the COM is higher than at the start (Figure 7).

The concept of an object's gain or loss of energy (positive or negative work/power) is directly related to the predominant form of muscle contraction during a movement. If the contraction is concentric, force and displacement/velocity are in the same direction and energy is gained by the system with work and power positive. If the contraction is eccentric, force and displacement/velocity are in opposite directions and energy is lost by the system with work and power negative. Finally, if the contraction is isometric, there will be no displacement/velocity and energy of the system will remain constant with work and power equal to zero.

**Conclusion**

The vertical jump is a very common movement and simple in its goal to reach a point as high above the ground as possible. The key mechanical elements to success also are relatively straightforward: achieve the highest possible \( V_{\text{COM}} \) and \( P_{\text{COM}} \) at takeoff and then rearrange the body once in the air to position the reach hand as high above the COM as possible. However, to analyze a jump in further detail, a thorough understanding of the basic mechanical principles is necessary, not only to train a person to jump as high as possible, but also to prevent injury. Better understanding of the aforementioned mechanical principles will not only help strength and conditioning professionals in the training of the and the analysis of the vertical jump, but other related movements as well.

**References**


5. **Eloranta, V.** Effect of postural and load variation on the coordination of
The mechanical energy attained at takeoff until contact is made with the ground upon landing. However, the PE and KE do not stay constant during flight. The mechanical work by gravity converts KE into PE during the upward phase of flight, and is the opposite on the way down. PE increases until peak height and then decreases, returning to the same value as takeoff at the end of the phase (Figure 7b). KE decreases from takeoff until peak height, becomes instantaneously zero at peak height along with $V_{COM}$ and then increases to takeoff level at the end of the phase (Figure 7c). The increase in PE is equal to the decrease in KE as the athlete reaches peak height, and the opposite holds true when the athlete falls back to the ground. As a result, there is no change in the total mechanical energy of the system over the course of the flight phase. The fact that the energy of a projectile is conserved makes flight readily analyzed, especially in conjunction with the projectile motion equations previously mentioned.

**Landing Phase**

The landing phase begins when the jumper's toes first touch back on the ground and ends when the person returns to the standing position. At the moment of contact, the GRF builds from zero, quickly rising generally to levels above those developed in the countermovement and propulsion phases before returning to body weight at the end (Figure 4). Paralleling this action, $A_{COM}$ builds up from $-9.8 \text{ m/s}^2$, passes through zero when the GRF first equals body weight and then becomes highly positive before returning to zero at the end (Figure 2c). As a result, the downward motion of the COM is arrested and the COM returns to standing height (Figure 2a). The process of
tating jump height regardless of a person's weight, to jump the same height, a heavier athlete would produce more power than a lighter athlete. Therefore, if vertical jump height is being used to estimate power output, care should be taken in the interpretation of results.

Power also may be thought of as the rate of doing mechanical work, or how slowly or quickly work is being performed. Conceptually, in this form it must be average power, because a period of time has elapsed:

\[ \text{Power} = \frac{\text{Work}}{\Delta t} \]

Work, like power, is a scalar quantity that is defined in relation to a force. Work is the product of the average force applied to an object and the displacement (\(\Delta P_{\text{COM}}\)) that occurs in the direction of the force:

\[ \text{Work} = F_{\text{avg}} \cdot \Delta P_{\text{COM}} \]

Unlike power, work cannot be thought of as both an instantaneous or average quantity. Because an object cannot be in two places at once, there conceptually is no such thing as instantaneous work.

Work may be increased during the propulsion phase by increasing the average vertical force (in this case, \(G_{\text{avg}}\)), by increasing the displacement (\(P_{\text{COM}} - P_{\text{COM}}\)) that occurs while the force acts, or preferably both (as with impulse). Increasing work through displacement brings up the same issue that emerged when discussing the impulse-momentum relationship. A lower than natural position at the bottom of the countermovement actually may reduce performance without appropriate training and conditioning, and the COM is most likely already at maximum height at takeoff. However, for the given displacement that is available during propulsion, it is important to maximize \(G_{\text{avg}}\). Therefore, just as you want to maximize the average power during the propulsion phase, you also want to maximize the work performed to achieve the greatest \(V_{\text{COM}}\) at takeoff possible.

