National Strength and Conditioning Association Position Statement on Weightlifting for Sports Performance

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Abstract

Comfort, P, Haff, GG, Suchomel, TJ, Soriano, MA, Pierce, KC, Hornsby, WG, Haff, EE, Sommerfield, LM, Chavda, S, Morris, SJ, Fry, AC, and Stone, MH. National Strength and Conditioning Association position statement on weightlifting for sports performance. *J Strength Cond Res* 37(6): 1163–1190, 2023—The origins of weightlifting and feats of strength span back to ancient Egypt, China, and Greece, with the introduction of weightlifting into the Olympic Games in 1896. However, it was not until the 1950s that training based on weightlifting was adopted by strength coaches working with team sports and athletics, with weightlifting research in peer-reviewed journals becoming prominent since the 1970s. Over the past few decades, researchers have focused on the use of weightlifting-based training to enhance performance in nonweightlifters because of the biomechanical similarities (e.g., rapid forceful extension of the hips, knees, and ankles) associated with the second pull phase of the clean and snatch, the drive/thrust phase of the jerk and athletic tasks such as jumping and sprinting. The highest force, rate of force development, and power outputs have been reported during such movements, highlighting the potential for such tasks to enhance these key physical qualities in athletes. In addition, the ability to manipulate barbell load across the extensive range of weightlifting exercises and their derivatives permits the strength and conditioning coach the opportunity to emphasize the development of strength-speed and speed-strength, as required for the individual athlete. As such, the results of numerous longitudinal studies and subsequent meta-analyses demonstrate the inclusion of weightlifting exercises into strength and conditioning programs results in greater improvements in force-production characteristics and performance in athletic tasks than general resistance training or plyometric training alone. However, it is essential that such exercises are appropriately programmed adopting a sequential approach across training blocks (including exercise variation, loads, and volumes) to ensure the desired adaptations, whereas strength and conditioning coaches emphasize appropriate technique and skill development of athletes performing such exercises.

Key Words: strength-speed, speed-strength, power, sports performance, long-term athletic development

Section 1: Biomechanics of Weightlifting—Considerations for Strength and Conditioning

Historical Perspective of the Evaluation of the Snatch, and Clean and Jerk in Weightlifting Competitions

The origins of weightlifting and feats of strength can be traced back ~4,000 years in Egypt and ~2,500 years in China and Greece (246,318), with the first world weightlifting championship being held in London in 1891 (27,278) and the introduction of the sport into the modern Olympic Games in Athens in 1896, where the 1-hand snatch, and clean and jerk lifts were contested. In 1925, the Féderation Internationale Haltérophile (predecessor of the International Weightlifting Federation) published the first authentic list of World Records, including the following exercises: 1-hand (right and left) snatch, 1-hand (right and left) clean and jerk, and the 2-hand lifts: press, snatch, and clean and jerk (246,318). However, when introduced at the Amsterdam Olympic Games in 1928, the weightlifting program was limited to 3 lifts: the press, snatch, and clean and jerk (commonly performed as a split snatch and split clean), with the press being excluded from competition after the 1972 Olympics, leaving only the snatch, and clean and jerk performed in competitions today (92,278,318). For more information, readers are referred to https://iwf.sport/weightlifting_/history/.

Weightlifting research, regarding the biomechanics of weightlifting, originated in the 1970s, highlighting the high forces, rate of force development (RFD), and power output produced during weightlifting movements (19,85,87,96,99–105,117–119,152,221). Much of this research focused on the biomechanics of the snatch, and clean and jerk during competition (19,99–102), comparisons between sexes (103), comparisons between levels of performance

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(152), methods of predicting performance (104), and derivatives of the component exercise (e.g., power clean and power snatch; pulling variations [i.e., weightlifting derivatives]) used by weightlifters (42,68,85,96,117,118). Of particular importance to strength and conditioning professionals is the dynamic correspondence between weightlifting movements and vertical jump performance (41,42,68,105) with Garhammer and Gregor (105) reporting similarities in the propulsive phases of the snatch and countermovement jump.

Additional observations supporting the notion that there is a dynamic correspondence between weightlifting exercise and other sporting activities are the fact that the transition phase during the pull, generally referred to as the "double knee bend," stimulates a stretch-shortening cycle (SSC) response (35,85–87,106,278) as does the initial dip during the jerk and its variations (97,107). By contrast, the second pull phase (aka. from the power position through to full extension) and the thrust phase during the jerk and its variations facilitate the production of the greatest forces, RFD, and power outputs because of the rapid extension of the knees, hips, and ankles (85,100,101,117,221). Such observations and biomechanical similarities highlight the potential for using these exercises to enhance overall athleticism in nonweightlifters. In fact, Chiu and Schilling (39) suggested that the factors related to the double knee bend in the weightlifting movements exert a dynamic correspondence with many of the central movements that underpin sports performance.

It is consistently noted that because of the lower barbell displacements required to successfully perform the clean compared with the snatch (55–65% vs. 62–78% of the lifters height), the loads lifted in the clean are ~18–20% heavier than those achieved during the snatch, as a result of the differences in barbell displacement (282). These observations highlight that the clean and jerk may be used to emphasize force production (strength-speed), whereas the snatch may be used to emphasize movement velocity (speed-strength) (152), although the actual targeted outcome will be mitigated by the load used when performing these exercises. Moreover, when performing the power snatch, where the barbell displacement is notably greater than the snatch, peak velocity during the pulling motion must be greater than what is typically observed during the snatch. Similarly, because of the increased displacement required in the power clean and power snatch, higher RFD and impulse have generally been observed when compared with the clean and snatch (152).

When pulling motions (i.e., pulling derivatives) have been examined, it has been noted that they allow the athlete to use loads well above those used during the snatch or clean (96) because of the removal of the catch from the movement (48,53,283,288). For example, it is well documented loads of between 100 and 140% of the athlete's maximum snatch or clean can be used when only performing the pulling motion, permitting a strength-speed emphasis. The use of higher loads in the pulling motions performed from the knee or midthigh does offer some benefits to nonweightlifters because programming pulls performed from the floor with loads between 80 and 102.5% of 1 repetition maximum (1RM) and the midthigh pull with loads between 105 and 135% of 1RM have been reported to result in enhanced jumping, sprinting, and change of direction (COD) performance (293,294). However, it is important to note that these activities should be carefully structured as part of a holistic periodized training plan.

Weightlifting movements are commonly divided into distinct phases to make each of these complex, multijoint movements easier to understand, coach, and perform. Breaking the movements into their key phases enables the strength and conditioning coach, and athlete, to develop a better grasp of each component and how to perform them and have permitted researchers to evaluate specific phases and components of each exercise. The snatch and clean consist of 5 phases: (a) first pull (aka. lift off), (b) transition (aka. double knee bend), (c) second pull (aka. power position to full extension), (d) catch, and (e) recovery. The jerk consists of 4 phases: (a) dip, (b) drive (aka. thrust), (c) catch, and (d) recovery.

Adoption of Weightlifting Exercises in Strength and Conditioning

Before weightlifting research becoming widely available, some coaches (often with weightlifting backgrounds) had already adopted weightlifting training methodologies to enhance the force-production capabilities of their athletes (258,306). For example, Alvin Roy, credited with being the first professional strength coach, originally implemented weightlifting style training with high school athletes in the early 1950s and in the National Football League later in the same decade (258,306). Similarly, Boyd Epley, the founder of the National Strength and Conditioning Association, implemented strength training, including weightlifting, at the University of Nebraska from the early 1970s (258). In addition, Harold O'Bryant (213), as part of his dissertation, implemented several weightlifting style programs, with an emphasis on squats and pulling derivatives, in high schools in Baton Rouge, Louisiana, from 1978 to 1980. Generally, strength and conditioning coaches incorporate weightlifting exercises and their derivatives (e.g., power clean, power snatch, clean pulls, and snatch pulls) into their athletes' training programs because of the high forces, RFD, and power outputs exerted during these exercises (85,119,133,152,276,283,288). Additional biomechanical similarities have been noted between weightlifting, jumping, sprinting, and COD in terms of the rapid and forceful extension of the knees, hips, and ankles (plantar flexion) (31,32,41,42,68,105,133), with maximal performance in weightlifting exercises reported to be strongly associated with performance in jumping (31,32,105,132), sprinting (132,271), and COD tasks (132). Weightlifting exercises have also been reported to result in some of the highest power outputs of any exercises commonly used in training (100,103,104,278), with weightlifters also demonstrating greater force and power outputs during unloaded and loaded jumps, when compared with powerlifters, sprinters, and wrestlers (190,277).

Interestingly, it is during the second pull phase of the clean and snatch and the thrust phase during the jerk where the greatest force, RFD, and power outputs are generated, whether the clean, snatch, pulling variations (catch phase excluded), or jerk variations are performed by weightlifters (35,85,100,101,117,134,152,155,156,158,161,163,221,276,316). However, it should be noted that the joint-level contributions to the whole lift do vary with load (158,159,162,163). Peak force and RFD are higher in the power clean and power snatch, compared with the clean and clean pull and snatch and snatch pull, respectively, when performed with maximal loads, although the loads are lower during these power variations (118). These differences are likely due to the greater impulse required to accelerate the barbell to achieve the greater displacement associated with the power variations. In addition, pulling variations are also commonly used by weightlifters to enhance barbell acceleration through the rapid production of high forces (85,87,274,276,278,280,281).

It was not until more recently that comparisons between weightlifting exercises and their derivatives have been evaluated in nonweightlifters, including the effect of load, on kinetic (i.e., force, RFD, and power) and kinematic (i.e., velocity and displacement) variables (43,45,46,48,50,53,68,284–286,301,302). Interestingly, the second pull phase still results in the greatest kinetic and kinematic outputs, even when performed in isolation (midthigh power clean and midthigh clean pull) (43,46,48,53). Such pulling derivatives also permit a strength-speed emphasis, with the use of loads ranging up to 140% of the 1RM during the power clean (48,49,51,53,195–197,283,288,293,294).

Comparisons With Other Modes of Exercise

There are numerous modes of training (e.g., general strength training, ballistic training, plyometric training, and bodyweight training) that are all beneficial to the development of muscular strength and power, with each mode having its own advantages and disadvantages (296). For example, bodyweight training is accessible for all and requires minimal or no equipment; however, adding load relies on one moving from a bilateral to split stance or unilateral stance and is therefore somewhat limited. General strength training is easy to progress in terms of load, but results in deceleration throughout a large part of the range of motion (115,211,270) with much lower rates of acceleration in traditional strength exercises (e.g., squat, bench press, and deadlift) when compared with weightlifting exercises (106). Ballistic training eliminates the deceleration phase associated with general strength training but cannot be loaded to the extent that traditional strength exercises and weightlifting movements can. As such, weightlifting movements are often considered to be semiballistic. Plyometric training provides excellent transference to some sporting tasks, emphasizes movement velocity and stimulation of the fast SSC (ground contact times <250 ms), but as with ballistic training, and is difficult to externally load while maintaining short ground contact time and the time under tension is limited. Weightlifting, especially certain derivatives, can be used to train across a wide variety of loads, such as ballistic training (e.g., jump shrug at loads of 30–60% 1RM hang power clean) (113,283,284,288,298–300,302), while pulling derivatives can be performed at high loads (e.g., midthigh clean pulls and hang clean pulls at loads $\leq$140% 1RM power clean) (48,53,146,195,197,283,288,317) with a ballistic intent, minimizing the deceleration phase associated with strength training. Ideally, a combination of these different training methods should be included in an athlete's training program, with each appropriately emphasized/de-emphasized, ensuring appropriate individualization to efficiently achieve the predetermined goals of each training block (113,296).

Weightlifting Training Interventions in Comparison With Other Training Modalities

Numerous training interventions have been published in which researchers have reported the improvements in sport and related performance (e.g., jump, sprint, and COD) being associated with the implementation of weightlifting-based training methods (10–12,37,38,40,44,127,131,137–139,142,143,216,217,227,236, 274,293,294,305,310). In addition, the authors of a recent meta-analysis concluded that weightlifting training results in greater ($g \geq 0.95$) improvements in maximum strength, jump height, linear sprint, and COD performance when compared with traditional resistance training (202). Furthermore, Morris et al. (202) also reported that when weightlifting training is compared with plyometric training, there was no significant ($p > 0.05$) differences in the improvements in performance between conditions, albeit with small to moderately ($g = 0.31$–0.69) greater improvements in favor of weightlifting. These findings are in line with findings reported in earlier meta-analyses (24,109). However, it is important to consider that one advantage that weightlifting training offers over ballistic and plyometric training is the fact that notable increases in maximal force production will also occur, in addition to improvements in rapid force production.

It is, however, important to note that not all study findings support the conclusions of Morris et al. (202), Hackett et al. (109), and Berton et al. (24). For example, Helland et al. (128) have reported that weightlifting does not transfer to jumping and sprint performance to the same degree as motorized strength and power training or free weight strength and power training. Careful inspection of Helland et al. (128) weightlifting-based training program reveals that the authors only used weightlifting movements (i.e., snatch, clean, power snatch, and power clean) and did not implement any weightlifting derivatives or other strength training methods commonly used by weightlifters as part of their training intervention, which may partially explain why there was a lack of transference to sports-based training methods. In addition, the subjects had minimal experience in strength training, particularly with weightlifting movements, and the weightlifting technique was not explicitly described. As such, it is likely that any improvements in weightlifting would be attributed to technique rather than muscular adaptations. Conversely, most of the studies in which the results illustrate enhanced performance with weightlifting exercises have used training programs that have integrated weightlifting movements into a training program that either includes combinations of weightlifting derivatives and traditional strength training methods (i.e., squatting and pressing) or traditional strength training and plyometric training. Based on the results of several meta-analyses (24,109,202), strength and conditioning professionals should integrate weightlifting, strength development, and plyometric training methods into a more holistic programming strategy when attempting to enhance sports performance in other sports.

