

Training For Power: Principles And Practice

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Developing an athlete's ability to generate power is a key goal of periodisation. This development can be enhanced through manipulation of the force-velocity curve, whereby athletes first increase force output (maximum strength), and then the ability to apply this force under progressively time constrained movement skills specific to their sport. The first part of this article looks at the physiological and biomechanical theories that govern the efficacy of power training, and reviews the effect of strength training and ballistic training on power development. The second part focuses on training prescription.

Introduction

Since power development amongst athletes is often considered a key component to successful sports performance (as most activities are force and time dependent), understanding this component of physical fitness is essential if it is to be efficiently integrated into strength and conditioning (S&C) programmes. Successful achievement of such an outcome however, is based on a sound understanding of the scientific principles that underpin power. The aim of this article therefore, is to provide an overview of these physiological and biomechanical determinates and suggest means to manipulate them in order to increase the efficacy of such integration. The second part of this article then discusses training theories for the development of power.

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Principles of power training

Power and the force-velocity curve

Quantitatively, power can be described as work per unit of time, or often, more specific to sport, force multiplied by velocity.^{72, 101} Therefore, an increase in either variable will increase power if the other variable remains constant. Our understanding can be further enhanced by the use of the force-velocity (F-V) curve (*Figure 1*) which illustrates that maximum strength is exerted under low velocities and maximum speed is produced under low loads. Thus, an inverse relationship exists between these two variables.

The placement of a sports motor skill on the F-V curve generally depends on the mass of the object to be moved, as most actions call for the movement to be executed as quickly as possible. For example, a rugby scrum requires relatively larger forces than those required to pitch a baseball and are hence at opposite ends of the curve (*Figure 2*). Furthermore, most sports require a variety of motor skills (e.g., jumping, tackling and kicking) that may span a large portion of, if not the entire, F-V curve (*Figure 3*).

It may be prudent therefore, to ensure that training programmes equally cover a large segment of the F-V curve rather than focusing on specific loads/velocities. This can be achieved through manipulation of exercise modality and/or training load and is described throughout this article. The F-

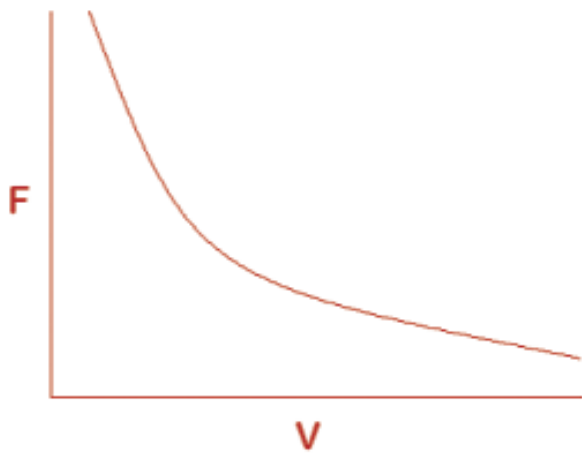


Figure 1. Theoretical illustration of the F-V curve.

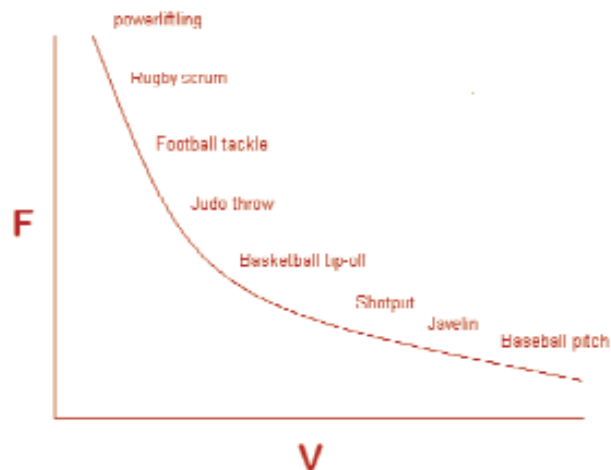


Figure 2. Theoretical placement of various sports motor skills on the F-V curve.

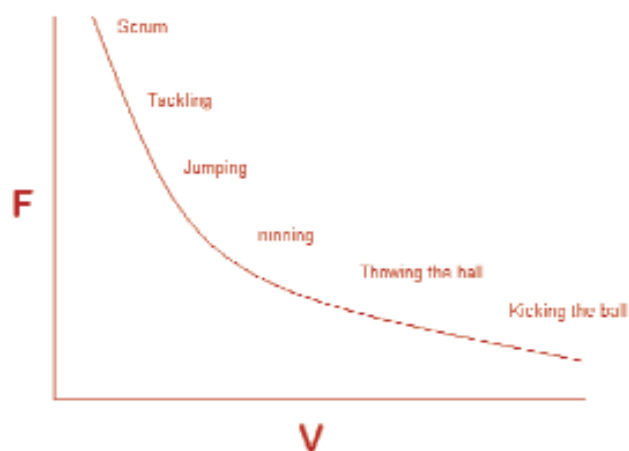


Figure 3. Theoretical placement of various sports motor skills from the game of rugby on the F-V curve.