Work also is defined as the means by which energy is transferred from one object to another. Mathematically, this may be expressed as the change in total mechanical energy of the object. This is commonly referred to as the work-energy relationship. Energy can take many forms, and often is defined circularly as the capacity to perform work. Mechanical energy takes two basic forms, potential energy (PE) and kinetic energy (KE). PE may be thought of as stored energy, whereas KE is energy of motion. Although there are several forms of PE, the one of interest here is the form related to gravity (PE\(_g\)). Due to the force of gravity on an object, an object that is of a higher height has more PE\(_g\) than one of the same height at a lower height. Therefore, PE\(_g\) is comparative in nature, being equal to the product of the weight of the object and the height relative to a reference line. KE also takes multiple forms, with an interest here in the form due to its linear motion (KE\(_l\)). The KE\(_l\) is equal to the product of one-half its mass and \(V_{\text{COM}}\) squared. Work performed during any two points of a vertical jump is then equal to the change in PE\(_g\) and KE\(_l\) over this time:

\[ \text{Work} = \Delta \text{PE\(_g\)} + \Delta \text{KE\(_l\)} \]

\[ = (W \cdot P_{\text{COM}} - W \cdot P_{\text{COM}}) + (\frac{1}{2} m \cdot V_{\text{COM}}^2 - \frac{1}{2} m \cdot V_{\text{COM}}^2) \]

Within this definition of work, it also can be seen that if work is to be maximized during the propulsion phase, both the height of the COM (\(P_{\text{COM}}\)) and velocity (\(V_{\text{COM}}\)) at takeoff should be as great as possible.

Although the goal is to have \(V_{\text{COM}}\) at its maximum right at takeoff, the peak actually occurs slightly before this (Figure 2b). Velocity begins to slow before takeoff due to a compromised ability of the active muscles to produce force right at takeoff. This reduced force production comes by way of the joint angles (hip, knee, and ankle) being close to or at full extension. At this point, the muscles producing these joint actions are in a shortened position, which is not optimal for force production based on the force-length property of muscle (14). The muscles also must reduce their force production to prevent overextension of the joints. Overextension would compromise the height of the COM at takeoff, by placing the person in a less than optimal position, as well as potentially place joints (most notably the knee) in a vulnerable position for injury. As a result, the GRF drops below \(W\), making \(A_{\text{COM}}\) negative, and the body begins to slow down. In fact, the GRF quickly drops, reaching zero at takeoff. At this time the \(A_{\text{COM}}\) has dropped to \(-9.8\) m/s², the value it will maintain during the flight phase.

**Flight Phase**

As previously discussed, the body goes through projectile motion once in the air. Because \(A_{\text{COM}}\) is constant at \(-9.8\) m/s² during this time (Figure 2c), \(V_{\text{COM}}\) will be a straight diagonal line with a slope of \(-9.8\) m/s² (Figure 2b). The upward rise of the COM is followed by a mirror image, downward fall. This mirror image is such that if you compared the same heights of the COM during the upward flight with those of the downward fall, the velocities would be equal in magnitude, but opposite in direction. Therefore, if the jumper's COM is at the same height upon landing as it was at takeoff, \(V_{\text{COM}}\) will be equally negative to that at takeoff in magnitude, but now negative instead of positive. Because there is no longer a GRF, power generated by the jumper drops to zero (Figure 6) and no work is performed by him or her during the flight phase. As a result, there is no change in the total mechanical energy of the body during flight (Figure 7a). It remains at the level of me-
the point that jump height is no greater than that achieved in a CMJ (4). The drop jump is further compromised relative to the CMJ due to a greater change in momentum required during the drop preceding the propulsive phase, compared with just a countermovement initiated from the standing position.

Ways to provide a greater time period for force to be applied are to ensure that the $P_{\text{COM}}$ is (a) as high as possible at takeoff and (b) as low as possible at the start of the propulsion phase. Combined, these two components will determine the distance that the body extends during the propulsion phase, which relates directly to the time spent in the phase. As previously mentioned, positioning the COM so that it is as high as possible at takeoff is also one of the keys to success. After extending the hip, knee, and ankle through the course of the propulsion, the body is already close to the optimal position for takeoff. The only other piece is to have the arms extended directly overhead (Figure 1). Most people learn to be in this extended position through trial and error, so little room for improvement in this area is usually possible. However, if a single-leg jump were to be performed (e.g., during a layup in basketball), the hip and knee of the off leg should be flexed as much as possible to maximize COM height at takeoff.