The combination of general strength training and weightlifting exercises in a complementary manner makes sense because strength underpins performance in athletic tasks (64,65,115,295–297), and increases in strength are associated with increases in RFD (2,3,7,8,181,323). This is supported by the findings of a recent study where training at high loads (80–90% 1RM) resulted in greater improvements in rapid force production (e.g., force at 50, 100, 150, 200, and 250 ms) compared with training at moderate loads (60–82.5% 1RM) (47). Increasing force over a given epoch results in an increased impulse (mean force $\times$ time), with relative impulse determining acceleration of the athlete or any object (e.g., barbell and ball) that the impulse is applied to, thereby enhancing performance through an increased movement velocity. In addition, using musculoskeletal modeling, Kipp (156) reported that both strength training and speed-strength training would reduce the relative effort during the first and second pull phases of weightlifting exercises.

Section 2: Weightlifting Derivatives

Weightlifting Catching, Pulling, and Overhead Derivatives

In addition to the main competitive lifts (i.e., snatch, and clean and jerk) associated with the sport of weightlifting, there are numerous weightlifting derivatives that can be programmed by strength and conditioning coaches. Weightlifting derivatives are modifications of the competition lifts that allow for key positions to be strengthened and enhanced. Weightlifting derivatives are broken into 3 classifications, including (a) catching, (b) pulling, and (c) overhead pressing. Catching derivatives alter the depth at which the barbell is caught, so that the top of the thigh is above parallel (usually with the term "power" before clean or snatch) and can also be initiated from a variety of positions (e.g., floor, knee, hang, or midthigh) (283,288,316) (Table 1). Pulling derivatives are modifications to the competitive lifts that remove the catch phase from the exercise and can be initiated from a variety of positions (e.g., floor, knee, hang, or midthigh) (283,288,316). Finally, the overhead pressing derivatives (e.g., push press, push jerk, and split jerk) are performed either separate to the clean, during training, by taking the bar off blocks or stands (266), or in combination to the clean, power clean, or front-squat exercises, exercises that may proceed the overhead pressing derivatives (Table 1), forming a training structure referred to as a weightlifting complex. In addition, weightlifting complexes may lead to a more efficient way of implementing weightlifting derivatives for enhancing athletic performance in nonweightlifters and improving sport performance in weightlifters. As an example, practitioners could prescribe a weightlifting complex composed of a power clean, front squat, and push jerk with a load equivalent to 70–80% 1RM of the power clean, targeting a strength-endurance emphasis (depending on the total number of repetitions), but using different derivatives.

Weightlifting Catching Derivatives. The historic use of catching derivatives is likely due to the familiarity of strength and conditioning coaches with the movements from the sport of weightlifting, but also due to the research that has supported their use over other resistance training methods (131,219,305,310). There are several advantages of weightlifting catching derivatives including postural strength, coordinated loaded triple extension and flexion of the knee, hip, and ankle joints providing a load acceptance stimulus (54,200,292), albeit comparable with that of a jump landing (200) and cocontraction of the spinal stabilizing muscles. In addition, having to catch the barbell ensures high levels of intent to sufficiently displace the barbell to the required catch height.

Table 1
Weightlifting exercises and derivatives.*

Catching derivatives†	Pulling derivatives‡	Overhead pressing derivatives
Midthigh clean/snatch	Midthigh pull	Push press
Countermovement clean/snatch	Countermovement shrug	Push jerk
Clean/snatch from the knee	Pull from the knee	Split jerk
Hang clean/snatch§	Hang pull§	Behind the neck push press/jerk‡
Clean/snatch	Pull from the floor Hang high pull Jump shrug	Behind the neck split jerk‡

*Variations from midthigh and the knee can start with the barbell resting on blocks, or with the athlete holding the barbell and lowering to the start position and briefly pausing. Currently, there is minimal research comparing the kinetics or kinematics of these variations.
†All clean/snatch variations can be performed with a partial-squat (power) or full-squat catch.
‡All derivatives may be performed with either clean or snatch grip.
§Starting with the legs extended, initiated by flexing the hips to perform a countermovement down to the knees (both above and below the knee commonly used), followed by the double knee bend and rapid triple extension.

Although catching derivatives are inherently more complex than pulling variations because of additional catching component, Haug et al. (126) indicated that 4 weeks (2 sessions per week [20–30 minutes]) of learning the hang power clean yielded improvements in squat jump and countermovement jump power output. It is important to note that although learning the weightlifting movements, the strength and conditioning coach can implement targeted strength development in other focused exercises such as squats, deadlifts, and presses. This ensures that although the athlete is learning the lifts, the barbell loads do not need to be excessive, with an emphasis on refining technique, because they are exposed to adequate stimuli from focused strength exercises to continue to develop their strength in key movements. As such, if the athlete is not familiar with weightlifting exercises, the load should be increased in a progressive and conservative manner, whereas appropriate technique is developed (see subsection "Pedagogical Approaches and Feedback Strategies" for more detail). Although some authors have suggested using loads calculated based on a percentage of body mass for novice lifters (178,179), this practice does not account for the notable differences in relative strength between individuals and should therefore be discouraged.

Weightlifting Pulling Derivatives. Weightlifting pulling derivatives have similar benefits as the catching derivatives, specifically the coordinated triple extension movement. In contrast to catching derivatives, pulling derivatives are less limited from a loading standpoint because of the removal of the catch phase, reducing the complexity and the need to displace the bar to a sufficient height to permit the catch, permitting loads >100% of the 1RM of the catching derivative (48,49,51,53,114,195–197,293,294). In fact, researchers have reported that certain pulling derivatives may be prescribed with loads up to 120% of a 1RM catch variation from the floor (114) and even 140% from the knee or midthigh (48,49,51,53,195–197,293,294). This opportunity for higher loads permits a greater strength-speed emphasis compared with catching variations, thereby enhancing maximal force and rapid force production (283,288,293,294). On the lower end of the loading spectrum (e.g., 30–60% 1RM), athletes can still maximize their effort because of the ballistic nature of certain pulling derivatives, such as the jump shrug (157,160,284,298–300,302) and the hang high pull (157,286,298,299,302–304). During the jump shrug and hang high pull, velocity and therefore power output tend to be maximized with loads as low as 30–45% of a hang power clean 1RM (285,298,299,302,304).

An additional benefit of weightlifting pulling derivatives may be a decreased technical complexity compared with catching derivatives. The omittance of the catch phase decreases the relative complexity of pulling derivatives, which may make them inherently easier to teach and learn. In fact, many of the pulling derivatives are key components of the International Weightlifting Federation–approved teaching progressions for the full competition lifts (148), as discussed in several coaching and technique articles (72–74,147,148,201,230,278,279,289–291). As such, these variations are more easily included in the training program for beginners, whereas the technique of the more technically demanding lifts is developed and refined. It is important that sound technique and maximal intent are used during pulling derivatives because the athlete could simply "go through the motions" when the need for maximal intent is reduced by removing the catch. When used in isolation from the weightlifting movements, pulling derivatives may lack the magnitude of cocontraction of the core musculature (i.e., erector spinae, rectus abdominus, and quadratus lumborum) associated with the catch phase of the catching derivatives; however, research is required to quantify potential differences. In addition, during pulling derivatives, as the bar does not have to be displaced to a sufficient height to ensure that the catch is possible, some athletes may lack intent when performing these exercises, as such the strength and conditioning coach should cue the athlete to use maximal intent or substitute the exercises for one where the athlete displays intent. Ideally, the pulling derivatives should not be used as replacements for catching derivatives but should serve as complementary exercises, which broaden the strength and conditioning coach's "toolbox" of exercises.

Weightlifting Overhead Pressing Derivatives. In weightlifting, the jerk phase of the clean and jerk is the primary weightlifting overhead pressing exercise that takes place during competitions (266,278,279). During training practices, the jerk can be subdivided into several groups of assistance exercises including (a) strengthening exercises as the overhead press, push press, jerk drives, and jerk dips and (b) technique exercises as the push/split jerk (depending on the preferred technique of the lifter and including the front rack and behind the neck variations), jerk lockouts, and jerk recoveries (147). However, in nonweightlifters, the push press, push jerk, and split jerk (including the front rack and behind the neck variations for all these lifts) are the most common overhead pressing derivatives used in strength and conditioning programs for developing athletic performance (Table 1) (266). These complex, ballistic multijoint movement patterns require the lifter to generate high forces through rapid extension of the knees, hips, and ankles (i.e., triple extension), transmitting these through the trunk to the upper extremities (214,266), to provide a sufficient impulse to accelerate the barbell overhead. These exercises share similar lower-body propulsion kinematics during the dip (unweighting and breaking phase of a quick partial squat) and drive/thrust phase (rapid extension of the knees, hips, and plantar flexion of the ankles) (166,167,262,265). The main differences between these lifts occur after the lower-body propulsion phase where there are differences in barbell displacements and the athlete's position during the catch phase (262,265). During the push press, the barbell is accelerated upward through the extension of the legs and pressed upward through the full flexion of the shoulders and extension of the elbows, whereas the feet remain in complete contact with the ground. When performing the push jerk, after completing the extension phase, the athlete rebends their knees and catches the barbell in a 1/4 squat position, whereas in the split jerk, the athlete moves their feet into a split position when receiving the barbell overhead (262,265,266). In addition, the position of the barbell with respect to the lifter's body and the hand spacing may subdivide the push press, push jerk, and split jerk into different complementary exercises such as the snatch grip push press or jerk, which is initiated from a position behind the neck (Table 1) (94,147,266).

Researchers have suggested that weightlifting overhead pressing derivatives may enhance muscular strength development in nonweightlifters (266) because these exercises allow athletes to lift heavy loads in a ballistic manner. In fact, the jerk is the only sporting task where the human being has been able to lift 3 times their body mass overhead (278). Recently, researchers have reported that there are differences between the 1RM performance for the push press, push jerk, and split jerk (261,262,265), where the largest loads are typically lifted during the split jerk, followed by push jerk (95% of the normalized split jerk performance) and push press (87% of the normalized split jerk performance) (261,262,265), with the differences attributable to differences in the required barbell displacement to complete each lift (e.g., lower barbell displacement in the split jerk). However, the differences in 1RM are likely greater in elite weightlifters because Roman (238) has previously reported that the push jerk was about 90% of the maximum split jerk performance. Therefore, it seems that these differences are related to technical competence, where greater differences between the push press, push jerk, and split jerk 1RM performances have been reported for skilled weightlifters (22%) when compared with CrossFit athletes (11%) and a mixed group of athletes (14%) (262). Therefore, strength and conditioning coaches should be aware of the differences in the 1RM performance between the push press, push jerk, and split jerk when prescribing training loads to achieve the desired adaptations and that these differences may also be affected by the athlete's technical competence.

According to Hori et al. (133), the weightlifting overhead pressing derivatives can be classified as strength-speed exercises because the jerk is the exercise where the largest loads are lifted to an overhead position, and, furthermore, to succeed in the lift, it must be performed quickly, with the propulsion phase lasting 259 ± 24 milliseconds (107,266,278). The combination of the force, because of the heavy loads that can be lifted, and velocity (barbell speeds: 1.06–1.9 $m \cdot s^{-1}$) (102,107,119,152,166), results in an ideal stimulus for targeting the ability to develop the strength-speed necessary to enhance athletic performance. This is also supported by several researchers who have reported high power outputs (2,500–6,760 W) and propulsion forces during the push press, push jerk, and split jerk (52,100,102–104,119,152,167), which are notably greater than those produced during the back squat (104). These higher power outputs are likely a result of the ballistic nature of the overhead lifts and the shorter range of motion necessary to complete each lift. Interestingly, the loads that maximize power production during these lifts are generally ≥70% of 1RM (52,94,119,152,166,167,180). Therefore, strength and conditioning coaches should consider using the push press, push jerk, and split jerk with loads ≥70% of 1RM to target the development of strength-speed in sporting populations (Figure 1).

Interestingly, there are no meaningful differences in lower-body kinetic differences between the push press, push jerk, and split jerk when performed at the same standardized load (80% of 1RM push press) (265). Although further research comparing the effect of load and exercise is needed, considering that heavier loads may hypothetically be lifted during the push jerk and split jerk based on the higher 1RM performances associated with these exercises (261,262,265), these exercises require the athlete to generate greater propulsion forces and power outputs at heavier loads (Figure 1). In fact, the ability to lift heavier loads depends greatly on the ability to rapidly generate force (103–105), so that a sufficient impulse (force × time) developed to accelerate the athletes' mass and the barbell. Therefore, it is important that athletes master the push jerk and split jerk exercises to achieve greater propulsion forces and power development by means of lifting heavier relative loads when the training goal is improving maximal strength-speed development.