V curve may therefore be described as the athlete's athletic journey, whereby they initially aim to increase strength and then attempt to apply this increase in force potential under progressively time constrained movement skills, specific to their sport. The significance of using multiple loads (and therefore velocities) may be further exemplified from studies demonstrating that neuromuscular adaptations are specific to training velocity.^{70, 80, 89}

It may be useful to note that within S&C, velocity and force are often regarded as synonymous with speed and strength respectively, and hence, power is often referred to as speed-strength. Moreover, Verkoshansky¹⁰⁸ distinguishes between speed-strength (SPD-STR) and strength-speed (STR-SPD), suggesting these are separate training modalities pertaining to defined areas of the curve and are an important distinction when devising S&C programmes. According to Siff,⁹⁹ SPD-STR can be defined as the ability to quickly execute a movement against a relatively small external resistance and is assessed in terms of speed of movement. Conversely, STR-SPD may be considered as the ability to quickly execute a movement against a relatively large external resistance and is assessed in terms of load. These terms are intended to signify a gradual shift in training emphasis from strength to speed as the athlete journeys along the curve. This can be achieved through appropriate exercise selection (see

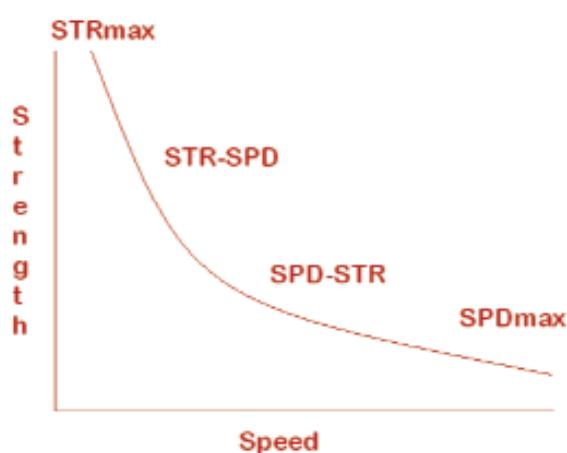


Figure 4. Adaptation of F-V curve with the inclusion of terms suggested by Verkoshansky¹⁰⁸ (STR =Strength; SPD = Speed).

Table 1 for examples), and the gradual reduction in resistance load (i.e., %1RM) as emphasis shifts from strength, STR-SPD, SPD-STR and finally to speed. For example, in a review by Newton & Dugan⁸⁵ it is suggested that high-load SPD-STR training be performed at <30%1RM and that low-load SPD-STR training be performed at >30%1RM. In line with the use of terminology suggested by Verkoshansky,¹⁰⁸ these load variations may distinguish between STR-SPD and SPD-STR respectively. A revised schematic (Figure 4) may further enhance the application of power training within S&C programmes.

Developing power through strength

Power is largely dependent on the ability to exert the highest possible force (i.e., maximum strength)^{98, 101, 102} and can be evidenced by the high and positive correlation between peak power and maximum strength ($r=0.77-0.94$)⁴ in both the upper-body^{6, 7, 8, 9, 10, 83} and lower-body.^{6, 13, 88, 91} For example, significant correlations have been found between the 1RM squat relative to body mass and countermovement jump (CMJ) peak power, CMJ peak velocity, and CMJ height.⁸⁸ This is further corroborated by Peterson *et al.*,⁹¹ who found significant linear relationships between the 1RM squat, vertical jump peak power and all explosive performance tests (vertical jump, broad jump, agility t-test, sprint acceleration, sprint velocity). In addition,

Table 1. Example exercises based on training emphasis. It should be noted that the emphasis of an exercise can be altered by changes in loading. As noted above, a change in intensity will inversely affect the velocity.

Strength	Strength-Speed	Speed-Strength	Speed
Bench press	Bench press throw	Push-up claps	Seated medicine ball throws
Squat	Squat snatch (i.e., bar starts from the floor and catch taken in deep squat position)	Power snatch from hang (i.e., bar starts from above the knees and catch taken in 1/4 squat position)	Box Jumps
Shoulder shrugs	Clean pull	Power clean from hang	Bounding
Shoulder press	Push press	Split Jerk	Wheelbarrow

Baker and Newton¹³ reported the change in lower body strength (1RM squat) and jump squat peak power for a group of six elite professional rugby league players across a 4-year period. The 14% increase in strength and 13% increase in jump squat peak power were highly correlated ($r=0.96$). Similar findings were also reported across one season in the upper body with both 1RM bench press and bench press throw peak power increasing by 14%.¹⁰ Finally, Ascii and Acikada⁴ examined the power production among different sports with similar maximum strengths and concluded that in order to improve power, athletes should be trained with maximum strength methods.

Siff⁹⁹ suggests that it is not difficult to corroborate the interdependence of strength and power by using $v = F \times t/m$ (where F = force; m = mass; a = acceleration; v = velocity; t = time). This equation represents a rearrangement of Newton's second law of motion: $F = ma \rightarrow F = m \times v/t \rightarrow v = F \times t/m$. The equation ($v = F \times t/m$) now reveals that to increase velocity (v), it is necessary to increase the magnitude or duration of the force applied (or both), or decrease the mass of the body. However, not all of these are possible as the athlete may be unable to decrease the mass of their body or sports apparatus, or increase the duration of movement. Consequently, only one option remains, namely to increase force (strength). Nuzzo *et al.*,⁸⁸ also uses a rearrangement of Newton's second law of motion: $a = F/m$. Therefore, by increasing force output, decreasing the mass, or both, acceleration and velocity can be improved. Finally, the impulse-momentum equation is also an important consideration for power activities.¹⁶ The equation, impulse = momentum = average force x time force acts; shows that a large impulse is needed to produce a large change of momentum. Again, force must predominate because of the explosive short duration of most sports movements. It may be deduced therefore, that maximum strength is a key factor in developing high power outputs and that, in order to fully develop an athlete's power

potential, S&C coaches should incorporate strength training within their periodised programmes (i.e., for athlete populations, maximal strength gains are elicited at a mean training intensity of 85% 1RM, ≤ 6 reps, 2 days training per week, and with a mean training volume of 8 sets per muscle group).⁹⁰ Moreover, because strength levels may only be maintained for 2 weeks,⁶⁷ it is advisable to include strength sessions throughout the entirety of a periodised programme so as to optimise and maintain high levels of power output.

