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Brief Review

The Optimal Training Load for the Development of Muscular Power

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Abstract. Kawamori, N., and G.G. Haff. The optimal training load for the development of muscular power. *J. Strength Cond. Res. 18(3):675–684. 2004.*—Muscular power is considered one of the main determinants of athletic performance that require the explosive production of force such as throwing and jumping. Various training methods have been suggested to improve muscular power and dynamic athletic performance. Although various acute training valuables (e.g., sets, repetitions, rest intervals) could be manipulated, the training loads used are some of the most important factors that determine the training stimuli and the consequent training adaptations. Many research results showed that the use of different training loads elicits the different training adaptations and further indicated the load- and velocity-specific adaptations in muscular-power development. Using the optimal loads at which mechanical power output occurs has been recommended, especially to enhance maximum muscular power. Additionally, introducing periodization and combined training approach into resistance-training programs may further facilitate muscular-power development and enhance a wide variety of athletic performances.

Key Words. resistance training, specificity, force-velocity curve, combined training method, periodization

Introduction

Many sports involve movements that require generation of force over a short period of time (40). Such movements include throwing, jumping, change of direction, and striking activities (46). In such activities, power is the main determinant of performance (5, 6, 25, 46). Therefore, resistance-training programs aimed at muscular-power enhancement are desired to improve sports performance.

Mechanical power can be defined as the rate of work or the force multiplied by the velocity of movement.

$$\begin{aligned} \text{Power} &= \text{Work/Time} \\ &= \text{Force} \times \text{Distance/Time} \\ &= \text{Force} \times \text{Velocity} \end{aligned}$$

Because power is the product of force and velocity, both components need to be addressed in a training program to develop muscular power. However, force and velocity are not independent of each other in muscle actions. As the velocity of movement increases, the force that muscle can produce decreases during concentric muscle actions. Therefore, the maximum power is achieved at a compromised level of maximal force and velocity (55). Maximal mechanical power has been thought to occur at a resistance of 30% of maximum isometric strength (19) or 30–45% of 1 repetition maximum (1RM) (31, 36, 43, 49). Wilson et al. (64) postulated that 30% of maximum isometric strength was the load that allowed for the attainment of the greatest mechanical power output. This idea is supported by the work of Moss et al. (43). However, other investigators have advocated resistances in the range of 10–80% 1RM to maximize mechanical power output, depending on the nature of the exercise (upper vs. lower body, single- vs. multijoint, traditional vs. explosive), the training experience of the athlete, and the training status of the athlete within a yearly training cycle (4–6, 8, 9, 23, 43, 44, 59, 63).

Considerable debate exists concerning which range of training loads (percentage of maximum isometric strength or 1RM) brings about the most favorable adaptations in power development during resistance training (8, 9). Some investigators (53, 54) have suggested the use of heavy loads (>80% of 1RM) to induce recruitment of high-threshold fast-twitch motor units, which produce more power output than do low-threshold slow-twitch motor units (19), on the basis of the size principle (21). On the other hand, several studies have shown that to increase power output, athletes should train with the velocity and resistance that maximizes mechanical power output (41, 46, 64).

Because there is controversy in the literature as to the load against which muscle can generate the highest power output (Figure 1) and the optimal load for muscular-power development (63), the focus of this paper is first to review the load that should be used in the training to improve muscular power and dynamic athletic performance. Second, the optimal load that maximizes the mechanical power output will be explored.

The Possible Neuromuscular Factors Contributing to High-Power Output

A wide variety of neuromuscular factors have been reported and suggested to contribute to high-power production (25, 42, 52, 56). Neural factors that could contribute to high-power output include motor-unit recruitment, rate coding, and synchronization. Generally, the high-threshold motor units, which are typically composed of type II muscle fibers, need to be recruited for high-power outputs. These larger and more powerful motor units are usually recruited only when a maximal voluntary effort is given, and some untrained athletes may not be able to recruit such high-threshold motor units (25, 52). Therefore, learning how to recruit high-threshold motor units through resistance training will theoretically improve one's high-power–producing capability. In addition, selective recruitment of motor units is possible. Although motor-unit recruitment usually follows a size principle (i.e., smaller motor units are recruited first, then larger motor units), larger motor units may be preferentially recruited over smaller motor units in ballistic muscle actions (25, 52). The use of ballistic muscle actions in a training pro-

