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Developing Maximal Neuromuscular Power

Part 1 – Biological Basis of Maximal Power Production

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Abstract

This series of reviews focuses on the most important neuromuscular function in many sport performances, the ability to generate maximal muscular power. Part 1 focuses on the factors that affect maximal power production, while part 2, which will follow in a forthcoming edition of *Sports Medicine*, explores the practical application of these findings by reviewing the scientific literature relevant to the development of training programmes that most effectively enhance maximal power production. The ability of the neuromuscular system to generate maximal power is affected by a range of interrelated factors. Maximal muscular power is defined and limited by the force-velocity relationship and affected by the length-tension relationship. The ability to generate maximal power is influenced by the type of muscle action involved and, in particular, the time available to develop force, storage and utilization of elastic energy, interactions of contractile and elastic elements, potentiation of contractile and elastic filaments as well as stretch reflexes. Furthermore, maximal power production is influenced by morphological factors including fibre type contribution to whole muscle area, muscle architectural features and tendon properties as well as neural factors including motor unit recruitment, firing frequency, synchronization and intermuscular coordination. In addition, acute changes in the muscle environment (i.e. alterations resulting from fatigue, changes in hormone milieu and muscle temperature) impact the ability to generate maximal power. Resistance training has been shown to impact each of these neuromuscular factors in quite specific ways. Therefore, an understanding of the biological basis of maximal power production is essential for developing training programmes that effectively enhance maximal power production in the human.

Maximal power describes the highest level of power (work/time) achieved in muscular contractions.[1] From an applied perspective, maximal power represents the greatest instantaneous power during a single movement performed with the goal of producing maximal velocity at take-off, release or impact.[2,3] This encompasses generic movements such as sprinting, jumping, changing direction, throwing, kicking and striking and therefore applies to the vast majority of sports. Empirical evidence supported by previous research has shown that superior ability to generate maximal power typically results in enhanced athletic performance.[2-6] A series of interrelated neuromuscular factors contribute to maximal power production. These factors, as well as any evidence of adaptations to these factors following training, will be discussed in part 1 of this review. Part 2, which will follow in a forthcoming edition of *Sports Medicine*, will explore the scientific literature relevant to the development of training programmes that most effectively improve maximal power production in dynamic athletic movements.

The search for scientific literature relevant to this review was performed using US National Library of Medicine (PubMed), MEDLINE and SportDiscus® databases and the terms 'maximal power' and 'muscular power'. Relevant literature was also sourced from searches of related articles arising from the reference list of those obtained from the database searches. The studies reviewed examined factors that could potentially influence the production of maximal muscular power.

1. Muscle Mechanics

1.1 Force-Velocity Relationship

The force-velocity relationship represents a characteristic property of muscle that dictates its power production capacities. Various levels of organization have been used to study the relationship including molecular and single-cell levels, whole muscle and multi-muscle movements, as well as single and multi-joint movements.[7-13] Regardless of the approach, the characteristic hyperbola (figure 1) can be used to describe the

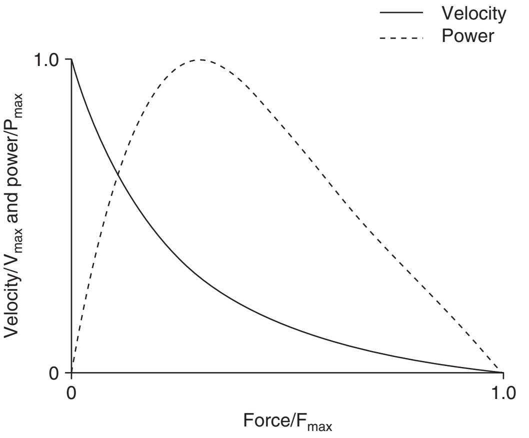

Fig. 1. The force-velocity and force-power relationships for concentric contractions of skeletal muscle. Force, velocity and power are normalized to the maximum isometric force (F_{max}), maximum velocity of shortening (V_{max}) and maximum power output (P_{max}), respectively.

inverse relationship between the force and velocity during concentric muscle contraction.[14] As the velocity of concentric muscle action is increased, less force is capable of being generated during that contraction. This is true for a given muscle or muscle group activated at a constant level as is due to actin-myosin cross-bridge cycling. Specifically, because it takes a fixed amount of time for cross-bridges to attach and detach, the total number of cross-bridges attached decreases with increasing velocity of muscle shortening. Due to the fact that the amount of force generated by a muscle depends on the number of attached cross-bridges, force production decreases as the velocity of the contraction increases and power, therefore, is maximized at a combination of submaximal force and velocity values.[15] Although the force-velocity relationship was first defined using isolated frog sartorius muscle,[14] all human movements are similarly limited by this fundamental property of muscles.[7,8,10-12,16,17] Maximal muscular power is therefore determined by the parameters of the force-velocity relationship: maximal isometric force (F_{max}), maximal velocity of shortening (V_{max}) and the degree of curvature (defined by a/F_{max} or b/V_{max}). Improvements in maximal power output of a muscle can be achieved through increasing F_{max} or V_{max} and/or decreasing the degree of curvature. Measurements of the force-velocity relationship during movements *in vivo* (more accurately termed load-velocity or torque-angular velocity relationship but referred to as force-velocity relationship throughout to prevent confusion) are complicated by mixed fibre composition,[16,18,19] architectural characteristics,[20,21] anatomical joint configuration[16] and levels of neural activation.[7,21-24] Despite these limitations, examination of the force-velocity relationship during such movements quantifies the ability of the intact neuromuscular system to function under various loading conditions. This information is essential in understanding maximal power production during human movements.

1.2 Length-Tension Relationship

The ability of skeletal muscle to generate force is critically dependent on sarcomere length.[25-27] The greatest potential for force production on activation of the cross-bridge cycle exists when the sarcomere length provides for optimal overlap between the actin and myosin filaments (described as the 'optimal length'). At this length, cross-bridge interaction is maximal, which allows for the greatest levels of active tension development.[25-27] Force production is impaired when sarcomere lengths are shortened below the optimal length due to overlap of the actin filaments from opposite ends of the sarcomere and the compression of the myosin filament as it comes in contact with the Z-disk.[15] Stretching a sarcomere beyond the optimal length also reduces the force production capacity. At longer lengths, cross-bridge interaction is decreased as a result of less overlap between actin and myosin filaments.[25-27] *In vivo* research has demonstrated that resting muscle lengths are generally slightly shorter than the optimal length[28] and, therefore, muscular force may be increased with a slight stretch prior to activation. While muscular power is defined by the force-velocity relationship, the length-tension relationship influences the ability of muscle fibres to develop force and, therefore, plays an important role in maximal muscular power production.

1.3 Type of Muscle Action

The ability of muscle to generate maximal power is influenced by the type of action involved; eccentric or concentric contractions as well as actions involving the combination of eccentric, isometric and/or concentric contractions.[29] Muscle function required in natural human movement rarely calls for the use of these muscle actions in isolation. The successive combination of eccentric and concentric actions forms the most common type of muscle function and is termed the stretch-shortening cycle (SSC).[29,30] When a muscle fibre is activated, stretched, then immediately shortened, the force and power generated during the concentric action is greater than a concentric-only contraction.[31,32] Therefore, maximal muscular power is superior in movements involving a SSC.[17,33-40] While there is a consensus within the literature regarding the potentiating effect of a SSC on performance, the mechanisms responsible for improved performance during SSC movements are an issue of debate amongst researchers.

1.3.1 Time Available to Develop Force

One of the proposed mechanisms driving the superior maximal power output observed during SSC compared with concentric-only movements is based on the fact that it takes time for muscle to generate force (due to time constraints imposed by stimulation, excitation and contraction dynamics[41]). The eccentric action during a SSC movement allows time for the agonist muscles to develop considerable force prior to the concentric contraction. In contrast, the concentric contraction starts as soon as force development (beyond that which is required to maintain a static position) begins in concentric-only movements. An alternate view of this same principle is that SSC contractions have enhanced power generation capability due to the greater distance over which force can be developed compared with concentric-only movements (i.e. based on the work-energy relationship). Hence, force during the concentric phase is greater in SSC movements, subsequently resulting in superior performance.[42-46] However, power output was observed to be higher in a SSC movement compared with a concentric-only movement immediately preceded by a maximal isometric action,[47] indicating that the time available to develop force is not the only factor contributing to enhance muscular power.

1.3.2 Storage and Utilization of Elastic Energy

The most generally reported mechanism believed to drive the SSC-induced enhancement of maximal power is the storage and utilization of elastic energy.[48] When an active muscle-tendon unit (MTU) is stretched, mechanical work is absorbed by the MTU and this work can be stored in part as potential energy in the series elastic component (SEC; includes fibre cross-bridges, aponeurosis and tendon).[31,34,49] It is believed that some of this potential energy can then be used to increase the mechanical energy and positive work during the following concentric contraction.[17,31,33,34,36,49] This recoil of the SEC is thought to contribute to the increased force at the beginning of the concentric phase in SSC movements and ultimately to enhanced maximal power production.[17,31,33,34,36,49]

1.3.3 Interactions of Contractile and Elastic Elements

In SSC movements, the interactions between the contractile and elastic elements play an important role in enhancing maximal performance. Tendinous recoil has been shown to influence the contribution of the contractile component of work produced during SSC movements.[50-52] Higher force at the beginning of the concentric phase during SSC movements results in greater tendinous lengthening with less fascicle lengthening.[53-57] As the concentric contraction progresses, the muscle fibre contracts at a nearly constant length (i.e. isometric), while the rapid shortening of the MTU largely depends on the shortening of the tendinous structure.[53-57] In contrast, while some tendinous displacement does occur, the majority of the MTU length change during concentric-only movements is due to fascicle shortening.[54] The minimal displacement of muscle fibres during the concentric phase of SSC movements is believed to be caused by the catapult action of the tendinous structures (i.e. lengthening-shortening behaviour).[58]

These interactions may influence performance in three distinct ways. First, elastic energy would be stored predominantly in the tendinous structures and therefore can be utilized with minimal dissipation via the tendon recoil during the concentric phase.[58,59] Second, the minimal displacement of muscle fibres during SSC movements means that they operate closer to their optimal length and, based on the length-tension relationship, can therefore produce more force.[53,55,56] Finally, while the net shortening velocity of the MTU is high, fascicle length change occurs at relatively slow velocities. Thus, fascicles are able to generate high forces according to the force-velocity relationship.[60] Therefore, during SSC movements, the contractile element acts as a force generator producing high forces at relatively low shortening velocities, while the tendinous structures act as an energy re-distributor and power amplifier.[60] The interaction of these components is vital in SSC movements because it allows for the muscle-tendon complex to generate superior maximal power output.

1.3.4 Potentiation of Contractile and Elastic Filaments

The potentiation of the actin-myosin cross-bridges is another mechanism thought to contribute to the SSC-induced enhancement in maximal power output.[34,47,50,61] In tetanized isolated muscle and single muscle fibres, an active stretch has been observed to enhance work output of the contractile machinery during subsequent shortening,[32,62-64] a finding supported by *in vivo* studies involving intact muscle-tendon complexes.[34,47,61] This potentiating effect is thought to be due to enhanced force production per cross-bridge rather than an increase in the number of active cross-bridges.[62,64] Woledge and Curtin[65] proposed that strained cross-bridges are detached in a state that permits them to re-attach more rapidly than cross-bridges not exposed to a pre-stretch. While suggestions have also been made that some cross-bridges may be left in a highly strained state after the stretch, it is not currently known precisely how the force per cross-bridge is enhanced.[61] Despite the convincing *in vitro* evidence, the extent to which the potentiation of the contractile filaments influences *in vivo* SSC performance has been questioned.[66] *In vivo* observations of isometric (rather than lengthening) action of muscle fascicles during a stretch[54,55] cast doubt on the possible contribution of force potentiation to enhanced SSC performance *in vivo*. Additionally, the potentiation of elastic filaments such as titin and/or nebulin has been proposed as another possible mechanism contributing to enhanced force production following an active stretch.[67-70] It has been theorized that an active stretch may be associated with a calcium-dependent increase in titin stiffness, which in turn contributes to enhanced force production compared with a non-activated stretch.[67-70] However, a recent investigation suggests that enhanced force production in the absence of actin-myosin overlap cannot be explained by calcium-induced stiffening of titin and proposes cross-bridge force-dependent titin-actin interactions to be responsible for non actin-myosin-based force enhancement observed following an active stretch.[71] Indeed, further research is required to establish if, and to what extent, potentiation of contractile and elastic filaments occurs during SSC movements *in vivo* as well as the relative contribution of this effect to maximal muscular power.