Incorporating a deeper squat into an athlete’s jump technique may be possible. Unfortunately, a deeper squat may not improve performance. In order for the increased time to be effective, the GRF produced must be greater than body weight. Going too deep in the squat compromises this ability, because muscles may be taken beyond their optimal lengths for active force production with reduced mechanical advantage of the muscles at the hip and knee (5). Additionally, because sport is highly reactionary in nature, an athlete would not want to spend more time in this phase. However, appropriate training and stretching has been shown to be successful in its ability to increase the depth of the countermovement while at the same time improving jump height (15).

A more practical approach for sport performance may be to train the muscles so that they can produce higher forces at higher velocities of shortening. As the velocity of shortening increases, based on the force-velocity property of muscle, muscles naturally lose their ability to produce force (14). However, with appropriate training focused on the speed of movement, this capacity may be enhanced (16, 19). If muscle force can be maintained at higher shortening velocities, then GRF$_{\text{avg}}$ can be elevated. This will increase the vertical impulse, even though the time component is being compromised. The greater impulse translates to an increased change in momentum and maximum $V_{\text{COM}}$ at takeoff.

The discussion of force and velocity usually includes the mention of power. Power is a scalar (nondirectional) product of force and velocity:

$$\text{Power} = F \cdot V_{\text{COM}}$$

Power will be positive when both the force on the object and the velocity of the object are acting in the same direction and negative when they are acting oppositely. Because the GRF always is acting upward on the feet and because velocity is negative during the countermovement and positive during the propulsion phase, power output will not only vary in magnitude with time, but also in direction during the vertical jump (Figure 6). During the propulsion phase, the average of the instantaneous power is important to consider, because it reflects the combined effect of the GRF and $V_{\text{COM}}$ over this time. Due to time and displacement constraints placed on many human movements, power is a common parameter to assess. Power, though important, should not be compared across athletes without considering the effect of body weight. It takes more power to move a heavier body at the same velocity as a lighter one, due to the increased force required to accelerate a heavier object. Because it is $V_{\text{COM}}$ at takeoff that is important, di-
ties with a note of caution related to how significantly they add to the CMJ.
Several recent, well-designed, and carefully conducted investigations have concluded that it is the altered "active state" of the muscles, necessitated by the previously described need to produce a large GRF at the end of the countermovement to arrest the downward motion of the COM (2, 9, 21), that is responsible for the increased height in the CMJ. However, because these biological properties may be significant for other activities, their discussion is still warranted.

First, as the body is lowered, many of the hip, knee, and ankle extensor muscles are lengthening. Therefore, once activated, they are performing eccentric contractions. From their force-velocity properties, muscles are able to generate greater forces when contracting eccentrically than when contracting isometrically or concentrically (14). This increases the ability to generate a large GRF and ACOM at the end of the countermovement, which could be carried over to start the propulsion phase. Second, a rapid stretch in the muscle, as created by the rapid rise in force from the eccentric contraction, could invoke the stretch-reflex from the muscle spindles (14, 20). This reflex increases the neural activation stimulus to the extensor muscles, further increasing their force potential. Third, as long as the eccentric contraction is followed rapidly by a concentric contraction, as in the immediate transition into the propulsion phase, elastic strain energy that is stored in the stretching of the musculotendinous unit may be recovered in the concentric shortening phase (1), increasing forces generated during the propulsion phase. Collectively, these three mechanisms are brought together in many human movements and are referred to as a stretch-shorten cycle of muscle contraction (1, 14, 20). Another neural reflex, the extensor thrust reflex (10), also may be invoked to increase the activation of extensor muscles if the countermovement is part of a landing that more dramatically increases the forces under the feet, such as in step-close and drop jumps where an athlete steps/drops into the jump location.

Even though the stretch-shorten cycle may not contribute significantly to the height attained in the CMJ, the addition of the countermovement phase yields GRF and ACOM values that are at or near maximal at the start of the propulsion phase (2, 3), with a 3- to 11-cm increase in the maximum height attainable in the CMJ relative to the SJ (2, 3, 21). Comparatively, in the SJ it takes a period of time for the GRF and ACOM to become maximal after the start of the propulsion phase as the muscles increase their active state and force production from that required just to hold the body statically in the starting position. The greatest effect of incorporating the countermovement appears to occur within the muscles crossing the hip joint (2, 8). Interestingly enough, people often will try to include a small countermovement in an SJ, oftentimes without consciously realizing it. However, this minor countermovement has not been found to significantly increase maximum height compared with an SJ with no countermovement (12).