Effect of Exercise and Load on Kinetics and Kinematics

The results of several surveys of strength and conditioning coaches have highlighted the perceived importance of prescribing weightlifting exercises and their derivatives (79–83,259). The

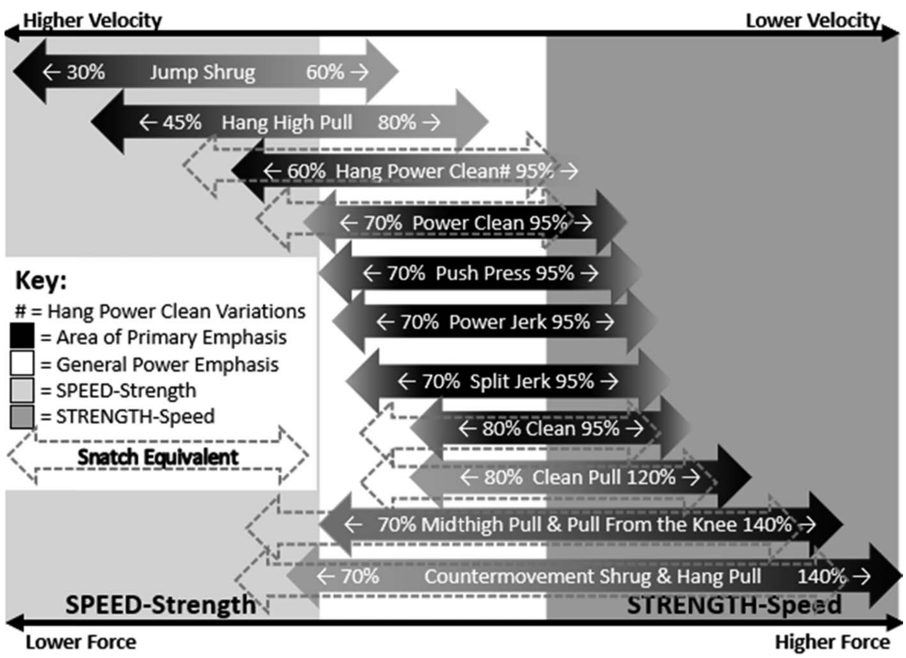


Figure 1. Schematic diagram comparing weightlifting exercise and the interaction of load (as a percentage of 1RM, pulling derivatives based on 1RM hang power clean/snatch) on speed-strength and strength-speed emphasis. Velocity is based on the velocity of the system center of mass and not the barbell. 1RM = 1 repetition maximum.

results of these surveys are not surprising because combining weightlifting exercises and their derivatives with traditional resistance training exercises (e.g., squat and deadlift variations) has been reported to provide a superior training stimulus over other forms of resistance training, ultimately resulting in greater improvements in sporting tasks (e.g., jumping, short sprint, and COD performance) (10–12,24,37,38,40,44,127,131,137–139,142,143,216,217,227, 236,293,294,305,310). Strength and conditioning coaches must, however, decide which exercise and load combinations will address specific training goals (e.g., strength-endurance, strength-speed, and speed-strength) while also considering the athlete's technical competency, mobility, relative strength, and injury status.

Comfort et al. (43,46) conducted the first known studies comparing weightlifting derivatives in nonweightlifters, identifying that the midthigh power clean and midthigh pull resulted in greater force, RFD, and power output compared with the power clean and the power clean from the knee, although there were no differences between the midthigh power clean and midthigh pull. Suchomel et al. (298,299,301,302) investigated alternative weightlifting derivatives, reporting that greater force, velocity, power output, RFD, impulse, and work were produced during the jump shrug and hang high pull when compared with the hang power clean across a spectrum of loads (30, 45, 65, and 80% 1RM hang power clean). Interestingly, the authors also indicated that the greatest differences existed at the lightest load, which is similar to the conclusions reached by other researchers who have compared the jump shrug (157,160) or hang high pull (304) with the hang power clean.

The effect of load on the kinetic and kinematic outputs of weightlifting derivatives has been evaluated by numerous researchers (45,48,49,51,53,157,160,195,197,284–286,300–304). A comparison of exercises and the interaction of load, on force and velocity, is illustrated in Figure 1. In general, lower loads result in a higher velocity allowing for a speed-strength emphasis, whereas higher loads result in greater force and RFD allowing for strength-speed to be emphasized, with the greatest power output occurring across a spectrum of loads, because of the interaction between force and velocity (45,48,49,51,53,58,60,195,197,285,286,302) (Figure 1). The highest velocities across weightlifting derivatives occur during the jump shrug when light loads (30–45% 1RM hang power clean) are used (157,160,284,285), with the highest force generated during the pulling variations when loads >100% of the 1RM power clean are used (48,49,51,53,195,197). The addition of a countermovement, during pulling derivatives (e.g., hang clean pull vs. clean pull from the knee, or countermovement shrug vs. midthigh clean pull), further increases the force, velocity, and therefore power at all loads (49,51,195,197), although it is essential that the athlete has sufficient postural control during the deceleration phase of the countermovement.

The snatch and clean permit higher loads to be used in comparison with the power snatch and the power clean, respectively, because of the requirement of a greater barbell displacement during the "power" variations. As a result of a greater barbell displacement with relatively lighter loads, higher RFD and impulse have been observed during the power clean and snatch when compared with the clean and snatch (152). Similarly, because of the lower barbell displacements required to successfully perform the clean (55–65% vs. 62–78% of the lifters height), the amount of load lifted in the clean and jerk is ~18–20% heavier than those achieved during the snatch (282), highlighting that the clean and jerk may be used to emphasize strength-speed, whereas the snatch may be used to emphasize movement speed-strength (152), although these are dependent on the loads used (Figure 1).

Although cross-sectional comparisons provide insight on the potential performance differences between the use of weightlifting derivatives, greater insight can be found from intervention studies. Comfort et al. (44) compared the effect of 8 weeks of in-season training with biomechanically similar catching or pulling derivatives (e.g., power clean vs. clean pull from the floor) using identical loading schemes (i.e., the same relative loads). Although both training groups improved, the authors indicated that there were no significant or meaningful differences in the changes between the groups when comparing peak or rapid force production during the isometric midthigh pull or countermovement jump performance. These findings are supported by the comparable force, velocity, and power output characteristics across weightlifting exercises when performed between loads of ~70–90% 1RM (Figure 1) (56,57,60,65,116,189,263,264,288).

Suchomel et al. (293,294) recently expanded this research, exploiting the force and velocity emphasis potential of pulling derivatives. In addition to the load-matched catch and pull groups examined by Comfort et al. (44), a third training group used the same pulling derivatives as the pull group, but also used phase-specific loading to provide either a force (e.g., loads >100% 1RM power clean) or velocity (e.g., lighter loads [30–60% 1RM power clean] and more ballistic exercises) overload stimulus. Based on the results of this work, the overload group demonstrated greater improvements in dynamic (1RM power clean) and isometric strength (isometric midthigh pull peak force), short sprint (10-, 20-, and 30-m sprint time), COD, and countermovement jump and squat jump performances compared with the other groups (293,294). As such, strength and conditioning coaches should program weightlifting exercises and their derivatives to emphasize specific characteristics (e.g., strength-speed or speed-strength) in a sequential manner to ensure appropriate adaptations.

Section 3: Physiological Adaptations and Required Stimuli

Desirable Physiological Adaptations Required to Enhance Specific Physical Characteristics

Numerous neuromuscular factors can be manipulated to improve characteristics of force production, with the process considered multifactorial, and adaptative responses intertwined, but with different adaptive processes emphasized depending on the stimulus (222,296). These adaptative responses include morphological changes (e.g., increased cross-sectional area [CSA], pennation angle, and fascicle length), increased bone mineral density, metabolic adaptations, alterations to tendon stiffness, and changes to several neurological factors (269,273). The progression of these adaptive responses is generally impacted by the individual's initial strength levels (62–65,225) and their training history (124,141,235). In fact, the sequence of the training process allows for the adaptations from one phase of training to influence the responses associated with subsequent training phases, which highlights that it is extremely important that the training process is carefully planned and appropriately sequenced (71,110,113,272,322).

Although a relationship between muscle CSA and force-production capacity is evident (14,15,34,120,135,188,199,203,244,321,322), the magnitude of this association varies notably, with neurological, architectural (e.g., pennation angle and fascicle length), and fiber-type differences likely explaining this variation (1,2,28,34,145,187). Narici, Roi, Landoni, Minetti, and Cerretelli (208) suggest that changes in CSA account for 50–60% of the changes in force production. More importantly, increasing muscle mass before a period of training in which strength development is emphasized allows for the strength phase to be potentiated (71,199,275,322), largely as a result of the increased work capacity and greater muscle mass available for neurological and architectural adaptations associated with strength development (14,15,275,279). In addition, hypertrophied muscles tend to have greater pennation angles than nonhypertrophied muscles, resulting in increased cross-bridge formation because of fiber packing (153,154) and muscle gearing, which may enhance force-production capability (13,75,234).

During the strength-endurance phase, the training aims are to improve or refine exercise technique in preparation for the subsequent, higher load phases, enhance physical work capacity, and increase the strength of connective tissues, so that they can tolerate greater loads, and potentially increase muscle mass (unless in a weight-categorized sport) (28,70,110,274,275). By contrast, during the strength-speed phase, the primary goal is to increase the force-generating capacity of the muscle, taking advantage of any morphological changes of the muscles. This is achieved through improved muscular efficiency through architectural (e.g., increased pennation angle and increased sarcomeres in parallel) (2,136,207) and neurological adaptations (e.g., synchronization of motor units and motor unit discharge rates) (4,5,21,169,198). In addition, increases in tendon stiffness because of adaptations during the high-volume strength-endurance phase and high-load strength-speed phase should enhance muscular force transmission, resulting in improvements in rapid force production (i.e., RFD) and power development during the speed-strength phase (181,237,269,273).

The aims during the speed-strength phase are to take advantage of the increased force-production capacity developed during the strength-speed phase, to optimize RFD, accelerative capability, movement velocity, and power development (70,71,110,113,124,186). Some improvements in these characteristics may occur simply because of supercompensation from the previous training phase because training volumes are generally reduced during the speed-strength phase with noncompatible training stimuli reduced or removed to minimize fatigue. In addition, some of the improvements are due to further neurological and architectural adaptations (2,3,7,8,181,272).

Progressive increases in volume load result in the greatest hypertrophic adaptations (29,98,212,249), achieved through moderate loads (60–80% 1RM) performed for relatively high repetitions (8–12 repetitions) (98,110,250), with the associated metabolic stress providing a potential stimulus for muscle hypertrophy and endurance-related adaptations (93,247,248). Interestingly, weekly volume load, rather than training frequency, seems to dictate the magnitude of hypertrophic adaptations, with greater improvements from more frequent training if there is an increase in total volume load (98,251,254). Slightly lower loads (<60% 1RM) that are performed for higher repetitions (≥15 repetitions) may be advantageous when emphasizing endurance-related adaptations because of metabolic stress (93,247,248,250).

High-load (≥80% 1RM, for ≤6 repetitions) training elicits the greatest increases in force production (110,184,225,250,252,253) and RFD (3,4,6,8,47,185). As with hypertrophy, when weekly volume is matched, training frequency does not seem to influence the magnitude of adaptations to strength training (69). However, by contrast, a mixed-methods approach (combination of high-load [≥80% 1RM] low-velocity and low-load [≤60% 1RM] high-velocity exercises) seems to be most effective at enhancing speed-strength (110,113,124,151,209,210,268,275,308,309), although simply enhancing strength in weaker individuals is equally as effective (59,61,62,65,296,297). During a speed-strength phase, the volume loads should be reduced compared with the strength-speed phase to offset any negative effects associated with cumulative fatigue (110,113,270,272,274,275,279).

Training Guidelines for Absolute Strength, Strength-Endurance, Strength-Speed, and Speed-Strength

The prescribed exercise and load combinations should elicit the desired adaptations within each resistance training phase. Although specific to weightlifting derivatives, Suchomel et al. (283,288,293,294) have suggested that this may be accomplished by prescribing specific exercise and load combinations based on their loading potential, and the force or velocity profile of each exercise (i.e., loads >100% 1RM catching variation for pulls vs. 30–45% 1RM hang power clean for the jump shrug), which can be particularly useful if adopting a mixed-methods approach during speed-strength development.

Strength-Endurance Phase. If strength and conditioning coaches aim to use weightlifting exercises in later training phases, it may be beneficial to incorporate pulling variations within this phase to solidify and refine the technique of the pull and increase work capacity (70,274,279,283,288). Moreover, using these exercises will help improve an athlete's work capacity because of the total body nature of the exercises. Although incorporating weightlifting derivatives within this phase is feasible (220,274,279), this practice results in a high metabolic cost (243), resulting in intraset fatigue, which may not be a concern when the athlete is not within a competitive phase of their annual training plan. To minimize fatigue within a training session, and provide an opportunity for additional coaching (e.g., in less-experienced athletes), researchers have reported that clean pulls from the floor may be incorporated in a strength-endurance phase (3 sets of 10 repetitions) using cluster sets (e.g., 2 sets of 5 repetitions within each set of 10) with a 30- to 40-second rest interval (111,293,294). Using cluster sets in this manner may not only promote a higher quality of work, but they may also allow for the strength and conditioning coach to provide feedback to the athlete and permit the use of greater loads for a higher number of repetitions (e.g., 12 repetitions of squats using 80% 1RM, using clusters of 2 or 4 repetitions) (312–314). As such, the higher loads and higher volumes could potentially lead to greater hypertrophy (215), increased work capacity, and greater force production (294). In fact, researchers have implemented loads as high as 82.5% of the subject's 1RM power clean using clean pulls from the floor, for sets of 10 repetitions, during the strength-endurance phase (293,294).

Although a spectrum of weightlifting exercises may be used during the strength-endurance phase, strength and conditioning coaches should consider an athlete's technical competency, relative strength, the complexity of the chosen exercise(s), and the goal(s) of the training phase. For example, if an athlete is unable to consistently perform the prescribed exercise(s) for a higher volume of repetitions because of either poor technique or a lack of positional strength, other exercises could be prescribed, or the load should be reduced. To improve work capacity within this phase, strength and conditioning coaches should use weightlifting exercises that have a moderate-large displacement and allow for moderate to moderately heavy loads to be implemented, such as pulling derivatives. However, because of the technical complexity and fatigue associated with strength-endurance training, the full lifts (i.e., clean and jerk, and snatch) are rarely incorporated during this phase.