Effect of muscle imbalances on power output

It has also been suggested that athletes that wish to develop power should develop and maintain strength in the antagonists, as this may increase both limb speed and accuracy of movement.^{68, 112} Athletes that display an agonist-antagonist imbalance may exhibit alterations in neural firing patterns leading to increased braking times and inaccurate movement mechanics during rapid ballistic movements.^{11, 68} These findings, along with a several other studies^{15, 39, 71} may suggest that throwing athletes and boxers for example, would benefit from training pulling movements at the shoulder joint (emphasising scapular retraction, depression and downward rotation)⁷¹ along with the external rotators of the rotator cuff. Moreover, the problem of upper body muscular imbalances may be exacerbated when athletes of this type overemphasise the function of the pectorals.⁷¹ However, the athlete should note that power for these movements is generated via the powerful extension of the ankle, knee and hip (triple extension).^{17, 43, 107} It appears prudent therefore, to train the antagonist for the purposes of power production (and not just injury prevention); however, this concept requires additional investigation and the development of sport specific, dynamic testing protocols to identify any imbalances.

Table 2. Resistance exercises and training loads that elicit P_{max}

Resistance Exercise	Resistance Load	Reference
Elbow flexors	30% 1RM	Kaneko <i>et al.</i> , ⁷⁰
Power cleans	80% 1RM	Cormie <i>et al.</i> , ²⁹
Jump squats	0% 1RM	Cormie <i>et al.</i> , ²⁹
Bench press throw	55% 1RM	Baker <i>et al.</i> , ⁸

Training load to optimise power P_{max} and its carryover to performance development

Almost 30 years ago, Kaneko *et al.*,⁷⁰ documented the significance of calculating and training at maximal power output (P_{max}). The authors concluded that for the elbow flexors, P_{max} occurred at 30% of maximal isometric strength and that following 12 weeks training at this load, maximal power output increased by 26%. This was higher than the result of training with 0, 60 or 100% of maximal isometric force. This study likely contributed to the common assumption that identifying and training at P_{max} is critical to performance. Moreover, this study along with classical experiments^{41, 63} that identified loading parameters for P_{max} in individual muscle fibres, likely compounded the generalisation that loads of 30% 1RM will elicit P_{max} across all movements. However, as illustrated in Table 2, there are exercise-specific differences in the load where P_{max} occurs and the S&C coach should be cognizant of this.

Cormie *et al.*,²⁸ suggest that S&C coaches use exercises that produce P_{max} at sport-specific loads. For example, they suggest that the jump squat may be the most specific mode for athletes required to produce high velocities with light loads, such as sprinters, jumpers and basketball and volleyball players. In contrast, the power clean is ideal for athletes whose on field demands dictate the need to move heavy loads as quickly as possible, for instance, Olympic weightlifters and football linemen. The latter point is corroborated by Stone *et al.*,¹⁰³ who report that weightlifters spend a considerable amount of time training using loads of 75-80% 1RM as this may optimise gains in power production. Finally, because of the plateauing of power output around P_{max} ,^{8, 29} the use of loads within +/- 10% of the resistance used to attain P_{max} will usually result in the athlete training at or very close to P_{max} .

Calculating P_{max} : methodological concerns

When considering the research to identify the optimal load to develop power, the reader must be aware of the methodology and calculations used within each study. For example, Cormie *et al.*,^{27, 28} advise that a force plate in combination with 2 linear transducers should be used when measuring power output in multidimensional, free weight movements, as this enables the investigators to track both the vertical and horizontal displacement of the bar. Moreover, using both linear transducers and a force plate is preferred as this requires fewer data manipulations.³⁵ In addition, for jump squats, the total system mass must be included (i.e., external load + body mass), however, as P_{max} occurs just before take-off (normally when the athlete reaches the 2nd pull position), shank mass (equivalent to 12% of body mass)⁹² must be excluded from the system mass.^{27, 28} Using this formula for calculation, the subjects body mass corresponds to 30% of their 1RM back squat.

In summary, whilst only using one linear transducer is invalid for determination of kinetic and kinematic variables within research, its convenience to monitor athlete training status in a practical setting is acceptable.²⁷

P_{max} and its carryover to performance

It may be contested that optimal power development (i.e., carryover to competition) requires training at loads that span the full journey of the F-V curve. Evidence for this may be illustrated in Figures 5 to 7, whereby focused load training is reported to produce results specific to defined areas of the F-V curve.^{72, 69, 70, 80, 83} In summary of these investigations, strength training has been shown to shift the curve upwards with the greatest improvements at the high force end of the F-V curve (Figure 5) and high-velocity training shifts the maximum velocity value to the right, with greater improvements toward the high velocity end of the curve (Figure 6). Training at maximum power output however, flattens the curve (Figure 7).

Based on these findings, and the fact that most sports involve motor skills covering the entire F-V curve (Figure 3), it may be hypothesised that to substantially achieve improvements in power, less sport specificity is required by using non-specific loads. This may be further corroborated when one considers the external loads experienced whilst tackling in a game of rugby. For example, the ability to tackle an opponent will depend on the opponent's body position. When the opponent is supported by only one leg such as while running, their resistance to being tackled will be smaller than when stationary (with a good base of support) or running towards the tackle. The latter examples would therefore require greater power outputs to overcome the opponent's inertia and successfully complete the tackle and therefore support the use of the power clean. The former example however, may support the use of jump squats to develop optimal power. In addition and using additional movement skill examples, power requirements will vary according to whether they are jumping, kicking the ball or running (Figure 3). As previously stated, it is evidently prudent to cover a large portion (if not all) of the resistance loads and training velocities of the F-V curve. This is in agreement with Harris *et al.*,⁶⁰ who suggest that the preoccupation of training at P_{max} may be misplaced and instead, biomechanical specificity to the functional task should be considered the fundamental tenet to training adaptations. Identification of P_{max} therefore, may have a greater theoretical significance than practical relevance.