1.3.5 Stretch Reflexes

Another mechanism proposed to contribute to the enhanced maximal power output during SSC movements is the activation of spinal reflexes. The forced lengthening of the MTU during the eccentric phase of SSC movements causes a mechanical deformation of the muscle spindles, which activates reflex mechanisms (stretch reflexes of α-motoneurons).[72] The stretch reflex subsequently increases muscle stimulation, resulting in increased contraction force during the concentric phase and ultimately contributes to enhanced maximal power output.[37,39,73-78] Despite some reservations, the consensus within the literature appears to be that SSC movements do evoke a stretch reflex of sufficient magnitude to contribute to the increase in muscular force during the concentric phase.[37,39,48,73-75,77] Therefore, the development of maximal power during SSC movements may be influenced in some degree by the activation of stretch reflexes.

1.3.6 Effect of Training on Stretch-Shortening Cycle Function

The beneficial effects of resistance training on SSC performance has been well documented.[79-84] However, to date, no conclusive evidence exists identifying how the aforementioned mechanisms contributing to enhanced SSC performance are affected by training. Several speculative theories exist but further research is required to identify the adaptations driving training-induced improvements in SSC performance.

2. Morphological Factors

The ability to generate maximal power during a movement is dictated by the contractile capacity of the muscles involved. The contractile capacity of muscle is influenced by a series of morphological factors but primarily its fibre type composition and architectural features. Additionally, the properties of tendon influence the function of the contractile elements within the MTU and therefore impact maximal power production.

2.1 Muscle Fibre Type

Due to the unique characteristics of each fibre type, the force-velocity properties of a muscle are determined by the fibre type contribution to whole muscle area.[8,12] Type II fibres have a greater capacity to generate power per unit cross-sectional area (CSA).[8,12,19,85-87] In an investigation of single fibres from the vastus lateralis, peak power per unit CSA was observed to be 5- and 10-fold greater in type IIa and IIx fibres, respectively, when compared with type I fibres.[87] However, these contractile properties were measured as sub-physiological temperatures (15°C) and thus may not reflect function *in vivo*.[88] Examination of results of studies using closer to *in vivo* muscle temperatures suggest that the differences in peak power per unit CSA are smaller than those observed at lower temperatures. In a study specifically addressing this issue, the propelling velocity of actin filaments by myosin from human muscle fibres was only 2-fold greater with type IIx versus type I myosin when measured at 35°C, compared with a 7.5-fold difference at 15°C.[88] In a rare study measuring the contractile properties of intact human muscle fibres at 37°C, bundles of type II fibres were found to have a 3-fold greater V_{max} and a 4-fold greater maximum power output (P_{max}) than bundles of type I fibres.[19] The differences in peak power per unit CSA are due to differences in specific force (i.e. F_{max}/CSA), V_{max} and the curvature of the force-velocity curve amongst the fibre types.[13,15,19,87] Using single fibre preparations, type II fibres have been observed to have significantly greater specific force than type I fibres.[13,87,89] Similar findings have been observed in whole skeletal muscle investigations (i.e. muscles composed mainly of type II fibres vs mainly type I fibres) although this is a somewhat controversial area in muscle physiology.[15] However, differences in V_{max} are theorized to have a much more pronounced influence on the difference in P_{max} values between fibre types.[15] Type II fibres are characterized by high sarcoplasmic reticulum and myofibrillar adenosine triphosphatase (ATPase) activities, and correspondingly high V_{max} and short contraction time/twitch duration (i.e. the heads of type II myosin isoforms split ATPase approximately 600 times/second vs approximately 300 times/second for type I myosin isoforms).[90-94] This allows for a short cross-bridge cycle time and, therefore, the ability to develop force rapidly. In contrast, type I fibres display comparatively low ATPase activity and V_{max} with long contraction times/twitch durations.[90-94] For example, V_{max} has been shown to vary from approximately 0.8 fibre lengths/second in type I fibres to approximately 3.5 fibre lengths/second and 5.6 fibre lengths/second in type IIa and IIx fibres, respectively[86,95,96] (note these investigations used sub-physiological temperatures and thus may not reflect function *in vivo*[88]). When this literature involving single fibre preparations is collated, a continuum of V_{max} (relative to fibre length) and P_{max} (relative to CSA) for the fibre types is evident as follows $IIx > IIa > I$. Furthermore, investigations of bundles of fibres reported a greater a/F_{max} ratio in type II versus type I fibres, indicating a greater degree of curvature of the force-velocity curve, and thus lower power output, for type I fibres.[19,94]

Therefore, the maximal power output of a muscle is influenced by its fibre type composition. Muscles with a high percentage of type II fibres display greater P_{max} in comparison to muscles with a high percentage of type I fibres.[8,12,97] However, future research is required in order to determine the magnitude of differences in P_{max} as well as V_{max} between fibre types and subtypes at physiological temperatures in intact fibres.

Cross-sectional comparisons have revealed that elite strength-power athletes have predominately type II fibres, whereas elite endurance athletes display a predominance of type I fibres.[98,99] While approximately 45% of the variance in muscle fibre type is believed to be associated with inherited factors,[100] findings of fibre type transformations from type I to II (and *vice versa*) after periods of intense training[101-105] and detraining[106,107] indicate plasticity in fibre type composition based on environmental conditions.[100] However, transformations between type I and II fibres have been debated throughout the literature and further research is required to understand the precise conditions under which they occur.[15] Additionally, resistance training has been shown to elicit transformations in myosin heavy chain gene expression within type I and II fibres. Transformations in type II subtypes have occurred following strength training whereby type IIx isoforms are reduced at the expense of an increase in the expression of type IIa isoforms.[87,108-110] When a muscle is chronically stressed with high loading requirements, it is theorized that the contractile protein properties are shifted to a more economical cross-bridge cycling system (i.e. increased oxidative capacity allowing for sustained power output over a longer period).[111,112] This shift in type II subtypes may be detrimental to P_{max} but is compensated for by the preferential hypertrophy of type II fibres following strength training (discussed further in section 2.2.1). Interestingly, a period of detraining following strength training has been observed to evoke an 'overshoot' in type IIx composition that is markedly higher than values observed prior to the strength training.[110] However, the influence of ballistic power training on possible myosin heavy chain isoform shifts is unclear, with conflicting reports of strong trends towards transformations from type IIx to IIa[86,113] and no such changes following training.[114,115] Further research is required to elucidate exactly how muscle fibre subtypes respond to ballistic power training. It is important to note that even if transformations between muscle fibre types and/or subtypes did occur, the contribution to improving maximal muscular power would be relatively small compared with alterations in other morphological properties (i.e. CSA or architectural characteristics).[15] Additionally, contractile properties can also improve following training without apparent changes in fibre type or subtype proportions. For example, Malisoux and colleagues[86,116] reported increases in V_{max} of all fibre types following plyometric training as well as improvements in several functional performance measures despite an increase in type IIa at the expense of IIx. Further research is necessary to determine the degree of training-induced adaptations in contractile properties evident across the fibre types and subtypes at physiological temperatures.

2.2 Muscle Architecture

2.2.1 Cross-Sectional Area

The maximal force generated by a single muscle fibre is directly proportional to its CSA, irrespective of the fibre type.[1,18,117-119] Due to the fact that power is heavily influenced by F_{max}, a muscle fibre with greater CSA can therefore generate higher P_{max}.[16,86,87,120] A comparison of single muscle fibres between sedentary men and men involved with regular resistance training for 7.6 ± 1.6 years highlights these findings.[120] The resistance-trained men had significantly greater CSA, F_{max} and P_{max} for type I and type II fibres compared with the sedentary men. However, the differences between the groups were no longer evident when F_{max} was normalized to CSA and P_{max} was normalized to fibre volume (which accounts for differences in both fibre CSA and length).[120] Evidence from single fibre studies is supported by research demonstrating that maximal voluntary isometric force is proportional to whole-muscle CSA.[121-123] For example, using CT scans to assess muscle CSA, Maughan and associates[123] reported significantly higher F_{max} in muscles with greater CSA. The F_{max}-to-CSA ratio was not significantly different between experienced strength-trained subjects and untrained controls, suggesting that variation in CSA accounted for the majority of the differences seen in F_{max}.[123] Strong relationships have also been reported between knee extension F_{max} and quadriceps CSA in both men ($r = 0.71$) and women ($r = 0.76$).[124,125] However, it is important to note that not all of the variation in whole-muscle F_{max} can be explained solely by variation in muscle CSA.[126] Factors such as neural drive,[127-129] fibre-type composition,[130] pennation angle[131] and the lever system through which F_{max} is measured[132] may also contribute.

In response to training, changes to F_{max} of single muscle fibres are proportional to changes in fibre CSA.[96,120,133] Increases in fibre CSA are brought about through increases in the size and number of myofibrils within the muscle fibre.[111,134,135] These hypertrophic adaptations occur in both type I and II muscle fibres in response to heavy strength training but to a greater degree in type II fibres.[109,136-141] Extensive research has established that heavy strength training is a very effective stimulus for eliciting a hypertrophic response in muscle.[87,109,112,124,129,131,142,143] Training-induced increases in CSA or F_{max} are typically accompanied by improvements in maximal muscular power.[10,16,84,86,87] However, much of this research involved relatively untrained subjects with low to moderate strength levels, in which improvements in muscular function are easily invoked. Increases in CSA following heavy strength training of stronger/more trained individuals are expected to be lower and take longer.[128] Therefore, the possible influence of increased CSA on muscular power is theorized to diminish as the training age of the athlete increases. Furthermore, the degree of muscle hypertrophy is highly dependent on the type of training and the specific programme variables (i.e. intensity, volume and frequency).[144] The relatively lighter loads used during ballistic power training are typically too small to elicit the necessary mechanical stimulus required to initiate a significant hypertrophic response.[144-150] However, observations of hypertrophic responses following plyometric training[86,151,152] indicate that further research is necessary to determine the important variables in plyometric and/or ballistic training that may elicit an increase in CSA (i.e. significant eccentric component to plyometrics, volume or time under tension, etc.). Consequently, increases in maximal muscular power mediated by improved CSA are achieved primarily through heavy strength training and, typically, not (or markedly less) in response to specific power training.

2.2.2 Fascicle Length

While sarcomere V_{max} differs quite significantly between various fibre types, the V_{max} of a muscle fibre is proportional to its length (assuming a constant level of activation).[16,18,118,153-155] For example, if a sarcomere shortens at two fibre lengths per second, a fibre containing ten sarcomeres in series would have a greater V_{max} than a fibre containing five sarcomeres in series (i.e. 20 vs 10 fibre lengths/second). Due to the fact that power is heavily influenced by V_{max}, a longer muscle fibre can therefore generate higher P_{max}.[16,18,118,153] Correlational studies have reported significant relationships between fascicle length of vastus lateralis and gastrocnemius lateralis and 100 m sprint time in both men and women ($r = -0.43$ to -0.57).[156,157] Furthermore, cross-sectional investigations have revealed the fascicle lengths of the vastus lateralis, gastrocnemius medialis and gastrocnemius lateralis to be significantly longer in sprinters compared with long-distance runners and untrained controls.[158] However, it is unclear if these observations are a result of genetic predisposition or if fascicle lengthening is an adaptation to the modalities of training commonly used by sprinters (i.e. high-intensity sprint training and high-intensity strength/power training). Regardless of the origin of this architectural difference, these data indicate the importance of relatively longer fascicle lengths to rapid force-generation and maximal power production during dynamic movements.

The adaptive response of fibre length following training is not well understood. Animal models have been used to investigate fibre length change following various training interventions but have returned inconclusive results.[159-161] Fascicle length in humans has been measured as an indicator of fibre length but the current literature offers little additional insight into the influence of training on fibre length. Training studies have reported fascicle length to increase in response to resistance training with heavy loads,[142,162-164] resistance training with light loads,[165] as well as in subjects who ceased strength training and performed jump and sprint training.[142] In contrast, an effective heavy strength training programme of the elbow extensors had no effect on fascicle length of the triceps brachii,[166] a finding supported by similar studies involving the lower body musculature.[167,168] While some of these changes were coupled with improvements in performance, it is unknown exactly how the changes in fascicle length affected muscle V_{max} or P_{max}. Further research is required to elucidate the most effective training stimulus for longitudinal growth of muscle fibres. Furthermore, while the addition of sarcomeres in series is theorized to occur through similar pathways as the addition of sarcomeres in parallel, factors determining which type of muscle growth occurs are unknown (the interested reader should refer to Blazevich and Sharp[169] for a more detailed discussion).

