REVIEW ARTICLE

Sports Med 2011; 41 (2): 125-146
0112-1642/11/0002-0125/$49.95/0

Developing Maximal Neuromuscular Power

Part 2 – Training Considerations for Improving 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, 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 $= 1.16 \pm 0.20$ 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 inter-muscular 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.

Acknowledgements

The authors have no potential conflicts of interest to disclose and no funding was received for this review.

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