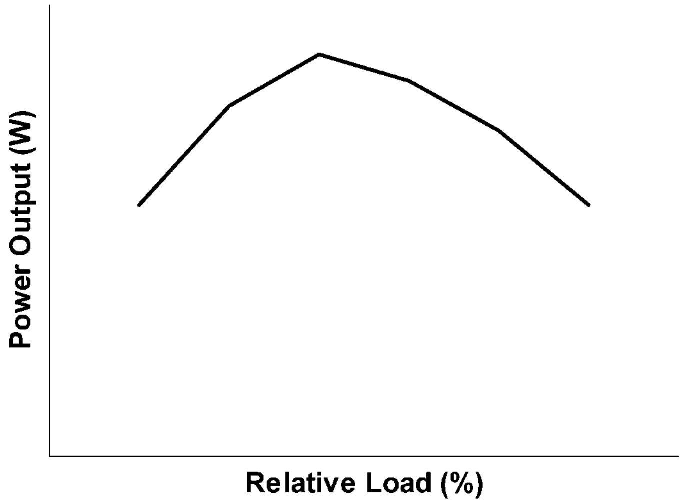

FIGURE 1. Schematic description of a power-load curve.

gram may therefore improve the ability to recruit high-threshold motor units sooner or more efficiently (25). Another neural mechanism, rate coding, is defined as motor-unit firing frequency. The greater the motor-unit firing frequency is, the greater the force output is up to a certain point (52). When the motor-unit firing frequency exceeds the level that is sufficient to achieve maximum force, the further increase in firing frequency contributes to an increase in rate of force development (RFD) (52). Rate of force development is considered an important factor in high-power production because time to exert force is usually limited in powerful muscle actions (46, 66). Therefore, increased rate-coding ability, or motor-unit firing frequency, is a possible adaptation for high-power production. In addition to motor-units recruitment and rate coding, greater synchronization, or synchronous activation of motor units, has been proposed to occur as a result of power training, and that may be associated with premovement silent period. Such neural mechanism could also contribute to high-power output (42).

Muscular factors that could contribute to high-power output include muscle cross-sectional area (CSA) and muscle fiber type. A strong relationship exists between muscle CSA and strength, and increases in muscle CSA (i.e., hypertrophy) contribute to strength gain (20, 51). Because muscle strength is a component of power, strength gain from muscle hypertrophy could possibly contribute to high-power production. On the other hand, excessive hypertrophy may be disadvantageous or detrimental because extreme muscle hypertrophy may be associated with decreased range of motion and alterations in muscle pennation angles, which could deteriorate high-power production (37, 46). Therefore, excessive muscle hypertrophy is unfavorable and should be avoided, though some hypertrophy training is necessary. Another muscular factor is muscle fiber type. Fast-twitch muscle fibers produce more power output than do slow-twitch muscle fibers (19). In addition, peak power has been shown to be correlated with percentage of fast-twitch muscle fibers (12). Therefore, having a higher percentage of fast-twitch muscle fibers may be advantageous in high-power outputs.

Numerous possible factors could contribute to high-power output in addition to those mentioned above. To improve such factors and consequently one's high-power–producing capability, different types of resistance training are proposed.

HEAVY RESISTANCE VS. EXPLOSIVE-TYPE RESISTANCE TRAINING

Although athletes can use a variety of resistance-training methods to enhance muscular power and dynamic athletic performance, 2 particular types of resistance training, heavy resistance training and explosive-type resistance training, appear to be the most effective and have been vigorously investigated (8, 18, 28, 29, 31, 41, 53, 64).

Heavy resistance training uses a relatively heavy load (>80% of 1RM) and is performed with a relatively slow velocity because of a large external resistance that must be overcome (29, 31, 32). This method has been reported to increase maximum muscular strength and to result in enhanced muscular power or dynamic performance (2, 18, 29, 64). The use of heavy resistance training is theoretically based on the size principle (21, 52), which suggests that it is necessary to use heavy loads to fully recruit and to fully train fast-twitch motor units with high thresholds (31, 41, 53, 64). Fast-twitch motor units are considered to produce more power output than are slow-twitch motor units and to be responsible for dynamic athletic performance (19, 31). Additionally, some investigators have suggested that speed of movement could be enhanced through heavy resistance training in which the actual movement velocity is low, provided that there is an intention to lift weights as rapidly as possible, which results in a high RFD (10, 14, 15, 65). In fact, Aagaard et al. (1) demonstrated increased isometric RFD after 14 weeks of heavy resistance training in untrained male subjects. This may reinforce the proposed efficacy of heavy resistance training to develop muscular power, though they did not mention if subjects were instructed to lift weights as rapidly as possible during training sessions. Furthermore, another possible reason to support heavy resistance training in developing muscular power is the high correlations that have been reported between maximum strength and high-power outputs at light as well as at heavy resistance (7, 43, 59). Stone et al. (59) suggested that maximum strength plays a major role in power output and that power may be increased with the improvement of maximum strength.