2.2.3 Pennation Angle

The pennation angle of a muscle, defined as the angle between the muscle's fascicles and the line of action,[155,170,171] has important physiological effects on the force-velocity relationship and thus P_{max}. As pennation angle increases, more sarcomeres can be arranged in parallel (i.e. more contractile tissue can attach to a given area of an aponeurosis or tendon) and the muscle can therefore produce more force.[154,172] Additionally, an increased pennation angle allows for muscle fibres to shorten less for a given tendon displacement due to the rotation of pennate muscle fibres during contraction.[173] This increases the likelihood that a fibre with a greater pennation angle operates closer to its optimum length and, based on the length-tension relationship, is able to generate more force.[173] These factors act to increase F_{max} and, therefore, pennation angle influences the maximal power output generated by a muscle. However, greater pennation angles are also associated with slower contraction velocities and thus, increasing a muscle's pennation angle may negatively impact V_{max}.[155] Despite this, the increase in F_{max} is theorized to have substantially greater impact on maximal power than increases to V_{max} brought about through an increase in pennation angle.[16]

Pennation angle is commonly thought to increase in response to heavy strength training and decrease in response to sprint training. These theories are based on observations of population differences whereby bodybuilders displayed greater pennation angles and CSA than untrained subjects,[174] and highly trained sprinters possessed smaller pennation angles than both lesser trained sprinters[157] and untrained controls.[156] Further support for possible adaptability of pennation angle to heavy strength training stemmed from the significant relationships between muscle thickness (indicative of CSA) and pennation angle in the triceps brachii ($r = 0.81$), vastus laterals ($r = 0.61$) and gastrocnemius medialis ($r = 0.56$) of over 700 people with various training backgrounds.[175] These observations were corroborated by studies involving training interventions in which heavy strength training significantly increased pennation angle,[131,166] while sprint/jump training significantly decreased pennation angle.[142] Increases in pennation angle following heavy strength training were accompanied by increased CSA and F_{max}[131,166] resulting in enhanced P_{max}.[107,110] However, other longitudinal studies have failed to establish pennation angle changes in response to heavy strength training in previously trained[176] and untrained[167,168] people. While the effectiveness of the training protocols implemented and the reliability of the techniques used may have prevented pennation angle changes being discovered, these findings highlight that the effects of heavy strength training on pennation angle are not clearly understood. Furthermore, it is unknown if ballistic power training and other training modalities elicit changes in pennation angle or if changes are influenced by the training status of the subject.

2.3 Tendon Properties

As previously discussed in section 1.3.3, fascicle behaviour is affected by interactions between the contractile and elastic elements of the

MTU.[53-57] The intrinsic compliance of tendon impacts these interactions (i.e. affects the amount of fascicle displacement) and, because a muscle's ability to generate force is both velocity and length dependent, the level of tendon compliance can influence maximal muscular power. Few data currently exist regarding the potential adaptability of tendon compliance in response to exercise[177,178] and the cross-sectional data to date have revealed mixed results.[179,180] Kubo and colleagues[179] reported a negative relationship between sprint performance and tendon compliance ($r = -0.757$) indicating that greater compliance is beneficial for sprint performance. In contrast, Bojsen-Møller and associates[180] observed knee extensor rate-of-force development (RFD) to relate positively to stiffness of the vastus lateralis tendon-aponeurosis ($r = 0.55$), suggesting that less compliance is associated with enhanced muscular performance. Thus, further research is essential in order to determine the specific influence of tendon compliance on maximal power production as to whether this tendon property is amendable to exercise.

3. Neural Factors

The ability to generate maximal power during a movement is not only governed by the muscles morphology, but also by the ability of the nervous system to appropriately activate the muscles involved. The nervous system controls the activation of muscles primarily through changes in motor unit recruitment, firing frequency and synchronization as well as inter-muscular coordination.

3.1 Motor Unit Recruitment

The force produced by a muscle is related to the number and type of motor units recruited. Motor units are recruited in a systematic order during graded, voluntary contractions of increasing force according to the size principle.[181,182] Relatively small α-motoneurons that innervate type I fibres are initially activated at low force levels while progressively larger α-motoneurons that activate type IIa and IIx fibres are typically activated after the slow-twitch motor units at higher thresholds of force.[181-183] The size principle is the general rule of recruitment not only for slow, graded contractions but also for isometric[184] and ballistic contractions.[185,186] However, compared with slow, graded contractions, the threshold of motor unit recruitment is typically lower during ballistic movements due to the rapid force escalation to high levels.[186,187] The maximum force capabilities of a motor unit has been estimated to vary by up to 50 times.[188] Thus, the force capable of being generated during a movement is affected by which motor units are recruited. During contractions typically required for maximal power production, recruitment of high-threshold motor units is very beneficial to force production as they innervate a relatively large number of high RFD/force-producing muscle fibres.[189] Therefore, the ability to rapidly recruit high-threshold motor units influences maximal muscular power.

There are three common theories of adaptation in motor unit recruitment that may occur in response to training. It is hypothesized that training may result in increased motor unit recruitment, preferential recruitment of high-threshold motor units and/or lowering of the thresholds of motor unit recruitment.[128,190] All of these possible adaptations would act to increase agonist activation resulting in increased tension development by the muscle and consequently improved power output.

Observations of increased electromyography (EMG) amplitude following training suggests that a possible adaptation associated with enhanced muscular power may be an increase in the level of motor unit recruitment.[128] However, current techniques are unable to definitively establish whether or not training elicits a true increase in motor unit recruitment as this would require the identification of previously uninvolved motor units that are recruited after training. Methodologies have been implemented to gain an indication of possible training-induced changes to the level of motor unit activation (which encompasses recruitment and firing frequency). These techniques involve the comparison of force produced during a maximal voluntary contraction (MVC) and either a maximal tetanic muscle stimulation, or a supra-maximal stimulus applied to the nerve of a muscle engaged in a MVC (i.e. interpolated twitch technique).[73,191-195] In both of these cases, the stimulus can cause a significant difference in force production between the voluntary and stimulated contractions if all motor units have not been recruited voluntarily (or the firing frequency of the recruited motor units is submaximal, as discussed in section 3.2). Results from early investigations indicated that despite considerable inter-subject variability, full voluntary activation was possible in a variety of muscles during single joint, isometric contractions in untrained but well motivated individuals.[73,128,191-194] Consequently, it was difficult to attribute training-induced increases in EMG to changes in the level of motor unit recruitment. However, advancements in techniques have allowed for more sensitive measurements, which have revealed levels of voluntary activation to range from 85% to 95% of maximum capacity in the quadriceps femoris and 95–100% in a range of other muscles.[195] Despite these differences and the theory that untrained individuals may not be able to consistently recruit the highest threshold motor units, resistance training studies involving healthy adults indicate that maximal voluntary activation does not increase following training.[196-203] It is important to note, however, that these longitudinal studies may have been impaired by use of less sensitive techniques than what are now available, the use of non-specific isometric tests to evaluate the effects of dynamic training, and the small window for improvement in some of the muscles assessed.[195] Furthermore, voluntary activation during maximal dynamic contractions has been shown to be 88–90%, significantly lower than voluntary activation during maximal isometric contraction (95.2%).[204] It may therefore be possible that training results in improved voluntary activation during dynamic movements and especially in more complex, multi-joint sport-specific movements. If future research was to demonstrate this, increased motor unit recruitment (or firing frequency) may in fact contribute to training-induced improvements in maximal muscular power.

The preferential recruitment of high-threshold motor units following training is a somewhat common theory of neural adaptation.[2,205,206] While few exceptions to the size principle exist, it has been theorized that well trained athletes may be able to activate high-threshold motor units in place of low-threshold motor units during ballistic movements in an attempt to enhance maximal muscular power.[2,206] This theory stems from selective recruitment of high-threshold motor units observed during very rapid stereotyped movements in the cat[207] as well as during eccentric[208,209] or electrically induced contractions[210,211] in humans. In one of the only studies to assess this theory, van Cutsem and co-workers[187] observed the orderly motor unit recruitment of the size principle to be preserved during both slow ramp and ballistic contractions following ballistic power training. However, this same study observed that motor units were recruited at lower thresholds after training during ballistic contractions.[187] The post-training recruitment thresholds underwent a significant shift to lower percentages of MVC than those observed during ballistic contractions at baseline and in comparison with a non-training control group. The earlier activation was reported to be likely to contribute to the observed significant increase in the speed of voluntary ballistic contraction.[187] Therefore, increases in maximal power output following training may be due in some part to lower recruitment thresholds during ballistic contractions. While preferential recruitment of type II fibres remains a possibility, the current evidence for it occurring in response to exercise in humans is not convincing. It is important to note that a motor unit is trained in direct proportion to its recruitment,[111] so movements that require the recruitment of high-threshold units must be incorporated into the training programme for changes in recruitment to have an impact on performance.

3.2 Firing Frequency

The motor unit firing frequency represents the rate of neural impulses transmitted from the α-motoneuron to the muscle fibres. The firing frequency of a motor unit can impact the ability of a muscle fibre to generate force in two ways. First, increasing the firing frequency enhances the magnitude of force generated during a contraction. It has been estimated that the force of contraction may increase by 300–1500% when the firing frequency of a motor unit is increased from its minimum to maximum rate.[188] Second, motor unit firing frequency impacts the RFD of muscle contraction. During ballistic contractions motor units have been reported to begin firing at very high frequencies followed by a rapid decline.[212] The high initial firing frequency, which is believed to be associated with an increase in the number of doublet discharges,[187,213] results in increased RFD, even if only maintained for a very short period of time.[214] Therefore, by influencing the force and RFD of muscle contraction, motor unit firing frequency plays a role in the development of maximal muscular power.

Training-induced enhancement of maximum motor unit firing frequency has been proposed as a possible mechanism driving improvements in neuromuscular performance.[215] A cross-sectional examination reported that weightlifters displayed greater maximum motor unit firing frequency during a MVC of the quadriceps compared with untrained controls,[216] thus indicating that training may increase the maximal firing frequency of motor units. As discussed in section 3.1, most resistance training studies involving healthy adults indicate that voluntary activation (which gives an indication of both motor unit recruitment and firing frequency) does not increase following training.[196-203] However, more recent research involving intramuscular EMG has reported training-induced increases in motor unit firing frequency during maximal contractions.[187,217,218] These observations were made following strength training during maximal isometric contractions of the abductor digiti minimi[217] and vastus lateralis[219] as well as during ballistic contractions in the tibialis anterior following ballistic power training.[187] In the two strength-training studies, rapid and pronounced improvements occurred in maximal firing frequency between subsequent testing sessions prior to training, which mirrored improvements in maximal force.[217,218] Maximal firing frequency remained elevated following vastus lateralis training[218] but returned to values similar to those observed at baseline in the abductor digiti minimi after training.[217] van Cutsem and co-workers[187] observed an increase in maximal motor unit firing frequency following 12 weeks of ballistic power training as well as enhanced maximal force and RFD values. These results suggest that increases in maximal motor unit firing frequency may contribute to improved force and power generation especially in the early phases of training.

Perhaps a more important consideration for improved athletic performance is the possible training-induced adaptations to the pattern of motor unit firing frequency and the subsequent impact on RFD. Compared with long-distance runners and untrained controls, Saplinskas et al.[220] observed sprinters to have the highest motor unit firing frequency during the onset of rapid isometric dorsiflexion. This observation was supported by an intervention study that reported the peak firing frequency at the onset of ballistic contraction to increase following ballistic training.[187] Furthermore, these higher firing frequencies were maintained for longer throughout the contraction after training.[187] Additionally, the authors reported a training-induced increase in the percentage of doublet discharges (i.e. a motor unit firing two consecutive discharges in a 5 ms or less interval) at the onset of a ballistic contraction that were reported to contribute to increases in RFD and time to peak force during ballistic contractions.[187] Therefore, ballistic power training may prompt adaptations to the pattern of motor unit firing frequency that contributes to enhanced maximal power production.