Another way to look at the propulsion phase and the attempt to keep ACOM as high as possible for as long as possible is through the impulse-momentum relationship. Impulse is defined as the product of a force and the time over which it acts, whereas momentum is the product of the mass of an object and its velocity, both of which are vector quantities. The impulse-momentum relationship states that the net external impulse equals the change in momentum of an object. The net external impulse is the product of the average sum of external forces (Σ F_{ext}) and the time over which the force acts (Δt), whereas the change in momentum is logically the final momentum minus initial momentum (m\cdot V^{\text{COM,final}} - m\cdot V^{\text{COM,initial}}) during a movement:

\[ Σ F_{ext} \cdot Δt = m(V^{\text{COM,final}} - V^{\text{COM,initial}}) \]

Even though it bears little resemblance in this form, the impulse-momentum relationship is an averaged form of Newton's Second Law. If both sides of the equation are divided by the time (Δt), the right-hand side then contains (V^{\text{COM,final}} - V^{\text{COM,initial}})/Δt. This term is the same as average acceleration presented previously and the equation becomes

\[ Σ F_{ext} = m \cdot A^{\text{COM,avg}} \]

Taking the next logical step, the goal of the propulsion phase is to maximize the upward impulse on the body, yielding the greatest change in momentum. Because V^{\text{COM,initial}} is zero at the start of the propulsion phase and body mass is constant, the greatest change in momentum also will generate the greatest V^{\text{COM,final}}, which is at takeoff.

Looking further at the components that impart the change in momentum during the propulsion phase, it becomes apparent that having a large external impulse is a difficult task. Basically, to increase the impulse, one needs to increase the Σ F_{ext} \cdot Δt, or preferably, both. For the vertical jump, Σ F_{ext} = GRF_{tot} - W. When GRF_{tot} is increased, ACOM also is increased, with V^{\text{COM,final}} following suit. Unfortunately, because the person extends through the propulsion phase more rapidly with increased ACOM and V^{\text{COM,final}}, Δt will naturally decrease. This complicates the "as long as possible" component of force production. Therefore, even though higher forces are more beneficial to jump performance, some of the benefits of the increased forces are not realized due to a reduction in the time over which they act. This occurs to such an extent in drop jumps that even though the GRF is elevated above those of other types of jumps, Δt is reduced to...
a free-body diagram (Figure 5). A free-body diagram is a simplified stick-figure image of the system of interest that includes only the external forces. External forces are those that have a potential to alter the motion of an object. Although muscles are highly responsible for the time-varying nature of the GRF, they are not considered external forces for a system representing the entire body and, therefore, are not included in the free-body diagram. To elucidate, during the flight phase your muscles can contract and produce force. However, at this time they can move your limbs, but not change the motion of your COM prescribed by projectile motion. Only when you make contact with another object can your muscles be used to push or to pull against it. As a result, it is the force interacting with an external object that may potentially alter your motion, not the muscle itself. Therefore, only the external forces made through contact with the environment, plus the gravitational force, are included on a free-body diagram.

From the free-body diagram, an equation describing the linear motion of the object's COM may be generated readily. The linear equation of motion is based on Newton's Second Law of Motion. This law, also known as the Law of Acceleration, states that the sum of the external forces (ΣF, where Σ = sum) on an object equals the product of the object's mass (m) and the \( A_{COM} \): 

\[
ΣF = m \cdot A_{COM}
\]

In the case of the vertical jump, a vertical direction analysis during ground contact yields 

\[
GRF - W = m \cdot A_{COM}
\]

where \( W \) is the weight of the person. From this equation of motion, we can see that \( A_{COM} \) will be positive as long as the GRF > W, which means that the COM will gather speed when traveling in the upward (positive) direction or will slow if traveling in the downward (negative) direction during this time. If GRF < W, \( A_{COM} \) will be negative and the object will slow in the upward (positive) direction or gather speed if traveling in the downward (negative) direction. In the case where GRF = W, \( A_{COM} \) will equal zero, so no change in motion occurs (i.e., velocity will remain constant).