Combination training (strength-power training)

As described by the principle of diminishing returns, the positive effects of strength training on power development may decline as the athlete's S&C age advances (due to diminished neuromuscular and/or hypertrophic responses).^{13, 60} The addition of ballistic training therefore may prove beneficial as it enables the S&C coach to also target the velocity component of the power equation ($P = F \times V$). Ballistic exercises can best be described as explosive movements (rapid acceleration against resistance), whereby the body or object is explosively subjected to full acceleration. Essentially, these exercises manipulate the load in order to train the velocity (and acceleration) component of the movement skill. For example, it is theorised that ballistic training (which emphasises the velocity component) produces a higher rate of force

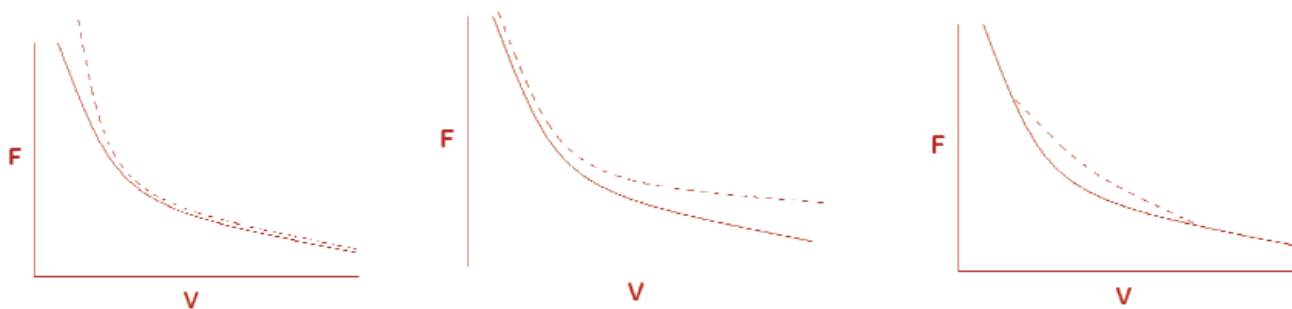


Figure 5-7. Hypothetical change in F-V curve based on training load. Figure 5 = strength training; Figure 6 = high-velocity training; Figure 7 = training at P_{max} .

development (RFD) and may therefore provide a superior stimulus for enhancing intra- and intermuscular coordination during sport specific movements.^{51, 53, 59, 98} This is also of significance because, while strength training may simultaneously increase maximum strength and RFD in untrained individuals,^{2, 18, 19} it may have less of an effect in highly trained athletes.⁷³

Bompa & Carrera²² effectively summate the role and interrelationship between strength training and ballistics. They suggest that power is developed through a physiological strategy involving two phases. The first phase involves the recruitment of fast-twitch fibres, (transformation of IIX to IIa) through strength training as described by the size principle of motor unit recruitment.⁶¹ This phase may be considered fundamental due to the high correlation ($r=0.75$) between the percentage of type II fibres and peak power output and their significant contribution as velocity increases.³⁰ The second phase involves increasing the discharge rates of these fibres (which are now of a greater quantity) through ballistics and training at loads resulting in high power outputs and high rates of force development.

Combination training is further corroborated by Toji *et al.*,¹⁰⁵ who concluded that training the elbow flexors using combined loads of 30 and 100% of maximal isometric strength improved power output to a greater extent than training with 30 and 0% of isometric strength (this may therefore be seen as a follow-up study to Kaneko *et al.*).⁷⁰ It was hypothesised that this combined approach (i.e., strength-power training) was more effective because of significant improvements in both maximal force and maximal velocity, in comparison to maximal velocity only (i.e., P_{max} training only). Similarly, Cormie *et al.*,²⁸ Harris *et al.*,⁵⁹ and Nuzzo *et al.*,⁸⁸ concluded that when considering the improvement of a wide variety of athletic performance variables requiring strength, power and speed, combination training produces superior results. The premise of this approach is thought to result from the additive improvements in both maximum force (through strength training) and maximum velocity (through power training), thus leading to a greater enhancements in power output across the entire F-V curve.¹⁰⁵

Finally, Cronin *et al.*,³¹ investigated the role of maximal strength and load in the initial 200ms of a bench press throw. However, one movement involved the stretch shortening cycle (SSC) and the other involved concentric only motion. They found that while maximal

strength was important when producing power during SSC activities across a range of external loads, there was no relationship with concentric only motions. They therefore suggest methods that improve the RFD for motor performances of short duration. Similarly, Winchester *et al.*,¹¹³ found significant increases in muscle power and RFD as result of ballistic training and these were independent of increases in strength. Whilst many more studies are required to validate these findings, the conclusions again support the need for combination training as RFD seems best developed through ballistic training methods.

It again appears apparent that high levels of strength are the prerequisite to optimal power development and while strength training can increase power output, it may begin to plateau if used in isolation. At this point, ballistics must be utilised to target the velocity component of the power equation. These studies further support the periodised model in line with the F-V curve which illustrates that the athlete progresses from strength training to explosive training in a logical sequence so as to optimise power output. It should also be noted however, that the model suggests a training emphasis for either strength training or power training and does not suggest that either should be used in isolation.

