

# Developing Maximal Neuromuscular Power

## Part 2 – Training Considerations for Improving Maximal Power Production

Prue Cormie,<sup>1</sup> Michael R. McGuigan<sup>2,3</sup> and Robert U. Newton<sup>1</sup>

- 1 School of Exercise, Biomedical and Health Sciences, Edith Cowan University, Joondalup, Western Australia, Australia
- 2 New Zealand Academy of Sport North Island, Auckland, New Zealand
- 3 Institute of Sport and Recreation Research New Zealand, Auckland University of Technology, Auckland, New Zealand

### Contents

Abstract . . . . .	125
1. Role of Strength in Maximal Power Production . . . . .	127
2. Movement Pattern Specificity . . . . .	129
2.1 Traditional Resistance Training Exercises . . . . .	129
2.2 Ballistic Exercises . . . . .	129
2.3 Plyometrics . . . . .	133
2.4 Weightlifting Exercises . . . . .	134
3. Load Specificity . . . . .	134
3.1 Heavy Loads . . . . .	135
3.2 Light Loads . . . . .	136
3.3 The 'Optimal' Load . . . . .	136
3.4 Combination of Loads . . . . .	137
4. Velocity Specificity . . . . .	138
4.1 Actual Movement Velocity . . . . .	138
4.2 Intention to Move Explosively . . . . .	139
4.3 Actual versus Intended Movement Velocity . . . . .	140
5. Window of Adaptation . . . . .	140
6. Integration of Power Training Modalities . . . . .	140
7. Conclusions and Implications . . . . .	141

### 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<sup>[1]</sup> 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.<sup>[2-9]</sup> 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<sup>[7,10-17]</sup> (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.<sup>[9,18-27]</sup> 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.<sup>[28]</sup> 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.<sup>[29-34]</sup> 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.<sup>[32]</sup> 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<sup>[35-56]</sup> as a result of increased myofibrillar CSA of type I and, to a greater degree, type II fibres.<sup>[35,37,41,42,44,45,57-60]</sup> It is highly likely that pennation angle<sup>[46,52]</sup> and possibly even fascicle length<sup>[48,49,55,61]</sup> would be greater. Additionally, neural drive<sup>[21,29,40,62-68]</sup> as well as inter- and possibly even intra-muscular coordination<sup>[66,68-73]</sup> 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.<sup>[9,20,25,26]</sup> As a result, maximal muscular power output would be far superior following the 3 years of strength training.<sup>[20,24-26,41,56,74,75]</sup> 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 $\pm$ SD)		Power test conducted	Maximal power (mean $\pm$ SD)	
	stronger	weaker	stronger	weaker		stronger	weaker		stronger	weaker
Bourque <sup>[10]</sup> (2003)	8	8	Well trained male volleyball and badminton players	Well trained M long-distance runners	Smith machine squat 1RM (kg/kg)	2.36* $\pm$ 0.74	1.74 $\pm$ 0.32	Maximum CMJ power (W/kg)	76.3* $\pm$ 10.8	59.2 $\pm$ 11.1
Baker and Newton <sup>[14]</sup> (2006)	6	6	M 1st division national rugby league players	M 2nd division state rugby league players	BP 1RM (kg/kg)	1.46* $\pm$ 0.12	1.19 $\pm$ 0.13	Maximum BP throw power (W/kg)	6.97* $\pm$ 0.64	5.51 $\pm$ 0.55
Baker and Newton <sup>[15]</sup> (2008)	20	20	M 1st division national rugby league players	M 2nd division state rugby league players	Squat 1RM (kg)	175.0* $\pm$ 27.3	149.6 $\pm$ 14.3	Maximum CMJ power (W)	1897* $\pm$ 306	1701 $\pm$ 187.0
Cormie et al. <sup>[17]</sup> (2010)	12	18	Stronger physically active men	Weaker physically active men	Squat 1RM (kg/kg)	1.97* $\pm$ 0.08	1.32 $\pm$ 0.14	Maximum CMJ power (W/kg)	59.8* $\pm$ 3.8	50.2 $\pm$ 5.2
Cormie et al. <sup>[11]</sup> (2009)	12	18	Division I M football and track athletes	Untrained men	Squat 1RM (kg/kg)	1.93* $\pm$ 0.22	1.40 $\pm$ 0.27	Maximum CMJ power (W/kg)	71.7* $\pm$ 10.7	55.9 $\pm$ 8.0
McBride et al. <sup>[12]</sup> (1999)	8	8	National level M power lifters	Moderately active men	Smith machine squat 1RM (kg/kg)	2.88* $\pm$ 0.14	2.13 $\pm$ 0.14	Maximum CMJ power (W/kg)	56.9* $\pm$ 2.5	49.4 $\pm$ 2.6
	6	8	National level M Olympic lifters	Moderately active men	Smith machine squat 1RM (kg/kg)	2.86* $\pm$ 0.15	2.13 $\pm$ 0.14	Maximum CMJ power (W/kg)	63.0* $\pm$ 2.7	49.4 $\pm$ 2.6
	6	8	National level M sprinters	Moderately active men	Smith machine squat 1RM (kg/kg)	2.66* $\pm$ 0.16	2.13 $\pm$ 0.14	Maximum CMJ power (W/kg)	63.8* $\pm$ 2.9	49.4 $\pm$ 2.6
Stoessel et al. <sup>[13]</sup> (1991)	14	13	National level F weightlifters	Untrained women				VJ height (m)	0.50* $\pm$ 0.08	0.32 $\pm$ 0.07
Stone et al. <sup>[7]</sup> (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* $\pm$ 8.4	95.0 $\pm$ 6.3	Maximum CMJ power (W)	5391* $\pm$ 2566	3785 $\pm$ 376
Ugrinowitsch et al. <sup>[16]</sup> (2007)	10	10	M track athletes with international experience	Physically active men	Leg press 1RM (kg)	364.5 $\pm$ 115.1	304.0 $\pm$ 47.3	Maximum CMJ height (m)	0.40* $\pm$ 0.05	0.30 $\pm$ 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,<sup>[9,18-24,27]</sup> 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.<sup>[28,31]</sup>