This third case is an example of Newton's First Law of Motion, also known as the Law of Inertia. This law states that an object in motion will maintain its motion and an object at rest will remain at rest unless acted upon by a net external force that is nonzero. As a result, in the vertical jump, just as the GRF changes with time, so does the \( A_{COM} \) (Figure 2c). In fact, because \( W \) and \( m \) are constant, the time-varying nature of \( A_{COM} \) will parallel the GRF in this movement.

Furthermore, as previously discussed, acceleration also may be thought of as the change in velocity with respect to time (\( \Delta V_{COM} / \Delta t \)), and because \( V_{COM} \) is zero at the start of the propulsion phase, it is beneficial to have \( A_{COM} \) as high as possible for as long as possible, yielding the highest possible \( V_{COM} \) at takeoff. This relates back to the GRF being as high as possible, because it translates to high acceleration through Newton's Second Law of Motion. One way to increase the GRF is through the use of a counter-movement immediately before the propulsion phase.

At the start of the counter-movement phase, the jumper alters muscle activity so that \( W \) exceeds the GRF. As a result, \( A_{COM} \) is negative, downward motion begins, and \( V_{COM} \) is negative. However, this negative motion cannot continue forever, so the extensor muscles must increase their activity to generate a GRF that is greater than \( W \). Once this happens, \( A_{COM} \) becomes positive, and \( V_{COM} \) becomes a negative value of smaller magnitude returning toward zero. When \( V_{COM} \) does return to zero, the propulsion phase begins immediately. At this time, even though \( V_{COM} \) is zero, \( A_{COM} \) is extremely high, as is the GRF. As a result, even though a person starts the propulsion phase in the same position and with the same \( V_{COM} \) in both the CMJ and SJ, a distinct advantage is gained compared with the SJ (2). In the SJ, the propulsion phase begins with \( A_{COM} \) at zero and the GRF equal only to \( W \). Therefore, the counter-movement serves to help make \( A_{COM} \) as high as possible for as long as possible during the propulsion phase.

There are also several biological properties in place that may help enhance the GRF at the end of the counter-movement phase/beginning of the propulsion phase, further increasing the potential for a greater jump height to be attained with a counter-movement. It is important to preface the discussion of these biological properties with how many people carefully consider the "activity" of their body's muscles, their role in producing a GRF to propel the body upward (as in the SJ), and the creation of a "jumping" effect (41), which may be paradoxical because the way it may be taught in the past.

First, it is important to understand the biological nature of muscles that are active in the SJ (41). Active muscles are not solely attached to bones; generally, the muscle attaches directly to tendons, which then attach to the bones (41). When a muscle contracts, this shortening of the muscle stimulates the motor neurons innervating the muscle via the nervous system (41). The motor neurons then stimulate the muscle to contract and generate force. This contraction of the muscles is via the process of excitation-contraction coupling, which is a process that is also responsible for the generation of force in the SJ (41). The force generated by the muscles is transferred to the bones, which then transfer the force to the ground, thereby propelling the body upward. This mechanism is the basis for the SJ, and it is this mechanism that allows for the generation of the GRF at the end of the counter-movement phase/beginning of the propulsion phase, further increasing the potential for a greater jump height to be attained with a counter-movement. It is important to preface the discussion of these biological properties with how many people carefully consider the "activity" of their body's muscles, their role in producing a GRF to propel the body upward (as in the SJ), and the creation of a "jumping" effect (41), which may be paradoxical because the way it may be taught in the past.
Velocity, acceleration, and velocity are independent of each other. One way to think of velocity relative to position is to view them plotted versus time, as in Figure 2. Velocity is equal to the slope of the position versus time plot. The slope of the position versus time plot is the change in position (ΔP_{COM}) relative to the amount of time that elapses (Δt), making slope no different from our previous definition of velocity (ΔP_{COM}/Δt). To find the instantaneous value of velocity from a position versus time plot, calculate the slope from a line drawn tangent to the point in time of interest (Figure 3). So, when the slope of the position versus time plot is positive, velocity will be positive. When the slope is zero, the velocity will be zero, and when the slope is negative, the velocity will be negative. It naturally follows that acceleration is the slope of the velocity versus time plot with the same relationships as those existing between position and velocity.