Perhaps the best example of athletes involved in combination training is Olympic Weightlifters. These athletes are reported to produce the highest values for isometric RFD,^{54, 59} power output and weighted and un-weighted vertical jumps.^{54, 59}

Explosive strength deficit

An additional concept to ensure the optimal development of power is the explosive strength deficit (ESD). It has become apparent that the S&C coach must logically decipher the most appropriate training emphasis for their athlete, i.e., strength training or ballistics. The ESD may assist in this decision. The ESD describes the difference between an athlete's maximum force and the peak force they attain during execution of a movement.¹¹⁹ This strength deficit reflects the percentage of maximal strength potential which is not being used within a given motor task.⁹⁹ In general, the difference increases as time of motion decreases, as less force can be produced.¹¹⁹ In movements such as takeoffs and delivery phases in throwing, ESD is estimated to be about 50%.¹¹⁹ When the ESD exceeds 50%, it is recommended that the athlete engage in ballistic training.¹¹⁹ Using Figure 8 as an example, If the athlete had performed a countermovement jump (CMJ)

corresponding to trace A, then he should train ballistics. Conversely, had the CMJ corresponded to performance tracing B, he should train maximum strength.

The ESD concept, i.e., the identification of a deficit in either strength or ballistic qualities of an athlete, can be approximated and applied within the field without the need for expensive equipment. For example, calculating the jump height difference between the squat jump (measure of lower body dynamic strength) and the counter-movement jump (measure of lower body power) may provide significant data to determine athlete training emphasis. In general, if the difference is large, train RFD through the use of ballistics such as plyometrics; if the deficit is small, train strength (and hypertrophy if applicable).⁹⁹ A review by Hori *et al.*,⁶⁵ suggests examining the 1RM power clean for high-load SPD-STR and vertical jump for low-load SPD-STR. If jump height is good but 1RM power clean is low, aim to improve high-load SPD-STR for which they suggest the use of weightlifting exercises. In the case of vice versa, train low-load SPD-STR through the use of plyometrics. Similar conclusions may be drawn through examining the load difference between the 1RM squat (for maximum strength) and the 1RM power clean. These values may determine an increased need and programme emphasis for either strength or high-load SPD-STR (i.e., STR-SPD).

While the ESD concept appears attractive, readers are advised to interpret its theory with prudence as it seems to be largely born from empiricism. Primary research is therefore required to address this hypothesis with scientific rigour and provide normative data from which S&C coaches can seek guidance. However, the need to identify training emphasis has been previously highlighted by Newton & Dugan.⁸⁵ They identified 7 independent qualities that contribute to an athlete's power capacity: maximum strength, high-load SPD-STR, low load SPD-STR, RFD, reactive strength, skill performance and power endurance. Newton and Kraemer⁸⁷ hypothesise that power development will be optimised if the S&C coach implements programmes that target the athlete's weakest component.

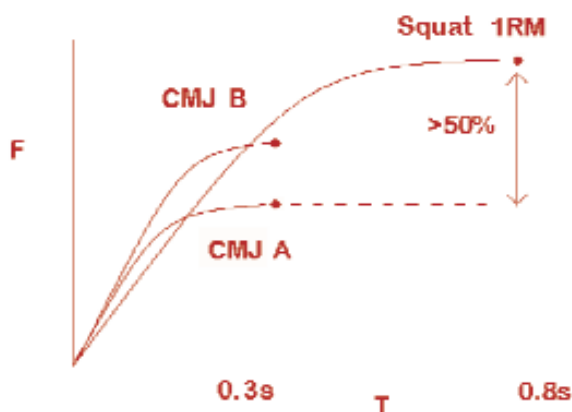


Figure 8. Hypothetical schematic illustrating the ESD between 1RM back squat and CMJ A and B. If the athlete had performed a CMJ corresponding to trace A, then he should train ballistics. Conversely, had the CMJ corresponded to performance tracing B, he should train maximum strength.

Training prescription

Quality not quantity

Power production is very much a consequence of efficient neuromuscular processes and as such, quality should be stressed at all times. Therefore, the effectiveness of a power programme may be related to the quality of each repetition. It has been hypothesised that each repetition should achieve $\geq 90\%$ of maximum power output or velocity⁴⁵ and that this, anecdotally, is best achieved with the use of 3 repetitions per set, at least 3 minutes rest between sets^{12, 45} and a maximum of 5 sets.⁴⁵

An additional method to ensure the quality of repetitions is through the use of cluster training.⁵² This form of training involves inter-repetition rest intervals of between 10 and 30s (interval length depends on exercise complexity) whereby the quality of performance is enhanced through decreases in repetition induced fatigue. It has been reported that following 5-9 maximal isometric contractions (single leg), RFD, maximal force production and rate of relaxation all decrease.¹⁰⁹ As an example, this deterioration could be reduced by performing 9 repetitions as 3 clusters of 3 repetitions, with a 10 second rest between clusters.

Continued maximal contractions result in significant reductions of ATP and phosphocreatine (PCr) stores, increases in lactate concentrations and concurrent reductions in force output.⁹⁵ Inter-repetition rest intervals may result in some replenishment of PCr stores and therefore a delay in the use of muscle glycogen and subsequent production of lactic acid and lactate.⁵² It is therefore hypothesised that quality of exercise performance is enhanced through decreases in repetition induced fatigue, and that cluster training may be regarded as a valid method to reduce the deterioration in power output across a set.^{12, 50}

In addition, cluster sets can be utilised in exercises in which maintenance of power and/or velocity is considered a critical factor during ballistic movements. For this purpose, the set can be undulated whereby during the inter-repetition rest period, the load is reduced to compensate for fatigue and subsequent loss of power output.⁵²

For the reasons mentioned above, it is generally advised to perform power training in a non-fatigued state, whereby neural adaptations can be enhanced via a more optimal training stimulus. Many high-power sports motor skills however, are required to be executed under fatigued conditions and thus power-training whilst fatigued may hold some sport specificity. However, through a review conducted by Wilson and Flanagan,¹¹¹ it was concluded that safety may be compromised due to a diminished capacity of the neuromuscular system to deal with impact loadings during activities such as plyometrics and power cleans. They further speculate that S&C coaches should be aware that despite the possible sport specificity afforded by performing power activities in the fatigued state, more research in this area is required to establish precise adaptations.