3.3 Motor Unit Synchronization

Motor unit synchronization occurs when two or more motor units are activated concurrently more frequently than expected for independent random processes.[221] Although it is yet to be convincingly demonstrated, synchronization has commonly been hypothesized to augment force production and positively influence RFD.[127,222] Furthermore, synchronization is theorized to be a nervous system adaptation that assists with the coactivation of numerous different muscles in order to enhance RFD.[223,224] The manner in which synchronization may influence force or RFD is not readily apparent. No difference in force production has been observed between asynchronous and synchronous motor unit activation at frequencies similar to those observed in MVC and asynchronous discharges of action potentials has been shown to result in greater force production at submaximal firing frequencies.[225,226] Furthermore, voluntary contractions have been shown to produce greater RFD than evoked tetanic contractions in which all motor units are stimulated to fire concurrently.[214] However, synchronization may actually be one of the strategies for inter-muscular coordination and therefore could impact force and/or RFD during complex, multi-joint movements as opposed to isolated, single-joint movements where synchronization does not appear to have a significant impact. It has been hypothesized that synchronization between muscles may be a strategy to simplify and coordinate the activity of muscles in control of mechanically unstable joints (e.g. the medial and lateral vasti muscles and the patellofemoral joint),[224] which would allow for greater transmission of muscular power in complex movements. Therefore, further investigation is required in order to determine if motor unit synchronization contributes to enhanced maximal power production especially during complex multi-joint movements.

Observations from cross-sectional comparisons have led to the theory that motor unit synchronization may improve as a result of training. Using surface EMG, Milner-Brown et al.[221] observed recreational weightlifters to display greater motor unit synchronization in the hand muscles than untrained subjects. This observation was corroborated by Semmler and Nordstrom[227] who, using techniques that measured motor unit discharges directly, demonstrated motor unit synchronization to be significantly greater in strength-trained subjects than both musicians and untrained subjects. In one of the only intervention studies examining motor unit synchronization, Milner-Brown et al.[221] reported a significant improvement in motor unit synchronization (measured by surface EMG) following 6 weeks of MVC training of the hand muscles. However, the validity of using surface EMG to assess motor unit synchronization has been questioned.[228] Therefore, further research is required to elucidate if changes to motor unit synchronization occur in response to training.

3.4 Inter-Muscular Coordination

Inter-muscular coordination describes the appropriate activation (both magnitude and timing) of agonist, synergist and antagonist muscles during a movement. For highly effective and efficient movement, agonist activation needs to be supplemented by increased synergist activity and decreased co-contraction of the antagonists.[190] The coordinated activation of these muscles is required to generate the greatest possible force in the direction of movement.[190] ‘Triple extension’ (i.e. extension of the hips, knees and plantar flexion of the ankles) of the lower limbs typical of jumping and sprinting involves quite complex interaction of uni- and multi-articulate musculotendinous units performing various actions. It is only with precise timing and level of activation and relaxation of the agonists, synergists and antagonists that power flow through the kinetic chain will be optimized, impulse on the ground maximized and, thus, performance in terms of takeoff velocity maximized. Therefore, the ability to generate maximal power output during athletic movements is considerably influenced by inter-muscular coordination.

3.4.1 Activation of Synergists

Synergists play a role in maximal power production and it is possible that improved activation and/or coordination of synergist muscles could contribute to enhanced performance. While there is much evidence of task-specific synergist coordination, little information is available monitoring possible changes to synergist activity brought about by training. While untrained people have been shown to activate agonists quite effectively,[191-193] it is theorized that enhanced activation and/or coordination of synergist muscles may contribute to performance improvements following training and are associated with the superior performance of trained individuals.[229] Furthermore, adaptations in synergist muscles may help explain the increases in force production observed independent of increased neural activation of the agonists, especially during the early phases of training. Additional research is required to clarify the nature of adaptations in synergists and the relative contribution to enhancing performance.

3.4.2 Co-Activation of Antagonists

The magnitude of antagonist co-activation is dependent on various factors including the type of contraction,[230] load, velocity and precision[231] of the movement as well as its range of motion.[232] Antagonist co-activation is counterproductive to movements in which maximal force must be generated due to the fact that the co-activation would produce torque about the joint acting in the opposite direction of the desired movement.[233-235] There is also evidence that co-activation may impair the full activation of agonist muscles through reciprocal inhibition.[236] However, antagonist co-activation is beneficial in coordinating movements and maintaining joint stability during actions, especially those ballistic in nature. Despite these advantages, excessive antagonist co-activation may negatively influence the ability to perform movements with maximal power.

It is hypothesized that training-induced improvements in performance are influenced to some degree by a decrease in antagonist co-activation. Comparisons of individuals with different training backgrounds have rendered inconclusive results and intervention studies have reported conflicting evidence of adaptations to antagonist co-activation. Hence, the possible training-induced adaptations in antagonist co-activation and subsequent impact on performance, remains unclear. Antagonist co-activation has been reported to be prominent during ballistic movements[237] and, therefore, the potential to reduce co-activation in such movements following training is relatively greater. Furthermore, the level of antagonist co-activation may be much greater during dynamic, multi-joint movements than during the single-joint, isometric movements commonly researched. Although these areas have not yet been investigated, it is theorized that a reduction in antagonist co-activation during such complex movements would contribute to improvements in maximal power following training.[143]

4. Muscle Environment

Acute changes in the muscle environment (i.e. alterations resulting from fatigue, changes in hormone milieu and muscle temperature) impact muscular performance and therefore the ability to generate maximal power. During fatigue, numerous muscle properties are altered including ionic changes on the action potential, extracellular and intracellular ions as well as intracellular metabolites (the interested reader should refer to recent comprehensive reviews of this topic[238,239]). Each of these alterations negatively affects maximal muscular power through impairing the force generation and/or the velocity of shortening during contractions.[238,239] Furthermore, recent evidence suggests that the combination of factors co-existing during fatigue *in vivo* result in even greater impairment than what has been observed for fatigue factors individually.[240] While the influence of endocrine factors on adaptational mechanisms in muscle and the resulting enhancement in muscular function have been well reviewed,[241,242] acute hormonal changes may potentially impact the ability to generate maximal muscular power immediately. Recent evidence indicating that treating bundle fibres with physiological concentrations of dihydrotestosterone increases specific force and phosphorylation of myosin light chains of type II fibres, suggests that changes in androgenic hormone concentrations in the blood may acutely impact maximal muscular power.[243] Additionally, alterations in muscle temperature also influence maximal power production as it has been shown that P_{max}, V_{max}, F_{max} as well as RFD decrease with a decrease in muscle temperature[244-246] (for extensive reviews of this topic please refer to[247-249]).

5. Conclusion

Maximal muscular power is influenced by a wide variety of neuromuscular factors including muscle fibre composition, cross-sectional area, fascicle length, pennation angle and tendon compliance as well as motor unit recruitment, firing frequency, synchronization and inter-muscular coordination. Maximal power is also affected by the type of muscle action involved and, in particular, the time available to develop force, storage and utilization of elastic energy, interactions of contractile and elastic elements, potentiation of contractile and elastic filaments as well as stretch reflexes. Furthermore, acute changes in the muscle environment (i.e. alterations resulting from fatigue, changes in hormone milieu and muscle temperature) impact the ability to generate maximal power. Development of effective training programmes that enhance maximal muscle power must involve consideration of these factors and the manner in which they respond to training.

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REVIEW ARTICLE

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Developing Maximal Neuromuscular Power

Part 2 – Training Considerations for Improving Maximal Power Production

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Contents

Abstract

This series of reviews focuses on the most important neuromuscular function in many sport performances: the ability to generate maximal muscular power. Part 1, published in an earlier issue of *Sports Medicine*, focused on the factors that affect maximal power production while part 2 explores the practical application of these findings by reviewing the scientific literature relevant to the development of training programmes that most effectively enhance maximal power production. The ability to generate maximal power during complex motor skills is of paramount importance to successful athletic performance across many sports. A crucial issue faced by scientists and coaches is the development of effective and efficient training programmes that improve maximal power production in dynamic, multi-joint movements. Such training is referred to as ‘power training’ for the purposes of this review. Although further research is required in order to gain a deeper understanding of the optimal training techniques for maximizing power in complex, sports-specific movements and the precise mechanisms underlying adaptation, several key conclusions can be drawn from this review. First, a fundamental relationship exists between strength and power, which dictates that an individual cannot possess a high level of power without first being relatively strong. Thus, enhancing and maintaining maximal strength is essential when considering the long-term development of power. Second, consideration of movement pattern, load and velocity specificity is essential when designing power training programmes. Ballistic, plyometric and weightlifting exercises can be used effectively as primary exercises within a power training programme that enhances maximal power. The loads applied to these exercises will depend on the specific requirements of each particular sport and the type of movement being trained. The use of ballistic exercises with loads ranging from 0% to 50% of one-repetition maximum (1RM) and/or weightlifting exercises performed with loads ranging from 50% to 90% of 1RM appears to be the most potent loading stimulus for improving maximal power in complex movements. Furthermore, plyometric exercises should involve stretch rates as well as stretch loads that are similar to those encountered in each specific sport and involve little to no external resistance. These loading conditions allow for superior transfer to performance because they require similar movement velocities to those typically encountered in sport. Third, it is vital to consider the individual athlete’s window of adaptation (i.e. the magnitude of potential for improvement) for each neuromuscular factor contributing to maximal power production when developing an effective and efficient power training programme. A training programme that focuses on the least developed factor contributing to maximal power will prompt the greatest neuromuscular adaptations and therefore result in superior performance improvements for that individual. Finally, a key consideration for the long-term development of an athlete’s maximal power production capacity is the need for an integration of numerous power training techniques. This integration allows for variation within power meso-/micro-cycles while still maintaining specificity, which is theorized to lead to the greatest long-term improvement in maximal power.

Part 1[1] of this review discussed the biological basis for maximal power production. Part 1 highlighted that maximal muscular power is influenced by a wide variety of interrelated neuromuscular factors including muscle fibre composition, cross-sectional area, fascicle length, pennation angle and tendon compliance as well as motor unit recruitment, firing frequency, synchronization and inter-muscular coordination. Maximal power is also affected by the type of muscle action involved and, in particular, the time available to develop force, storage and utilization of elastic energy, interactions of contractile and elastic elements, potentiation of contractile and elastic filaments as well as stretch reflexes. Furthermore, acute changes in the muscle environment impact the ability to generate maximal power. Thus, development of training programmes that enhance maximal power must involve consideration of these factors and the manner in which they respond to training. The purpose of part 2 is to explore the practical applications of the findings of part 1 by reviewing the scientific literature relevant to the development of training programmes that most effectively improve maximal power production in dynamic athletic movements.

The search for scientific literature relevant to this review was performed using the US National Library of Medicine (PubMed), MEDLINE and SportDiscus® databases. The specific search terms utilized included 'maximal power', 'muscular power', 'power training', 'ballistic training', 'plyometric training' and 'weightlifting training'. Relevant literature was also sourced from searches of related articles arising from the reference list of those obtained from the database searches. The studies reviewed examined factors that could potentially influence the ability to improve maximal power production through training.

1. Role of Strength in Maximal Power Production

A fundamental relationship exists between strength and power, which dictates that an individual cannot possess a high level of power without first being relatively strong. This assertion is supported by the robust relationship that exists between maximal strength and maximal power production as well as countless empirical observations of the differences in strength and power capabilities between elite and sub-elite athletes.[2-9] Cross-sectional comparisons have revealed that individuals with higher strength levels have markedly superior power production capabilities than those with a low level of strength[7,10-17] (table I). Furthermore, research has demonstrated that heavy strength training programmes involving untrained to moderately trained subjects resulted not only in improved maximal strength but also increased maximal power output.[9,18-27] While strength is a basic quality that influences maximal power production, the degree of this influence diminishes somewhat when the athlete maintains a very high level of strength.[28] As maximal strength is increased, the window of adaptation for further strength enhancement is reduced. Consequently, increases in maximal power output following strength training are expected to be lower in stronger individuals and more velocity specific in that the changes would impact primarily on the high-force end of the force-velocity relationship.[29-34] Theoretically, if a well trained, strong athlete was able to enhance maximal strength at the same rate as an untrained novice through either steroid use and/or creative strength training protocols, the degree to which strength training would influence maximal power production would be quite similar. In any case, the current strength level of an athlete will always dictate the upper limit of their potential to generate maximal muscular power because the ability to generate force rapidly is of little benefit if maximal force is low.[32] Therefore, the ability to generate superior maximal muscular power is considerably influenced by the individual's level of strength.