**Achieving Maximum V_{COM} and P_{COM} at Takeoff**

To achieve maximum V_{COM} and P_{COM} at takeoff, an athlete pushes down against the ground through forceful extensions of the hip, knee, and ankle from a squat/semisquat position (Figure 1). Another important component to maximizing V_{COM} is arm swing (also visible in Figure 1). A rapid downward, then upward, arm swing contributes roughly 10% to the V_{COM} at takeoff (11, 18), resulting in a 2- to 9-cm increase in jump height (7, 11, 17). The arm swing also helps to naturally increase P_{COM}, because as takeoff the arms will be above the head rather than alongside the body.

Pushing downward against the ground in an attempt to move your COM upward is an example of Newton's Third Law of Motion. This law, also known as the Law of Action-Reaction, states that for every contact force, there is an equal and opposite force on a contrary body. In this case, whereas the ground is subject to a force pushing down on it, the person feels the exact opposite force acting upward on him or her. This force is often referred to as the ground reaction force (GRF). Because air resistance is negligible, the only other force acting on the person during the propulsion phase is the force of gravity pulling down on the jumper. The net effect of gravity is a force equal to his or her body weight, acting through the COM. Whereas the GRF varies with time during the course of the jump (Figure 4), the force of gravity is constant and remains the only force acting on the body once airborne.

One way to visualize the forces acting on an object is through the construction of...
After making appropriate substitutions in the equations that predict the motion of a projectile (See references 6 and 10 or any basic physics or biomechanics text), the maximum height that the COM of a projectile will reach \( h_{\text{COM, max}} \) is equal to its initial starting height \( h_{\text{COM, ini}} \) minus the square of its initial vertical velocity at takeoff \( V_{\text{COM,0}} \) divided by twice its acceleration \( a_{\text{COM}} \):

\[
P_{\text{COM, max}} = P_{\text{COM, ini}} - \frac{V_{\text{COM,0}}^2}{2 \cdot a_{\text{COM}}}
\]

The \( a_{\text{COM}} \) is the vertical acceleration due to gravity (\(-9.8 \text{ m/s}^2\)) that is constant during flight. This acceleration slows down a projectile that is moving upward and speeds up a projectile that is moving downward. Therefore, raising your \( V_{\text{COM,0}} \) and \( P_{\text{COM, ini}} \) as high as possible at takeoff is fundamental to reaching a point as high above the ground as possible during the course of a vertical jump.

Although you no longer have any control over the path of your COM while you are in the air, there remains some control over the height that your hand will reach, because you can still move your arms and legs. To create the greatest distance between the reach hand and your COM, the body should be arranged so that the hand is as far from the rest of your body mass as possible. This is accomplished by extending the hips and knees, plantar flexing the ankles (Figure 1), and lowering the non-reach arm along the side of the body. This is generally learned through trial and error. However, it can sometimes be forgotten when emphasis is placed heavily upon the propulsion phase.

Before discussing how maximum \( V_{\text{COM,0}} \) and \( P_{\text{COM, ini}} \) are achieved at takeoff, it is important to understand the relationships between position, velocity, and acceleration. As previously discussed, velocity is the time rate of change of position \( \Delta P_{\text{COM}}/\Delta t \). Similarly, acceleration is the time rate of change of velocity \( \Delta V_{\text{COM}}/\Delta t \). Therefore, position, ve-
- Raise the vertical position of your center of mass ($P_{COM}$) as high as practically possible at takeoff (again, projectile motion dictates center of mass [COM] travel).
- Once in the air, position the body in such a way that the reach hand is as far above $P_{COM}$ as possible when it is at peak height.

The COM is defined as a point in space about which all the mass of the body is balanced. There is an even distribution of all the matter that makes up the body around this point. When standing in the anatomical position, the human COM is typically at 55–57% of standing height, near waist level, as well as in the midline of the body side-to-side and front-to-back (10). This point logically changes as movement occurs and body segments are repositioned relative to each other, as during the course of a vertical jump (Figure 1 and Figure 2a). The vertical jump is often broken down into phases based on the motion of the COM. In the CMJ, a counter movement phase starts with the initial downward movement of the COM and ends when the COM is at its lowest point. A propulsion phase continues with the COM moving vertically from its lowest point, ending at takeoff. A flight phase begins at takeoff and continues as the COM rises to its highest point and then falls until the landing. A landing phase begins when the toes first touch the ground and continues as the COM lowers while absorbing the landing forces, and finally rises until the athlete returns to rest and the COM is stationary in the standing position once again. The SJ follows the same progression, but does not include the counter movement phase.