Rate of force development and ballistic training

Table 3 illustrates that S&C coaches must also be aware of the time available within a sports motor skill to produce maximum force. It has been hypothesised that maximum force takes 0.25 – 0.4s to develop^{1, 119} but may require up to 0.6 to 0.8 s.^{38, 75} The time delay in reaching peak force is in part due to the finite rate of increase of muscle stimulation by the central nervous system, the propagation of the action potential on the muscle membrane, time constraints of calcium release and cross-bridge formation and the interaction between the contractile elements and the series elastic components.^{21, 84, 117} This delay in reactivity is known as the electromechanical delay (EMD) and describes the interval between the time of onset of muscle activity and the time of onset of mechanical output.^{24, 84} The EMD is consequential to commencing movement from zero to low muscular tension and its negative effects can be reduced by enabling the muscle to build up tension (e.g., through preloading or a countermovement) prior to the initiation of movement.^{21, 117}

The vast majority of athletic movements however, occur within 0.251,¹⁰³ to 0.3s¹¹⁷ and therefore the opportunity to develop peak force is not a time luxury afforded to most athletes. This data suggests that during quickly executed motor skills, the strongest athletes are not necessarily at an advantage but rather those who can produce the greatest force (strength) in the shortest time. Using the example illustrated in Figure 9, athlete A would be at an advantage if the sports movement was time dependent (e.g. a jab in boxing) whereas athlete B would be at an advantage if maximum strength values were the objective within a non-time constrained movement task (e.g. powerlifting).

It is hypothesised that if the time available for force development is less than 0.3s, training should focus on improving RFD^{1, 86, 98, 119} as this makes it possible to reach higher forces and velocities during fast movements.¹ RFD may be defined as the change in force development divided by the change in time¹⁰⁴ and is enhanced with an increase in efferent neural drive, particularly by increases in the firing frequency of

motor units.¹ Because RFD is a function of neuromuscular activation⁹⁷ and is representative of an individual's ability to accelerate objects,⁹⁸ many authors recommend ballistic (explosive) training to improve this quality.^{19, 51, 55, 56, 113} Moreover, the force generated in the first 30ms has been termed the 'starting strength' while the peak RFD has been termed 'explosive strength'⁹⁸ (Figure 10). Both qualities are necessary to accelerate light loads, with explosive strength becoming increasingly significant as the load increases.⁸² In addition, it is generally recognised that while heavy resistance training improves the final height of the force-time (F-T) curve, ballistic training improves the slope of the initial portion of the F-T curve, specifically within the first 200ms⁵⁵ to 300ms⁸⁶ (Figure 10).

Ballistic exercises can best be described as explosive movements, (rapid acceleration against resistance) whereby the body or object is explosively subjected to full acceleration. Full acceleration is an important term within this definition as athletes often perform speed repetitions under the illusion that they are improving RFD. However, using the example of speed repetitions performed on a bench press, this misconception can be dispelled through the study conducted by Newton *et al.*⁸⁷ These researchers revealed that during the final half of the repetition, power decreased significantly in order to decelerate the bar and reach zero velocity. This is to enable the athlete to maintain a hold of the bar without injury to the shoulder and/or arm joints. It has been reported that deceleration accounts for 24% of the movement with a heavy weight and 52% of the movement with a light weight.⁴⁰ When the weight could be released however, (through the use of a smith machine or vertical chest press for example) power and acceleration could be enhanced throughout the entire range of motion.⁸⁷ Newton *et al.*,⁸⁷ reported that ballistic movements therefore produce significantly higher outputs for average velocity, peak velocity, average force, average power and peak power throughout the lift, especially during the later stages. Moreover, according to Clark *et al.*,²⁶ ballistic bench press throws, even under loading conditions that would severely restrict the ability to propel the barbell, are superior to the traditional bench press in terms of force production.

Table 3. Duration of 'explosive' force production in various athletic movements (M = males' F = females) (adapted from Zatsiorsky)¹¹⁷.

Sport and Motion	Resistance Load	Reference
Take-off		
Sprint running	0.101 (M) 0.108 (F)	Mero and Komi ⁸¹
Long jump	0.105 – 0.125 (M)	Zatsiorsky ¹¹⁸
High Jump	0.15-0.23 (M) 0.14-0.14 (F)	Dapena ³²
Platform diving	1.33 (standing take-off) 0.15 (Running dives)	Miller ⁸²
Ski jumping	0.25-0.30	Komi and Virmavirta ⁷⁶
Delivery		
Shot putting	0.22-0.27 (M)	Lanka ⁷⁸

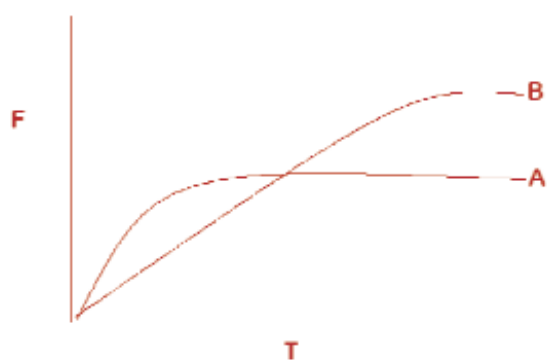


Figure 9. Athlete A vs. Athlete B. Athlete A would be at an advantage if the sports movement was time dependent, whereas athlete B would be at an advantage if maximum strength values were the objective.