## 2. Movement Pattern Specificity

The ability to generate maximal power in dynamic, multi-joint movements is dependent on the nature of the movement involved.<sup>[76,77]</sup> 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 weight-lifting 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.<sup>[77,84]</sup> 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.<sup>[84]</sup> 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.<sup>[77]</sup> 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.<sup>[76,77]</sup> 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.<sup>[77]</sup> 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.<sup>[22-24,32,85-88]</sup> 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.<sup>[35,85,89]</sup> 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.<sup>[29-32]</sup> 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.<sup>[32,90]</sup> 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).<sup>[77]</sup> 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) <sup>a</sup>	No. of subjects	Subject demographics	Experimental groups	Power training programme <sup>b</sup>	Training duration (wk)	Major findings
Cormie et al. <sup>[17]</sup> (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. <sup>[27]</sup> (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. <sup>[78]</sup> (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. <sup>[79]</sup> (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. <sup>[80]</sup> (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

*Continued next page*

Table II. Contd

Study (year) <sup>a</sup>	No. of subjects	Subject demographics	Experimental groups	Power training programme <sup>b</sup>	Training duration (wk)	Major findings
Kaneko et al. <sup>[20]</sup> (1983)	20	M who had not been specifically trained before; 1RM, NR	0% F <sub>max</sub> TRTE training (n=5); 30% F <sub>max</sub> TRTE training (n=5); 60% F <sub>max</sub> TRTE training (n=5); 100% F <sub>max</sub> TRTE training (n=5)	3 sessions/wk: TRTE: elbow flexion, 0% F <sub>max</sub> group: 1 × 10 at 0% F <sub>max</sub> ; 30% F <sub>max</sub> group: 1 × 10 at 30% F <sub>max</sub> ; 60% F <sub>max</sub> group: 1 × 10 at 60% F <sub>max</sub> ; 100% F <sub>max</sub> group: 1 × 10 holds at 100% F <sub>max</sub>	12	All TRTE groups: ↑ maximal P in elbow flexion*, ↑ maximal velocity in elbow flexion*; 0% and 30% F <sub>max</sub> groups: ↔ F <sub>max</sub> in elbow flexion; 60% and 100% F <sub>max</sub> groups: ↑ F <sub>max</sub> in elbow flexion*; no difference in ↑ maximal P between groups
Kyröläinen et al. <sup>[81]</sup> (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. <sup>[82]</sup> (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. <sup>[21]</sup> (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. <sup>[9]</sup> (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

Continued next page

Table II. Contd

Study (year) <sup>a</sup>	No. of subjects	Subject demographics	Experimental groups	Power training programme <sup>b</sup>	Training duration (wk)	Major findings
Newton et al. <sup>[33]</sup> (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 <sup>[25]</sup> (2004)	21	M college students who had not exercised regularly for at least 1 y; 1RM, NR	30+60% F <sub>max</sub> TRTE training (n=7); 30+100% F <sub>max</sub> TRTE training (n=7); 30+60+100% F <sub>max</sub> TRTE training (n=7)	3 sessions/wk: TRTE: elbow flexion, 30+60% F <sub>max</sub> group: 1×6 at 30% F <sub>max</sub> and 1×6 at 60% F <sub>max</sub> ; 30+100% F <sub>max</sub> group: 1×6 at 30% F <sub>max</sub> and 1×6 5 s holds at 100% F <sub>max</sub> ; 30+60+100% F <sub>max</sub> group: 1×4 at 30% F <sub>max</sub> , 1×4 at 60% F <sub>max</sub> and 1×4 5 s holds at 100% F <sub>max</sub>	8	All TRTE groups: ↑ maximal P in elbow flexion*, ↑ maximal velocity in elbow flexion*, ↑ F <sub>max</sub> in elbow flexion*; ↑ maximal P greater in 30%+60%+100% F <sub>max</sub> group vs 30%+100% F <sub>max</sub> group†
Toji et al. <sup>[26]</sup> (1997)	12	M college students who had not exercised regularly for at least 1 y; 1RM, NR	30+0% F <sub>max</sub> TRTE training (n=6); 30+100% F <sub>max</sub> TRTE training (n=6)	3 sessions/wk: TRTE: elbow flexion, 30+0% F <sub>max</sub> group: 1×5 at 0% F <sub>max</sub> and 1×5 at 60% F <sub>max</sub> ; 30+100% F <sub>max</sub> group: 1×5 at 30% F <sub>max</sub> and 1×5 3 s holds at 100% F <sub>max</sub>	11	Both TRTE groups: ↑ maximal P in elbow flexion*, ↑ maximal velocity in elbow flexion*; 30%+0% group: ↔ F <sub>max</sub> in elbow flexion; 30%+100% group: ↑ F <sub>max</sub> in elbow flexion*; ↑ maximal P greater in 30%+100% F <sub>max</sub> group vs 30%+0% F <sub>max</sub> group†
Wilson et al. <sup>[24]</sup> (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 <sub>max</sub> ; 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 <sub>max</sub> *; plyometric: ↑ PD in CMJ*. CON: ↔ any outcome measures; no difference in ↑ maximal P between the training groups
Winchester et al. <sup>[83]</sup> (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; **F<sub>max</sub>**=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≤0.05) change following training; † indicates significant (p≤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.<sup>[76,77]</sup> As a result, many researchers and coaches recommend the inclusion of ballistic exercises rather than traditional resistance training exercises in power training programmes.<sup>[24,28,31,33,76,77,91]</sup> 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.<sup>[21,24,33,78,81–83,92]</sup> Furthermore, the ability to generate power is also improved across a variety of low- and high-load conditions following training.<sup>[21,33,78]</sup> 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.<sup>[33]</sup> 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.<sup>[19,21,33,78,81]</sup> 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.<sup>[93]</sup> 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.<sup>[93]</sup> 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.<sup>[94]</sup> 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).<sup>[95]</sup> 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.<sup>[24,80,82,88,96–102]</sup> These improvements are, however, typically restricted to low-load/high-velocity SSC movements.<sup>[24,102]</sup> 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.<sup>[98,103]</sup> Adaptations to the aforementioned mechanisms driving enhanced performance during SSC movements are also hypothesized to contribute to improved maximal power production following plyometric training.<sup>[98,103]</sup> 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.<sup>[24,80,82,97-99]</sup>