Stronger individuals possess favourable neuromuscular characteristics that form the basis for superior maximal power production. For example, following the first 3 years of a periodized strength training programme the neuromuscular profile would be significantly enhanced. Whole muscle cross-sectional area (CSA) would be considerably greater[35-56] as a result of increased myofibrillar CSA of type I and, to a greater degree, type II fibres.[35,37,41,42,44,45,57-60] It is highly likely that pennation angle[46,52] and possibly even fascicle length[48,49,55,61] would be greater. Additionally, neural drive[21,29,40,62-68] as well as inter- and possibly even intra-muscular coordination[66,68-73] would be far superior after the 3 years of training. These neuromuscular characteristics would result in a shift in the force-velocity relationship so that the force generated by muscle would be greater for any given velocity of shortening.[9,20,25,26] As a result, maximal muscular power output would be far superior following the 3 years of strength training.[20,24-26,41,56,74,75] Therefore, enhancing maximal strength is a vital consideration when designing training programmes that maximize the long-term development of maximal muscular power.

While previous research has demonstrated that improvements in strength are accompanied

Table I. Summary of cross-sectional studies comparing maximal power production between stronger and weaker subjects

Study (year)	No. of subjects		Subject demographics		Strength test conducted	Strength level (mean ± SD)		Power test conducted	Maximal power (mean ± SD)	
	stronger	weaker	stronger	weaker		stronger	weaker		stronger	weaker
Bourque[10] (2003)	8	8	Well trained male volleyball and badminton players	Well trained M long-distance runners	Smith machine squat 1RM (kg/kg)	2.36* ± 0.74	1.74 ± 0.32	Maximum CMJ power (W/kg)	76.3* ± 10.8	59.2 ± 11.1
Baker and Newton[14] (2006)	6	6	M 1st division national rugby league players	M 2nd division state rugby league players	BP 1RM (kg/kg)	1.46* ± 0.12	1.19 ± 0.13	Maximum BP throw power (W/kg)	6.97* ± 0.64	5.51 ± 0.55
Baker and Newton[15] (2008)	20	20	M 1st division national rugby league players	M 2nd division state rugby league players	Squat 1RM (kg)	175.0* ± 27.3	149.6 ± 14.3	Maximum CMJ power (W)	1897* ± 306	1701 ± 187.0
Cormie et al.[17] (2010)	12	18	Stronger physically active men	Weaker physically active men	Squat 1RM (kg/kg)	1.97* ± 0.08	1.32 ± 0.14	Maximum CMJ power (W/kg)	59.8* ± 3.8	50.2 ± 5.2
Cormie et al.[11] (2009)	12	18	Division I M football and track athletes	Untrained men	Squat 1RM (kg/kg)	1.93* ± 0.22	1.40 ± 0.27	Maximum CMJ power (W/kg)	71.7* ± 10.7	55.9 ± 8.0
McBride et al.[12] (1999)	8	8	National level M power lifters	Moderately active men	Smith machine squat 1RM (kg/kg)	2.88* ± 0.14	2.13 ± 0.14	Maximum CMJ power (W/kg)	56.9* ± 2.5	49.4 ± 2.6
	6	8	National level M Olympic lifters	Moderately active men	Smith machine squat 1RM (kg/kg)	2.86* ± 0.15	2.13 ± 0.14	Maximum CMJ power (W/kg)	63.0* ± 2.7	49.4 ± 2.6
	6	8	National level M sprinters	Moderately active men	Smith machine squat 1RM (kg/kg)	2.66* ± 0.16	2.13 ± 0.14	Maximum CMJ power (W/kg)	63.8* ± 2.9	49.4 ± 2.6
Stoessel et al.[13] (1991)	14	13	National level F weightlifters	Untrained women				VJ height (m)	0.50* ± 0.08	0.32 ± 0.07
Stone et al.[7] (2003)	5	5	Strongest out of a pool of 22 resistance trained men	Weakest out of a pool of 22 resistance trained men	Squat 1RM (kg)	212.5* ± 8.4	95.0 ± 6.3	Maximum CMJ power (W)	5391* ± 2566	3785 ± 376
Ugrinowitsch et al.[16] (2007)	10	10	M track athletes with international experience	Physically active men	Leg press 1RM (kg)	364.5 ± 115.1	304.0 ± 47.3	Maximum CMJ height (m)	0.40* ± 0.05	0.30 ± 0.05

1RM = one-repetition maximum; **BP** = bench press; **CMJ** = countermovement jump with no arm swing; **F** = female; **kg/kg** = the ratio between 1RM in kg and body mass in kg; **M** = male; **VJ** = vertical jump a CMJ with an arm swing; * indicates significant ($p \leq 0.05$) difference between stronger and weaker groups.

by increased power output,[9,18-24,27] much of this research involved training relatively novice subjects with low to moderate strength levels, in which improvements in muscular function are easily invoked and relatively non-specific. Further improvement in maximal muscular power and performance enhancement in well trained athletes, requires a multifaceted approach incorporating a variety of training strategies targeting specific areas of the force-velocity relationship.[28,31]

2. Movement Pattern Specificity

The ability to generate maximal power in dynamic, multi-joint movements is dependent on the nature of the movement involved.[76,77] Therefore, the exercises selected for a power training programme may influence the magnitude of performance improvements and type of adaptations observed. A range of movements have been previously prescribed for improving maximal power output including traditional resistance training exercises, ballistic exercises, plyometrics and weightlifting exercises (table II).

2.1 Traditional Resistance Training Exercises

Inherent in traditional resistance training exercises such as the squat or bench press, is a substantial period where the load is decelerated towards the end of the range of motion.[77,84] For example, in the bench press the deceleration has been reported to last for 23% of the total duration of a one-repetition maximum (1RM) and is increased to 52% of the total duration when the load was reduced to approximately 80% of 1RM.[84] When the movement is performed rapidly with a lower load of 45% of 1RM in an attempt to increase sports specificity, the deceleration phase still extends for approximately 40–50% of the total movement duration.[77] Thus, even if traditional resistance training exercises are performed with light loads and the athlete is instructed to perform these movements rapidly, this deceleration results in movement velocities lower than those typically encountered in sporting movements such as jumping or throwing.[76,77] Furthermore, this deceleration phase is associated with decreased muscle activation of the agonists and the possibility of increased muscle activity in the antagonist muscles in order to stop the load at the end of the range of motion.[77] As a result of this decreased mechanical specificity, the transfer of training effect following a programme involving traditional resistance training exercises is reduced. Despite this, traditional resistance training exercises have been successfully used to improve maximal power output in dynamic, sports-specific movements.[22-24,32,85-88] While performance of these exercises requires the generation of relatively high power outputs, improvements in maximal power following training have primarily been a result of the physiological adaptations responsible for increasing maximal strength including increased CSA and neural drive.[35,85,89] Consequently, significant increases in maximal power following training with traditional resistance training exercises occur in relatively untrained subjects with low to moderate strength levels and diminish as strength level increases.[29-32] It is possible, however, that if maximal strength did not become asymptotic as a result of anabolic steroid use, enhancing maximum strength through the use of traditional resistance training exercises would continue to improve maximal muscular power. Therefore, without consideration of anabolic steroid use, increases in maximal power output following training with these exercises are prominent in the early phases of training or in athletes who maintain a relatively low level of strength such as endurance athletes.[32,90] While the use of traditional resistance training exercises are vital in the development of strength and power, further training induced improvement in maximal power requires the involvement of other, more mechanically specific movements.

2.2 Ballistic Exercises

Ballistic exercises including the jump squat and bench press throw circumvent any deceleration phase by requiring athletes to accelerate throughout the entire range of motion to the point of projection (i.e. takeoff or release).[77] Ballistic exercises are overloaded by increasing the load required to be projected. Typically, these

Table II. Summary of studies examining changes in maximal power production following a power training intervention

Study (year)[a]	No. of subjects	Subject demographics	Experimental groups	Power training programme[b]	Training duration (wk)	Major findings
Cormie et al.[17] (2010)	24	Physically active men with a variety of training backgrounds; squat 1RM : BM ~1.35–1.97	Ballistic training in weaker subjects (n = 8); ballistic training in stronger subjects (n = 8); control (n = 8)	3 sessions/wk: Ballistic: jump squats, session 1 and 3, 7 × 6 at 0% 1RM; session 2, 5 × 5 at 30% 1RM	10	Both weaker and stronger ballistic: ↑ PP, MP and PD in 0%, 20% and 40% 1RM*, ↑ PD in CMJ*; ↑ RFD in isometric squat and CMJ*, ↑ 40 m sprint performance*, ↔ squat 1RM; no difference in ↑ maximal P between the training groups; CON: ↔ any outcome measures
Cormie et al.[27] (2010)	24	Physically active men who could perform a back squat with proficient technique; squat 1RM : BM ~1.34	Ballistic training (n = 8); TRTE training (n = 8); control (n = 8)	3 sessions/wk: Ballistic: jump squats 5–7 × 5–6 at 0–30% 1RM; TRTE: squats, 3 × 3–5 at 75–90% 1RM	10	Ballistic: ↑ PP, MP and PD in 0%, 20% and 40% 1RM*, ↑ PD in CMJ*; ↑ RFD in isometric squat and CMJ*, ↑ 40 m sprint performance*, ↔ squat 1RM; TRTE: ↑ PP, MP and PD in 0%, 20%, 40% and 60% 1RM*, ↑ PD in CMJ*; ↑ RFD in CMJ*, ↑ 40 m sprint performance*, ↑ squat 1RM*; no difference in ↑ maximal P between the training groups; CON: ↔ any outcome measures
Cormie et al.[78] (2007)	26	Recreationally trained men; squat 1RM : BM ~1.47	Ballistic training (n = 10); ballistic + TRTE training (n = 8); control (n = 8)	2 sessions/wk: Ballistic: jump squats, 7 × 6 at 0% 1RM; strength-ballistic + TRTE: jump squats, 5 × 6 at 0% 1RM and squats, 3 × 3 90% 1RM	12	Ballistic: ↑ PP and PD in 0, 19% 1RM*, ↔ squat 1RM; strength-power EXP: ↑ PP and PD in 0%, 17%, 35%, 52%, 70% 1RM*, ↑ squat 1RM*; no difference in ↑ maximal P between the training groups; CON: ↔ any outcome measures
Hawkins et al.[79] (2009)	29	Non-athlete college-aged M; squat 1RM : BM ~1.35	TRTE training (n = 10); plyometric training (n = 10); weightlifting training (n = 9)	3 sessions/wk: TRTE: squat, deadlift, lunges, etc., 3 × 4–10RM; plyometric: drop jumps, CMJ, hops, bounding, etc. 3 × 3–10; weightlifting: hang clean, high pull, split jerks, etc. 3 × 2–8RM	8	TRTE: ↑ PD in VJ*, ↑ squat 1RM*; plyometric: ↑ PD in VJ*, ↑ squat 1RM*; weightlifting: ↑ PP in CMJ*, ↑ PD in VJ*, ↑ squat 1RM*; no difference in ↑ maximal P between the training groups
Holcomb et al.[80] (1996)	51	Men recruited from university physical education classes; 1RM, NR	Ballistic training (n = 10); TRTE training (n = 12); plyometric training (n = 10); 'modified' plyometric training (n = 10); control (n = 9)	3 session/wk: Ballistic: jump squat, 9 × 8 at 0% 1RM; TRTE: leg press, knee extension, knee flexion, etc., 3 × 4–8RM; plyometric: drop jumps, 3 × 8 at 0.4–0.6 m heights; 'modified' plyometric: drop jump variations, 3 × 8 at 0.4–0.6 m heights	8	All training groups: ↑ PP in CMJ and static jump*, ↑ PD in CMJ and static jump*; no difference in ↑ maximal P between any of the training groups; CON: ↔ any outcome measures