On the contrary, explosive-type resistance training uses relatively light loads (<60–80% of 1RM) that are lifted in an explosive manner, which results in a high velocity of movement and a high RFD (24, 30, 31, 34, 46). The rationale for the explosive-type resistance-training method is based on the velocity specificity of resistance training (11, 35), on the fact that it brings about high RFD (24), and on the notion that one should use the load that maximizes mechanical power output to develop muscular power (8, 36, 41, 43, 64). The concept of the velocity specificity is that muscular strength and power increase most either at or near the velocity of training, and one should train at a velocity that is closer to the actual velocity of athletic performance (11, 35). Rate of force development is an important factor contributing to explosive-power production and dynamic performance, especially when performance or the time in which one can exert force lasts less than 250 milliseconds (46, 53, 66). Some investigators recommend that relatively light intensities should be used in an explosive manner to maximize adaptations in RFD (24, 26, 30).

TABLE 1. A comparison of the effects of heavy resistance and explosive-resistance training.

	Increase in jump height (%)	Increase in maximum force (%)	Reference
Heavy resistance training	7	16	Wilson et al. (64)
	7	30	Hakkinen and Komi (28, 29)
Explosive-resistance training	15	NS	Wilson et al. (64)
	21	7	Hakkinen and Komi (28, 29)

* NS = not significant.

Comparing the effects of heavy resistance with explosive-type resistance training, several studies have shown the superiority of explosive-type resistance training in enhancing muscular power and dynamic athletic performance (Table 1). Wilson et al. (64) compared the effects of 3 training modalities (traditional heavy-resistance squat, depth jump, and explosive jump squat with the load that maximized mechanical power output) on performance of dynamic athletic activities such as the 30-m sprint, the static jump, and the countermovement jump. Although all training groups showed increases in static jump performance, the explosive jump-squat group produced statistically greater improvement (15%) in static jump performance than did the other training groups (7% both for the heavy-resistance squatting group and the depth-jump group). Furthermore, the explosive jump-squat training group achieved the best overall results in a battery of dynamic athletic performance tests. Similarly, Hakkinen and Komi (28, 29) reported that 24 weeks of explosive-type training (various jumping exercises performed with and without light weights) resulted in a 21% increase in jump height compared with a 7% increase by 24 weeks of heavy-resistance squat training with loads of 70–120% of 1RM. The studies by Wilson et al. (64) and Hakkinen and Komi (28, 29) indicate that explosive-type resistance training with a relatively light load tends to enhance muscular power and dynamic athletic performance to a greater extent than does heavy resistance training. Although some other investigators found or insisted that resistance training at relatively heavy load is more effective than lighter loads in developing muscular speed and power (10, 53, 54), the majority of researchers support the use of explosive-type resistance training to improve muscular power and dynamic athletic performance (16, 28, 31, 34, 36, 41, 43, 64).

LOAD AND VELOCITY SPECIFICITY FOR MUSCULAR-POWER DEVELOPMENT

Although the results of the studies by Wilson et al. (64) and Hakkinen and Komi (28, 29) favor explosive-type resistance training as a training method to enhance maximum muscular power, they also demonstrate the superiority of heavy resistance training in improving maximum muscular strength. Wilson et al. (64) reported that heavy resistance training significantly increased maximum isometric force (16%) after 5 weeks of training, whereas explosive-type resistance training showed no significant improvement in maximum isometric force. Similarly, Hakkinen and Komi (28, 29) showed 30% and 7% increase in maximal force after 24 weeks of heavy resistance and explosive-type training. On the basis of these studies (28, 29, 64), it is hypothesized that specific training adaptations may exist to heavy resistance vs. explosive-type resistance training. This idea is supported and extended by the studies of Kaneko et al. (36) and Moss et al. (43), who showed load specificity in the increase in muscular power, that is, the greatest increase in power output was found at the loads used during training. Heavy resistance training improves high-force portions of the force-velocity curve (i.e., power output at low velocity and against heavy load), whereas explosive-type resistance training improves high-velocity portions of the force-velocity curve (i.e., power output at high velocity and against light load) (Figures 2 and 3) (18, 34, 36, 41, 43, 46, 56). These load- and velocity-specific changes have been reported to be associated with changes in muscle electrical activity (28, 29, 41) or changes in muscle-fiber contractile properties (18). Because the ability to develop power at a certain load is a limiting factor for performance (43), athletes need to adopt specific training strategies so that they can develop power-producing capabilities of neuromuscular systems against specific external resistances that they often encounter in their own sport events (39). For example, improvement in muscular power against heavy loads might be advantageous to rugby players who have to overcome relatively large external resistance (body mass of the opponent) during the game, and such athletes may benefit from training with relatively heavy weight (e.g., heavy resistance training) in their training programs (5). On the other hand, throwing a baseball represents much smaller external resistance (16, 46); therefore, developing muscular power at high ve-