It is also important to understand how the physiological demand of the exercise impacts exercise technique and perceived exertion. Hardee et al. (123) reported that performing 6 consecutive repetitions, in a traditional set format, with the power clean at 80% 1RM led to an increased horizontal displacement of the barbell by the final repetition, which was not observed when cluster sets were implemented. This research group also indicated that perceived exertion increased across multiple sets using this exercise and load combination, but was reduced when using cluster sets (122). During the strength-endurance phase, catching variations may be best implemented using cluster sets to ensure maintenance of technique and movement velocity, while also providing an opportunity for additional feedback and coaching.

Because weightlifting pulling derivatives have decreased complexity because of the omittance of the catch phase, it may be possible to maintain technique across additional repetitions, with heavier loads, compared with catching derivatives, especially when the displacement is reduced (e.g., hang pull, midthigh pull, and countermovement shrug) (196). Meechan et al. (196) recently reported no change in kinetics, kinematics, or rate of perceived exertion (RPE) during the countermovement shrug for 3 sets of 6 repetitions using traditional set structures or when implementing rest-redistribution. Thus, to address the work capacity demands of a strength-endurance phase, exercises such as the clean/snatch pull from the floor may serve as effective exercises. However, because the first pull (i.e., moving the load from the floor to the knee) may double the work and duration of a repetition (152), less technical derivatives that remove the first pull may serve as effective alternatives and may not require cluster sets to be used (196).

Strength-Speed Phase. The primary goals of strength phases include increasing maximal force-production capacity (i.e., peak force) and rapid force production (70,272,296). The strength-speed phase can be divided into subphases of general strength (e.g., 3 sets of 5 repetitions, moderately heavy to heavy loads [70–80% 1RM]) and absolute strength (e.g., 3 sets of 3 repetitions, heavy to very heavy loads [80–90% 1RM]) to elicit increases in maximal force production. Weightlifting exercises that use heavier loads often have a decreased displacement (e.g., clean vs. power snatch) and fall under the strength-speed category (Table 1 and Figure 1) (152,282). As such, along with the clean and the snatch performed at high loads (e.g., 80–95% 1RM), weightlifting pulling derivatives may be favored during strength-speed phases because of the ability to prescribe loads ≥100% 1RM of an athlete's 1RM catching variation (48,53,96,114,117,118,192–195,197,238,242). As noted above, researchers have examined loads as high as 140% 1RM with several pulling variations (e.g., hang pull, pull from the knee, midthigh pull, and countermovement shrug) (48,53,195–197), although for pulls from the floor loads of <120% 1RM may be preferred, depending on the targeted training outcome (96,193,194,238). This may provide strength and conditioning coaches with several options based on their athletes' technical competency while also addressing positional strength demands. For example, sprinters require large magnitudes of force and high RFD when accelerating from the starting blocks and to maintain high speeds and may thus benefit from using pulling derivatives that develop these characteristics within these positions (74).

Although heavy pulling derivatives may aid in the development of maximal force production, the development of rapid force-production characteristics may also require the use of loads lighter than those previously discussed, ensuring that an appropriate range of loads is used (64,65,113,209,210,283,287,288). During the strength-speed phase, weightlifting exercises that use moderately heavy loads (70–80% 1RM; Table 1 and Figure 1) may be prescribed to promote rapid force production (293,294);

however, Comfort et al. (47) reported greater improvements in rapid force production in response to heavy loads (80–90% 1RM) compared with moderate loads (60–82.5% 1RM), albeit that this may have been influenced by their relatively low strength levels. It is likely that weaker athletes will enhance both maximal and rapid force production effectively by simply emphasizing high loads with maximal intent (21,59,61,62,65). Although researchers have reported improved force-production characteristics using exclusively catching or pulling derivatives (293,294), prescribing combinations of pulling, catching, and overhead pressing derivatives within strength phases may also provide athletes with a unique training stimulus and prevent staleness, while maximizing increased in performance.

Speed-Strength Phase. The objectives during a speed-strength phase include further development and peaking of rapid force production and power output (70,272,296). Because these neuromuscular characteristics may be enhanced with the combination of exercises that emphasize either force or velocity, it is recommended that a combination of both heavy and light loads be implemented (71,113,151,209,210,272,288,296,307–309). Using this strategy, strength and conditioning coaches can prescribe a wide variety of exercises from both the strength-speed and speed-strength categories to ensure that the targeted outcomes are developed (Table 1 and Figure 1). Training focusing on heavy loads vs. loads that elicit peak power have been reported to result in preferential adaptations at those specific loads rather than across a spectrum of loads (124,125,151,307–309), with the use of a combination of loading paradigms, resulting in greater adaptations across loads (124,209,307–309). For example, loads as high 110% of 1RM with the countermovement shrug (force emphasis, e.g., strength-speed) and as low as 30% of 1RM with the jump shrug (velocity emphasis, e.g., speed-strength) have been shown to be an effective programming strategy when integrated into the same phase of training (293,294). It is also important that when implementing this type of strategy, strength and conditioning coaches need to be mindful of the total training volume programmed during this phase to minimize residual fatigue.

It is important to note that strength and conditioning coaches may provide several exercise and load combinations that address an athlete's needs based on their sport/event and position. For example, American football linemen require a greater strength-speed emphasis. Thus, although the primary exercise and load combinations prescribed to these athletes may emphasize strength-speed, speed-strength exercises that can be loaded with moderately heavy loads (e.g., hang power clean/snatch) may enhance rapid force production for these individuals. By contrast, a defensive back may require a greater emphasis on exercises that target speed-strength development but will also benefit from using heavier loads (e.g., hang clean/snatch pull) to develop strength-speed. Ideally, a phased sequential approach to training should be adopted, with the targeted attributed being based on the results of an assessment of the athlete's athletic performances and force-production characteristics at the end of each training phase.

Section 4: Coaching Weightlifting Exercises

Pedagogical Approaches and Feedback Strategies

Learning of a motor skill often occurs more rapidly with greater capacity to maintain it during highly sensitive periods of life, such as adolescence (260). This is likely a result of the brain's plasticity during these developmental periods, allowing for greater development of neural circuits (260). It is often argued that weightlifting movements are too time-consuming or complex to teach athletic populations. By contrast, Solum et al. (260) found that motor skill learning can be indifferent between adolescents and adults, with greater variability in skill acquisition observed in adolescents because of their lack of movement repertoire. Therefore, strength and conditioning coaches should ensure appropriate technique is developed, and refined, to reduce injury risk, maximize the athlete's opportunity to adapt, and enhance transferability into sports performance (230). The purpose of this section, therefore, is to provide the reader with a pedagogical template and feedback considerations to develop weightlifting skills regardless of age and/or ability.

Each of the weightlifting movements (i.e., snatch, and clean and jerk) can be taught to be performed as the full version; however, within the progressions provided for each movement, partial movements, or derivatives may also be used as specific training tools. Depending on the training age, physical capabilities, demands, or goals of the sport the athlete is involved in, a strength and conditioning coach may decide that some of these derivatives are better suited to meet the needs of the athlete at a particular point in time.

Phases of the Weightlifting Movements. Morris et al. (201) (Table 2) highlight the specific positions of each phase of the snatch, and clean and jerk, illustrating where the bar starts and finishes in each of the subsequent phases for the clean and jerk, and the snatch. Breaking the movements into these phases enables the strength and conditioning coach, and athlete, to obtain a better grasp of each component and how to perform them, which is especially important once the athlete starts the task of "chaining" the elements together. The snatch and clean consist of 5 phases: (a) first pull (aka. lift off), (b) transition (aka. double knee bend), (c) second pull (aka. power position to full extension), (d) catch, and (e) recovery (Table 2). The jerk consists of 4 phases: (a) dip, (b) drive, (c) catch, and (d) recovery (Table 2).

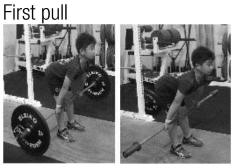
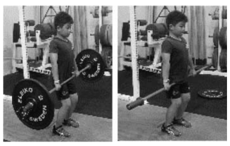
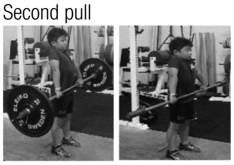
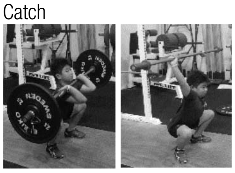
Pedagogical Approaches. A key issue that strength and conditioning coaches must consider is the order in which they will teach the component parts of the weightlifting movements. The method chosen will likely exert a notable bearing on how easily the athlete can achieve fluidity in the movement when all parts are "chained" together, creating the complex movement patterns associated with weightlifting. The need to adopt a step-by-step teaching method has been supported in the scientific and coaching literature (77,78,84). There are 2 common teaching approaches typically used when instructing weightlifting: (a) forward chaining (aka. bottom-up approach) and (b) reverse chaining (aka. top-down approach). Briefly, in forward chaining, parts of the skill are learned in the order in which they will naturally occur, whereas with reverse chaining, the key parts of the skill are learned in reverse.

The main argument for using forward chaining is that it seems logical and is readily justified on the grounds that if a skill is not initiated properly, it will not be completed correctly. However, the use of forward chaining potentiates other behaviors, which as skill complexity increases, become detrimental to both the learning process and performance outcomes (239). Forward chaining progressions usually result in skills that are executed well in the initial stages but deteriorate and exhibit weaknesses and faults as the sequences progress (239).

With reverse chaining, as each new step is learned, it is followed by parts of the lift that are already familiar and practiced. The

Table 2

Phases of the clean and jerk, and snatch, reproduced with permission from Morris et al. (201).

Phase	Clean and jerk	Snatch
First pull 	From lifting the barbell off the floor to a position in which the barbell is immediately at the patella	From lifting the barbell off the floor to a position in which the barbell is immediately at the patella
Transition 	From a position in which the barbell is immediately at the patella to a position in which the barbell is positioned midthigh	From a position in which the barbell is immediately at the patella to a position in which the barbell is positioned at the upper thigh
Second pull 	From a position in which the barbell is positioned at the midthigh the athlete should extend at the hips, knees, and ankles moving the bar to a position of maximal barbell height	From a position in which the barbell is positioned at the upper thigh the athlete should extend at the hips, knees, and ankles moving the bar to a position of maximal barbell height
Catch 	From a position of maximal barbell height to a position in which the bar is caught resting on the anterior deltoids, in a front-squat position	From a position of maximal barbell height to a position in which the bar is caught above head in an overhead-squat position
Recovery 	From a position in which the bar is caught resting on the anterior deltoids to a standing position with the bar remaining in a front-rack position	From a position in which the bar is caught above head in an overhead-squat position to a standing position with the bar remaining above head
Dip 	From standing, with the bar in a front-rack position to a quarter-squat position with the bar remaining in a front-rack position	
Drive 	From a quarter-squat position with the bar remaining in a front-rack position to a position of maximal barbell height, with the athlete extending at the hips, knees, and ankles	
Catch 	From a position of maximal barbell height to a position in which the bar is caught above head in a split-stance position	
Recovery 	From a position in which the bar is caught above head in a split-stance position to a standing position with the bar remaining above head	

rationale behind this approach is to provide lower complexity movements to the athlete during early stages of development, as illustrated in Figures 2–4. The complexity, in this instance, is governed by the number of phases an athlete must chain together and/or the speed of movement. For example, the overhead squat provides a key opportunity for the strength and conditioning coach to assess movement quality under load, at a slow speed, before advancing on to more ballistic derivatives, such as the snatch balance

(Figure 2). In some cases, the progression need not be from the top (i.e., the overhead squat), but can also be from a point where the strength and conditioning coach is able to optimize adaptation while concurrently laying the foundation to a more complete movements, adding to the athlete's exercise toolbox (i.e., using snatch pulls from the power position [aka. start of the second pull] to power snatches from the knee).

The major advantages of reverse chaining over forward chaining progressions are as follows (239):

- Interference does not occur because each new element precedes all previously "learned" elements (i.e., the learner thinks of and executes a new technique element and follows it with what has been performed successfully before).
- Each step in the progression does not increase in difficulty because undivided attention can be focused on the new skill.
- Attention is focused only on the new step, and then, established elements are performed to finish in the terminal position.
- There is a lack of tension/anxiety in the learner because of the simplicity of the task and its steps.
- Step sizes are small, providing a high rate of success.

It is important to note that the reverse-chain approach of teaching weightlifting movements is the chosen method advocated by both the NSCA (23) and the International Weightlifting Federation (148).

Figures 2–4 illustrate the teaching and learning progressions of the snatch, and clean and jerk. In Figures 2 and 3, the first column identifies the phase of the lift with the second column providing the exercise that best develops that phase. Naturally, not all athletes will be able to execute the progressions, and therefore, regressions have also been provided in column 3 to help further simplify the movement and develop relevant movements competencies. The last 2 columns, "Transitions" and "Auxiliary," provide exercises, which help develop the appropriate sequencing and positional strength required to achieve the exercises outlined in the progression and regressions. Much like Figures 2 and 3, the first 2 columns of Figure 4 identify the phase of the lift and the exercise that best develops that phase. Columns 3 and 4 provide transitional and auxiliary exercises to help develop the appropriate sequencing and positional strength required to achieve the exercises outlined in the progression. However, column 4 provides an alternative progression to aid in the transition from the back to the front of the head by further simplifying the order to all movements from behind, then all movements from in front.

Stages of Learning. In 1967, Paul Fitts and Michael Posner proposed 3 stages of learning motor skills, which they defined as the cognitive, associative, and autonomous stages (144). They proposed that although learning a new motor skill, an individual passes through several changes that can be categorized into one of the 3 stages. It is important to note that transition from one stage to the next is not an acute change, but one that happens gradually. Recognizing the stage that the athlete is performing in will help the strength and conditioning coach address their needs appropriately.