Each of the three keys to success depends on the fact that the body acts as a projectile once in the air. A projectile is any object that has only the vertical force of gravity acting on it. Technically, to be classified as a projectile, air resistance must be nonexistent. However, for the short period of time that a person is in the air and the relatively low velocity of movement, a reasonable assumption is that the effects of air resistance are negligible, allowing for treatment as a projectile. Furthermore, treatment as a projectile vastly decreases the complexity of the computations incorporated into the analysis. The parabolic path of a projectile's COM is determined by its position and velocity at the time it starts its flight; the COM cannot be altered once in the air until contact is made with the ground, another surface, object, or other player.

Velocity is the time rate of change of position, or how fast or slow an object is moving in a given direction. Although it is often expressed as an instantaneous value, average velocity ($V_{COMave}$) yields an expression which reveals its definition. $V_{COMave}$ equals the difference between the final and initial position ($P_{COMf} - P_{COMi}$) divided by the difference between the final and initial time ($t_f - t_i$) over which the average is being computed:

$$V_{COMave} = \frac{P_{COMf} - P_{COMi}}{t_f - t_i}$$

$P_{COMf} - P_{COMi}$ often is shortened to just $\Delta P_{COM}$, where $\Delta$ is read as "change in." This difference in final relative to initial position also is referred to as displacement. Similarly, $t_f - t_i$ is often shortened to $\Delta t$ and average velocity becomes

$$V_{COMave} = \frac{\Delta P_{COM}}{\Delta t}$$

Velocity, position, displacement, acceleration, and force (as well as several other parameters) are vector quantities. Vector quantities are defined by both a magnitude and a direction. For the purposes of this analysis, because the vertical direction is the only one of interest, the horizontal aspects of these vector quantities will be ignored.
Building a Better Understanding of Basic Mechanical Principles Through Analysis of the Vertical Jump

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Summary
An understanding of the basic mechanical principles governing movement is essential for the development of training programs, performance improvement, and injury prevention. The goal of this article is to review these principles through an analysis of the vertical jump.

The vertical jump is a common and essential motor skill in sport, training, and performance evaluation. The ability of an athlete to reach a point high above the ground from a jump can often determine the difference between success and failure, wins and losses, or playoffs and end of season. The vertical jump, however, is as complicated as it is common. A successful jump requires a combined and coordinated effort of muscle recruitment throughout the entire body, from the head down through the toes. Therefore, interactions between muscle excitation, joint motion (kinematics), and force production (kinetics) are complex and warrant thorough understanding. Complete understanding of the vertical jump also requires comprehension of basic mechanics, to include relationships between position, velocity, and acceleration, Newton's laws of motion, impulse-momentum and work-energy relationships, and power.

With this requirement in mind, the goal of this article is to review basic mechanical principles with concentration on two similar, but slightly different, jump styles for comparative purposes: the countermovement jump (CMJ) and the squat jump (SJ) (Figure 1). The CMJ consists of an initial downward movement (often referred to as a countermovement, because it is in a direction opposite of the eventual jump) that ends in a squat/semisquat position, followed by immediate and forceful hip, knee, and ankle extension that propels the athlete upward, resulting in takeoff. The SJ consists of similar hip, knee, and ankle extension and also results in takeoff, but begins from a static squat position and does not provide quite the same jump height (2, 3, 21). Better understanding of the aforementioned mechanical principles will alleviate confusion, clarify terminology, and result in increased abilities of strength and conditioning professionals to enact changes that will improve training and analysis of the vertical jump and other related movements.

Before conducting any analysis, it is important to define the specific goal of the task. Without a clearly defined goal, it is extremely difficult to structure an analysis that will lead to useful results. For a maximum effort vertical jump, the most basic goal is to touch a point as high above the ground as possible. Three key, mechanically-based elements are involved in achieving this goal (13):

- Raise the vertical velocity of your center of mass (V_{COM}) as high as possible at takeoff (projectile motion ensues once in the air).