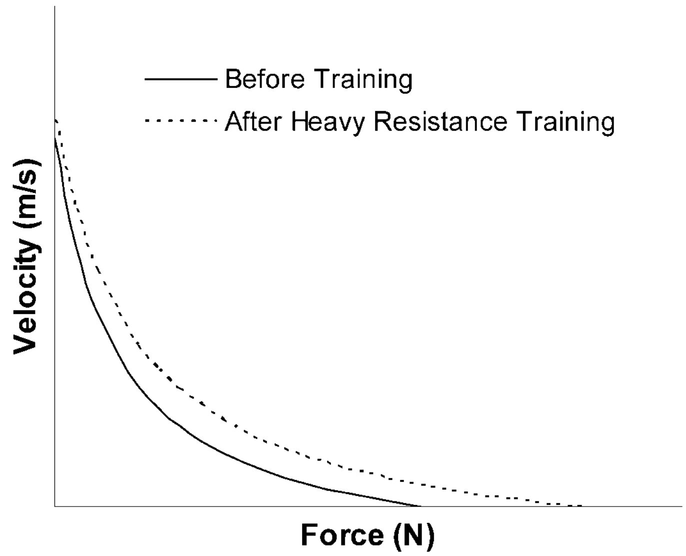

FIGURE 2. Effects of heavy resistance training on force-velocity curve.

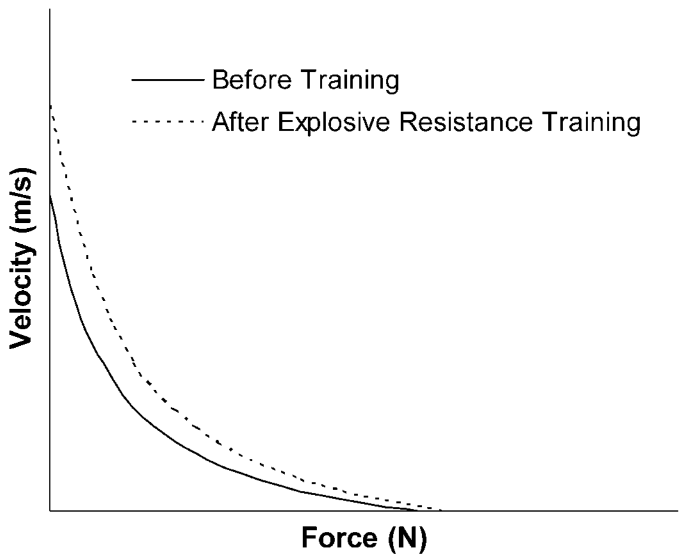

Figure 3. Effects of explosive-type resistance training on force-velocity curve.

locity and against light resistance would be necessary for baseball players.

Interestingly, a recent study by Stone et al. (59) found high correlations between maximum strength (1RM squat) and power output even at relatively light weight (jump squat at 10% of 1RM) ($r = 0.78$ for countermovement and $r = 0.84$ for static conditions), indicating the possibility that heavy resistance training may improve power output even against light resistance. However, other investigators indicated that the influence of maximum strength on power production diminishes as the external load decreases (43, 53). Therefore, further research is warranted to elucidate the exact relationship between maximum strength and power production against different external loads.

Optimal Load for Highest Power Output

On the basis of the specificity of muscular-power development, training at the load that maximizes mechanical power output is recommended to improve maximum muscular power. In fact, Kaneko et al. (36) revealed that training at the load that produced the highest mechanical power output was most effective in increasing maximum muscular power. In addition, training at this load increased muscular power over a wide range of loads. Although many investigators support this idea of using the optimal load to develop maximum muscular power (8, 36, 41, 43, 64), there is inconsistency in the optimal load reported to generate the highest power production (Table 2). Whereas some studies have insisted the load of 30% of maximal isometric force or 30–45% of 1RM to maximize mechanical power output (19, 36, 43, 49), other studies have suggested that maximum mechanical power output occurs at higher percentage of maximum load (40–70% of 1RM) (5, 6, 8, 9, 13, 32, 33, 39, 50, 55, 63) or at lower percentage of maximum load (10% of 1RM) (59). Close review of the past research tells us that studies that used untrained subjects, single-joint exercises, or upper-body exercises tend to support lower percentages of maximum load (30–45% of 1RM), whereas studies that used trained subjects, multijoint exercises, or lower-body exercises tend to support higher percentages (30–70% of 1RM) to maximize mechanical power output (5, 6, 8, 9, 13, 32, 36, 39, 43, 49, 50, 55, 63), though this is not always the case (59). It appears that the optimal load for maximum mechanical power output depends on the nature of the exercise or the experience of the athlete (5). Furthermore, training status of the athlete within a yearly training cycle could also affect the optimal load (4, 44).

