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The Stretch-Shortening Cycle and Plyometric Training

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I recently overhead a new CrossFit trainee mention that the kipping pull-up he was being taught was "kind of cheating." This is a very common response that shows that many people are unaware that functional movements often require contributions of eccentric (lengthening), isometric (static), and concentric (shortening) muscle actions and that one very common power movement uses a stretch immediately prior to the muscle shortening. This pattern is called the *stretch-shortening* cycle, as the muscle is lengthened (while actively working) prior to shortening. Rather than cheating, kipping is just one example of an athlete utilizing this natural mechanical response. Cutting from right to left when playing a sport or performing a drop-down counter-movement before jumping are also examples of stretch-shortening cycles.

Maybe I should quickly review some terminology. When a muscle is active but lengthening, the muscle action is called *eccentric* ("away from the center"). This is different from trying to lengthen a muscle while doing a stretch. In the latter case, the muscle is not actively trying to shorten; it is trying to relax. The opposite movement—the work of a muscle actively shortening, or contracting— is called a *concentric* ("toward the center") contraction. When a muscle engages (tries to shorten) but does not change length (or produce motion) it is called an *isometric* contraction.

When you lower yourself slowly into a chair, your hip, knee, and ankle joints flex. Does this mean that your hip flexors, knee flexors (e.g., hamstrings), and ankle flexors (tibialis anterior) are contracting to produce this movement? No, because if you relaxed your leg musculature, the force of gravity would pull you down, and your hips, knees, and ankles would flex without any significant muscular action. In fact, you would descend quite quickly. What in fact happens is that your extensors (gluteals at the hips, quads at the knee, and calf muscles at the ankle) activate to slow you down so you do not plunk down into the seat uncontrolledly. In effect, you just resist gravity a bit but ultimately let it win. The same kind of movement and muscle use also happen in a front, back, or overhead squat with weight. You lower yourself slowly, letting gravity win as you control the descent. Your extensor muscles are the ones working eccentrically on the way down and concentrically on the way up. Numerous muscle groups in the trunk are working statically (isometrically) during these movements to stabilize the spine. So again we see this functional combination (and coordination) of all three types of muscle action.

OK, I know some of you are thinking about Tabata squats. Yes, when doing high-rep air squats at speed you would use flexor muscles to drive the hips, knees, and ankles into flexion. This is because you do not want to wait for gravity to do the job, as it is a bit slow if you want to do 20 or more squats in 20 seconds. But toward the end of the descent you will activate the extensor muscles to slow your descent and then reverse the movement to drive back upwards. So, toward the end of the descent in a fast air-squat sequence, the extensor muscles lengthen (work eccentrically) while the leg joints flex. Therefore there will be an eccentric phase prior to the concentric phase, which is known as a stretch-shortening cycle (SSC). In fact, during Tabata squats you drive yourself upward so fast (extending the ankles, knees, and hips) that your flexors will contract near full extension to help break your upward motion and then "turn you around" fast to begin the downward drive—yet another SSC.

Why do we utilize the stretch-shortening cycle so frequently in human movement? There are several reasons, but the bottom line is that the subsequent concentric contraction is more powerful when preceded by an eccentric phase. It is a well-established fact that muscular forces during maximal eccentric action are greater than during maximal isometric or concentric muscular contractions. So the eccentric phase of the movement is characterized by high muscular forces. But the external force of gravity or the momentum of a limb, the whole body, or a barbell still overpowers the muscle force (initially), and the muscle must stretch. As the muscle stretches, energy is stored within the muscle and connective tissue. So in the subsequent concentric phase, the muscle force is already high due to the eccentric work, plus there is a return of stored energy from elastic structures within the muscle. Research suggests that this return of stored energy generated during the eccentric movement of the SSC accounts for about 70 to 75 percent of the increase in work capacity in the concentric phase. What this means is that in a properly timed SSC, energy is stored in the elastic structures of the muscle and that energy is returned in the concentric phase. It is OK to think of this as stretching out a rubber band (storing elastic energy) and then letting it go. It is obviously not as simple as that but it does help you visualize the storage of energy.