## 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.<sup>[104-106]</sup> 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.<sup>[107,108]</sup> 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.<sup>[76,109,110]</sup> 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.<sup>[111]</sup> Empirical observations are supported by evidence of similarities in the kinetic features of the propulsive phase in both weightlifting and jumping movements.<sup>[107,112]</sup> Significant relationships have also been observed between weightlifting exercises and power output during jumping ( $r=0.58-0.93$ ) as well as sprint performance ( $r=-0.57$ ).<sup>[4,113]</sup> Despite the widespread use of weightlifting exercises to enhance power and the evidence highlighting its specificity to athletic movements common to many sports, little re-

search exists examining the efficacy of power training with weightlifting exercises. In previously untrained men, Tricoli et al.<sup>[102]</sup> observed significant improvements in static jump and CMJ height as well as 10m 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.<sup>[102]</sup> 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.<sup>[9,20,76,114,115]</sup> 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  $6332 \pm 1085$  W at 0% of 1RM to  $3986 \pm 564$  W at 85% of 1RM, a 37% variation.<sup>[76]</sup> 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.<sup>[20]</sup> 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.<sup>[20]</sup> 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  $\geq 80\%$  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.<sup>[9,19,20,22,24,41,56,74]</sup> The second theory forming the basis for the prescription of heavy loads is related to the size principle for motor unit recruitment.<sup>[116–118]</sup> 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.<sup>[119–121]</sup> 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.<sup>[21,24,95,122]</sup> 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.<sup>[9,19,20,22,24,41,56,74]</sup> 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.<sup>[27,56,62,74,89,123]</sup> Changes to maximal power following such training in strong, experienced athletes are of a much smaller, non-statistically significant magnitude.<sup>[29–32]</sup> 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.<sup>[28]</sup>

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.<sup>[21,76]</sup> Ballistic and/or weightlifting training with heavy loads would still allow for the recruitment of high threshold motor units.<sup>[124,125]</sup> 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.<sup>[19,21]</sup> 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.<sup>[9,20,21]</sup> 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.<sup>[102]</sup> 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.<sup>[102]</sup> McBride et al.<sup>[21]</sup> 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.<sup>[21]</sup> 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.<sup>[9,19–21,24,80,82,83,97–99]</sup> 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.<sup>[19–21]</sup> 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.<sup>[9,19–21,24,78,80–83,97–99,126]</sup> 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.<sup>[20,21]</sup> 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.<sup>[19,21,33,78,81]</sup> 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.<sup>[114]</sup> 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.<sup>[31,77]</sup>

### 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.<sup>[24,76,109,114,127]</sup> 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.<sup>[20,21]</sup> Power is maximized at approximately 30%  $F_{\max}$  in single muscle fibres and single-joint movements.<sup>[20,25,26,128–132]</sup> 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<sup>[17,27,76,133-136]</sup> to 30–45% of bench press 1RM in the bench press throw<sup>[115,135]</sup> and up to 70–80% of snatch and/or clean 1RM in weightlifting exercises.<sup>[76,109,110]</sup> 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.<sup>[76]</sup> 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.<sup>[7,137]</sup> However, conflicting evidence exists indicating that the 'opti-

mal' load does not vary between individuals with significantly different strength levels (i.e. stronger vs weaker individuals).<sup>[17,136]</sup> 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.<sup>[19-21]</sup> 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.<sup>[9,20,21,24]</sup> 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).<sup>[9,19-21,62,130,138]</sup> 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.<sup>[25,26]</sup>

Research has established that significant improvements in maximal power output and various athletic performance parameters occur following training with a combination of loads.<sup>[25,26,33,78,81,82,88,122,139]</sup> 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.<sup>[25,26,78,88,122]</sup> However, most of these studies did not control for the total work completed by various groups<sup>[25,26,88,122]</sup> 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.<sup>[78]</sup> 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.<sup>[78]</sup> 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.<sup>[20,40,140–144]</sup> 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.<sup>[18]</sup> 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.<sup>[40,140–144]</sup> 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.<sup>[140–144]</sup> Some evidence also indicates smaller but significant improvements in force and power at velocities both above and below the specific training velocity.<sup>[140,143]</sup>

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.<sup>[9,20]</sup> Less research is available examining whether a velocity-specific response occurs following isoinertial training with dynamic, sports-specific movements. McBride and co-workers<sup>[21]</sup> 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.<sup>[21]</sup> 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<sup>[19,62]</sup> 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.<sup>[19]</sup> 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.<sup>[62]</sup> 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.<sup>[123]</sup> Specific adaptations to muscle architecture and contractile mechanics may also contribute to velocity-specific improvements in performance. For example, Blazevich and colleagues<sup>[49]</sup> 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.<sup>[49,145]</sup> 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.<sup>[18]</sup> 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.”<sup>[18]</sup> 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.<sup>[18]</sup> 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.<sup>[72,73]</sup> 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.<sup>[87,146]</sup>

#### 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.<sup>[18,146]</sup> 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.<sup>[9,19-21,40,49,62,140-144]</sup> 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<sup>[1]</sup> 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<sup>[22-24,32,85-88]</sup> but not in stronger or more experienced athletes.<sup>[32,33]</sup> 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.<sup>[31]</sup> 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.<sup>[31]</sup> 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<sup>[32]</sup> 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  $1.80 \pm 0.26$ , 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,<sup>[9,20,78,82,88]</sup> whereas well trained athletes require much greater specificity and variation.<sup>[33]</sup> 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.<sup>[147-150]</sup> Through the use of cycles within an overall programme, periodization allows for variations in the intensity, volume and specificity of strength training.<sup>[147-150]</sup> 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.<sup>[151]</sup> 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.<sup>[151,152]</sup> 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.<sup>[148,151,152]</sup> 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 over-training.<sup>[151,152]</sup> 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.<sup>[147-150]</sup> 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.<sup>[147-150]</sup>

