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REVIEW ARTICLE

Resistance Priming to Enhance Neuromuscular Performance in Sport: Evidence, Potential Mechanisms and Directions for Future Research

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Abstract

Recent scientific evidence supports the use of a low-volume strength–power ‘resistance priming’ session prior to sporting competition in an effort to enhance neuromuscular performance. Though research evidence relating to this strategy is presently limited, it has been shown to be effective in improving various measures of neuromuscular performance within 48 h. Post-activation potentiation strategies have previously been shown to enhance strength–power performance within 20 min of completing maximal or near-maximal resistance exercise. Comparably, a delayed potentiation effect has been demonstrated following ‘resistance priming’ at various times between 1 and 48 h in upper- and lower-body performance measures. This may have significant implications for a range of athletes when preparing for competition. Various exercise protocols have been shown to improve upper- and lower-body neuromuscular performance measures in this period. In particular, high-intensity resistance exercise through high loading ($\geq 85\%$ 1 repetition maximum) or ballistic exercise at lower loads appears to be an effective stimulus for this strategy. Although current research has identified the benefits of resistance priming to some physical qualities, many questions remain over the application of this type of session, as well as the effects that it may have on a range of specific sporting activities. The aims of this brief review are to assess the current literature examining the acute effects (1–48 h) of resistance exercise on neuromuscular performance and discuss potential mechanisms of action as well as provide directions for future research.

1 Introduction

Elite athletes typically engage in long-term training programmes to develop physical attributes such as strength, power and endurance [1]. Muscular strength and power contribute to a range of sport-specific attributes in addition to reducing injury risk [2–7]. As such, various resistance training methods, including heavy strength, power and ballistic training, are used by athletes to improve long-term development and performance [8]. However, while this type of training has traditionally been performed over extended periods to elicit chronic adaptations in strength and power, research has identified that low-volume resistance training stimuli may also acutely enhance athletic performance [9–16].

One strategy to acutely enhance performance involves completing short-duration maximal or near-maximal resistance exercise within minutes of performing a strength–power activity [10]. This has been termed post-activation potentiation (PAP), and occurs when an initial resistance exercise stimulus temporarily enhances neuromuscular performance for a period typically lasting between 4 and 12 min [10, 17–22]. PAP strategies have been effective in enhancing jumping [20, 22–24] and sprinting [18, 25] performance, which are key activities in numerous sports. However, due to the small window of opportunity to influence performance, PAP is difficult to use in competition for many athletes. Some investigations suggest that there may be another window of potentiation for up to 48 h following a low-volume resistance exercise stimulus [12–16, 26]. Fry et al. [26] were the first to

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Key Points

Low-volume strength–power ‘resistance priming’ has been shown to be effective in enhancing upper- and lower-body neuromuscular performance for up to 48 h, termed a ‘delayed potentiation’ effect.

Resistance exercise ranging between 30% and 95% 1 repetition maximum (RM) may elicit delayed potentiation, though high-load (≥ 85% 1RM) traditional exercise or low-load (30–40% 1RM) ballistic exercise appears to be most effective.

Resistance priming may be best performed 6–33 h prior to competition; however, benefits may also occur outside of this period and this warrants further investigation.

explore this by examining the effects of a ‘pre-competition training session’ in competitive weightlifters. More recent studies [12–16] have shown that a range of neuromuscular performance measures may be enhanced for up to 48 h following resistance exercise [12–15, 27, 28]. The term ‘delayed potentiation’ appears appropriate to describe the neuromuscular potentiation response in this 48-h window and is used throughout this review. There is currently no consensus on the terminology to describe this approach to enhancing performance; terms such as ‘morning priming’, ‘morning exercise’, ‘pre-activation’, ‘pre-competition training’, ‘priming’ and ‘resistance training priming’ have previously been used [12, 15, 26–29]. However, while resistance training is appropriate to describe sessions targeting long-term adaptation, when resistance exercise is strategically completed prior to competition to maximise performance, ‘resistance priming’ is similar to previously used terms [26–28] and appears appropriate to describe this type of session. Whilst there is no literature detailing the prevalence of this strategy in elite sport, anecdotal evidence suggests that resistance priming strategies are currently applied pre-competition in some elite sporting environments [29].

Despite anecdotal evidence of its application in some settings, the 48-h period leading into competition is more typically used to taper training loads [30]. To avoid muscle damage and residual fatigue, resistance training in particular is often avoided in the days leading into competition, even in elite strength–power sports [31, 32] and team sporting environments [33]. If the strategic prescription of resistance priming exercise in the 48-h pre-competition period can indeed enhance subsequent physical performance, this has significant implications for athletes as they prepare for competition. Though the research evidence relating to this strategy is presently limited, the practice continues to attract considerable interest. The aim of this brief review is to assess the current literature that has investigated the acute effects (1–48 h) of low-volume resistance exercise on subsequent neuromuscular performance. Additionally, potential mechanism(s) of action, application of resistance priming across a range of sporting competition and directions for future research are addressed.