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Table II. Contd

Study (year)[a]	No. of subjects	Subject demographics	Experimental groups	Power training programme[b]	Training duration (wk)	Major findings
Kaneko et al.[20] (1983)	20	M who had not been specifically trained before; 1RM, NR	0% F_{max} TRTE training (n = 5); 30% F_{max} TRTE training (n = 5); 60% F_{max} TRTE training (n = 5); 100% F_{max} TRTE training (n = 5)	3 sessions/wk: TRTE: elbow flexion, 0% F_{max} group: 1 × 10 at 0% F_{max}; 30% F_{max} group: 1 × 10 at 30% F_{max}; 60% F_{max} group: 1 × 10 at 60% F_{max}; 100% F_{max} group: 1 × 10 holds at 100% F_{max}	12	All TRTE groups: ↑ maximal P in elbow flexion*, ↑ maximal velocity in elbow flexion*; 0% and 30% F_{max} groups: ↔ F_{max} in elbow flexion; 60% and 100% F_{max} groups: ↑ F_{max} in elbow flexion*; no difference in ↑ maximal P between groups
Kyröläinen et al.[81] (2005)	23	Recreationally active men; 1RM, NR	Ballistic + plyometric training (n = 13); control (n = 10)	2 sessions/wk: Ballistic + plyometric: jump squat, 5–10 repetitions at 30–60% 1RM; drop jumps from 0.2 m to 0.7 m heights; hops and hurdle jumps	15	Ballistic + plyometric: ↑ knee joint P during a drop jump*, ↑ PD in a drop jump*, ↑ RFD in isometric knee extension*; CON: ↔ any outcome measures
Lyttle et al.[82] (1996)	33	Men who participate in various regional level sports but had no resistance training experience; squat 1RM : BM ~1.33	Ballistic training (n = 11); TRTE + plyometric training (n = 11); control (n = 11)	2 sessions/wk: Ballistic: jump squat, and bench press throw, 2–6 × 8 at 30% 1RM; TRTE + plyometric: squat, 1–3 × 6–10RM; bench press, 1–3 × 6–10RM; drop jump, 1–2 × 6–10 at 0.2 m–0.6 m heights and drop medicine ball throws, 1–2 × 6–10 at 0.0–1.6 m drop heights	8	Both ballistic and TRTE + plyometric: ↑ MP in 6 s cycle*, ↑ PD in CMJ*, ↑ squat 1RM*, ↑ PD in medicine ball and shot put throws*, ↑ impulse during SSC and concentric-only push up*; no difference in ↑ maximal P between the training group; CON: ↔ any outcome measures
McBride et al.[21] (2002)	26	Athletic men with varying levels of resistance training experience; Smith machine squat 1RM : BM ~1.84	30% 1RM ballistic training (n = 9) 80% 1RM ballistic training (n = 10) control (n = 7)	2 sessions/wk: Ballistic: jump squats, 30% 1RM group: 5 sets at 30% 1RM; 80% 1RM group: 4 sets at 80% 1RM; as many reps until a 15% ↓ in PP	8	30% 1RM ballistic: ↑ PP in 30%, 50% and 80% 1RM jump squat*, ↑ squat 1RM*, NS ↑ 20 m sprint performance; 80% 1RM ballistic: ↑ PP in 50% and 80% 1RM jump squat*, ↑ squat 1RM*, ↓ 20 m sprint performance*; no difference in ↑ maximal P between the training groups; CON: ↑ PP in 80% 1RM jump squat*; ↔ any other outcome measures
Moss et al.[9] (1997)	30	M physical education students; elbow flexion 1RM ~20 kg	90% 1RM TRTE training (n = 9); 35% 1RM TRTE training (n = 11); 15% 1RM TRTE training (n = 10)	3 sessions/wk: TRTE: elbow flexion, 90% 1RM group: 3–5 × 2 at 90% 1RM; 35% 1RM group: 3–5 × 7 at 35% 1RM; 15% 1RM group: 3–5 × 10 at 15% 1RM	9	All TRTE groups: ↑ PP at 2.5 kg, 15%, 25%, 35% 1RM in elbow flexion*, ↑ 1RM elbow flexion*; 90% and 35% 1RM group: also ↑ PP at 50%, 60% and 90% 1RM in elbow flexion*; no difference in ↑ maximal P between TRTE training groups; CON: ↔ any outcome measures

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Table II. Contd

Study (year)^{a}	No. of subjects	Subject demographics	Experimental groups	Power training programme^{b}	Training duration (wk)	Major findings
Newton et al.[33] (1999)	16	NCAA division I, M volleyball players; squat 1RM : BM ~1.69	Ballistic training (n = 8); TRTE training (n = 8)	2–4 sessions/wk: Ballistic: jump squats 2 × 6 at 30% 1RM, 2 × 6 at 60% 1RM, 2 × 6 at 80% 1RM; TRTE: squat 3 × 6RM and leg press 3 × 6RM	8	Ballistic: ↑ PP and PD in 30%, 60% and 80% 1RM jump squat*, ↑ PD in VJ*, ↑ 3-step approach VJ*, ↔ squat 1RM; TRTE: ↑ PP and PD in 30% 1RM jump squat*, ↔ any other outcome measures; no difference in ↑ maximal P between the training groups
Toji and Kaneko[25] (2004)	21	M college students who had not exercised regularly for at least 1 y; 1RM, NR	30 + 60% F_{max} TRTE training (n = 7); 30 + 100% F_{max} TRTE training (n = 7); 30 + 60 + 100% F_{max} TRTE training (n = 7)	3 sessions/wk: TRTE: elbow flexion, 30 + 60% F_{max} group: 1 × 6 at 30% F_{max} and 1 × 6 at 60% F_{max}; 30 + 100% F_{max} group: 1 × 6 at 30% F_{max} and 1 × 6 5 s holds at 100% F_{max}; 30 + 60 + 100% F_{max} group: 1 × 4 at 30% F_{max}, 1 × 4 at 60% F_{max} and 1 × 4 5 s holds at 100% F_{max}	8	All TRTE groups: ↑ maximal P in elbow flexion*, ↑ maximal velocity in elbow flexion*, ↑ F_{max} in elbow flexion*; ↑ maximal P greater in 30% + 60% + 100% F_{max} group vs 30% + 100% F_{max} group↑
Toji et al.[26] (1997)	12	M college students who had not exercised regularly for at least 1 y; 1RM, NR	30 + 0% F_{max} TRTE training (n = 6); 30 + 100% F_{max} TRTE training (n = 6)	3 sessions/wk: TRTE: elbow flexion, 30 + 0% F_{max} group: 1 × 5 at 0% F_{max} and 1 × 5 at 60% F_{max}; 30 + 100% F_{max} group: 1 × 5 at 30% F_{max} and 1 × 5 3 s holds at 100% F_{max}	11	Both TRTE groups: ↑ maximal P in elbow flexion*, ↑ maximal velocity in elbow flexion*; 30% + 0% group: ↔ F_{max} in elbow flexion; 30% + 100% group: ↑ F_{max} in elbow flexion*; ↑ maximal P greater in 30% + 100% F_{max} group vs 30% + 0% F_{max} group†
Wilson et al.[24] (1993)	64	Previously trained men; 1RM : BM, NR	Ballistic training (n = 16); TRTE training (n = 16); plyometric training (n = 16); control (n = 16)	2 sessions/wk: Ballistic jump squats 3–6 × 6–10 at ~30% F_{max}; TRTE: squat 3–6 × 6–10RM; plyometric: drop jumps 3–6 × 6–10 at 0.2–0.8 m heights	10	Ballistic: ↑ MP in 6 s cycle*, ↑ PD in CMJ and SJ*, NS ↑ 30 m sprint performance; TRTE: ↑ PD in CMJ and SJ*, ↑ $F_{max}{}^{*}$; plyometric: ↑ PD in CMJ*. CON: ↔ any outcome measures; no difference in ↑ maximal P between the training groups
Winchester et al.[83] (2008)	14	M with at least 3 mo training experience; squat 1RM : BM ~1.45	Ballistic training (n = 8); control (n = 6)	3 session/wk: Ballistic: jump squat 3 × 3–12 at 26–48% 1RM	8	Ballistic: ↑ PP in 30% 1RM jump squat*; ↑ RFD in isometric mid-thigh pull*; ↔ squat 1RM; CON: ↔ any outcome measures

a Only studies that included a specific measurement of power output were included in this table.

b Training programme is expressed as sets × repetitions.

BM = body mass; **CMJ** = countermovement jump with no arm swing; **CON** = control group; $\mathbf{F_{max}}$ = maximal isometric force; **M** = male(s); **MP** = mean power; **NCAA** = National Collegiate Athletic Association; **NR** = not reported; **NS** = non-statistically significant change; **P** = power; **PD** = peak displacement; **PP** = peak power; **RFD** = rate of force development; **RM** = repetition maximum; **SJ** = concentric-only jump with no arm swing; **SSC** = stretch shorten cycle; **TRTE** = traditional resistance training exercise; **VJ** = vertical jump a CMJ with an arm swing; ↑ indicates improvement following training; ↓ indicates decrease following training; ↔ indicates no change following training; ~ indicates approximately; * indicates significant ($p \leq 0.05$) change following training; † indicates significant ($p \leq 0.05$) difference between training groups.

exercises are performed across a variety of loading conditions from 0–80% of 1RM in a similar traditional resistance training exercise such as the squat or bench press based on the specific exercise utilized and the requirements of the sport. Stemming from the continued acceleration throughout the range of motion, concentric velocity, force, power and muscle activation are higher during a ballistic movement in comparison to a similar traditional resistance training exercise.[76,77] As a result, many researchers and coaches recommend the inclusion of ballistic exercises rather than traditional resistance training exercises in power training programmes.[24,28,31,33,76,77,91] These recommendations are based on the fact that ballistic exercises are generally more sport specific for a vast number of sports and therefore may prompt adaptations that allow for greater transfer to performance. Supporting such recommendations is research demonstrating significant improvements in maximal power output during sports-specific movements following training with ballistic exercises.[21,24,33,78,81-83,92] Furthermore, the ability to generate power is also improved across a variety of low- and high-load conditions following training.[21,33,78] For example, an 8-week training intervention involving well trained male volleyball players with a squat 1RM to body mass ratio of approximately 1.69 revealed that training with ballistic jump squats resulted in a significantly greater change in sport-specific vertical jump performance than training with traditional resistance training exercises including the squat and leg press.[33] Therefore, training with ballistic exercises allows for athletes with various training ages and strength levels to improve power production in a variety of sports-specific movements. The precise mechanisms driving adaptation to power training involving ballistic exercises are not clearly defined. It is possible that these movements elicit adaptations in neural drive, the rate of neural activation and inter-muscular coordination that are specific to movements typically encountered in sports. These adaptations are hypothesized to contribute to observations of enhanced rate of force development (RFD) and result in the ability to generate more force in shorter periods of time.[19,21,33,78,81] Hence, the use of ballistic exercises in power training programmes is very effective at enhancing maximal power output in sports-specific movements as well as power production capabilities under a variety of loading conditions.

2.3 Plyometrics

Plyometrics are exercises characterized by rapid stretch-shorten cycle (SSC) muscle actions.[93] A great deal of exercises are classified as plyometric including a range of unilateral and bilateral medicine ball throws, push ups, bounding, hopping and jumping variations.[93] While plyometric exercises are ballistic in nature, they are delineated from specific ballistic exercises within this review due to the way these exercises are overloaded. Typically, plyometric exercises are performed with little to no external resistance, such as with body mass only or light medicine ball, and overload is applied by increasing the stretch rate by minimizing the duration of the SSC and/or stretch load by, for example, increasing the height of the drop during drop jumps.[94] Plyometric exercises can therefore be tailored to train either short SSC movements characterized by a 100–250 ms duration (i.e. ground contact in sprinting, long or high jump), or long SSC movements characterized by duration greater than 250 ms (i.e. countermovement jump [CMJ] or throw).[95] As a result of the ability to target both short and long SSCs as well as the ballistic nature of these movements, plyometric exercises are very specific to a variety of movements typically encountered in sport. Hence, it is not surprising that the use of plyometrics in power training programmes has been shown to significantly improve maximal power output during sports-specific movements.[24,80,82,88,96-102] These improvements are, however, typically restricted to low-load/high-velocity SSC movements.[24,102] The current literature involving the use of plyometric training does not provide much insight into the mechanisms driving improvements in maximal power. Similar to ballistic exercises, plyometrics are theorized to elicit specific adaptations in neural drive, the rate of neural activation and inter-muscular control, which result in improved RFD capacity.[98,103] Adaptations to the aforementioned mechanisms driving enhanced performance during SSC movements are also hypothesized to contribute to improved maximal power production following plyometric training.[98,103] Therefore, the high degree of specificity of plyometric training to a range of sporting movements make power training programmes incorporating plyometric exercises very effective at improving maximal power in sports-specific movements.[24,80,82,97-99]

2.4 Weightlifting Exercises

Weightlifting exercises such as the snatch or clean and jerk and their variations, some of which include the hang/power clean, hang/power snatch and high pull, are commonly incorporated into power training programmes of athletes who compete in all types of sports.[104-106] Similar to ballistic exercises, weightlifting exercises require athletes to accelerate throughout the entire propulsive phase or second pull, causing the projection of the barbell and often the body into the air.[107,108] However, they differ from ballistic exercises in that they require the athlete to actively decelerate their body mass in order to catch the barbell. The inherent high-force, high-velocity nature of weightlifting exercises creates the potential for these exercises to produce large power outputs across a variety of loading conditions. In fact, power output during weightlifting exercises has commonly been found to be greatest at loads equivalent to 70–85% of 1RM in snatch or clean.[76,109,110] Additionally, the movement patterns required in weightlifting exercises are generally believed to be very similar to athletic movements common to many sports such as jumping and sprinting.[111] Empirical observations are supported by evidence of similarities in the kinetic features of the propulsive phase in both weightlifting and jumping movements.[107,112] Significant relationships have also been observed between weightlifting exercises and power output during jumping ($r = 0.58–0.93$) as well as sprint performance ($r = –0.57$).[4,113] Despite the widespread use of weightlifting exercises to enhance power and the evidence highlighting its specificity to athletic movements common to many sports, little research exists examining the efficacy of power training with weightlifting exercises. In previously untrained men, Tricoli et al.[102] observed significant improvements in static jump and CMJ height as well as 10 m sprint performance following 8 weeks of power training with weightlifting exercises. In addition, the improvement in CMJ height was greater than the improvement following 8 weeks of plyometric training.[102] Power training with weightlifting exercises is theorized to significantly improve not only maximal power output but, more specifically, power output against heavy loads. Thus, the use of these movements in training is ideal for athletes who are required to generate high velocities against heavy loads including wrestlers, rugby union front rowers and American football linemen. The mechanisms responsible for improvements following power training using weightlifting exercises have not yet been investigated. The skill complexity involved with such movements together with the use of heavy loads are hypothesized to elicit unique neuromuscular adaptations that allow for improved RFD and superior transfer to performance. Therefore, the nature of weightlifting exercises coupled with the specificity of their movement patterns to numerous athletic movements, creates the potential for weightlifting exercises to be very effective power training exercises.