The cognitive stage is characterized by inconsistent and inefficient performance, slower movements, and a high degree of mental effort. In this stage of learning, movements are generally performed slowly with deliberate intention because the novice athlete is unable to use internal or kinesthetic feedback to adjust movement and will often require a lot of external feedback. It is best for athletes in this stage to eliminate distractions and provide adequate space for the desired skill to be performed. Even a seasoned athlete will experience the cognitive stage when learning a new skill. They may progress at a faster rate because they may have previous skill experience related to the new movement, but they will still display characteristics from the cognitive stage (144).

As athletes move into the associative stage, movements become more fluid, consistent, and efficient. Some parts of the skill become more "automatic" because less thinking is required. However, there will still be aspects of the skill that require mental attention. Utilization of internal feedback begins to occur for the athlete because they begin to sense what proper movement patterns feel like and identify when they do not perform them accurately, but they may not know how to

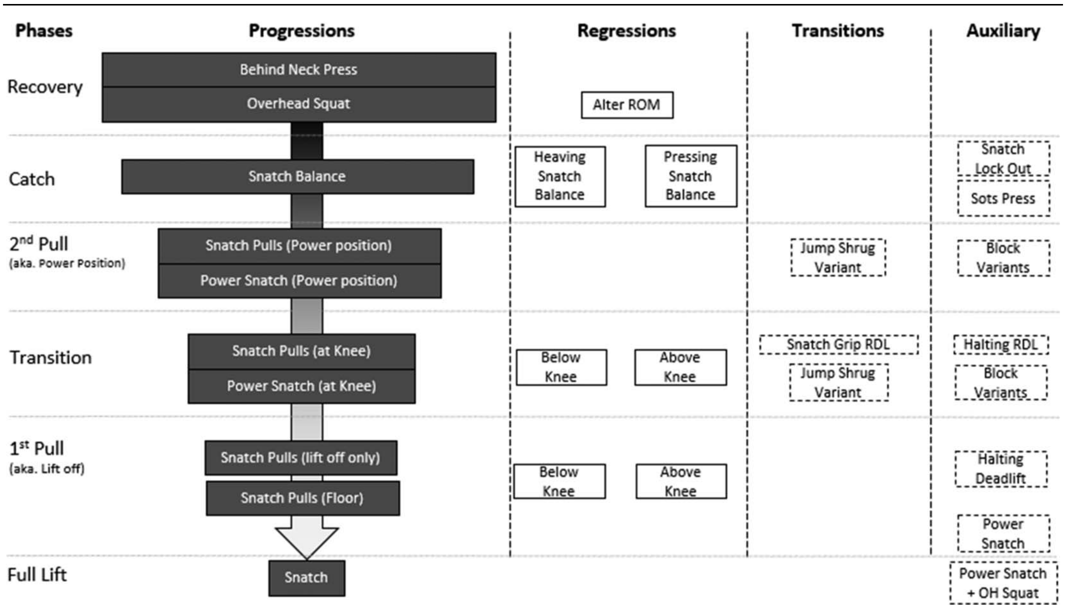


Figure 2. Snatch progression.

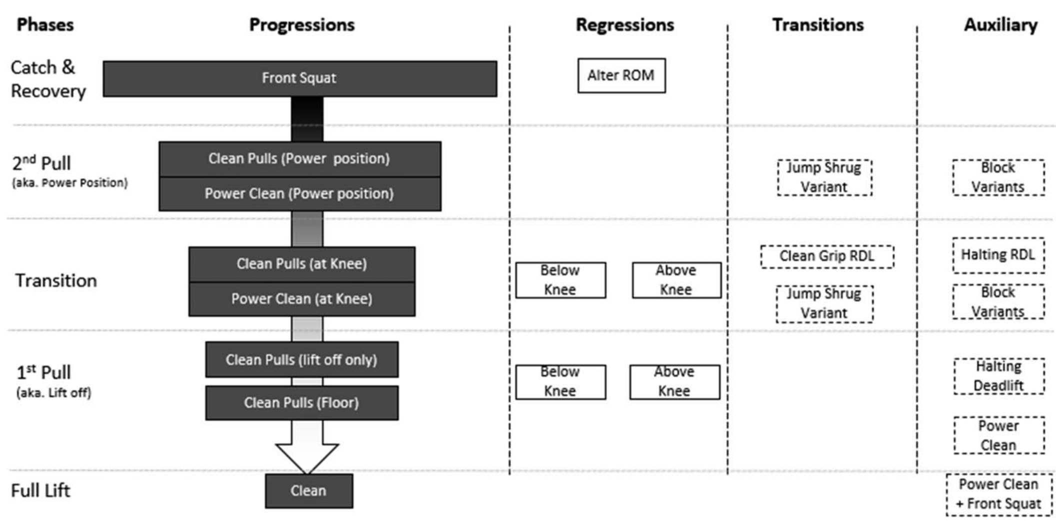


Figure 3. Clean progression.

adjust their movement to correct it. A coach's feedback can reinforce the athlete's internal feedback and help them to identify areas needing improvement as well as how to make corrections (144).

The final stage of learning is the autonomous stage. At this point, motor programs are well-defined and ingrained. Movement is smooth, accurate, and consistent, requiring little mental attention to perform the skill because it has become automatic. Athletes, at this stage, can use their thought processes on other important aspects of the lift instead of thinking of how to produce the desired skill movement (144). Feedback will allow such athletes to fine-tune the skill, improving the effectiveness and efficiency of the movement.

Types of Feedback and Forms of Communication. To aid the beginner athlete in the development of positional awareness, movement fluency, and practicing accuracy and timing of movement, a variety of communication methods should be used. These methods all fall in 3 principal areas: verbal, visual, and kinesthetic (Table 3). A key factor differentiating these methods is the extent to which they are effective in communicating meaningful feedback to the athlete. Because athletes learn best through a variety of ways, it is recommended that different methods be used in combination when teaching weightlifting movements to a beginner. Whichever method or methods are used, it is essential that when providing feedback to the athlete the strength and conditioning coach must consider how the athlete is interacting with the given task and ensure that all feedback is simple, precise, and clearly delivered.

Verbal instruction and cues both have pivotal roles in coaching weightlifting, where instruction provides the necessary information about the task with cues providing an opportunity to shift the athletes focus of attention toward movement outcomes (165). The cues provided should be short in their delivery while

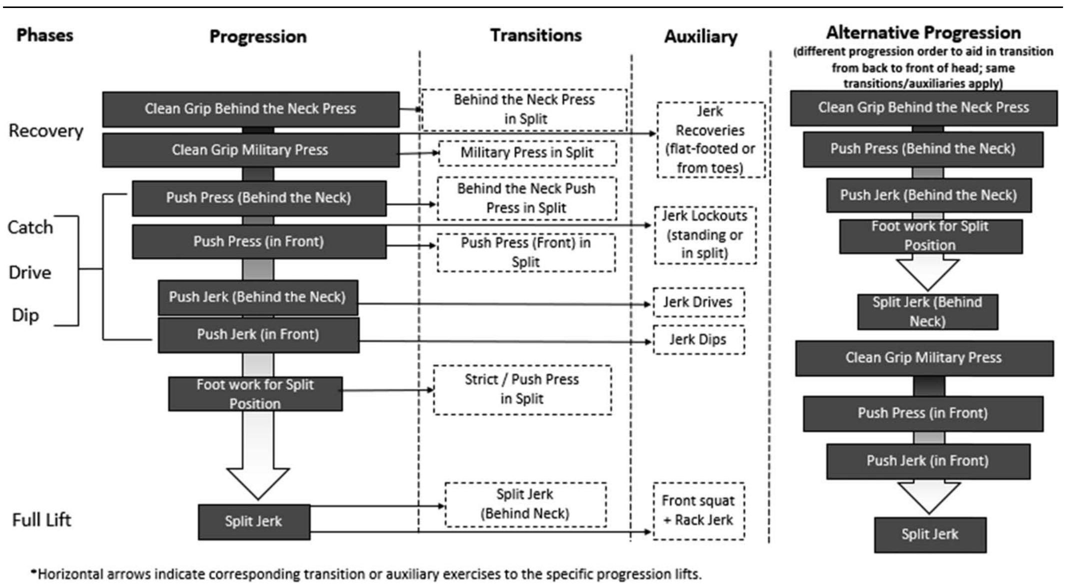


Figure 4. Jerk progression.

using "buzz" words as opposed to long sentences, thus avoiding exposing the athlete to information overload, which can increase cognitive load (240) and negatively impact physical performance (191). The choice of the appropriate "buzz" words as well as the timing of implementing them is critical. Likewise, verbal communication should be appropriate to the individual's stage of development (164). For example, children typically possess lower levels of vocabulary and comprehension skills; therefore, language should be simple and nontechnical, and dialog should be clear and concise. In this scenario, analogies and metaphors can serve as a useful tool to encourage an external focus of attention, while also helping children process information more effectively making the content relatable to them and condensing several task-relevant cues into a single metaphor. An example of a feedback loop is provided in Figure 5.

Visual feedback and instruction through video capture or demonstrations can be coupled with verbal feedback to enable the athlete to contextualize the information provided to them (218).

Table 3
Advantages/disadvantages of different communication methods.*

Method	Advantages: (effective in…)	Disadvantages: (less effective in…)	Possible issues
Verbal instruction	✓ Providing short, simple movement instruction (e.g., "finish" and "aggressive") ✓ Providing work quantity (e.g., "do another rep" and "3 rep's please") ✓ Providing safety instruction (e.g., "stay in the center of the platform") ✓ Providing meaningful communication to a beginner when using analogies and metaphors	✖ Describing body/limb positions during phases of the lift ✖ Making changes in movement patterns ✖ Correcting timing issues	! Avoid using terminology that beginners will be unfamiliar and/or will not have sufficient proprioceptive knowledge to associate it with a particular body action ! Relying too frequently on verbal cuing in early skill acquisition ! May lead to the athlete becoming overly reliant on verbal feedback over kinesthetic/spatial skill development
Reinforcement	✓ Strengthening/increasing the frequency of desired behavior through positive (and sometimes negative) reinforcement ✓ Rewarding efforts and improvements to training behavior and/or technical performance ✓ Motivating the continued use of current strategies to improve technique ✓ Reassuring current efforts that are having a beneficial effect	✖ Maintaining value if used too frequently ✖ Situations where the coach is not able to observe performance or all of an athlete's performances	! Reinforcement should be intermittently provided, or it diminishes in value ! Appropriate use depends on the coach's interpersonal skills ! Appropriate use is dependent on coach's knowledge and understanding of weightlifting technique
Demonstrating (aka modeling)	✓ Providing spatial and temporal information naturally and instinctively ✓ Providing information in an expedient manner ✓ Providing a basic plan of what's going to be performed (e.g., new exercise introduction) ✓ Providing a contrast of correct and incorrect position(s) or movement(s)	✖ Creating immediate change in body positions or movement patterns ✖ Situations where the coach is unable to perform an adequate demonstration	! Demonstrations usually need to be performed multiple times for the learner to process the necessary information appropriately ! A beginner can miss the main point of the demonstration ! Poor demonstrations can cause problems for the athlete's skill acquisition
Video replay	✓ Enhancing understanding of the skill (replayed at a slower speed) ✓ Enhancing understanding of the skill (as it can be replayed) ✓ Showing a specific position or technical element that requires correction ✓ Identifying movement characteristics (by using slow motion or video scrubbing)	✖ Less valuable if not accompanied by quality verbal information ✖ Dependent on the knowledge and analytical skills of the viewer ✖ Time intensive ✖ Can be disruptive to the normal flow of coaching and training ✖ Can be overwhelming to beginners because of the amount of information provided (visually and/or verbally)	! Too frequent viewing may lead to being over conscious of errors, developing more internal focus, and/or become negative toward their abilities ! Too frequent viewing may lead to being overly dependent on visual over kinesthetic development ! Video/movement analysis requires specific skills not necessarily developed by coaches ! Coaches need to be cognizant of the coaching objective striving for and stick to it ! Video in training can be disruptive to the athlete and/or to the training environment
Discovery learning	✓ Improving timing, coordination, and fluency of movement ✓ Developing balance and stability ✓ Developing the kinematics of performance of complex movements (e.g., speed and acceleration characteristics of the body; vertical and horizontal displacement of the bar)	✖ Introduction of new exercises or movements to a beginner ✖ Developing basic body positions (they are not always intuitive or "natural") ✖ Solving persistent technical errors or problems	! Success of this strategy depends on the knowledge, experience, and confidence of the coach to best know when to allow the beginner to experiment and when to intervene ! The coach needs to know how and when to impose appropriate spatial or temporal constraints
Manual manipulation	✓ Providing proprioceptive information as to how the required body position should feel ✓ Correcting basic body or limb positions (although the athlete is stationary) ✓ Time saving	✖ Correcting movement errors (vs. positional errors)	! Requires practice to perfect appropriate methods/strategies to use ! Requires the athlete's permission first to perform ! Relies on a thorough understanding and knowledge of body positions as they relate to weightlifting technique

*Adapted with permission from Isaac (140).

In addition, video feedback that captures key phases of the lift enable the strength and conditioning coach and athlete to monitor and highlight technical faults and/or improvements over time. This also provides further learning opportunities for the athlete to become more aware of how to optimize technique (267). It is important to note, however, that with beginners, too frequent use of video to provide feedback may lead to the athlete becoming over conscious of technical errors and/or become negative toward their abilities (140), leading to overdependence on visual over kinesthetic feedback. When using video feedback, strength and conditioning coaches need to be cognizant of the coaching objective that they are striving for and not deviate from it simply to incorporate video feedback.