In addition to the benefit of returned stored energy, the muscle stretch (eccentric action) will initiate a stretch reflex via a reflex arc. A reflex arc is the neural pathway that controls a reflex action. Simply put, stretch receptors (sensory receptor organs located at the tendon-muscle junction) register the stretch and initiate this reflex arc to activate and protect the muscle. Most sensory neurons do not pass directly into the brain, but connect with motor neurons in the spinal cord. So a reflex arc allows reflex actions to occur relatively quickly by activating spinal motor neurons without the delay of routing signals through the brain. This means the muscle force rises faster than it would if starting from a paused position, since neural pathways to the brain are bypassed. Obviously the eccentric action means the muscle is already active prior to the concentric phase of the SSC, which further reduces the time to reach high-force outputs.

Jumping

The fact that muscle can produce higher forces when being stretched is easy to demonstrate. The vast majority of us would have no trouble generating enough eccentric force to control the landing when jumping down from a 46-inch box. On June 22, 2007, in the WOD demo video on CrossFit.com, Brendan showed us that he could jump up to a 46-inch box. But the majority of us couldn't. To jump up requires concentric work and we just can't generate enough force (and hence power) to get back up even with a SSC. Most of us could land into a squat (without rolling) in a jump down from a 5-foot box, but few of us could jump back up. This shows that muscles are stronger during eccentric work.

Jump video WMV MP4

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I have included a video that illustrates the benefits of the SSC. This video shows variations of the vertical jump, a common fitness test used to estimate leg power.

In jump #1 in the video, the athlete, Jeff Thornhill from CrossFit Vancouver, executes a vertical jump without any preceding countermovement. Interestingly, this is a common test protocol, intended to remove a skill component and test just leg power. But it is very difficult not to do at least a "mini" countermovement and get some stretch-shortening effect. We are just naturally hard-wired to coordinate such movements in this way. You can see in the slow-motion replay of this jump that despite being asked to jump up from a static position, Jeff does use a small countermovement. If he could tell his body not to do that, his jump would be even lower.

Jump #2 is Jeff performing the jump with a full, natural countermovement. Jeff had chalk on his fingertips so he could leave a mark on the black wall to compare the heights of the different jumps. Not surprisingly, he achieves a greater jump height in the second attempt. I prefer this movement as a test protocol because it is more natural. So it has a bit of a skill component. So what? That skill is part of the athletic ability and potential that the test is supposed to be measuring anyway.

In Jump #3, Jeff has been allowed a two-step approach. Again he jumps higher because, although the extra momentum is generated in the horizontal plane, the extensor muscles have to break this momentum and hence they store additional energy, which can be returned in the concentric phase. This would be a good test protocol for volleyball or basketball athletes. Jeff played a lot of basketball in high school, so he really benefits from the added momentum as he has the skill and experience to coordinate it into an effective SSC. Due to the skill required in timing this kind of jump, it is not a commonly used test protocol.

In Jump #4, Jeff performs the movement with a depth jump off a low plyometric box. This time, he has momentum in the vertical plane that must be stopped and in doing so energy is stored in the muscle during the eccentric phase. The ideal height of the drop depends on the athlete's strength and muscle composition (fast twitch type 2a and 2b versus slow twitch) so there is no one ideal drop height. In a classic experiment, researchers Komi and Bosco (1978) found that the stretch load (drop height) improved jump height when drop heights were between 10 and 24 inches for males and between 8 and 20 inches for females. If you jump from the optimum height for you, this method will often produce your highest vertical jump score. In our video, Jeff does quite well in jump #4, but because he is skilled using the two-step approach and because we didn't experiment to find his optimum drop height for the depth jump, he doesn't beat his third jump.

We must also be aware that experimental data from researchers and field data from coaches do not always concur. Komi and Bosco did not use elite athletes for their study, so the optimal drop height for athletes experienced at depth jumps may be above 24 inches. Many coaches suggest that once an athlete is conditioned to tolerate depth jumps, a drop height equal to the athlete's vertical jump will produce some of the best results.