3. Load Specificity

Not only is the ability to generate maximal power during sports-specific movements dependent on the type of movement involved but also the load applied to that movement. Power output varies dramatically as the load an athlete is required to accelerate during a movement changes.[9,20,76,114,115] For example, absolute peak power output during a jump squat, which is defined as a CMJ with a bar held across the shoulders, ranges from 6332 ± 1085 W at 0% of 1RM to 3986 ± 564 W at 85% of 1RM, a 37% variation.[76] Consequently, the loading parameters utilized in power training programmes influence the type and magnitude of performance improvements observed as well as the nature of the physiological adaptations underlying the improvements. Kaneko et al.[20] illustrated that different training loads elicited specific changes in the force-velocity relationship and subsequently power output. Four groups completed 12 weeks of elbow flexor training at different loads – 0%, 30%, 60% and 100% of maximum isometric force (F_{max}). While all groups displayed significant improvements in maximal power, the most pronounced alterations in the force-velocity relationship were seen at, and around, the load utilized during training. For example, the 0% F_{max} group predominately improved power in low-force, high-velocity conditions while the 100% F_{max} group predominately improved power under high-force, low-velocity conditions.[20] Stemming from this seminal research, a range of loading conditions have been endorsed to elicit improvements in maximal power output throughout the literature including heavy loads, light loads, the 'optimal' load as well as a combination of loads (table II).

3.1 Heavy Loads

Despite the ensuing low movement velocity, training with heavy loads equivalent to ≥80% of 1RM has been suggested to improve maximal power output based on two main theories. First, due to the mechanics of muscle contraction (i.e. force-velocity relationship) and the positive association that exists between strength and power, increases in maximal strength following training with heavy loads results in a concurrent improvement in maximal power production.[9,19,20,22,24,41,56,74] The second theory forming the basis for the prescription of heavy loads is related to the size principle for motor unit recruitment.[116-118] According to the size principle, high-threshold motor units that innervate type 2 muscle fibres, are only recruited during exercises that require near maximal force output.[119-121] Therefore, the type 2 muscle fibres, which are considered predominately responsible for powerful athletic performances, are theorized to be more fully recruited and thus trained when training involves heavy loads.[21,24,95,122] Heavy loads are typically utilized in conjunction with either traditional resistance training exercises in strength training programmes or both ballistic and weightlifting exercises in power training programmes in an attempt to improve maximal power.

Heavy loads are often prescribed in conjunction with traditional resistance training exercises in strength training programmes with the primary goal being to improve maximal strength. As a result of the subsequent increase in F_{max} following training, and based on the inherent force-velocity relationship of muscle, the stronger athlete is able to generate greater maximal power output and improved power output throughout the loading spectrum.[9,19,20,22,24,41,56,74] These observations hold true for relatively weak individuals or those with a low training age and are driven by increases in myofibrillar CSA especially of type II muscle fibres, maximal neural drive and RFD capabilities.[27,56,62,74,89,123] Changes to maximal power following such training in strong, experienced athletes are of a much smaller, non-statistically significant magnitude.[29-32] While it is possible that even small increases in elite athletes are meaningful, the use of traditional resistance training exercise with heavy loads plays an important role in initial improvements in maximal power but typically not beyond the time in which a reasonable level of strength is reached and maintained.[28]

Heavy loads are also commonly used in power training programmes incorporating ballistic and/or weightlifting exercises. While there is a paucity of research investigating the adaptations following such training, the adaptations are theorized to be different to heavy load training with traditional resistance training exercises.[21,76] Ballistic and/or weightlifting training with heavy loads would still allow for the recruitment of high threshold motor units.[124,125] However, improvements in power output following such training are hypothesized to also be due to improved RFD capabilities as well as improved rate of neural activation and inter-muscular coordination rather than being primarily driven by increased maximal strength, CSA and maximal neural activation typical of training at heavy loads with traditional resistance training exercises.[19,21] While these adaptations are theorized to positively influence maximal power output, they would have their greatest impact at the loads utilized during training resulting in load/movement velocity specific adaptations.[9,20,21] Thus, heavy load ballistic and/or weightlifting training has the potential to beneficially influence power output in both novice/weak and experienced/strong athletes. Unfortunately, little research exists examining the efficacy of power training with heavily loaded ballistic and/or weightlifting exercises. Tricoli et al.[102] reported that weightlifting training using 4–6RM loads resulted in significant improvements in maximal jump height and 10 m sprint performance. However, this study involved relatively untrained individuals who also performed 6RM half squats as part of their programme and showed a significant improvement of approximately 43% in half squat 1RM following the training.[102] McBride et al.[21] observed improvements in peak power during 55% and 80% of 1RM jump squats but not during a 30% of 1RM jump squat following 8 weeks of ballistic jump-squat training with 80% of 1RM. These improvements were associated with improved muscle activity of the vastus lateralis during 55% and 80% of 1RM jump squats suggesting load/velocity specific adaptations.[21] While more research is required to elucidate the impact of heavy load ballistic and weightlifting training on power production and the mechanisms responsible for performance improvements, such training is theorized to be ideal for athletes required to generate high power outputs against heavy loads such as wrestlers, rugby union front rowers and American football linemen.

3.2 Light Loads

The use of light loading conditions equivalent to 0–60% of 1RM in conjunction with ballistic and/or plyometric exercises is commonly recommended and utilized in power training programmes.[9,19-21,24,80,82,83,97-99] Such training parameters permit individuals to train at velocities similar to those encountered in actual on-field movements. Furthermore, light loads are recommended due to the high RFD requirements and the high power outputs associated with such resistances.[19-21] A great deal of research has demonstrated that ballistic and/or plyometric training with light loads results in increases in maximal power output during sports-specific movements and improved athletic performance including various jumping, sprinting and agility tasks.[9,19-21,24,78,80-83,97-99,126] Furthermore, comparisons between light and heavy loads in ballistic training programmes that involve exercises with the same movement patterns have revealed that maximal power has a tendency to be improved to a greater degree following training with light loads.[20,21] Thus, it is well established that ballistic and/or plyometric power training with light loads is very effective at improving maximal power output in sports-specific movements. Research investigating the mechanisms responsible for these improvements is limited. The high movement velocity, RFD and power requirements of ballistic and/or plyometric power training involving light loads are theorized to elicit adaptations in the rate of neural activation and inter-muscular coordination that drive improvements.[19,21,33,78,81] Therefore, ballistic and/or plyometric training with light loads is recommended for athletes who are required to generate high power outputs during fast movements against low external loads such as in sprinting, jumping, throwing and striking tasks.[114] It is important to note, however, that these findings are only relevant when light loads are utilized with ballistic and plyometric exercise. The use of light loads with traditional resistance training exercises is not recommended because such training would not provide an adequate stimulus for adaptation in either the force or velocity requirements of such exercises.[31,77]

3.3 The 'Optimal' Load

Throughout the literature, the load that elicits maximal power production in a specific movement is commonly referred to as the 'optimal' load.[24,76,109,114,127] Training with the 'optimal' load provides an effective stimulus to elicit increases in maximal power output for a specific movement as improvements in power are most pronounced at the load used in training.[20,21] Power is maximized at approximately 30% F_{max} in single muscle fibres and single-joint movements.[20,25,26,128-132] However, the load that maximizes power in multi-joint, sports-specific movements varies depending on the type of movement involved. For example, the 'optimal' load typically ranges from 0% of squat 1RM in the jump squat[17,27,76,133-136] to 30–45% of bench press 1RM in the bench press throw[115,135] and up to 70–80% of snatch and/or clean 1RM in weightlifting exercises.[76,109,110] These 'optimal' loads vary significantly across different exercises because power output is influenced by the nature of the movement involved. Ballistic exercises allow for high forces to be generated in light load situations due to the continued acceleration throughout the movement. While the jump squat and bench press throw are both ballistic exercises, the 'optimal' load differs when expressed relative to a 1RM due to the differences in the load that must be projected. The jump squat requires both the mass of the body as well as any external load to be projected while only the external load is projected in the bench press throw. Although jump squats and weightlifting exercises are characterized by similar degrees of ankle, knee and hip joint kinematics, they differ markedly in the load that maximizes power output.[76] This is due primarily to the fact that only the external load is being projected in weightlifting movements and the ballistic versus semi-ballistic nature of the movements. While weightlifting exercises are performed at high velocities, the body mass must be actively decelerated in order to catch the barbell so these exercises require greater external load in order to generate the high forces necessary to optimize power output. Furthermore, the 'optimal' load of weightlifting exercises would be much lower if expressed as a percentage of an equivalent traditional resistance training exercise such as the deadlift, which would be similar to how the load is expressed for ballistic exercises. Additionally, the load that maximizes power in multi-joint, sports-specific movements may also vary depending on the strength level and/or training history of the athlete. Previous research has observed the 'optimal' load to occur at higher loads in individuals with significantly greater maximal strength.[7,137] However, conflicting evidence exists indicating that the 'optimal' load does not vary between individuals with significantly different strength levels (i.e. stronger vs weaker individuals).[17,136] Further study is required to clarify the role of maximal strength level and/or training history on the load-power relationship.

Although the exact mechanisms underlying superior adaptations after training with a specific load remain unidentified, it is theorized that the 'optimal' load provides a unique stimulus due to specific adaptations in the rate of neural activation.[19-21] This theory is supported by several investigations demonstrating that training with the 'optimal' load resulted in superior improvements in maximal power production than other loading conditions.[9,20,21,24] While the scientific evidence illustrates that training at the 'optimal' load is very effective for improving maximal power output in a specific movement over short-term interventions lasting only 8–12 weeks, this does not necessarily mean that training at the 'optimal' load is the best or only way to increase maximal power over a long-term training programme. Furthermore, it is unknown if similar results would be observed when training well trained or elite athletes as much of this research has involved homogeneous groups of low to moderately trained subjects. Even so, power training programmes in which movements are performed at the 'optimal' load are a potent stimulus for improving maximal power output in a specific movement.