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.<sup>[31]</sup> 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 ex-

posure to a single power training modality renders inferior long-term developments due to the exhaustion phase being reached.<sup>[30,151,152]</sup> 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.<sup>[31]</sup>

## 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.

## References

1. Cormie P, McGuigan MR, Newton RU. Developing maximal neuromuscular power. Part I: biological basis of maximal power production. *Sports Med* 2010; 41 (1): 17-38
2. Baker D, Nance S. The relation between strength and power in professional rugby league players. *J Strength Cond Res* 1999; 13 (3): 224-9
3. Blackburn JR, Morrissey MC. The relationship between open and closed kinetic chain strength of the lower limb and jumping performance. *J Orthop Sports Phys Ther* 1998; 27: 430-5
4. Carlock JM, Smith SL, Hartman MJ, et al. The relationship between vertical jump power estimates and weight-lifting ability: a field-test approach. *J Strength Cond Res* 2004; 18 (3): 534-9
5. Miyaguchi K, Demura S. Relationships between stretch-shortening cycle performance and maximum muscle strength. *J Strength Cond Res* 2008; 22 (1): 19-24
6. Nuzzo JL, McBride JM, Cormie P, et al. Relationship between countermovement jump performance and multi-joint isometric and dynamic tests of strength. *J Strength Cond Res* 2008; 22 (3): 699-707
7. Stone MH, O'Bryant HS, McCoy L, et al. Power and maximum strength relationships during performance of dynamic and static weighted jumps. *J Strength Cond Res* 2003; 17 (1): 140-7
8. Wisloff U, Castagna C, Helgerud J, et al. Strong correlation of maximal squat strength with sprint performance and vertical jump height in elite soccer players. *Br J Sports Med* 2004; 38 (3): 285-8
9. Moss BM, Refsnes PE, Abildgaard A, et al. Effects of maximal effort strength training with different loads on dynamic strength, cross-sectional area, load-power and load-velocity relationships. *Eur J Appl Physiol Occup Physiol* 1997; 75 (3): 193-9
10. Bourque PJ. Determinant of load at peak power during maximal effort squat jumps in endurance and power trained athletes [dissertation]. Fredericton (NB): University of New Brunswick, 2003
11. Cormie P, McBride JM, McCauley GO. Power-time, force-time, and velocity-time curve analysis of the countermovement jump: impact of training. *J Strength Cond Res* 2009; 23 (1): 177-86
12. McBride JM, Triplett-McBride NT, Davie A, et al. A comparison of strength and power characteristics between power lifters, Olympic lifters, and sprinters. *J Strength Cond Res* 1999; 13 (1): 58-66
13. Stoessel L, Stone ME, Keith R, et al. Selected physiological, psychological and performance characteristics of national-caliber United States women weightlifters. *J Appl Sport Sci Res* 1991; 5 (2): 87-95
14. Baker DG, Newton RU. Adaptations in upper-body maximal strength and power output resulting from long-term resistance training in experienced strength-power athletes. *J Strength Cond Res* 2006; 20 (3): 541-6
15. Baker DG, Newton RU. Comparison of lower body strength, power, acceleration, speed, agility, and sprint momentum to describe and compare playing rank among professional rugby league players. *J Strength Cond Res* 2008; 22 (1): 153-8
16. Ugrinowitsch C, Tricoli V, Rodacki AL, et al. Influence of training background on jumping height. *J Strength Cond Res* 2007; 21 (3): 848-52
17. Cormie P, McGuigan MR, Newton RU. Influence of strength on magnitude and mechanisms of adaptation to power training. *Med Sci Sports Exerc* 2010; 42 (8): 1566-81
18. Behm DG, Sale DG. Intended rather than actual movement velocity determines velocity-specific training response. *J Appl Physiol* 1993; 74 (1): 359-68
19. Häkkinen K, Komi PV, Alen M. Effect of explosive type strength training on isometric force- and relaxation-time, electromyographic and muscle fibre characteristics of leg extensor muscles. *Acta Physiol Scand* 1985; 125 (4): 587-600
20. Kaneko M, Fuchimoto T, Toji H, et al. Training effect of different loads on the force-velocity relationship and mechanical power output in human muscle. *Scand J Med Sci Sports* 1983; 5 (2): 50-5
21. McBride JM, Triplett-McBride T, Davie A, et al. The effect of heavy- vs. light-load jump squats on the development of strength, power, and speed. *J Strength Cond Res* 2002; 16 (1): 75-82