When I used the analogy of a rubber band earlier, I pointed out that the situation is actually more complex that that. I do not want to get into the details of muscle anatomy but it is very important that you do not consider muscles as having the same elastic properties as elastic bands. Although I have explained that much of the benefit of the SSC is the return of energy stored in the muscle, a lot of this energy is stored in structures called cross bridges that attach to binding sites on protein chains. If you pause after the eccentric phase of the movement, these cross bridges detach from their binding sites and you lose their stored energy. This is why a SSC must be executed with small amplitude, at high velocity, and with no delay. Watch a football running back cut to the side to avoid a tackle. Does he go into a deep knee bend to initiate the evasive move? No; it is a short, sharp flexion-extension movement (an explosive SSC). In the vertical jumps Jeff does not pause at the bottom of the countermovement; the movement is a quick reversal of momentum.

Jump #5 attempts to illustrate the above point. In this case, we asked Jeff to jump from a high plyo box before executing his vertical jump. It seems logical that Jeff would jump his highest in this test, but he doesn't. Although he has no trouble controlling the landing, he has to go into a deeper knee bend to do so. He generates a lot of eccentric work, but the muscle has stretched so much that many cross bridges have had to detach and re-attach as the muscle lengthens. Each time they detach from their binding sites, stored energy is lost. Jeff is very strong and does quite well in this jump—but clearly not better than with the two-step approach. Dropping from even higher boxes would result in increasingly lower jumps. If you watched the June 22 WOD demo, you will notice that

Brendan doesn't jump straight back up from the landing. Forty-six inches is simply too high to be a good height to do repeated bounding plyometric jumps. However, he does start each jump with a countermovement to utilize the benefits of a SSC. Obviously, some elite athletes who are specialized in jumping (like elite basketball players) may be able to do repeated jumps from higher heights but this does not mean those heights are optimal in terms of the rebound vertical jump height.

It makes sense that our muscular system has a large capacity for force production during an eccentric muscle action. This allows us to efficiently control movement and protect less pliable structures of the neuromuscular system from damage from high-impact forces or repeated low-force activity. Every time our foot lands in running and jumping, our muscles work eccentrically to control the landing and stop our downward descent. If we had no strength in the eccentric phase, our muscles would be torn apart from the high-impact forces we experience.

Kipping pull-ups

So back to those kipping pull-ups.

The kipping pull-up uses the momentum from the down phase to stretch the lats, pecs, and numerous other muscles that cross the shoulder, prior to the concentric phase (hence a SSC is initiated). The brachialis and biceps will also undergo a SSC if you allow the elbows to fully extend (as you should). So the kipping pull-up is similar to the situation in jump #3, where the amount of momentum that must be reversed by eccentric forces is beneficial, even if most of it is in a horizontal plane in this case. You push out from the bar and swing down and forward, so that as you move under the bar you are moving horizontally. But you will still initiate a good SSC and then power back and up. The speed of the ascent is greatly increased as the positive concentric work is enhanced. A word of warning: although we showed the benefits of a vertical drop for jumping, do not try a fast straight drop down from the pull-up bar. Because the shoulder is less stable than the hip and protected by smaller muscles (and smaller, less dense ligaments), you shouldn't do a purely vertical fast drop. Strict pull-ups that descend vertically are performed much more slowly than kipping pull-ups.

In plyometric training, athletes perform multiple jumps and other activities that utilize the SSC. Research has shown that the high forces generated by the eccentric phases cause beneficial adaptations. These muscle adaptations include increased rate of force development and hypertrophy of type 2b fast-twitch fibers. In a study using rats, Dooley found that plyometric training increased force output by 15 percent, increased the maximum speed of force development by 3 percent, increased fatigability by 15 percent, and decreased the cross-sectional area of fatigue-resistant fast-twitch fibers (type 2a) by 4 percent.