Finally, having the athlete associate specific phases with something tangible may also provide an opportunity to develop technical proficiency, which is commonly referred to as kinesthetic awareness (201). Kinesthetic awareness can be defined as the athlete's ability to "feel" a position, whether that be a certain muscle group under strain (e.g., the quadriceps, hamstrings, and back during the first pull), or knocking over an upright foam roller with the barbell's weight plate to signify a rearward trajectory of the barbell during the first pull. This can also then be associated with a coaching cue to reinforce appropriate movement patterns. An example of how these varying methods of feedback can be used within a session is provided in Table 3.

Feedback Timing. It is important to note that when coaching weightlifting movements, the timing of feedback is crucial. Terminal feedback is given at the end of the attempt whether this is after a particular repetition within a set or at the end of the set itself. This can be helpful for athletes learning a new skill because it permits them to concentrate on performing the skill or movement itself and not solely focusing on feedback (144). Withholding immediate feedback gives the athlete time to evaluate their performance, identify positive elements (e.g., did the athlete effectively perform the movement cues that the strength and conditioning coach provided), and mistakes made. Although an athlete in the cognitive stage of learning is unable to effectively use internal and kinesthetic feedback, it is still good to start asking the athlete questions as to how the movement felt to begin the process of listening for the internal voice.

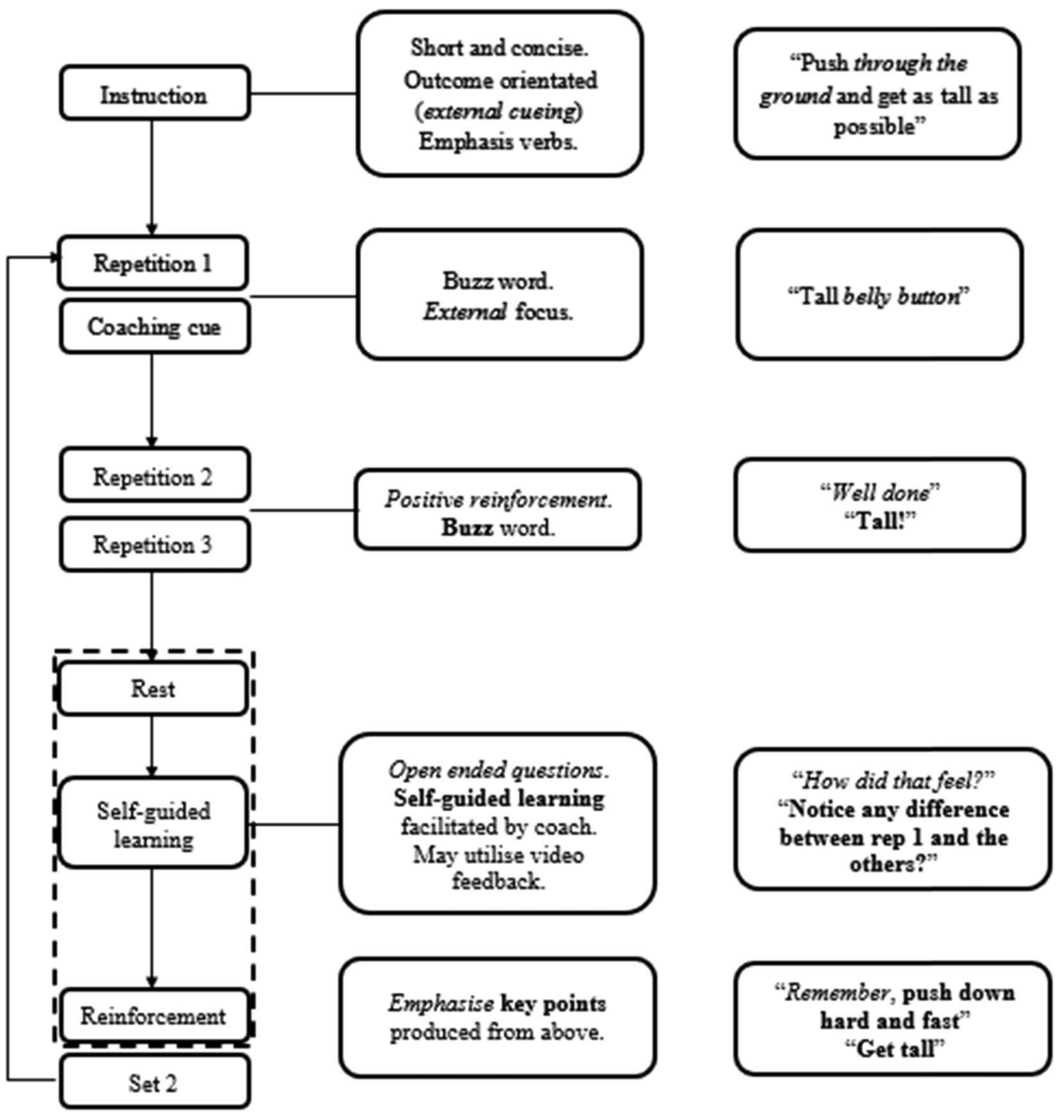


Figure 5. Feedback loop example within a working set. Feedback is not always needed at every stage because this may lead to too much information being provided to the athlete.

Athletes who are more skilled or are in the stages of refining their technique can be provided concurrent feedback, which is given during the performance of a skill or movement. Athletes in the autonomous stage of learning benefit more from this type of feedback timing as the skill or movement that they are performing requires little thought allowing attention to be shifted to areas where they can improve. However, a strength and conditioning coach must be careful about providing too much feedback. An athlete, especially in the early stages of learning, can come to rely solely on that feedback at a detriment to their spatial and kinesthetic awareness. It is also important to note that athletes respond differently to feedback, in general, and to different types of feedback. Ultimately, a strength and conditioning coach needs to know their athlete, learn how they respond to feedback, and which types of feedback are the most effective for them.

Considerations for Beginners

The term beginner, or novice, applies to individuals who have little to no previous experience with, in this case, the weightlifting movements. This could include athletes who have a higher training age with other strength training activities (i.e., resistance training and powerlifting) or knowledge about resistance training, but have not performed the weightlifting movements. A beginner to weightlifting movements will experience notable challenges when learning these highly complex movement patterns that test body position, balance, and stability as well as the speed and timing of each movement (140). As such, some strength and conditioning coaches are reluctant to introduce novice athletes to weightlifting-based training methods because they feel that they are overly time-consuming and/or too difficult to teach. However, the use of a well-organized, disciplined, and systematic plan with investment in technical development of weightlifting movements and ongoing technical refinement in weightlifting training will promote later success in an athlete's career (126,201). This occurs by promoting habitual improvements in athleticism over time to improve performance, reduce injury risk, and enhance health and wellbeing (89). This is a common and important goal in a long-term athlete development plan.

Preparation of Training. When preparing to introduce weightlifting movements to a beginner, it is essential that a structured teaching plan is established to guide the athlete in the development of their weightlifting literacy. The purpose of this plan is to ensure that the important phases in the teaching progression are not missed, and the athlete is provided with a movement curriculum that allows them to develop their weightlifting skills more easily. In the initial stages of development, to ensure proper technique is developed, strength and conditioning coaches should follow appropriate coaching progressions to aid the implementation of a structured and systematic approach that progresses logically based on technical competency to ensure that the athlete learns the movements in a timely and effective manner (201). To obtain technical competency, the full lifts are often broken into several key phases referred to as movement chaining (e.g., reverse chaining), or "chunking" (201), allowing the athlete to focus on learning discrete parts of the lift. Ultimately, this is performed the complex, multijoint movements associated with weightlifting are broken into smaller, more manageable pieces that can be combined to create more complex movement patterns (Figures 2–4). By decreasing the range of movement and overall lift complexity, the learning situation is simplified for the beginner. Another benefit of this approach is that it allows strength and conditioning coaches to identify movement deficiencies or technical errors and allows for more specific exercise prescription targeting the identified issues. Based on the theory of "chunking," beginner athletes can work on these components in isolation and then string the individual exercises/movements together to create a sequenced movement pattern (112).

The use of an exercise progression (Figures 2–4) provides a comprehensive approach to integrate different phases of each weightlifting movement for training, from beginner to advanced, identifying the training focus and coaching considerations at each stage (201). Regardless of the stage of training, the simultaneous development of movement skills (i.e., competency, autonomy, and refinement), and physical capacities (i.e., motor and body control, basic strength, strength-speed, and speed-strength) should be considered, with exercise prescription and selection adjusted accordingly (201). The amount of time spent in any phase of the progression should be based on individual ability and need. It is, however, important to note that each athlete's rate of progression through the learning process will be highly individualized. Although the athlete's stage of maturation should be considered, their level of technical competency should dictate how quickly they advance through the teaching progression.

Building Confidence. The role of the strength and conditioning coach is far greater than just developing the athlete's physical competency or their overall performance capacity. A strength and conditioning coach is an educator, teaching the athlete not only the skills of weightlifting, in this case, but also how to train effectively as well as develop as a person (140). Building confidence, developing positive self-worth, responsibility, and integrity are important outcomes of the beginner's coaching process (149). To establish the development of such attributes, it is essential that the strength and conditioning coach ensures that the athlete maintains an appropriate progression rate, which is based on their abilities. Central to this process, the strength and conditioning coach should select challenges with a relatively low task difficulty that will allow the athlete to train the optimal challenge point based on the benefits of an errorless learning strategy. Finding the right balance between the task difficulty and the athlete's confidence will lead to an increase in the athlete's self-efficacy, further improving the learning process (165).

Technique and Accuracy Focused. In the initial stages of learning, strength and conditioning coaches should focus on developing the athlete's technical literacy over maximizing their strength development. Such loading should be incremental and progressive, albeit conservative. This is an essential aspect of developing sound lifting technique because (a) lifting to maximal or near-maximal loads, as a beginner, may lead to technical errors which may become ingrained, making it more difficult to modify or rectify technical errors during the later stages of the athlete's development and (b) athletes who develop sound technique during the early stages of their development tend to have more opportunities to use progressively heavier loads to target specific neuromuscular adaptations. Training adaptations may be affected by lifting technique because this can influence an athlete's ability to produce force which is especially relevant in weightlifting. Therefore, if proper technique enhances or improves force production, then poor technique has the potential to impair improvements in motor control, coordination, muscle activation, and motor unit recruitment (201).

Another important focus when teaching a beginner, a complex skill, such as weightlifting, is developing accuracy rather than the speed of the movement. The long-term result of this strategy, known as the speed-accuracy trade-off (245), is that athletes will exhibit improved technical performance, consistency, and confidence. As accuracy is gained and the learner moves with improved consistency in the part of the skill being learned, greater attention can be given to the speed of the movement and use of maximal intent. Furthermore, by concentrating on accuracy and consequently slowing down the movement, the athlete will be better able to acquire, process, and interpret proprioceptive feedback. This will also help the strength and conditioning coach intervene and provide appropriate feedback in a timely manner. Conversely, if the initial focus is on speed of movement, it is more likely that errors in technical performance will become evident, ingrained, and harder to fix as the athlete develops (140). Beginner athletes may find learning certain phases of the weightlifting movements difficult. In their effort to achieve "perfect" technique, the body's ability to perform naturally organized the motor actions is interrupted, thus becoming overly conscious and slowing it down (255). Therefore, to avoid this issue, providing a single externally focused cue that helps minimize the biggest limiting factor will likely yield a positive outcome and enhance the learning process.

A key issue that strength and conditioning coaches must consider is the order in which they will teach the component parts of the key weightlifting movements (i.e., snatch, and clean and jerk). The method chosen will likely have a bearing on how easily the athlete can achieve fluidity in the movement when all parts are chained together to create the complex movement patterns associated with weightlifting. There are 2 common teaching methods that have been previously discussed in subsection "Pedagogical Approaches and Feedback Strategies": forward chaining (aka. bottom-up approach) and reverse chaining (aka. top-down approach).

Fundamental Movement Skills. Solid weightlifting technique is based on underlying fundamental skills and movement abilities. In the early stages of learning, it is critical to develop body awareness and control as well as foundational movement competencies before advancing the beginner to higher order tasks. The goal of starting with these developmental skills and capacities is to establish underpinning qualities from which specific weightlifting technical competency can be set. Exercises that focus on the proper position and control of the back and torso, hip hinging, squatting (both unilateral and bilateral), overhead stability, and general bodyweight control are essential prerequisites used to not only establish fundamental skills but also to develop base strength levels to progress onto more weightlifting specific movements (Figure 6).

Chaining of Skills. An athlete is ready to begin chaining different skills together based on the following factors:

- No key elements of technique are poorly performed or constant errors in either lift.
- Demonstrates movement fluency in performing both exercises. Movement fluency is the ability to perform repetitions repeatedly without hesitation or excessive conscious control (140). This includes small degrees of natural movement variability that commonly occur.
- Responds effectively to coaching instruction or feedback to vary their body position, body movement, or movement of the bar.

It is important to note that timing issues will usually occur when the beginner makes initial attempts to chain 2 or more parts of a skill together. As the athlete works through the chaining process, the athlete should be given autonomy to work through these challenges under the guidance and positive reinforcement from the strength and conditioning coach. To ingrain these new movement patterns, the strength and conditioning coach should ensure that an appropriate amount of time is allotted for the athlete to master the new movement skill.