2 Literature Search Methodology

Original research articles were included in the review and were retrieved from electronic searches of the PubMed, MEDLINE (EBSCO), CINAHL, SPORTDiscus, SCOPUS, Web of Science and Google Scholar databases up to December 2018. The search strategy included terms such as ‘priming’, ‘resistance priming’, ‘morning priming’, ‘pre-competition training’, ‘morning exercise’, ‘acute response’, ‘short term response’, ‘neuromuscular performance’, ‘resistance training’, ‘resistance exercise’, ‘strength training’, ‘power training’ and ‘post activation potentiation’. Search terms were combined by Boolean logic and included only articles published in the English language.

Articles were included in the review if the study examined neuromuscular performance measures during the 1–48-h period following resistance exercise compared with control or baseline measures. To identify research investigating resistance priming-type sessions, the exercise interventions must have involved exercises utilising external load as resistance or maximal effort unloaded jumping.

3 Delayed Potentiation of Neuromuscular Performance

Delayed potentiation effects have been identified in a number of neuromuscular performance measures [12–16, 27, 28] following resistance priming stimuli (Table 1). The neuromuscular responses following various resistance priming-type exercise sessions are summarised in Table 2. Potentiation in jumping performance has been observed in several studies 6–48 h following low-volume resistance exercise [12–14, 16]. Cook et al. [12] and Saez Saez de Villarreal et al. [14] noted improvements in jumping at 6 h of recovery, whilst other studies reported delayed potentiation at 24 h [13], 33 h [16] and 48 h [13]. Specifically countermovement jump (CMJ) [12, 13, 16], drop jump [14] and reactive strength index (RSI) [13] measures have been shown to be enhanced across this period, indicative of an increased ability of the neuromuscular system to utilise the stretch-shortening cycle (SSC) following a low-volume, high-intensity resistance exercise stimulus. This quality is particularly important in

Table 1 Physical performance measures displaying delayed potentiation following resisting priming [12–16, 27, 28]

Physical attributes	Performance measures	Evidence base
Lower-body strength and power	3RM back squat strength Countermovement jump peak power Countermovement jump height Drop jump height Isometric RFD Drop jump RSI	Four studies [12–14, 16]
Upper-body strength and power	3RM bench press strength Bench throw peak force Bench throw peak power	Two studies [12, 27]
Sprinting	40 m sprint time 40 m sprint time (with 180° turn)	Two studies [12, 28]
Full-body power	Backward overhead squat throw	One study [15]

RM repetition maximum, *RFD* rate of force development, *RSI* reactive strength index

running and jumping, which involve repeated SSC contractions of the lower limb [34].

Additionally, findings from Ekstrand et al. [15] and Tsoukos et al. [13] have demonstrated the benefits of resistance priming on lower-body power, noting significant improvements in backward overhead squat throw (BOST) performance and rate of force development during the isometric squat, respectively. Russell et al. [28] and Cook et al. [12] also showed improvements in sprinting performance following upper- and full-body priming stimuli, respectively, whilst further findings by Cook et al. [12] found 3 repetition maximum (RM) back squat strength (+4.2%, $p < 0.001$) to be significantly improved at 6 h of recovery compared with resting control. These improvements in lower-body strength, power and sprinting performance highlight that various neuromuscular qualities may be enhanced following resistance priming. However, it is unknown whether this neuromuscular potentiation effect may benefit athlete performance in sporting competition.

Though investigation has been limited, resistance priming has also been reported to improve measures of upper-body performance. 3RM bench press strength [12] and bench throw peak force and peak power [27] have been shown to be significantly improved following upper-body resistance priming. As such, upper-body resistance priming completed in the pre-competition period may be an effective strategy to maximise sporting performance involving upper-body movements. However, further research examining these effects would be beneficial, particularly in elite athletes.