22. Stone ME, Johnson R, Carter D. A short term comparison of two different methods of resistive training on leg strength and power. *Athl Train* 1979; 14: 158-60
23. Stowers T, McMillan J, Scala D, et al. The short-term effects of three different strength-power training methods. *Natl Strength Cond Assoc J* 1983; 5 (3): 24-7
24. Wilson GJ, Newton RU, Murphy AJ, et al. The optimal training load for the development of dynamic athletic performance. *Med Sci Sports Exerc* 1993; 25 (11): 1279-86
25. Toji H, Kaneko M. Effect of multiple-load training on the force-velocity relationship. *J Strength Cond Res* 2004; 18 (4): 792-5
26. Toji H, Sui K, Kaneko M. Effects of combined training loads on relations among force, velocity, and power development. *Can J Appl Physiol* 1997; 22 (4): 328-36
27. Cormie P, McGuigan MR, Newton RU. Adaptations in athletic performance after ballistic power versus strength training. *Med Sci Sports Exerc* 2010; 42 (8): 1582-98
28. Kraemer WJ, Newton RU. Training for muscular power. *Phys Med Rehabil Clin N Am* 2000; 11 (2): 341-68
29. Häkkinen K. Neuromuscular and hormonal adaptations during strength and power training. *J Sports Med* 1989; 29: 9-26
30. Häkkinen K, Komi PV, Alen M, et al. EMG, muscle fibre and force production characteristics during a 1 year training period in elite weight-lifters. *Eur J Appl Physiol* 1987; 56: 419-27
31. Newton RU, Kraemer WJ. Developing explosive muscular power: implications for a mixed method training strategy. *Strength Cond J* 1994; 16 (5): 20-31
32. Wilson G, Murphy AJ, Walshe AD. Performance benefits from weight and plyometric training: effects of initial strength level. *Coaching Sport Sci J* 1997; 2 (1): 3-8
33. Newton RU, Kraemer WJ, Häkkinen K. Effects of ballistic training on preseason preparation of elite volleyball players. *Med Sci Sports Exerc* 1999; 31 (2): 323-30
34. Häkkinen K, Pakarinen A, Alen M, et al. Neuromuscular and hormonal adaptations in athletes to strength training in two years. *J Appl Physiol* 1988; 65 (6): 2406-12
35. Campos GE, Luecke TJ, Wendeln HK, et al. Muscular adaptations in response to three different resistance-training regimens: specificity of repetition maximum training zones. *Eur J Appl Physiol* 2002; 88: 50-60
36. Costill DL, Coyle EF, Fink WF, et al. Adaptations in skeletal muscle following strength training. *J Appl Physiol* 1979; 46 (1): 96-9
37. Green H, Goreham C, Ouyang J, et al. Regulation of fiber size, oxidative potential, and capillarization in human muscle by resistance exercise. *Am J Physiol Regul Integr Comp Physiol* 1998; 276 (45): R591-6
38. Hather BM, Tesch PA, Buchanan P, et al. Influence of eccentric actions on skeletal muscle adaptations to resistance training. *Acta Physiol Scand* 1991; 143: 177-85
39. Jackson CG, Dickinson AL, Ringel SP. Skeletal muscle fiber area alterations in two opposing modes of resistance-exercise training in the same individual. *Eur J Appl Physiol Occup Physiol* 1990; 61 (1-2): 37-41
40. Narici MV, Roi GS, Landoni L, et al. Changes in force-cross-sectional area and neural activation during strength training and detraining of the human quadriceps. *Eur J Appl Physiol* 1989; 59: 310-9
41. Roman WJ, Fleckenstein J, Stray-Gundersen J, et al. Adaptations in the elbow flexors of elderly males after heavy-resistance training. *J Appl Physiol* 1993; 74 (2): 750-4
42. Staron RS, Karapondo DL, Kraemer WJ, et al. Skeletal muscle adaptations during the early phase of heavy-resistance training in men and women. *J Appl Physiol* 1994; 76: 1247-55
43. Staron RS, Leonardi MJ, Karapondo DL, et al. Strength and skeletal muscle adaptations in heavy-resistance trained women after detraining and retraining. *J Appl Physiol* 1991; 70: 631-40
44. Staron RS, Malicky ES, Leonardi MJ, et al. Muscle hypertrophy and fast fiber type conversions in heavy resistance-trained women. *Eur J Appl Physiol* 1989; 60: 71-9
45. Thorstensson A, Hulten B, von Döbeln W, et al. Effect of strength training on enzyme activities and fibre characteristics in human skeletal muscle. *Acta Physiol Scand* 1976; 96: 392-8
46. Aagaard P, Andersen JL, Dyhre-Poulsen P, et al. A mechanism for increased contractile strength of human pennate muscle in response to strength training: changes in muscle architecture. *J Physiol* 2001; 534 (Pt 2): 613-23
47. Alegre LM, Jimenez F, Gonzalo-Orden JM, et al. Effects of dynamic resistance training on fascicle length and isometric strength. *J Sports Sci* 2006; 24 (5): 501-8
48. Blazeovich AJ, Cannavan D, Coleman DR, et al. Influence of concentric and eccentric resistance training on architectural adaptation in human quadriceps muscles. *J Appl Physiol* 2007; 103 (5): 1565-75
49. Blazeovich AJ, Gill ND, Bronks R, et al. Training-specific muscle architecture adaptation after 5-wk training in athletes. *Med Sci Sports Exerc* 2003; 35 (12): 2013-22
50. Folland JP, Williams AG. The adaptations to strength training: morphological and neurological contributions to increased strength. *Sports Med* 2007; 37 (2): 145-68
51. Jones DA, Rutherford OM, Parker DF. Physiological changes in skeletal muscle as a result of strength training. *Q J Exp Physiol* 1989; 74 (3): 233-56
52. Kawakami Y, Abe T, Kuno SY, et al. Training-induced changes in muscle architecture and specific tension. *Eur J Appl Physiol* 1995; 72 (1-2): 566-73
53. Komi PV. Training of muscle strength and power: interaction of neuromotoric, hypertrophic, and mechanical factors. *Int J Sports Med* 1986; 7 Suppl. 1: 10-5
54. McDonagh MJN, Davis CTM. Adaptive responses of mammalian skeletal-muscle to exercise with high loads. *Eur J Appl Physiol Occup Physiol* 1984; 52: 139-55
55. Seynnes OR, de Boer M, Narici MV. Early skeletal muscle hypertrophy and architectural changes in response to high-intensity resistance training. *J Appl Physiol* 2007; 102: 368-73
56. Widrick JJ, Stelzer JE, Shoepe TC, et al. Functional properties of human muscle fibers after short-term resistance exercise training. *Am J Physiol Regul Integr Comp Physiol* 2002; 283 (2): R408-16
57. Thorstensson A. Muscle strength, fibre types and enzyme activities in man. *Acta Physiol Scand* 1976; 443: S1-44