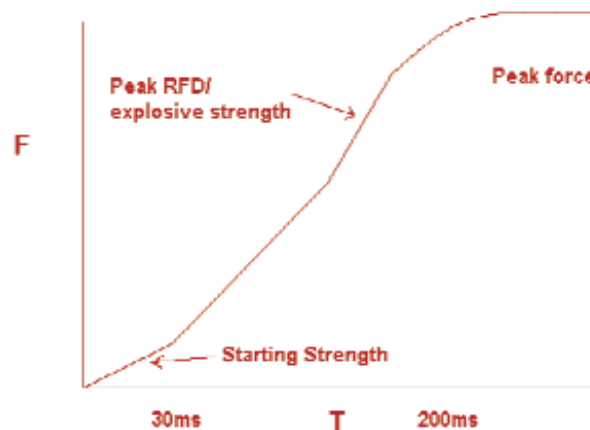


Figure 10. Hypothetical isometric F-T curve.

In essence, unless full acceleration is ensured, the athlete is merely training the neuromuscular system to decelerate the barbell to ensure zero outputs for velocity, force and power at the end range of motion when arguably the highest of these values should be attained. It should also be noted that deceleration is often an inherent issue with single-joint exercises when training for power development and therefore exercise selection requires careful scrutiny.

Reviews by Flanagan and Comyns⁴⁴ and Hori *et al.*,⁶⁶ recommended the use of plyometric training and Olympic lifts respectively to train RFD, as in addition to their ability to be adapted to the specifics of the sport, they encourage full acceleration with zero velocity achieved only by the effects of gravity. For example, weightlifting exercises allow the athlete to accelerate the barbell through the entire range of motion and does not actively require the athlete to decelerate the barbell velocity. Instead, the barbell's upward movement is controlled by the influence of gravity. In addition, Olympic lifts produce some of the highest power outputs of any exercise modality. For example, Garhammer⁴⁷ reported that the snatch and clean and jerk exhibit much greater power outputs compared with the squat and deadlift. For example, the relatively slow velocities involved in powerlifting (i.e., back squat, deadlift and bench press) produce approximately 12 watts per kilogram of body weight.⁴⁷ However, during the second pull phase of both the clean and snatch, an average of 52 watts per kilogram of body weight is produced.⁴⁷ Because of these characteristics, it has been speculated that weightlifting exercises are beneficial in improving an athlete's capability of power production.^{25, 66, 86}

Velocity specificity

Velocity specificity is an essential consideration when designing S&C programmes. It was previously suggested that the intention to move explosively is more important than the actual velocity.^{18, 19} The researchers hypothesised that because rapid ballistic movements utilise feed-forward mechanisms (i.e., they are pre-programmed and therefore do not rely on proprioceptive feedback), the stimulus for adaption is the same between differing loads and velocities.¹⁸

These studies however, used subjects with no resistance training experience and adaptations were likely to be predominantly neural in nature. Contradictory research from Kaneko *et al.*,⁷⁰ and McBride *et al.*,⁸⁰ suggests that training adaptations are velocity dependent and Pereira and Gomes⁸⁹ suggest that training adaptations are greatest at or near the training velocity. In support, Blazeovich *et al.*,²⁰ reported that training with light loads (e.g., body weight jumps and sprints) decreased the fascicle angle demonstrating an architectural adaptation favouring speed of movement. Conversely, concurrent body weight power exercises and heavy resistance training increased the fascicle angle, thus favouring force production. This is in agreement with Duchateau and Hainaut³⁴ who reported that RFD explained the speed of movement for small loads, and maximal strength explained the speed of movement for heavy loads. The investigators further reported that the latter may be explained by changes in cross sectional area whereas the former maybe due to increased myosin ATPase activity and/or calcium release from the sarcoplasmic reticulum. In addition, the quality and/or quantity of sarcoplasmic reticulum may have been improved. Kawakormi and Newton⁷³ speculate that both neural and muscular adaptations contribute to the force-velocity-power relationship and it remains unclear whether these adaptations are consequential to the shortening velocity of muscle fibres or the frequency of neural input.

Finally, it is important to note that the intention to move explosively is important regardless of the load and that this should therefore be stressed when training athletes.^{3, 42, 115}

Post activation potentiation

Pre-competition warm-up

Recently, investigators have researched the inclusion of S&C type exercises within a warm-up routine such as half squats,⁴⁸ drop jumps⁶² and plyometrics.⁷⁹ This modern warm-up protocol has provided successful results in enhancing power output during the subsequent event or practice session and is likely due to improvements in acceleration, RFD and force

production.⁶² Mechanisms for this enhanced performance have been attributed to the phenomenon known as post activation potentiation (PAP)¹¹⁴ which describes an increased twitch contraction force following maximal or near maximal contractions⁶² generally of 3-5RM.³³ In addition, if PAP is to be optimised, the movement in which the potentiation effect is to be realised should be biomechanically similar to the exercise it followed.^{33, 49, 116} An example would be 3 repetitions of the squat at 3RM followed by a vertical jump, or 5 repetitions of the bench press at 5RM followed by a bench press throw. The exact mechanism of PAP remains unclear but may be due to an enhanced neuromuscular drive⁶⁴ or muscular factors such as increased phosphorylation of myosin regulatory light chains^{62, 95, 114} and increased activity of myosin light chain kinase.⁹⁶ Despite the mechanisms involved, the end result is likely greater and faster cross-bridge attachments allowing the muscle to generate more force.⁹⁶

A study by Chatzopoulos *et al.*,²³ demonstrated the benefits of using PAP prior to a sports event. In their investigation, 10 single repetitions of the back squat performed at 90%1RM, followed by a 5 minute rest period significantly ($p < 0.05$) improved 10 and 30m sprint times. They concluded that heavy resistance training could be used to enhance running speed and acceleration during training or competition. Similar results were reported by Yetter and Moir¹¹⁴ who suggested that heavy back squats performed 4 minutes before multiple sprint trials can significantly increase speed. The use of PAP prior to sports competitions is therefore an exciting prospect that may provide the athlete with an ergogenic advantage.