Prioritizing Errors and Frequency of Feedback. It is likely that beginners will demonstrate multiple errors and inconsistencies in their movement patterns while they are trying to master the skills associated with weightlifting. As such, the beginner needs consistent and positive guidance from the coach to help them understand how to interpret the proprioceptive feedback they will receive from weightlifting movements. Strength and conditioning coaches should avoid attempting to correct or provide feedback for every problem that is noted during each lift and be more focused in their approach. As discussed in

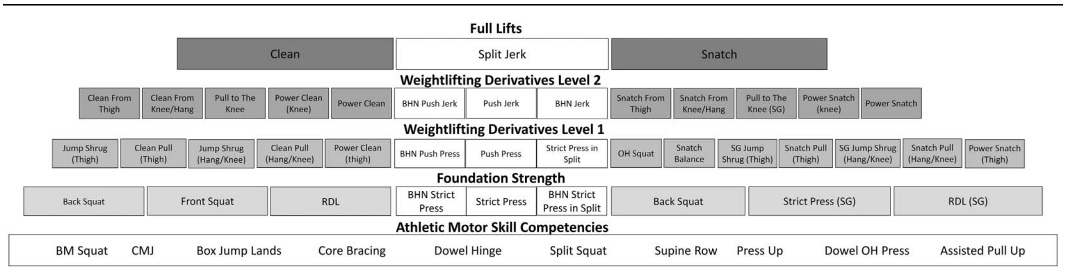


Figure 6. Weightlifting exercise progressions. Exercises are ordered by increasing movement complexity and increasing technical specificity from the bottom of the pyramid working upward as indicated by increased color depth. Adapted with permission from Morris et al. (201). RDL = Romanian deadlift; BHN = behind neck; OH = overhead; CMJ = countermovement jump; BM = body mass; SG = snatch grip.

subsection "Pedagogical Approaches and Feedback Strategies," strength and conditioning coaches should prioritize and attempt to address 1 error at a time, precisely and clearly, through a variety of communication methods. Feedback need only be given if the athlete's performance is outside the bandwidth of correctness (168).

The bandwidth approach is a useful method for reducing the frequency of feedback for small errors in technical performance that occur (241). The need to provide feedback is typically triggered when errors in performance are outside what the strength and conditioning coach might consider a tolerance limit. This tolerance limit, or "bandwidth of correctness" as it is referred to by Lee et al. (168), is determined largely by the width (wide or narrow) of the bandwidth that the strength and conditioning coach sets. The narrower the bandwidth, the more frequent feedback is provided because more efforts for a beginner will likely fall outside the tolerance limits. Conversely, the wider the bandwidth, the strength and conditioning coach will feel less need to provide feedback.

From the learner's point of view, overly frequent correction by the strength and conditioning coach will likely lead to a loss in confidence in one's performance ability as well as a loss of movement fluency. In determining how wide to set the bandwidth, the crucial concept to be considered is that lower frequencies of feedback have been shown to facilitate skill learning (140) and provide the athlete with a degree of ownership of their training. The beginner may benefit from the use of the performance-bandwidth approach because it may increase their proprioceptive sense and reduce the possibility of becoming hypersensitive to technical flaws. The strength and conditioning coach should strive to reinforce what the athlete is doing well and prioritize technical errors for feedback and coaching intervention. From a skill acquisition perspective, it is not necessary to provide immediate feedback after a performance because delaying this feedback will allow the athlete to reflect on their performance and process internal feedback (9). This can aid in building movement confidence and autonomy because the athlete learns through kinesthetic awareness. Possessing considerable knowledge and understanding of the technical model of a particular movement will help to guide a strength and conditioning coach to how narrow or wide to set their view of the "bandwidth correctness" and assist in determining when and when not to provide feedback to the athlete.

Types of Errors. A strength and conditioning coach will be able to better construct and implement appropriate correction feedback strategies and techniques as well as help to prioritize the correction of errors (i.e., critical vs. noncritical) when they understand the different types of errors they will come across, including how, when, and why they occur. Errors typically can be found in the following categories:

- Body position;
- Movement characteristics;
- Balance and stability;
- Lack of confidence;
- Flexibility or movement limitations;
- "Bracing" ability of the body.

Table 4 illustrates each type of error and provides weightlifting examples that strength and conditioning coaches will likely see when working with beginners (140). Some errors may be classified as more critical than others and require immediate intervention, whereas others pose less consequence and can be addressed later (Table 5). The underlying principle is that it is difficult, if not impossible, for the athlete to implement corrective action on 2 faults simultaneously (140). If a strength and conditioning coach affirms any of the following, then the error should be considered a high priority and necessitates an immediate response:

- If the error is not fixed now, will it become ingrained and harder to fix later? (e.g., pulls with arms, raises hips at the start of the pull)
- Does the error immediately impact overall movement success? (e.g., excessive horizontal displacement of the bar leading to an inability to stabilize overhead)
- Does the error prevent the achievement of the primary objective of the exercise? (e.g., torso collapses in the transition between the dip/drive phases of the jerk)
- Does the error endanger the safety of the athlete? (e.g., athlete puts the bar too far behind the head in a snatch balance)

However, it is important to note that in early learning, athletes typically display multiple errors where some, occasionally, are not more than a random event and not typical of an athlete's skill. Therefore, careful observation, examination, and evaluation by the strength and conditioning coach are warranted in determining what, if any, feedback, or intervention is needed. It is recommended to observe and assess the athlete for several sets, and over several sessions, to obtain a valid evaluation of the quality of their body positions and movement characteristics before making their assessment known to the athlete. Before any feedback or corrective action being provided, the strength and conditioning coach should consider when the best time to implement it would be. Athletes do not always benefit from immediate intervention by a strength and conditioning coach to correct an error (140). For information regarding feedback timing, please refer to subsection "Pedagogical Approaches and Feedback Strategies."

Considerations for Children and Adolescents

Despite misconceptions regarding the safety of using weightlifting-based training with children and adolescents, there is a substantial body of evidence advocating weightlifting as a safe and beneficial form of resistance training for children and adolescents (20,88,89,170–172,174–176,228,230,319). Lower injury incidence rates are also reported from long-term weightlifting in comparison with other sports (30,121,228). However, appropriate instruction and logical progression, based on technical proficiency, is a key premise for ensuring safe and effective weightlifting training with youth populations (30,228,229).

Benefits of Weightlifting for Youth. As with adult populations, exposing children and adolescents to weightlifting-based training can elicit improvements in motor control, strength, power, speed, COD speed, and cardiorespiratory fitness (36–38,137–139,150,227,257,320). Furthermore, weightlifting can improve body composition (36), reduce injury risk factors (227), and result in adaptations beneficial for bone formation and growth (55,315). The benefits of using weightlifting-based exercises with youth arguably outweigh the risks, with researchers suggesting the injury risk of weightlifting-based training is markedly less than in other popular youth sports (e.g., soccer, rugby, cricket, and athletics) (30,121,228). Children have a lower risk of resistance training-related joint sprains and muscle strains than adults, with most injuries in children being accidental in

Table 4

Movement errors associated with weightlifting.*

Body position errors	Balance and stability errors
Shoulders behind the bar at midthigh position in the pull	Loss of balance in receiving positions for the snatch, clean, or jerk
The upper body is not vertical in the dip for the jerk	Loss of balance at any stage of the pull (not always obvious)
Foot placement too wide or too narrow in receiving positions	Inability to land and remain flat-footed in the snatch or clean receiving position
Excessive anterior pelvic tilt in the receiving position for the jerk	Loss of balance in recovery
Hips too high in the start position of the pull	Forward rotation of the upper body in the dip for the jerk
Less than 180° extension of the body at the finish of the pull	Rigidity errors
Receiving position for the snatch is not sufficiently upright	Rounding of the back in the pull
Elbows too low in the receiving position for the clean	Inability to brace the upper body in the dip for the jerk
Arms bending in the pull before full extension of the body	Hyperextension of the back in the jerk receiving position
Knees not tracking over the toes in squats	Back foot instability or collapse in the jerk
	Inability to brace the body in the receiving position for the clean
Errors in movement characteristics	Errors because of lack of confidence
Movement under the bar before achieving full extension in the pull	Abrupt changes in foot movement and landing as the bar weight approaches perceived maximum
Dipping too fast in the jerk	Hesitancy to drop under the bar as the bar weight approaches perceived maximum
Foot lift too high during movement under the bar	Increased effort at the start of the pull causing changes in body position and timing
Lack of acceleration in the final stages of the pull	Diving under the bar—attempts to drop quickly under the bar but resulting in incomplete extension in the pull
Hips rising before the shoulders at the start of the pull	Lack of commitment to complete the lift
Bar slows significantly in the middle of the pull	Errors because of lack of flexibility
Excessive backward rotation of the upper body in the middle or end stages of the pull	Inability to position the bar on the shoulders correctly in the clean or jerk because of shoulder flexibility issues
Inability to keep the bar close to the body in the pull	Restricted shoulder girdle elevation, resulting in poor lockout
Uneven extension of the arms in the lockout (press out)	Inability to extend the elbows to 180°
	Lack of depth in receiving position

*Adapted with permission from Isaac (140).

nature and preventable with appropriate supervision (206). It is recommended that a strength and conditioning coach to athlete ratio of 1:10, or lower, is used when coaching young athletes, to ensure proper technique and establish a safe environment (311). To enhance training adaptations and reduce injury risk, adult-based training programs should not be superimposed on children or adolescents. In accordance with leading consensus on long-term athletic development (170), the design, delivery, and progression/regression of a young athlete's training program should consider the influence of growth and maturation and the psychosocial needs of the individual.

Trainability of Weightlifting Performance in Youth. Childhood is the optimal time to develop coordination and movement competency because neuroplasticity is at its highest (22,33). Childhood is also a timeframe during which bone mineral density can be enhanced (108). To take advantage of this heightened sensitivity during childhood, strength and conditioning coaches should consider introducing athletes to weightlifting-based training methods before the adolescent growth spurt (76,108). When coaching novice, inexperienced children, it is important that athletic motor skill competencies (AMSC), proposed as the foundational movements that underpin all athletic movements (175), are developed first. Once movement proficiency in the AMSC is established, weightlifting literacy can then be developed (201). Such an approach aims to avoid any motor proficiency barriers manifesting as the exercise complexity increases (256). Less-structured, exploratory training using "animal or superhero shapes," obstacle courses or playground-based games may be used to introduce the AMSC, before progressing on to more structured versions of the weightlifting movements with increased load (173,201). As well as providing an element of novelty to training, these game-based activities enable children to learn and refine AMSC with fun-based challenges. Although there is no minimum age requirement for performing the weightlifting movements, athletes should have the emotional maturity to accept and follow coaching instructions and handle the attention demands, before being introduced to a structured training program (88,205).

Table 5

Examples of bandwidths of correctness.*

Inside the bandwidth of correctness (no feedback needed)	Outside the bandwidth of correctness (feedback needed)
■ The error made is not a safety issue	■ The error may increase injury risk if repeated
■ The error is just a natural variation of human performance	■ The error results from a deliberate and unhelpful strategy made (invented) by the athlete
■ The error is the first instance, see what happens next rep	■ The athlete repeats the same error on 2 consecutive attempts: provide feedback before third attempt
■ The error made is due to fatigue or anxiety	■ The athlete shows no change in movement despite being given time and opportunity to implement feedback given
■ The error is a result of the individualization of technique because of limited flexibility or joint range of motion	■ The athlete interprets feedback incorrectly
■ The athlete makes a different error after correctly attempting to implement the coach's feedback	

*Adapted with permission from Isaac (140).

Strength and conditioning coaches should be mindful that children within the same chronological age group will likely differ in biological maturation, which can influence training responsiveness, movement competency, and associated injury risk (95,171,174,176). When working with youth athletes, strength and conditioning coaches should be mindful of the circumpubertal stage of maturation, which is commonly indicative of a period of "adolescent awkwardness." This phase is synonymous with potential disruptions in motor coordination because of increases in lever lengths, height of center of mass, and body mass, accompanied by a reduction in mobility, possibly owing to reduced musculotendinous stiffness and alterations in collagen properties within the tendon (130,175,176,182). During this phase, the coach may consider prescribing weightlifting derivatives (e.g., hang variations) which have a reduced complexity in comparison with the full movements, in addition to reducing external load. Supplementary strength training in isometric positions or performing exercises with reduced ranges of movement (i.e., power variations) may be advantageous to continue to develop strength during this "awkward adolescent" stage.

The postpubertal stage of maturation is associated with altered sex hormone concentrations, leading to natural increases in muscle mass and force producing capabilities (95,233). Therefore, adolescent athletes may respond more favorably to training methods that also promote structural changes in addition to targeting the neuromuscular system (174,223,224). Provided technical proficiency in the weightlifting movements has been established, greater external loads may be used during weightlifting-based training to provide a progressive overload stimulus and take advantage of the naturally occurring physiological adaptations. In addition, adolescents may experience improved proprioception at this stage (174) and increased cognitive maturity (164). These changes may allow them to better understand and adapt to the complexities of the weightlifting movements and increase their ability to self-correct movement errors.

Cumulatively, the existing pediatric exercise literature indicates that growth and maturation can influence how youth respond to acute and chronic forms of exercise (22,76,170,177,223,224,233). By considering the relationship between training-induced adaptations and those resulting from growth and maturation, researchers suggest that a strength and conditioning coach can heighten the training response (177,223,224). However, although the influence of maturation is important to consider, of all the variables that will likely influence program design and exercise prescription, technical competency in the movements should be the primary factor that dictates an athlete's program prescription and rate of progression.