Nature of Exercises

Studies that used single-joint exercises (e.g., elbow flexion) demonstrated consistently that 30–45% of maximum isometric force or 1RM produced the highest mechanical power output (36, 43). On the other hand, there is a large discrepancy in the optimal load reported in multijoint exercises (10–70% of 1RM), yet the highest mechanical power output tends to be attained at higher percentages of maximum load compared with single-joint exercises (8, 9, 32, 33, 39, 49, 50, 55, 63). Funato et al. (22) stated that although each muscle or muscle group has its own fundamental force-velocity relationship (i.e., parabolic), mul-

Table 2. A comparison of the optimal loads that maximize mechanical power output.*

Type of exercise	Optimal load	Reference
Upper-body and single-joint exercise		
Elbow flexion	30% of MVC	Kaneko et al. (36)
Elbow flexion	35 and 50% of 1RM	Moss et al. (43)
Upper-body and multijoint exercise		
Bench press	40–50% of 1RM	Mayhew et al. (39)
Bench press	30–45% of 1RM	Izquierdo et al. (32, 33)
Bench press and bench throw	50–70% of 1RM	Cronin et al. (13)
Bench throw	55% of 1RM	Baker et al. (8, 9)
Bench throw	15–45% of 1RM	Newton et al. (49)
Lower-body and multijoint exercise		
Jump squat	55–59% of 1RM	Baker et al. (8, 9)
Squat jump (static and countermovement)	10% of 1RM	Stone et al. (59)
Half-squat	60–70% of 1RM	Izquierdo et al. (32, 33)
Half-squat	45–60% of 1RM	Izquierdo et al. (32, 33)
Smith machine squat	60% of 1RM	Siegel et al. (55)
Double-leg press machine	60% of 1RM	Thomas et al. (63)

* MVC = maximum voluntary contraction (maximum isometric strength); 1RM = 1 repetition maximum.

tijoint movements demonstrate a relatively linear force-velocity relationship. This is supported by the recent study by Rahmani et al. (50) and may indicate the specific characteristics of multijoint exercises. Funato et al. (22) further suggested that power output is maximized at higher load conditions in multijoint movements, and they attributed these differences between single-joint exercises and multijoint exercises to "the disproportionate recruitment of many muscle groups in response to the increased load." Therefore, it is recommended that the optimal loads be determined specifically for each multijoint movement that involves different muscle groups.

Siegel et al. (55) found a difference in the optimal load for the highest power production between upper- and lower-body exercises. They reported that peak power output occurred between 50 and 70% of 1RM for the squat exercise and between 40 and 60% of 1RM for the bench press exercise for the same subject group. Additionally, the shapes of the power-load curves were different between upper- and lower-body exercises. They ascribed these differences to different muscle groups used, different range of motion, or different exercise techniques used in the test. Recently, Izquierdo et al. (33) investigated the power-load curves in half squat and bench press exercises in 70 male subjects from different sport events (weightlifting, handball, road cycling, middle-distance running, and control). They revealed that maximal power output was produced at higher load condition (45–60% of 1RM) in half squat than in bench press (30–45%), and these results are in good agreement with that of Siegel et al. (55). Izquierdo et al. (33) suggested that differences observed between upper- and lower-body exercises in power-producing characteristics may be explained by the extremity-related differences in maximal strength, type of training, muscle CSA, fiber-type distribution, and muscle architecture (i.e., muscle length, muscle pennation angle) as well as functional differences according to the joint position and geometry of joint and levers. Another possible explanation for these differences may be that during lower-body exercises (e.g., squat) a larger portion of body mass must be lifted compared with upper-body exercises (e.g., bench press). Therefore, even when lifting the same external resistance in the squat and bench press, it might be necessary to exert more force during the squat to complete the lift because of body mass being an additional load. No matter what the reason for these differences between upper- and lower-body exercises, determining the optimal loads for the highest power output specifically for each upper- and lower-body exercise is recommended.

Ballistic Exercise

Newton et al. (48) investigated the kinematic, kinetic, and electromyographic differences between traditional bench press performed explosively and explosive bench throw in which the load was actually released at the end of the motion, which is classified as a "ballistic" exercise (46). Performance was significantly higher during the explosive bench throw for average velocity, peak velocity, average force, average power, and peak power through the concentric portion, especially during the later phase. This study revealed that such kinematic and kinetic differences were associated with significantly higher average electromyographic differences of muscles involved in the movement during the explosive bench throw compared with the traditional bench press. These differences were attributed to traditional bench press movements in which it is necessary to decelerate the bar toward the end of the range of motion to avoid excessive stress on the joint structures (e.g., ligaments), which could result in injuries. Such a deceleration phase is accompanied by the reduced electric activity of the agonist muscles and probably by the increased activation of the antagonist muscles (46, 48). On the basis of these findings, several investigators have recommended ballistic resistance training as a better training method to improve muscular power and dynamic athletic performance because it limits the problem of deceleration phase and appears more specific to explosive movements observed in the actual sports scene (13, 46–48, 64).