The conclusion can therefore be made that the contractile history of skeletal muscle affects subsequent performance. However, careful programme design is required as the contractile history may present itself as a decrease in performance due to the effects of fatigue (neurologic and metabolic) or an increase in performance due to the effects of potentiation.^{93, 94} For example, research suggests that total contraction time should be less than 10s to avoid fatigue which would reduce the positive effect of PAP.^{46, 106} In addition, the dominant effect will likely be determined by the rest period, whereby there must be adequate time to dissipate fatigue but not so much as to decrease the potentiation effect.^{14, 74, 110} Rest periods have varied from 15s to 18.5mins, but are generally recommend at 3-4mins rest between the preload activity and the performance measure.³³ The optimal point however, appears very individualistic and subject to much debate. Kilduff *et al.*,⁷⁴ concluded that potentiation resulting from heavy strength repetitions are realised following 8 to 12 minutes for lower body exercises and 12 minutes for upper body exercises. This was measured in elite rugby players however, and its applicability to other athletes is debatable. Furthermore, the efficacy of PAP may be dependent on training experience, strength levels, repeated exposure to potentiation training³³ and the muscles concentrations of type IIa/x fibres.^{30, 58, 62} In addition, it is in the opinion of the author that sufficient strength training experience is needed to allow for adaptation of the endocrine system, whereby increases in testosterone (TST) are noted. This may allow for increased TST-nervous interactions thus further facilitating PAP. The former hypothesis is yet to be elucidated but if it were true, it would suggest that PAP

would be most effective following ≥ 2 years strength training when increases in TST concentrations are most significant.^{57, 77}

It may therefore be advisable that in order to capitalise on the benefits of PAP, S&C coaches need to determine this data separately for each athlete and for each exercise. In addition, athletes need to first be accustomed to strength training, enabling them to recruit sufficient type II fibres and have an appropriately developed neuromuscular system with respect to the involved exercises/movement patterns. Moreover, even if PAP were effective, the question arises of whether it could be logistically included into S&C sessions, i.e. the S&C coach would have to implement rest periods of up to 8-12 minutes. This may suggest that it is best utilised as an ergogenic warm-up intervention.

Complex training

PAP may also be utilised within the S&C session and is termed complex training. In a review by Ebben,³⁶ it was concluded that this method was at least as effective if not superior to additional combinations of resistance training and plyometric training. Mixed results however, have been reported as complex training usually infers the use of a heavy loaded exercise (1-5RM) quickly followed by a biomechanically similar plyometric exercise in a set-for-set combination.^{33, 49, 116} As discussed above, this may not allow for the dissipation of fatigue and consequently mask any potentiation effect. However, if rest intervals are appropriately determined, and exercises logically sequenced (to further manage fatigue and potentiation) its inclusion within S&C programmes may be an effective method for enhancing power.^{49, 116} For example, Stone *et al.*,¹⁰⁴ presents the use of complex pairs such as shoulder shrugs followed by power snatches and clean pulls and 1/3 squats followed by speed squats. These complexes however, are not performed as a set for set combination but as a single strength set prior to each ballistic exercise.

It is also worth noting that, assuming complex training is not effective, then at worst it is not reported to be detrimental and at least provides organisational advantages.³⁷ This is of particular significance to S&C coaches who are limited to one or two S&C sessions per week with their athlete. They must therefore manage their time efficiently to allow the inclusion of strength training methods and ballistics such as weightlifting and plyometrics. Complex training can effectively utilise the rest period with exercises such as plyometrics. Moreover, a strength training set may precede weightlifting or plyometric exercises allowing not only for a possible potentiation affect, but for the maintenance of athlete strength levels (the importance of which, was highlighted earlier in this article).

Conclusion

The F-V curve may be used to describe the changing emphasis of S&C programmes, whereby the athlete's initial focus (following achievement of a sufficient work capacity, usually through the strength-endurance phase) is on strength development. From this phase the athlete should see positive adaptations in neuromuscular programming and an increase in type IIa fibres. These adaptations can then be exploited to further enhance power and velocity through ballistic exercises utilising full acceleration. Furthermore, because strength is seen as the prerequisite of power, and as performance levels may only be maintained for

2 weeks, strength training should be incorporated throughout the entire cycle, albeit with a regression in frequency. In addition, antagonistic muscle strength should be progressed in line with agonist adaptations to ensure optimal neuromuscular programming and reductions in injury potential.

Rather than focusing on an athlete's P_{max} , it may be prudent to cover a larger range of loads to accommodate the ever changing resistance and velocities experienced during competition. This is also important as adaptations appear specific to training load (i.e., %1RM) and velocity. Towards the peaking phase however, resistance loads can be concentrated at that which is most frequently experienced during competition. For single event sports such as shot put, javelin and weightlifting, it may be appropriate to train within narrow loads of the sports implement, focusing just above and below the load (to train type IIa recruitment and neural discharge respectively). However, strength training and plyometric drills are

often part of their programme which inevitably entails training the full curve.

When training strength and power, cluster sets are recommended as they better maintain output values of all key variables, e.g., force, velocity and power, and can be manipulated to ensure output is $\geq 90\%$ maximum. This can be further ensured with repetitions of 3, ≤ 5 sets and rest periods of ≥ 3 minutes. It is also important to note that the intention to move explosively at a given load is important regardless of the load and that this should therefore be stressed when training athletes.

Finally, complex training utilising PAP may be an efficient means to enhancing power output providing fatigue is well managed. At worst it provides organisational advantages when time efficiency becomes paramount. In such a scenario, the heavy preload set may serve to maintain strength levels and the rest period may provide the opportunity to integrate plyometric drills.

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