Some studies examining the performance response following resistance priming exercise have reported less clear outcomes. For instance, whilst Ekstrand et al. [15] found significant improvements in BOST performance, there were no benefits to CMJ performance 4–6 h following a morning strength and power session. In addition, Mason et al. [27] demonstrated potentiation of upper-body but not lower-body performance 1 h 45 min following upper- and lower-body resistance priming. Findings from Fry et al. [26] indicate that performance responses following resistance priming are highly variable between individuals. Following morning resistance priming involving the clean pull and snatch pull exercises, no overall potentiation effect was evident when weightlifting performance was assessed 5 h 30 min following the session. Despite this, a group of 'responders' displayed improvements in vertical jump (3 cm, ≈4.5%), snatch (5.8 kg, ≈6.0%), and clean and jerk (6.2 kg, ≈5.2%) performance following the resistance training session. Characteristics such as age, strength and body mass were all similar between responders and non-responders. However, the authors noted anxiety levels (measured by self-report scale 0–4) were significantly higher at all timepoints in the responders, and concluded that weightlifters or other high-power athletes exhibiting high levels of anxiety may benefit from applying this training strategy prior to competition. Although it is unclear how anxiety levels may have been related to the performance response following the priming session, these results highlight the numerous factors that may influence performance. Additionally, these findings suggest that the performance response following priming strategies may differ considerably between individuals and that this variability should be considered in the practical environment and for future investigation.

In some circumstances, both upper- and lower-body performance may benefit from resistance priming sessions up to 48 h before competition. This type of session appears most effective for activities involving short bouts of maximal force such as jumping [12–14, 16], throwing [15, 27], strength [12] and sprinting [12, 28] performance. Although benefits from this strategy appear particularly effective in improving strength–power performance such as jumping [12–14, 16], it is less clear if these improvements may remain over multiple SSC contractions, as required in running and sprinting sports [12]. Furthermore, it is also conceivable that fatigue that occurs in activities involving repeated or continuous bouts of activity may reduce or eliminate the potential benefits of

Table 2 Summary of studies examining neuromuscular performance measures 1–48 h following resistance priming-type exercise

Study	Participants	Resistance stimulus	Lower-body resistance loading and volume (volume load)	Performance effect following 3–6 h	Performance effect following 7–12 h	Performance effect following 13–24 h	Performance effect following 25–36 h	Performance effect following 37–48 h
Raastad and Hallén [16]	8 power lifters, 1 javelin thrower, 1 speed skater Age 27.5 years Body mass = 84.5 kg 3RM squat = 169 kg	3 × 3 back squat (70% 3RM), 3 × 3 front squat (70% 3RM) and 3 × 6 leg extension (70% 6RM)	65% 1RM^{a} 36 (2340 AU)	↗ CMJ height at 3 h	↗ CMJ height at 7 and 11 h	↗ CMJ height at 22 h	↗ CMJ height at 26 and 30 h ↑ 5% CMJ height at 33 h	
Cook et al. [12]	18 semi-professional rugby union players Age 22.1 years Body mass = 93.7 kg 3RM squat = 168 kg	3 × 3 back squat (80%, 90%, 100% 3RM) and 3 × 3 bench press (80%, 90%, 100% 3RM)	75–94% 1RM^{a} 9 (762 AU)	↑ 4.2% 3RM squat, ↑ 3.5% 3RM bench press, ↑ 1.3% 40 m sprint and ↑ 3.9% CMJ peak power at 6 h				
Tsoukos et al. [13]	17 national-level power and team sport athletes Age 22.7 years Body mass = 80 kg 1RM half squat = 163 kg	5 × 4 jump squats (40% 1RM)	40% 1RM 20 (800 AU)			↑ 5% CMJ height, ↑ 10% RSI, and ↑ RFD at 24 h		↑ 3% CMJ height and ↑ RFD at 48 h
Ekstrand et al. [15]	14 field throwers, including some national level Age 20.7 years Body mass = 95.1 kg	1 × 6 back squat at 85% 1RM, 1 × back squat to failure at 85% 1RM and 1 × power clean exercise to fatigue completed in sets of 4 repetitions	85% 1RM Unknown	↑ 2.6% BOST and ↘ 0.6% CMJ peak power at 4–6 h				
Mason et al. [27]	13 state-level rugby players Age 18.5 years Body mass = 98.2 kg	4 × 3 banded back squat (46.7 kg resistance at standing) and 4 × 3 banded bench press (46.7 kg resistance at full extension)	Unknown 12 (unknown)	↘ 3.4% CMJ peak power, ↘ 1.5% CMJ peak velocity, ↘ 2.3% CMJ peak force, ↑ 8.5% bench press peak power, ↑ 3.8% bench press peak velocity and ↑ 13.9% bench press peak force at 1 h 75 min				

Table 2 (continued)