Table 6

Ten pillars for successful long-term athletic development.*

Pillar	Description
1	Long-term athletic development pathways should accommodate for the highly individualized and nonlinear nature of the growth and development of youth
2	Youth of all ages, abilities, and aspirations should engage in long-term athletic development programs that promote both physical fitness and psychosocial wellbeing
3	All youth should be encouraged to enhance physical fitness from early childhood, with a primary focus on motor skill and muscular strength development
4	Long-term athletic development pathways should encourage an early sampling approach for youth that promotes and enhances a broad range of motor skills
5	Health and wellbeing of the child should always be the central tenet of long-term athletic development programs
6	Youth should participate in physical conditioning that helps reduce the risk of injury to ensure their on-going participation in long-term athletic development programs
7	Long-term athletic development programs should provide all youth with a range of training modes to enhance both health- and skill-related components of fitness
8	Strength and conditioning coaches should use relevant monitoring and assessment tools as part of a long-term athletic development strategy
9	Strength and conditioning coaches working with youth should systematically progress and individualize training programs for successful long-term athletic development
10	Qualified professionals and sound pedagogical approaches are fundamental to the success of long-term athletic development programs

*Reproduced with permission from Lloyd et al. (170).

Long-Term Athletic Development

Long-term athletic development (LTAD) refers to the "habitual development of athleticism over time to improve health and fitness, enhance physical performance, reduce the relative risk of injury, and develop the confidence and competence of all youth" (170). In addition to improving health, physical activity, and sports performance, LTAD takes a holistic approach and considers physical and psychological factors in youth development. The NSCA LTAD position statement includes 10 pillars to assist strength and conditioning coaches in its successful implementation (Table 6).

For LTAD to be successful, growth and maturation need to be considered. Growth refers to the quantifiable change in anthropometrics, body composition, body size, or the size of specific regions of the body, and is a constantly evolving process, whereas maturation refers to the qualitative structural and functional system change toward a mature state and is variable among body systems (26). During this time, as bodies are evolving in a nonlinear fashion (183), youth may go through a period of temporary disruption in motor control and coordination termed "adolescent awkwardness" (231). Adolescent awkwardness may also lead to reduced force production and decreased performance in speed and jumping ability (25,232), which can lead to an increased risk of injury (129). The increase in height of the center of mass and body mass during the adolescent growth spurt, without corresponding neuromuscular adaptations, can lead to altered movement patterns and the development of risk factors for injury (129). The extent, timing, and tempo of maturation can significantly vary between youth of the same chronological age (26). This also means that how youth respond and recover from training can vary immensely (22), such as during adolescent awkwardness. Therefore, strength and conditioning coaches should consider growth-related changes when implementing LTAD programs and be able to modify motor patterns with reduced loads.

In addition to navigating physical development throughout the maturation process, a sound approach to LTAD is needed to counteract the effects of lack of movement skills and general physical activity seen in youth today. Inactivity during childhood is associated with being overweight or obese (204), leading to undeveloped fundamental movement skills and, therefore, a lack of confidence and competence in their ability to perform movements (17,18). This can lead to a decrease in physical activity and eventually negative health outcomes later in life (90,91). Therefore, to encourage an active lifestyle and facilitate longer sporting careers, youth should engage in a variety of sports or activities (referred to as sampling) (67,174).

Several models to create a framework for youth development have been proposed over the past 3 decades. In a recent review, Pichardo et al. (227) reported 3 models that have largely

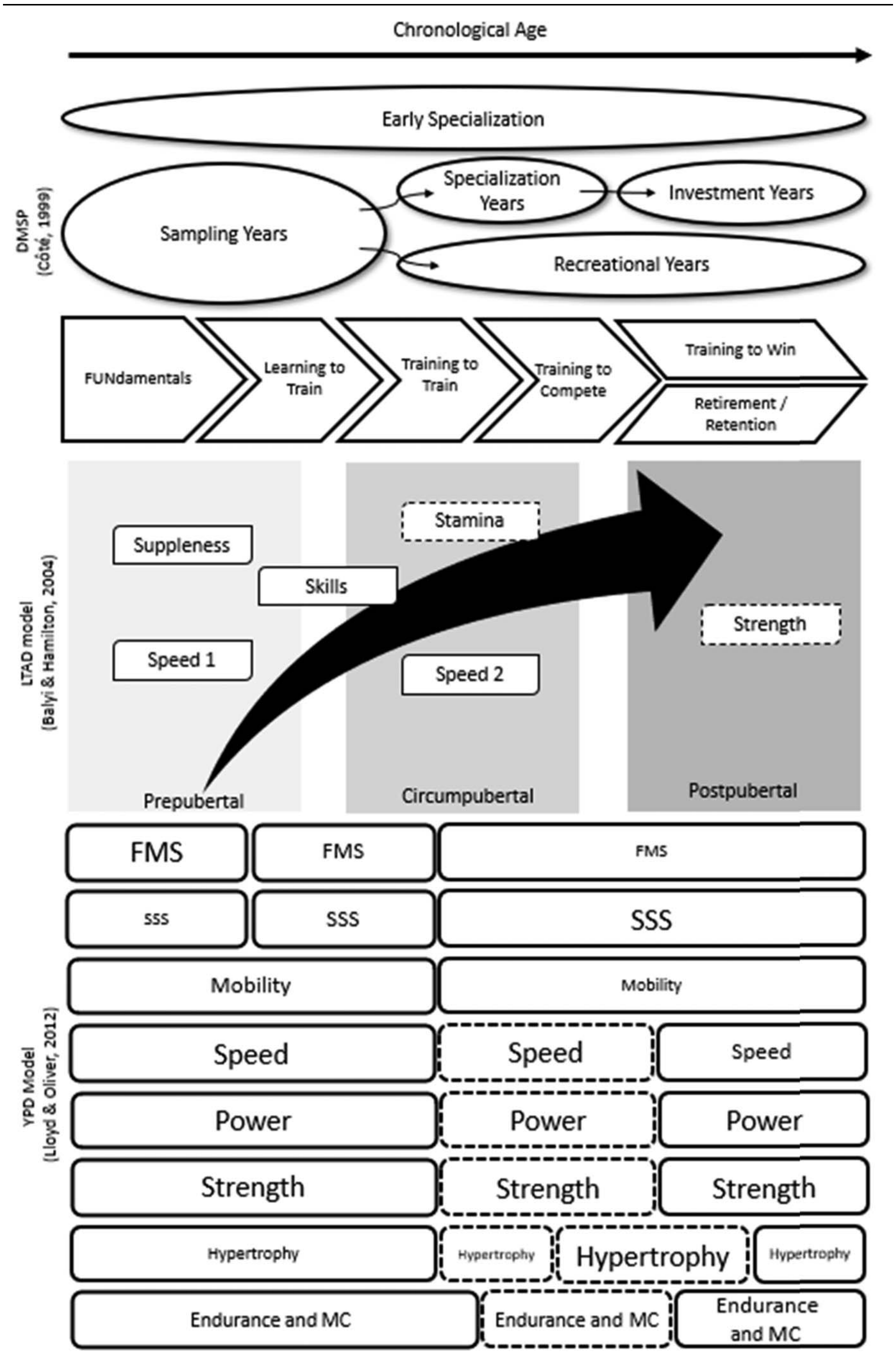


Figure 7. Illustration comparing 3 models of long-term athletic development. In the LTAD model, closed boxes align to chronological age and dashed boxes to maturation. In the YPD model, the font size represents the importance of a fitness component at a given stage, shaded boxes identify interactions between training adaptations and maturation: Bold box = puberty (mainly neural adaptations), dashed box = pubertal (hormonal and neural adaptations. Adapted from Pichardo et al. (226)). DMSP = Development Model of Sports Participation; LTAD = Long-Term Athlete Development model; YPD = Youth Physical Development Model; FMS = fundamental movement skills; SSS = sport-specific skills; MC = metabolic conditioning.

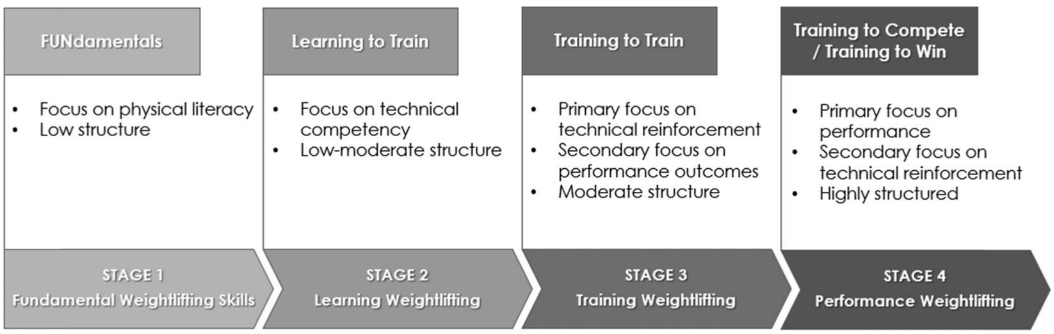


Figure 8. A summary of weightlifting training models. Adapted from Pichardo et al. (226).

influenced how athletes are developed: the Developmental Model of Sports Performance (66), the LTAD model (16), and the Youth Physical Development model (174). These models provide a framework to develop athleticism based on chronological age and/or maturation. The NSCA's position statement on LTAD refers to athleticism as "the ability to repeatedly perform a range of movements with precision and confidence in a variety of environments, which require competent levels of motor skills, strength, power, speed, agility, balance, coordination, and endurance" (170). Figure 7 illustrates how each model aligns with each other and how the emphasis may change as youth move toward adulthood. It should be noted that if an adult or novice/beginner youth athlete has not gone through the early stages of development (e.g., fundamentals), then the athlete should enter the model at the beginning as opposed to the stage that corresponds to their chronological age (171). Irrespective of age, a novice/beginner athlete must exhibit technical competency in fundamentals before moving on to more complex movements.

Pichardo et al. (226) proposed a model for developing weightlifting in youth based on the LTAD model of Balyi and Hamilton (16) and adapted from the youth weightlifting LTAD model presented by Lloyd et al. (171). This model uses 4 stages: Fundamental Weightlifting Skills (FUNdamentals), Learning Weightlifting (Learning to Train), Training Weightlifting (Training to Train), and Performance Weightlifting (Training to Compete/Win). Figure 8 illustrates that training structure should increase with each stage and that training emphasis shifts from physical literacy (fundamental movement skills) to technical competency to performance. These guidelines can help strength and conditioning coaches design training sessions and realistic outcomes during each stage of training.

Similarly, Morris et al. (201) detail a long-term approach to develop weightlifting skills progressing from beginner to advanced, highlighting the training prescription, exercise selection, skill development, and physical capacity at each stage (Figure 9).

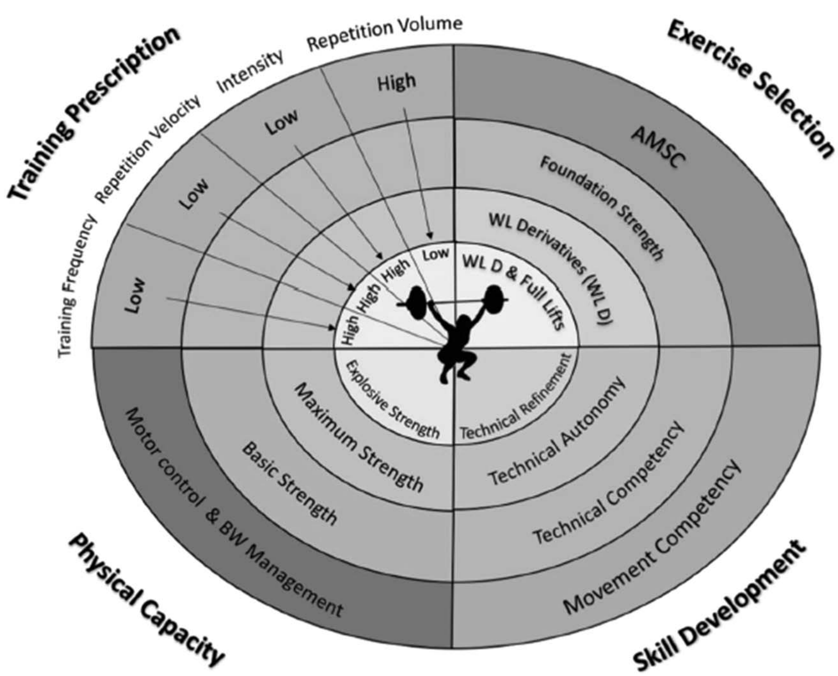


Figure 9. Long-term development of weightlifting performance progression scheme. Novice athletes are introduced at the outside of the circle and training progressions inward in all directions, progressing from beginner to novice, intermediate, and advanced stages indicative of a reduced color depth. Reproduced with permission from Morris et al. (201).

Physical capacities (motor control and bodyweight management) and skill development (movement competency) need to be considered at each stage before progressing to the next stage to develop the highest level of skill and performance and prevent injuries. Similarly, weightlifting exercise progressions should start with motor competencies (e.g., squat, hinge, push, pull, and brace) and progress to foundational strength exercises (e.g., back squat, Romanian deadlift, and strict press) and then to specific weightlifting movements and derivatives (e.g., clean from thigh, push jerk, and power snatch) (Figure 6). As with any training, it is imperative to consider individual needs and maturation status and have a qualified professional implement these programs, so that youth can enjoy life-long physical activity.

Summary

The inclusion of weightlifting exercises into appropriately planned training programs, that are appropriately sequenced to take advantage of the development of specific physical characteristics, results in enhanced force-production characteristics and performance in athletic tasks. It is important to ensure that the exercise selection, including loading, sets, repetitions, and frequency, is carefully selected to ensure an appropriate stimulus to elicit the desired neuromuscular adaptations. While making such decisions, the strength and conditioning coach should also be mindful of the skill level and the technical competent in performing the selected weightlifting exercise(s), to ensure that they are performed safely and with intent. To assist with the development of technique, it is important to adopt a long-term development approach, not only to develop technical competency, but also to continue to refine the skilled aspects of these exercises, to maximize desired stimulus and the resulting adaptations.

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