3.4 Combination of Loads

Power training using light loads improves muscular performance in the high-velocity area of the force-velocity relationship (i.e. power at high velocities against low loads), and the use of heavy loads enhances muscular performance in the high-force portion of the curve (i.e. power at low velocities against heavy loads).[9,19-21,62,130,138] The theory behind the use of a combination of loads in a power training programme is to target all areas of the force-velocity relationship in an attempt to augment adaptations in power output throughout the entire curve. Thus, it is argued that training with a combination of loads may allow for all-round improvements in the force-velocity relationship that results in superior increases in maximal power output and greater transfer to performance than either light or heavy load training alone.[25,26]

Research has established that significant improvements in maximal power output and various athletic performance parameters occur following training with a combination of loads.[25,26,33,78,81,82,88,122,139] Furthermore, results from some of these investigations suggest that improvements in maximal power and athletic performance are more pronounced in combined light and heavy load training programmes compared with programmes involving training at a single load or other load combinations.[25,26,78,88,122] However, most of these studies did not control for the total work completed by various groups[25,26,88,122] and thus it is difficult to delineate whether the loading parameters or the differences in total work performed contributed to their observations. While equalizing the work of different training programmes has the potential to impact the optimum programme design, it is an important consideration when examining the efficacy of using a combination of loads. Cormie et al.[78] reported no differences in maximal power output or maximal jump height between a light load only programme and a combined light and heavy load programme when the total work done during training was equivalent. However, the combined training group also displayed improvements in power and jump height throughout a range of loaded jump squats and improved both F_{max} and dynamic 1RM. No such improvements were observed in the light load only group.[78] These results suggest that the combination of light and heavy loads elicits greater all round improvements in the strength-power profile than power training with a light load only. However, each of the research investigations relevant to this topic were conducted on relatively in-experienced, weak subjects and typically involved a combination of ballistic exercises and traditional resistance exercises such as jumps and squats rather than a combination of ballistic exercises or weightlifting exercises with light and heavy loads (i.e. 0–80% of 1RM jump squats or 40–80% of 1RM snatch/clean). Consequently, it is unknown if these findings apply to well trained athletes who already maintain a high level of strength. Additionally, it is not clear if a combination of loads within 10–30% of 1RM of the ‘optimal’ load may be more beneficial at enhancing maximal power in subjects who are well trained. Further research is also required to determine if adaptations are influenced by whether the combination of loads are used within a single set such as with complex training, a single session or in separate training sessions.

4. Velocity Specificity

The theory of velocity specificity in resistance training suggests that adaptations following training are maximized at or near the velocity of movement used during training.[20,40,140-144] However, another theory exists in which training adaptations are theorized to be influenced to a greater degree by the intention to move explosively regardless of the actual movement velocity.[18] These conflicting theories have led to confusion surrounding the appropriate selection of loads and exercises to utilize during power training. Therefore, the development of an effective power training programme must include consideration of the actual and intended velocity of movement involved with training exercises.

4.1 Actual Movement Velocity

Research comparing isokinetic training at a variety of different velocities has found a velocity-specific response to training.[40,140-144] The results of these investigations typically show that high-velocity training produces greater improvements in force and power at higher movement velocities than those seen at low movement velocities. This research also demonstrates that training with low velocities results in increased force and power predominately at low movement velocities, with non-significant changes at higher velocities.[140-144] Some evidence also indicates smaller but significant improvements in force and power at velocities both above and below the specific training velocity.[140,143]

Results of research comparing isoinertial loading in single-joint movements have also indicated a velocity-specific response. Specifically, improvements in both force and power output were most pronounced at the velocities encountered in training.[9,20] Less research is available examining whether a velocity-specific response occurs following isoinertial training with dynamic, sports-specific movements. McBride and co-workers[21] observed subjects who trained with low velocities using jump squats with 80% of 1RM to improve performance at low and moderate velocities and no changes in performance at high velocity. In contrast, training with the higher velocity movement of jump squats with 30% of 1RM resulted in significant improvements in power across high, moderate and low velocities. Furthermore, training with high movement velocities resulted in a trend towards improved 20 m sprint performance while training with low velocities significantly decreased sprint performance.[21] These results suggest that the training did elicit some velocity-specific adaptations that transferred to athletic performance.

While the bulk of the current research indicates the presence of a velocity-specific response, the mechanisms responsible for this effect have not been determined. A comparison of the results from two studies conducted by Häkkinen and associates[19,62] offer some insight into possible mechanisms. High-velocity training involving jump squats with 0–60% of 1RM resulted in a 24% improvement in isometric RFD and 38% increase in the rate of onset in muscle activation during an isometric knee extension.[19] In contrast, low-velocity training involving squats with 70–120% of 1RM did not affect either the isometric RFD or rate of muscle activation onset during the isometric knee extension.[62] These findings suggest that velocity-specific adaptations in the rate of neural activation contribute to a velocity-specific response in RFD capabilities. However, more recent research has reported that both the RFD and the rate of neural activation are enhanced in response to heavy strength training that is performed at relatively low velocities.[123] Specific adaptations to muscle architecture and contractile mechanics may also contribute to velocity-specific improvements in performance. For example, Blazevich and colleagues[49] reported pennation angle to decrease following high-velocity training involving jumping and sprinting, and increase in response to low-velocity training involving heavy squatting. Due to the rotation of fibres required during contractions in pennate muscles, these architectural adaptations favour high and low velocity of muscle shortening, respectively.[49,145] Therefore, while it is possible that neuromuscular adaptations to training are specific to the actual velocity of movement, further research is necessary to determine the precise mechanisms driving velocity-specific adaptations.

4.2 Intention to Move Explosively

The theory that training with the intention to move explosively determines velocity-specific adaptations centres primarily on the findings of a study by Behm and Sale.[18] The study involved untrained, physical education students who trained using unilateral ankle dorsiflexions for two 8-week training blocks separated by a 3-week non-training period. One limb was trained with isometric contractions, while the other limb was trained using a high-velocity dynamic movement. Subjects attempted to make maximal ballistic dorsiflexion movements with both legs, being specifically instructed to "attempt to move as rapidly as possible regardless of the imposed resistance."[18] When data were pooled across both legs, the results indicated a velocity-specific response in peak torque typically expected following training with a high-velocity movement. Specifically, the greatest significant improvement in torque occurred at the training velocity and progressively smaller increases were observed as the velocity of movement decreased. No significant differences in peak torque across any of the velocities were observed between the isometric and dynamically trained legs. Based on these findings, the authors concluded that training with high-velocity movements is not necessary to elicit high-velocity-specific improvements in performance. They hypothesized that improvements are instead driven by the characteristic high rate of neural activation associated with intended ballistic contractions and the high RFD requirements of such contractions regardless if the resulting movement is isometric or dynamic.[18] These findings have not been attempted to be replicated in a different exercise to ankle dorsiflexions, with a similar subject pool of relatively untrained students or with well trained athletes – a population commonly expected to show more sensitive adaptations to training.[72,73] Investigations comparing purposefully fast and slow movements with the same load offers no further support or rejection of this theory as these studies cannot delineate if adaptations were due to the intention to move explosively or the ensuing higher velocity movement of intentionally fast contractions.[87,146]

4.3 Actual versus Intended Movement Velocity

Two different paradigms have been suggested as the critical stimulus for velocity-specific adaptations, actual versus intended movement velocity. Training with the intention to move explosively is believed to influence adaptations to training and is vitally important during power training irrespective of the contraction type, load or movement velocity of the exercises used.[18,146] However, the bulk of the literature indicates that velocity-specific improvements in maximal power are more likely elicited by the actual movement velocity utilized during training.[9,19-21,40,49,62,140-144] Therefore, the intention to move explosively and the actual movement velocity are both vital stimuli required to elicit neuromuscular adaptations driving performance improvements following training. In order to maximize the transfer of training to performance, training should include loads that allow for similar movement velocities to those typically encountered in their sport. Additionally, athletes should attempt to perform these exercises as explosively as possible.

5. Window of Adaptation

The ability to generate maximal power is influenced by a multitude of neuromuscular factors including muscle mechanics, muscle morphology, neural activation as well as the muscle environment, and the interested reader should refer to part 1[1] in this series of reviews for a detailed discussion of these factors. The multifaceted nature of maximal power production is reflected in the variety of different training stimuli that have been previously shown to effectively improve maximal power in some individuals but not in others. For example, heavy strength training improved maximal power output in relatively untrained subjects[22-24,32,85-88] but not in stronger or more experienced athletes.[32,33] The magnitude of potential adaptations in maximal power or the window of adaptation to training is heavily influenced by the specific neuromuscular characteristics of each individual athlete.[31] These neuromuscular factors can be classified by a number of main components contributing to maximal power production: slow-velocity strength, high-velocity strength, RFD, SSC ability as well as intra- and inter-muscular coordination and skill.[31] As an athlete develops a certain component and the associated neuromuscular factors to a high level, the potential for further improvements to contribute to increases in maximal power diminish. Therefore, the window of adaptation for that component decreases. For example, Wilson and associates[32] showed that 8 weeks of heavy strength training improved vertical jump and sprint performance in weak individuals, but not already strong individuals (squat 1RM : body mass = 1.16 ± 0.20 and 1.80 ± 0.26, respectively). As a result of a large window of adaptation for maximal power development in untrained individuals, they tend to respond to virtually any type of training,[9,20,78,82,88] whereas well trained athletes require much greater specificity and variation.[33] A training programme that focuses on the least developed component contributing to maximal power will prompt the greatest neuromuscular adaptations and thus result in superior performance improvements. Therefore, it is vital to consider an individual's window of adaptation for each component contributing to maximal power production when developing effective and efficient power training programmes.

6. Integration of Power Training Modalities

The concept of periodization has been endorsed and used frequently to maximize long-term improvements in strength.[147-150] Through the use of cycles within an overall programme, periodization allows for variations in the intensity, volume and specificity of strength training.[147-150] This systematic approach to training is based on the General Adaptation Syndrome, which describes the ability of the body to react and adapt to stress.[151] When exposed to a new or more intense stress, their initial response usually involves a temporary drop in performance that is classified as the alarm stage.[151,152] The resistance phase represents the period in which the body is going through the process of adapting to the stimulus and is typically associated with improved performance.[148,151,152] However, if the stress is too great or continues for an extended period of time, the desired adaptations are no longer possible. Under these circumstances the exhaustion phase is reached and will result in a continued decrease in performance associated with overtraining.[151,152] The variations involved with a periodized strength training programme, which include alterations in the load, volume and exercises selected, allow for athletes to continuously adapt to training by moving from the alarm phase to the resistance phase whilst avoiding the exhaustion phase.[147-150] Therefore, the integration of various strength training techniques such as hypertrophy, basic strength and strength/power is commonly used to elicit superior long-term improvements in maximal strength and sports performance.[147-150]

Based on the same principle, there is a need for the integration of power training modalities (i.e. a periodized power training programme) if long-term improvements in maximal power are to be optimized.[31] Such an integrated approach would, for example, allow for the use of traditional resistance training with heavy loads to develop strength at slow velocities and RFD, ballistic training with light loads to enhance high-velocity strength and RFD, plyometric training to improve SSC performance and sport-specific technique training in order to advance intermuscular coordination and skill. While the use of some of these methods will improve maximal power and transfer to sports performance to a greater degree in the short term, exclusive exposure to a single power training modality renders inferior long-term developments due to the exhaustion phase being reached.[30,151,152] It is imperative that each of the modalities used involve a degree of movement, load and velocity specific to the requirements involved with the athlete's sport. Furthermore, programme design must also specifically target the components of maximal power with the greatest window of adaptation for each athlete. A key limitation of most of the literature examining improvements in maximal power production following training is the fact that interventions typically represent an isolated mode of training monitored over a short period of time. However, with the aforementioned considerations in mind, the neuromuscular adaptations resulting from an integrated approach to power training are theorized to result in greater improvements in maximal power production than any of these modalities used in isolation.[31]

7. Conclusions and Implications

The ability to generate maximal muscular power is considerably influenced by the individual's level of strength therefore enhancing and maintaining maximal strength is essential when considering the long-term development of power. Strength training using traditional resistance training exercises with heavy loads is therefore a pivotal component of any athlete's training programme. In order to maximize the transfer of training to performance, power training must involve the use of movement patterns, loads and velocities that are specific to the demands of the individual's sport. Ballistic, plyometric and weightlifting exercises can be used effectively as primary exercises within a power training programme that enhances maximal power in dynamic, multi-joint movements common to many sports. The loads applied to these exercises will depend on the specific requirements of each particular sport and the type of movement being trained. The use of ballistic exercises with loads ranging from 0% to 50% of 1RM and/or weightlifting exercises performed with loads ranging from 50% to 90% of 1RM appears to be the most potent loading stimulus for improving maximal power in complex movements. Furthermore, plyometric exercises should involve stretch rates as well as stretch loads that are similar to those encountered in each specific sport and should involve little to no external resistance. These loading conditions allow for superior transfer to performance because they require similar movement velocities to those typically encountered in sport. The window of adaptation in maximal muscular power, or the magnitude of potential for training-induced improvement following different training stimuli must be considered in light of the neuromuscular characteristics of the individual athlete. Such consideration will allow for the least developed neuromuscular factors to be targeted and, therefore, the greatest potential for improvements in maximal power output. The integration of numerous power training techniques is essential as it allows for variation within power meso-/micro-cycles while still maintaining specificity, which is theorized to lead to the greatest long-term improvement in maximal power.

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