58. MacDougall JD, Elder GCB, Sale DG, et al. Effects of strength training and immobilization on human muscle fibers. *Eur J Appl Physiol* 1980; 43: 25-34
59. Dons B, Bollerup K, Bonde-Petersen F, et al. The effect of weight-lifting exercise related to muscle fiber composition and muscle cross-sectional area in humans. *Eur J Appl Physiol* 1979; 40: 95-106
60. Häkkinen K, Komi PV, Tesch PA. Effect of combined concentric and eccentric strength training and detraining on force-time, muscle fibre and metabolic characteristics of leg extensor muscles. *Scand J Sports Sci* 1981; 3: 50-8
61. Reeves ND, Narici MV, Maganaris CN. In vivo human muscle structure and function: adaptations to resistance training in old age. *Exp Physiol* 2004; 89 (6): 675-89
62. Häkkinen K, Alen M, Komi PV. Changes in isometric force- and relaxation-time, electromyographic and muscle fibre characteristics of human skeletal muscle during strength training and detraining. *Acta Physiol Scand* 1985; 125 (4): 573-85
63. Narici MV, Hoppeler H, Kayser B, et al. Human quadriceps cross-sectional area, torque and neural activation during 6 months strength training. *Acta Physiol Scand* 1996; 157 (2): 175-86
64. Thorstensson A, Karlsson J, Vitasalo JHT, et al. Effect of strength training on EMG of human skeletal muscle. *Acta Physiol Scand* 1976; 98: 232-6
65. Häkkinen K, Komi PV. Electromyographic changes during strength training and detraining. *Med Sci Sports Exerc* 1983; 15: 455-60
66. Häkkinen K, Alen M, Kallinen M, et al. Neuromuscular adaptation during prolonged strength training, detraining and re-strength training in middle-aged and elderly people. *Eur J Appl Physiol* 2000; 83: 51-62
67. Komi PV, Viitasalo JT, Rauramaa R, et al. Effect of isometric strength training on mechanical, electrical and metabolic aspects of muscle function. *Eur J Appl Physiol* 1978; 40: 45-55
68. Häkkinen K, Newton RU, Gordon SE, et al. Changes in muscle morphology, electromyographic activity, and force production characteristics during progressive strength training in young and older men. *J Gerontol A Biol Sci Med Sci* 1998; 53 (6): B415-23
69. Behm DG. Neuromuscular implications and applications of resistance training. *J Strength Cond Res* 1995; 9 (4): 264-74
70. Carolan B, Cafarelli E. Adaptations in coactivation after isometric resistance training. *J Appl Physiol* 1992; 73: 911-7
71. Rabita G, Perot C, Linsel-Corbeil G. Differential effect of knee extension isometric training on the different muscles of the quadriceps femoris in humans. *Eur J Appl Physiol* 2001; 83: 531-8
72. Sale DG. Neural adaptation to resistance training. *Med Sci Sports Exerc* 1988; 20 (5 Suppl.): S135-45
73. Sale DG. Neural adaptations to strength training. In: Komi PV, editor. *Strength and power in sport*. 2nd ed. Oxford: Blackwell Science, 2003: 281-313
74. Malisoux L, Francaux M, Nielens H, et al. Stretch-shortening cycle exercises: an effective training paradigm to enhance power output of human single muscle fibers. *J Appl Physiol* 2006; 100 (3): 771-9
75. MacIntosh BR, Holash RJ. Power output and force-velocity properties of muscle. In: Nigg BM, MacIntosh BR, Mester J, editors. *Biomechanics and biology of movement*. Champaign (IL): Human Kinetics, 2000: 193-210
76. Cormie P, McCaulley GO, Triplett NT, et al. Optimal loading for maximal power output during lower-body resistance exercises. *Med Sci Sports Exerc* 2007; 39 (2): 340-9
77. Newton RU, Kraemer WJ, Hakkinen K, et al. Kinematics, kinetics, and muscle activation during explosive upper body movements. *J Appl Biomech* 1996; 12: 31-43
78. Cormie P, McCaulley GO, McBride JM. Power versus strength-power jump squat training: influence on the load-power relationship. *Med Sci Sports Exerc* 2007; 39 (6): 996-1003
79. Hawkins SB, Doyle TL, McGuigan MR. The effect of different training programs on eccentric energy utilization in college-aged males. *J Strength Cond Res* 2009; 23 (7): 1996-2002
80. Holcomb WR, Lander JE, Rutland RM, et al. The effectiveness of a modified plyometric program on power and the vertical jump. *J Strength Cond Res* 1996; 10 (2): 89-92
81. Kyröläinen H, Avela J, McBride JM, et al. Effects of power training on muscle structure and neuromuscular performance. *Scand J Med Sci Sports* 2005; 15 (1): 58-64
82. Lyttle AD, Wilson G, Ostrowski KJ. Enhancing performance: maximal power versus combined weights and plyometrics training. *J Strength Cond Res* 1996; 10 (3): 173-9
83. Winchester JB, McBride JM, Maher MA, et al. Eight weeks of ballistic exercise improves power independently of changes in strength and muscle fiber type expression. *J Strength Cond Res* 2008; 22 (6): 1728-34
84. Elliott BC, Wilson DJ, Kerr GK. A biomechanical analysis of the sticking region in the bench press. *Med Sci Sports Exerc* 1989; 21: 450-62
85. Lamas L, Aoki MS, Ugrinowitsch C, et al. Expression of genes related to muscle plasticity after strength and power training regimens. *Scand J Med Sci Sports* 2010; 20 (2): 216-25
86. Berger RA. Effects of dynamic and static training on vertical jumping ability. *Res Q* 1963; 34 (4): 419-24
87. Young WB, Bilby GE. The effect of voluntary effort to influence speed of contraction on strength, muscular power, and hypertrophy development. *J Strength Cond Res* 1993; 7 (3): 172-8
88. Adams K, O'Shea JP, O'Shea KL, et al. The effect of six weeks of squat, plyometric and squat-plyometric training on power production. *J Appl Sport Sci Res* 1992; 6 (1): 36-41
89. Häkkinen K, Kallinen M, Izquierdo M, et al. Changes in agonist-antagonist EMG, muscle CSA, and force during strength training in middle-aged and older people. *J Appl Physiol* 1998; 84 (4): 1341-9
90. Häkkinen K, Mero A, Kauhaneen H. Specificity of endurance, sprint and strength training on physical performance capacity in young athletes. *J Sports Med Phys Fitness* 1989; 29 (1): 27-35