As for the optimal loads in ballistic exercises, Newton et al. (49) found that the highest peak and average power output were produced at 15–30% and 30–45% of 1RM during ballistic bench press throw. In addition, Baker and colleagues (5, 6, 8, 9) demonstrated that the optimal loads are achieved at 50–60% of 1RM during ballistic exercises such as bench press throw and squat jump. However, we know of only 1 research study (13) that compared the optimal loads between traditional resistance exercises and ballistic resistance exercises that involve relatively similar movement patterns and muscle groups (bench press vs. bench throw). Although Cronin et al. (13) found loads of 50–70% of 1RM were superior for generating greater power output during both bench press and bench throw exercises, further research might find differences in the optimal loads that maximize the power output during traditional and ballistic resistance exercises considering the significant differences in kinematics, kinetics, and muscle activation (48).

Olympic Lifts

Olympic-style weightlifting movements are known to produce some of the highest average human power outputs of all the resistance-training exercises (25, 56). For example, a 100-kg male weightlifter produces 3,000 W absolute power output in snatch compared with 1,100 W in squat (56). Because of the potential of these lifts to produce high-power outputs and their movement- and velocity- specificities to many sport activities (e.g., jumping, running, throwing), Olympic-style lifts are considered as some of the best training exercises to maximize dynamic athletic performance (23, 25, 56). The optimal loads to maximize power outputs in Olympic-style exercises appear to be higher compared with traditional resistance exercises (e.g., squat, deadlift). Garhammer (23) suggested 80% of 1RM maximized mechanical power output in Olympic-style lifts. This higher percentage for the optimal loads in Olympic-style lifts may be due to their inherent nature (i.e., high-force and high-velocity movement). However, few studies actually measure power outputs under various load conditions and determine the optimal loads for the maximum power output in Olympic-style exercises. Although Haff et al. (24) investigated power output during midthigh pull at 80%, 90%, and 100% of 1RM and found a general trend of increasing power output as the load was decreased from 100 to 80%, they failed to use lighter loads (<80% of 1RM) and did not find the peak of the power-load curve. Thus, future research might be necessary to measure power outputs against various load conditions during Olympic-style exercises to find the optimal load for the highest power production. Further interest is to investigate whether the optimal loads are different among Olympic-style exercises (e.g., power clean), traditional exercises (e.g., squat), and ballistic exercises (e.g., squat jump) by the same subject group. In addition, as suggested by Baker et al. (8), examining whether competitive lifters attain the highest power output at different percentage of 1RM compared with athletes other than weightlifters (e.g., sprinters, football players, shot putters) would provide useful information for athletes and coaches.

Strength Level of Athlete

Besides the nature of the exercise, the strength level or training history of the athlete could also affect the optimal load. Stone et al. (59) found that stronger subjects produced the maximal power output at higher percentage of maximum load (40% of 1RM) than did weaker subjects (10% of 1RM) in squat jump and suggested that an upward shift in the optimal load may be present as maximum strength levels of subjects increase. On the other hand, Baker (5, 6) demonstrated the contrary results suggesting that stronger athletes used lower percentages of 1RM than did the weaker athletes to attain the maximum mechanical power output during bench press throw and jump squat. Observing these research results about the relationship between the optimal load and the subject's strength level or training history, training could be expected to shift the percentage of maximum strength at which the highest power is produced (i.e., the optimal load) either upward or downward. That is, optimal loads are sensitive to and possess more complicated adaptation mechanisms to training demands. For example, Duchateau and Hainaut (18) demonstrated the optimal load shifted from 35 to 41% of maximum isometric strength after 3 months of isometric training. Although more research is required, frequent measurement of the optimal load may provide useful information concerning the strength and power levels of athletes, effects of specific training, athletes' adaptation to specific training, and training status of athletes (44).

Training Status of Athlete Within Yearly Training Cycle

The loads that maximize mechanical power output could fluctuate even within a yearly training cycle in response to the type of training undertaken and depending on where the athlete is located within the macrocycle (6). Baker (4) suggested that the optimal load shifts toward higher percentage of 1RM during phases that emphasize strength-oriented training (i.e., training with high resistance and low velocity) and toward lower percentage during phases that emphasize speed-oriented training (i.e., training with low resistance and high velocity). On the basis of this, Newton and Dugan (44) proposed the measure of the optimal load as a useful tool to monitor the effects of manipulating training emphasis in a periodized training program and to detect overtraining. Unfortunately, there is a lack of scientific research that investigated the fluctuation of the optimal load within a yearly or macrocyle-length periodized training program. Furthermore, we do not know of any research that examined the relationship between the changes of the optimal load and the markers of overtraining (e.g., testosterone/cortisol ratio, decreased performance); thus, further research is warranted.