The increased fatigability and decrease in cross-sectional area of the type 2a fibers seem like a negative effect. But this just shows that the benefits of plyometric training in this study was specific to the explosive fast-twitch fibers (type 2b)—the ones you would use in an Olympic lift or short sprint. Distance running and other endurance activities would focus on slow-twitch fibers and decrease the cross-sectional area of the explosive type 2b fast-twitch fibers compared to fatigue resistance slow-twitch type 1 and fast-twitch 2a fibers. As CrossFitters know, for broad capability it is best to not specialize but to develop all aspects of fitness. Plyometric jumps and medicine ball throws are exercises that will help you develop high power outputs. Just don't overuse them—i.e. don't specialize!

Incorporating plyometrics into your training

If you want to add some plyometric training into your program, the ExRx website shows several plyometric drills. Of course, we can add kipping pull-ups to the few upper-body plyometric exercises on this list.

Anything with a traditional wind-up involves a SSC: for example, swinging a discus back and then hurling it forward, or driving the body ahead of the arm in a baseball pitch (which results in a SSC at the front of the shoulders). A lot of medicine ball work can be done on your own, and if you use an eccentric action to stop the backward momentum of the backswing and then have an explosive concentric phase, it is plyometric work. The reversals of momentum we see in Olympic style lifts are also plyometric in nature. For example, a clean recreates, in a very controlled manner, the joint loading forces seen during a depth jump. Because you do not have a high-impact landing, the power clean is a wonderful plyometric exercise that can be programmed very precisely and safely.

As with any good type of exercise, plyometric work can be overdone. Many athletes tend to believe that if two

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aspirins are good for you, eight must be four times better. Plyometrics is not the one magic bullet; don't overdo it. Many athletes have overtrained with depth jumps and injured themselves. The ground contact forces are high with depth jumps, but you can find arguments that they are no more dangerous than running. You can also find arguments that they are very dangerous. Impact force at the feet while running is typically around three times body weight while it can be seven to ten times higher during depth jumps. However, you are landing on two feet, and you are focused on controlling the jump and rebounding, so some studies have shown that the forces on the ankles, knees, and hips are actually not much higher than running. It will obviously depend on the specific exercise and the skill and strength of the athlete.

Whatever the truth is regarding impact forces on the joints, you must always be aware of injury potential in any type of training. Many coaches limit the number of foot-strikes their athletes perform in a training session to reduce the risk of injury. I do not have time for a detailed discussion on plyometrics training sessions but it is worth noting that the intensity of the drill affects the number of contacts you would do of each type. Two-legged hopping, for example, is low-intensity and you can do many repetitions. Two-legged bounding (over a hurdle for example) and single leg hopping are moderate intensity so you would use fewer repetitions. Depth jumps and single-leg jumping and bounding are more advanced plyometric exercises that are beneficial in developing power, but, because they are high intensity and increase the loading on the leg significantly, it is important use very few repetitions. Used appropriately, plyometric training is safe. The American Sports Medicine Association, American Council on Exercise, and the National Strength and Conditioning Association have all supported plyometrics, even for children. Is it any wonder? Kids naturally jump all over the place. Do we really need "experts" to say it's OK?

As ever, the trick is not to overdo a good thing. The doom-and-gloom reports on plyometric-related injuries include athletes who simply did too many jumps, those who added weight to their depth jumps, and those who began plyometric with an insufficient base of strength or fitness. One rule of thumb that is sometimes cited is that, until you can squat your body weight on a bar for five reps with no pauses, you shouldn't start training plyometric jumps. On the other side of the coin, I have heard of athletes doing depth jumps holding dumbbells and/or wearing weight vests. This will obviously increase the impact forces and does carry a higher injury risk. It is also important to be especially careful if you are not jumping on appropriate flooring. Concrete floors are unforgiving and, although we can handle them to an extent, the number of jumps onto such surfaces should be limited. As I have discussed, kipping pull-ups, and some medicine ball throws are plyometric in nature, but they do not have a floor impact phase so they are usually tolerated in higher numbers.

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