91. Cronin J, McNair PJ, Marshall RN. Developing explosive power: a comparison of technique and training. *J Sci Med Sport* 2001; 4 (1): 59-70
92. Baker D. A series of studies on the training of high-intensity muscle power in rugby league football players. *J Strength Cond Res* 2001; 15 (2): 198-209
93. Wathen D. Position statement: explosive/plyometric exercises. *NSCA J* 1993; 15 (3): 16-9
94. de Villarreal ES, Kellis E, Kraemer WJ, et al. Determining variables of plyometric training for improving vertical jump height performance: a meta-analysis. *J Strength Cond Res* 2009; 23 (2): 495-506
95. Schmidtbleicher D. Training for power events. In: Komi PV, editor. *Strength and power in sport*. Oxford: Blackwell Scientific Publications, 1992: 381-95
96. Blattner SE, Noble L. Relative effects of isokinetic and plyometric training on vertical jumping performance. *Res Q* 1979; 50 (4): 583-88
97. Brown ME, Mayhew JL, Boleach LW. Effect of plyometric training on vertical jump performance in high school basketball players. *J Sports Med Phys Fitness* 1986; 26 (1): 1-4
98. Chimera NJ, Swanik KA, Swanik CB, et al. Effects of plyometric training on muscle-activation strategies and performance in female athletes. *J Athl Train* 2004; 39 (1): 24-31
99. Matavulj D, Kukolj M, Ugarkovic D, et al. Effects of plyometric training on jumping performance in junior basketball players. *J Sports Med Phys Fitness* 2001; 41 (2): 159-64
100. Fatouros IG, Jamurtas AZ, Leontsini D, et al. Evaluation of plyometric exercise training, weight training, and their contribution on vertical jumping performance and leg strength. *J Strength Cond Res* 2000; 14: 470-6
101. Gehri DJ, Ricard MD, Kleiner DM, et al. A comparison of plyometric training technique for improving vertical jump ability and energy production. *J Strength Cond Res* 1998; 12: 85-9
102. Tricoli V, Lamas L, Carnevale R, et al. Short-term effects on lower-body functional power development: weightlifting vs. vertical jump training programs. *J Strength Cond Res* 2005; 19 (2): 433-7
103. Schmidtbleicher D, Gollhofer A, Frick U. Effects of a stretch-shortening typed training on the performance capability and innervation characteristics of leg extensor muscles. In: de Groot G, Hollander AP, Huijing PA, et al., editors. *Biomechanics XI-A*. Amsterdam: Free University Press, 1988: 185-9
104. Ebben WP, Hintz MJ, Simenz CJ. Strength and conditioning practices of major league baseball strength and conditioning coaches. *J Strength Cond Res* 2005; 19 (3): 538-46
105. Ebben WP, Carroll RM, Simenz CJ. Strength and conditioning practices of national hockey league strength and conditioning coaches. *J Strength Cond Res* 2004; 18 (4): 889-97
106. Simenz CJ, Dugan CA, Ebben WP. Strength and conditioning practices of national basketball association strength and conditioning coaches. *J Strength Cond Res* 2005; 19 (3): 495-504
107. Garhammer J, Gregor R. Propulsion forces as a function of intensity for weightlifting and vertical jumping. *J Appl Sport Sci Res* 1992; 6 (3): 129-34
108. Schilling BK, Stone MH, O'Bryant HS, et al. Snatch technique of collegiate national level weightlifters. *J Strength Cond Res* 2002; 16 (4): 551-5
109. Kawamori N, Crum AJ, Blumert PA, et al. Influence of different relative intensities on power output during the hang power clean: identification of the optimal load. *J Strength Cond Res* 2005; 19 (3): 698-708
110. Haff GG, Stone MH, O'Bryant HS, et al. Force-time dependent characteristics of dynamic and isometric muscle actions. *J Strength Cond Res* 1997; 11 (4): 269-72
111. Hori N, Newton RU, Nosaka K, et al. Weightlifting exercises enhance athletic performance that requires high-load speed strength. *Strength Cond J* 2005; 27 (4): 50-5
112. Canavan PK, Garrett GE, Armstrong LE. Kinematic and kinetic relationships between an Olympic-style lift and the vertical jump. *J Strength Cond Res* 1996; 10 (2): 127-30
113. Hori N, Newton RU, Andrews WA, et al. Does performance of hang power clean differentiate performance of jumping, sprinting, and changing of direction? *J Strength Cond Res* 2008; 22 (2): 412-8
114. Kawamori N, Haff GG. The optimal training load for the development of muscular power. *J Strength Cond Res* 2004; 18 (3): 675-84
115. Newton RU, Murphy AJ, Humphries BJ, et al. Influence of load and stretch shortening cycle on the kinematics, kinetics and muscle activation that occurs during explosive upper-body movements. *Eur J Appl Physiol Occup Physiol* 1997; 75 (4): 333-42
116. Schmidtbleicher D, Buehrle M. Neuronal adaptation and increase of cross-sectional area studying different strength training methods. In: de Groot G, Hollander AP, Huijing PA, et al., editors. *Biomechanics X-B*. Amsterdam: Free University Press, 1987: 615-20
117. Schmidtbleicher D, Haralambie G. Changes in contractile properties of muscle after strength training in man. *Eur J Appl Physiol Occup Physiol* 1981; 46 (3): 221-8
118. Sale DG. Influence of exercise and training on motor unit activation. *Exerc Sport Sci Rev* 1987; 15: 95-151
119. Hannerz J. Discharge properties of motor units in relation to recruitment order in voluntary contraction. *Acta Physiol Scand* 1974; 91 (3): 374-85
120. Henneman E, Clamann HP, Gillies JD, et al. Rank order of motoneurons within a pool, law of combination. *J Neurophysiol* 1974; 37: 1338-49
121. Henneman E, Somjen G, Carpenter DO. Functional significance of cell size in spinal motoneurons. *J Neurophysiol* 1965; 28: 560-80
122. Harris GR, Stone ME, O'Bryant HS, et al. Short-term performance effects of high power, high force, or combined weight-training methods. *J Strength Cond Res* 2000; 14 (1): 14-20
123. Aagaard P, Simonsen EB, Andersen JL, et al. Increased rate of force development and neural drive of human skeletal muscle following resistance training. *J Appl Physiol* 2002; 93 (4): 1318-26
124. Desmedt JE, Godaux E. Ballistic contractions in man: characteristic recruitment pattern of single motor units of the tibialis anterior muscle. *J Physiol* 1977; 264: 673-93