Exercise Selection for Muscular-Power Development

In addition to intensity or load of training, exercise selection is also important when considering training programs for muscular-power development because exercise selection would dictate the mechanical specificity of training. Mechanical specificity refers to kinetic and kinematic similarity of a training exercise to the actual athletic performance. Such kinetic and kinematic variables include, but are not limited to, force and power exerted, RFD, velocity of movement, movement pattern, type of muscle action, range of motion, and duration of movement (11, 21, 46, 60). It is suggested that the degree of transfer of training effects is high when the training exercise is mechanically specific or similar to the actual performance (60). Therefore, although various exercise modalities are available, athletes and coaches should select training exercises as similar as possible to the actual athletic performance of their own events.

Because most athletic activities are multijoint movements rather than isolated-joint movements (e.g., running, jumping, throwing), it seems appropriate to choose multijoint exercises as training modality for power development and for athletic-performance enhancement (46, 60). Other rationales for the favorable use of multijoint exercises over single-joint exercises are ideas that muscles act as functional task groups rather than as an isolated apparatus and that intra- and intermuscular coordination of movement pattern, which probably is improved through multijoint or complex movements, is an important factor contributing to high-power output (3, 46, 47, 60). In addition, a particular problem limits the use of single-joint exercises for power development: When athletes try a rapid and powerful movement in a single-joint exercise, they have to decelerate the implement or limb toward the end of the range of motion in order to prevent excessive stress on the joint structure, which inhibits high-power output (46). Although this problem is inherent not only in single-joint exercises but also in traditional multijoint exercises such as bench press, it could be overcome by ballistic exercises (e.g., bench press throw, squat jump), which allow the acceleration throughout the range of motion without the risk of injuries (48). Therefore, ballistic exercises are considered to be favorable training exercises for power development. In addition, Olympic-style lifts and their derivatives (e.g., power clean, snatch) are also considered the best training exercises to maximize muscular power and dynamic athletic performance because they are multijoint exercises, they do not have the problem of deceleration phase, and they produce some of the highest average human power outputs of all the resistance-training exercises (23, 25, 56).

On the basis of the ideas mentioned above, investigators suggest that athletes include multijoint ballistic exercises or Olympic-style lifts and their derivatives that are mechanically specific to the actual athletic movements in their training programs to develop muscular power and enhance dynamic athletic performance. However, it is not our intention to be against the use of traditional resistance exercises such as squat and bench press. Investigators strongly believe in the importance of these exercises to improve maximum strength, which would contribute to the muscular-power development (7, 59). We suggest the use of different types of exercises (e.g., traditional, ballistic, Olympic-style exercises) in a logical sequence to enhance muscular power and a wide variety of athletic performances (31, 46, 60). This concept will be discussed further in the next section.

CONSIDERATION IN PROGRAM DESIGN FOR MUSCULAR-POWER DEVELOPMENT

Based on the load, velocity, and mechanical specificity of muscular-power development, it appears plausible to train continually at the load that maximizes mechanical power output in order to improve maximal muscular power. However, Baker (5) recommended that athletes train with the loads that are a little lighter than the optimal load that maximizes power output, and that the optimal load should be used only in the last few weeks of a training cycle. In addition, he criticized the dogmatic prescription of only 1 optimal power load for the development of muscular power. Monotonous power training, which uses the same relative intensity (percentages of 1RM) and the same resistance exercise over a long period of time without any variation, could result in overtraining in which the athletes' performance deteriorates and takes several weeks or even months to fully recover (57). Therefore, periodization of training programs is important for the optimum muscular-power development. In fact, several investigators have demonstrated and insisted the superiority of periodized training programs, in which the training emphasis is initially on the general strength with the later emphasis on the more specific power development, compared with nonperiodized training programs with no or little variation (31, 56, 58, 61, 62).

In addition to periodization, a combined training method has also been proven useful to develop muscular power and a wide variety of athletic performances (2, 14, 27, 31, 38–40, 45, 46). This combination could be heavy resistance/plyometric training (2, 38), heavy resistance/explosive-type resistance training (27, 31, 40), heavy resistance training/sports-specific task (14, 39), or explosive-type resistance training/sports-specific task (14). The superiority of a combined training method is supported by cross-sectional study. McBride et al. (40) compared strength and power characteristics of Olympic lifters, power lifters, and sprinters who are considered to be involved in high-force/high-velocity, high-force/low-velocity, and low-force/high-velocity training protocols, respectively. In the study, Olympic lifters, who use both heavy resistance training and explosive-type resistance training, achieved better results in jump height and muscular-power measures than did power lifters who use only heavy resistance training. This result indicates that both heavy resistance and explosive-type resistance training should be included in resistance-training programs to develop muscular power and athletic performance. Newton and Kraemer (46) suggested a more multifaceted combined training approach that addresses various components of explosive muscular power (e.g., maximum strength, RFD capability, reactive strength, coordination), and such combined or mixed method seems important. For example, RFD capability is considered to contribute significantly to power production, especially when movement lasts for only a short time (e.g., less than 250 milliseconds) (46, 53, 66), and training RFD could increase muscular power. In addition, muscle hypertrophy is also considered important in muscular-power development because hypertrophy of trained muscle contributes to development of maximum strength, which is related to muscular power (43, 59, 63). However, just adding various training methods to the training program to train all the components of explosive power at one time might lead to the increased training volume, and, as a consequence, overtraining may occur. Additionally, the development of some fitness components (e.g., maximal strength) should be a prerequisite to the development of other components (e.g., speed strength, power) (17). Therefore, it is crucial to train different components in the logical sequence (i.e., periodization) so athletes can maximally develop muscular power toward the end of a macrocycle or a yearly cycle, when the most important competitions are scheduled, while minimizing the risk of overtraining or injuries. In fact, this idea is supported by some of the previous studies (17, 31, 58, 61).