125. Desmedt JE, Godaux E. Ballistic contractions in fast or slow human muscles: discharge patterns of single motor units. *J Physiol* 1978; 285: 185-96
126. Newton RU, Rogers RA, Volek JS, et al. Four weeks of optimal load ballistic resistance training at the end of season attenuates declining jump performance of women volleyball players. *J Strength Cond Res* 2006; 20 (4): 955-61
127. Dugan EL, Doyle TL, Humphries B, et al. Determining the optimal load for jump squats: a review of methods and calculations. *J Strength Cond Res* 2004; 18 (3): 668-74
128. Bottinelli R, Pellegrino MA, Canepari M, et al. Specific contributions of various muscle fibre types to human muscle performance: an in vitro study. *J Electromyogr Kinesiol* 1999; 9 (2): 87-95
129. de Haan A, Jones DA, Sargent AJ. Changes in velocity of shortening, power output and relaxation rate during fatigue of rat gastrocnemius muscle. *Pflugers Arch* 1989; 412 (4): 422-8
130. Duchateau J, Hainaut K. Isometric or dynamic training: differential effects on mechanical properties of human muscle. *J Appl Physiol* 1984; 56: 296-301
131. Faulkner JA, Claflin DR, McCully KK. Power output of fast and slow fibers from human skeletal muscles. In: Jones NL, McCartney N, McComas AJ, editors. *Human muscle power*. Champaign (IL): Human Kinetics Inc., 1986: 81-94
132. van Leeuwen JL. Optimum power output and structural design of sarcomeres. *J Theor Biol* 1991; 149: 229-56
133. Cormie P, McBride JM, McCaulley GO. Power-time, force-time, and velocity-time curve analysis during the jump squat: impact of load. *J Appl Biomech* 2008; 24 (2): 112-20
134. Sheppard JM, Cormack S, Taylor KL, et al. Assessing the force-velocity characteristics of the leg extensors in well-trained athletes: the incremental load power profile. *J Strength Cond Res* 2008; 22 (4): 1320-6
135. Bevan HR, Bunce PJ, Owen NJ, et al. Optimal loading for the development of peak power output in professional rugby players. *J Strength Cond Res* 2010; 24 (1): 43-7
136. Nuzzo JL, McBride JM, Dayne AM, et al. Testing of the maximal dynamic output hypothesis in trained and untrained subjects. *J Strength Cond Res* 2010; 24 (5): 1269-76
137. Driss T, Vandewalle H, Quievre J, et al. Effects of external loading on power output in a squat jump on a force platform: a comparison between strength and power athletes and sedentary individuals. *J Sports Sci* 2001 Feb; 19 (2): 99-105
138. Jones K, Bishop P, Hunter G, et al. The effects of varying resistance-training loads on intermediate- and high-velocity-specific adaptations. *J Strength Cond Res* 2001 Aug; 15 (3): 349-56
139. Newton RU, Hakkinen K, Hakkinen A, et al. Mixed-methods resistance training increases power and strength of young and older men. *Med Sci Sports Exerc* 2002; 34 (8): 1367-75
140. Moffroid MT, Whipple RH. Specificity of speed of exercise. *Phys Ther* 1970; 50: 1692-700
141. Lesmes G. Muscle strength and power changes during maximal isokinetic training. *Med Sci Sports Exerc* 1978; 10: 266-9
142. Caiozzo VJ, Perrine JJ, Edgerton VR. Training-induced alterations of the in vivo force-velocity relationship of human muscle. *J Appl Physiol* 1981; 51 (3): 750-4
143. Coyle EF, Feiring DC, Rotkis TC, et al. Specificity of power improvements through slow and fast isokinetic training. *J Appl Physiol* 1981; 51 (6): 1437-42
144. Kanehisa H, Miyashita M. Specificity of velocity in strength training. *Eur J Appl Physiol Occup Physiol* 1983; 52 (1): 104-6
145. Blazeovich AJ, Sharp NC. Understanding muscle architectural adaptation: macro- and micro-level research. *Cells Tissues Organs* 2005; 181 (1): 1-10
146. Fielding RA, LeBrasseur NK, Cuoco A, et al. High-velocity resistance training increases skeletal muscle peak power in older women. *J Am Geriatr Soc* 2002; 50 (4): 655-62
147. Bompa TO, Carrera M. *Periodization training for sports*. 2nd ed. Champaign (IL): Human Kinetics, 2005: 3-349
148. Stone ME, O'Bryant HS. *Weight training a scientific approach*. Edina (MN): Burgess International Group Inc., 1987: 121-65
149. Zatsiorsky VM, Kraemer WJ. *Science and practice of strength training*. 2nd ed. Champaign (IL): Human Kinetics, 2006: 17-46
150. Wathen D, Baechle TR, Earle RW. Training variation: periodization. In: Baechle TR, Earle RW, editors. *Essentials of strength training and conditioning*. 2nd ed. Champaign (IL): Human Kinetics, 2000: 513-27
151. Selye H. *The stress of life*. New York: McGraw-Hill, 1956
152. Garhammer J. *Periodization of strength training for athletes*. Track Tech 1979; 73: 2398-9

---

Correspondence: Dr Prue Cormie, School of Exercise and Biomedical Health Sciences, Edith Cowan University, 270 Joondalup Drive, Joondalup, WA 6027, Australia.  
E-mail: p.cormie@ecu.edu.au