Harris et al. (31) investigated the effects of high force, high power, and combined weight-training methods on various athletic-training variables. The high-force training group performed heavy resistance training for 9 weeks. The high-power training group performed explosive-type resistance training with the loads that maximized power output for 9 weeks. The combination training group performed a similar training program to that of the high-force training group for 5 weeks and then switched to high-force/high-velocity training protocol for the last 4 weeks. In addition, the combination training group further incorporated the factor of periodization (i.e., heavy and light day within a microcycle, or a week). The result of the study demonstrated that combination training with periodization improved a wider variety of athletic-performance variables that require strength, power, and speed. Although more research is required, it appears crucial to design training programs that include periodization and combined training strategy in order to maximize power development and a wide variety of performance variables without high risks of overtraining or injuries (25, 31).

The following is a list of directions for future research:

- Examine if high RFD results from traditional resistance exercises (e.g., squat, bench press) in which relatively heavy resistance is lifted with an intention to move loads as rapidly as possible.
- Further investigate the relationship between maximum strength and power output against different external loads.
- Compare the optimal loads between traditional resistance exercises and ballistic resistance exercises (e.g., squat vs. squat jump).
- Measure power outputs under various load conditions and determine the optimal loads for maximum power output in Olympic-style exercises and related exercises.
- Investigate whether the optimal loads are different between Olympic-style exercises (e.g., power clean) and ballistic exercises (e.g., squat jump).
- Examine if competitive lifters attain the highest power output at different percentages of 1RM compared with athletes other than weightlifters (e.g., sprinters, football players, shot putters).
- Investigate the relationship between the maximum strength level and the optimal load that maximize power output.

- Investigate the fluctuation of the optimal load within a yearly or macrocyle-length periodized training program.
- Examined the relationship between the changes of the optimal load and the markers of overtraining (e.g., testosterone/cortisol ratio, decreased performance).
- Investigate the effects of combined and periodized training programs on various strength/power measures and athletic-performance variables.

CONCLUSIONS

The ability of neuromuscular systems to produce high-power output is one of the most important fitness components in sport performance. Although there is a controversy among investigators and coaches concerning the training loads that should be used to develop muscular power, many research results indicate the existence of load and velocity specificity for the muscular-power adaptation. Therefore, athletes are suggested to select the training loads so that they can improve the ability to develop power against a specific resistance that they often encounter in their athletic events. Training with the optimal load that maximizes mechanical power output is strongly recommended, especially to improve maximum muscular power or muscular power over a wide range of loads. However, inconsistent results have been reported about the load that produces the highest power output. Because no single optimal load is applicable to any exercise, to any athlete, and in any situation, the optimal loads should be determined specifically according to the nature of the exercise, the experience of the athlete, and the training status of the athlete within a yearly cycle. Accordingly, it might be necessary to assess each athlete's strength and power qualities for each exercise or movement with sufficient frequency to determine strength and power-development level of athletes, to increase training efficiency by prescribing the appropriate training loads, and to minimize the possibility of injuries. Next, training programs should be designed and manipulated properly based on such information with a periodized and combined training approach, which seems to develop muscular power and dynamic athletic performance to a greater extent than do any other training strategies.

PRACTICAL APPLICATIONS

The literature reviewed indicates the load- and velocity-specific adaptations in muscular-power development. Therefore, athletes should train with the loads and velocities similar to those encountered in the actual sport activities to improve athletic performance on the field. Additionally, biomechanical and physiological needs analysis might be useful to provide information on load ranges that should be used in resistance training and on exercise selection. Furthermore, training with the optimal load is especially recommended to develop maximum muscular power or muscular power against a wide range of resistances. Frequent measurement and determination of the optimal loads might be necessary to provide appropriate stimuli to the neuromuscular system and might provide useful information about the effect of training programs, training status of athletes, and so on. In addition, athletes and coaches are strongly encouraged to incorporate the idea of periodization and combined training strategy into their training programs.

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