Study	Participants	Resistance stimulus	Lower-body resistance loading and volume (volume load)	Performance effect following 3–6 h	Performance effect following 7–12 h	Performance effect following 13–24 h	Performance effect following 25–36 h	Performance effect following 37–48 h
Saez Saez de Villarreal et al. [14]	12 trained males Age 22.8 years Body mass = 76.9 kg 1RM squat = 158.3 kg	3 × 5 CMJ (optimally loaded)	30–40% 1RM 15 (≈520 AU)	↑ 4.2% DJ height, ↗ CMJ height and ↑ loaded CMJ height at 6 h				
		2 × 4 half squat (80% 1RM) and 2 × 3 half squat (85%)	80–85% 1RM 14 (1150 AU)	↑ 3% DJ height and ↗ CMJ height at 6 h				
		2 × 4 half squat (80% 1RM), 2 × 2 half squat (90% 1RM) and 2 × 1 (95% 1RM)	80–95% 1RM 14 (1190 AU)	↑ 5.5% DJ height, ↗ CMJ height and ↗ 9.0% loaded CMJ height at 6 h				
		3 × 5 drop jump from optimal height (bodyweight)	Bodyweight 15	↗ DJ height, ↗ CMJ height and ↗ loaded CMJ height at 6 h				
		Volleyball warm-up: 5 min run at 9 km/h, 2 min multi-directional run, plyometric hopping and jumping, and 5 min light stretching		↗ DJ height and ↗ CMJ height at 6 h				
		3 × 5 half squat (30% 1RM)	30% 1RM 15 (450 AU)	↗ DJ height, ↗ CMJ height and ↗ loaded CMJ height at 6 h				
Russell et al. [28]	15 elite male rugby players Age 24.0 years Body mass = 98.2 kg	5 × 10 bench press (75% 1RM)		↑ 2 sprints in 6 × 40 m sprint with 180 ° change of direction ↔ CMJ height at 5 h				
McCaulley et al. [35]	10 males Age 21.8 years Body mass = 92.4 kg 1RM squat = 170.8 kg 1.9 × body mass	8 × 6 squat jumps (unweighted)	Bodyweight 48			↗ Isometric squat peak force ↗ Isometric squat RFD		↗ Isometric squat peak force ↗ Isometric squat RFD

Table 2 (continued)

Study	Participants	Resistance stimulus	Lower-body resistance loading and volume (volume load)	Performance effect following 3–6 h	Performance effect following 7–12 h	Performance effect following 13–24 h	Performance effect following 25–36 h	Performance effect following 37–48 h
Gonzalez-Badillo et al. [36]	9 males Age 23.3 years Body mass = 75.3 kg 1RM = 108.7 kg 1.4 × body mass	3 × 4 back squat (80% 1RM) and 3 × 4 bench press (80% 1RM)	80% 1RM 12 (960 AU)	↗ 0.8% bench press velocity 1 m/s ↗ 0.9% squat velocity load 1 m/s ↘ 0.7% CMJ height		↗ 0.9% bench press velocity 1 m/s ↘ 1.2% squat velocity load 1 m/s ↘ 0.5% CMJ height		↗ 4.9% bench press velocity 1 m/s ↗ 2.1% squat velocity load 1 m/s ↗ 1.9% CMJ height
Howatson et al. [37]	6 elite male track and field athletes: Mean age 28.0 years Body mass = 81.2 kg 1RM squat = 190 kg 2.3 × body mass 4 elite female track and field athletes: Age 26.0 years Body mass = 60 kg 1RM squat = 107.5 kg 1.8 × body mass	4 × 5 back squat, 4 × 5 split squat jump and 4 × 5 power press at 30% of load at RPE 16–17/20	23% 1RM[a] 40 (920 AU)			↗ 3.4% CMJ height		
Fry et al. [26]	19 male national-level weightlifters Age 17.3 years Body mass = 72.8 kg 1RM back squat = 163.7 kg 2.2 × body mass	5 × 3 clean pulls at 85% 1RM and 3 × 3 snatch pulls at 85% 1RM	85% 1RM 24 (2040 AU)	Responders ($n = 6$): ↑ ≈ 4.5% vertical jump, ↑ ≈ 6.0% snatch, and ↑ ≈ 5.2% clean and jerk at 5 h 30 min Non-responders ($n = 13$): ↘ ≈ 1.5% vertical jump, ↘ ≈ 3% snatch, and ↘ ≈ 1.5% clean and jerk at 5 h 30 min				

Table 2 (continued)

Study	Participants	Resistance stimulus	Lower-body resistance loading and volume (volume load)	Performance effect following 3–6 h	Performance effect following 7–12 h	Performance effect following 13–24 h	Performance effect following 25–36 h	Performance effect following 37–48 h
McGowan et al. [38]	13 competitive male ($n = 7$) and female ($n = 6$) swimmers Age 19.0 years Body mass = 70.1 kg and 60.7 kg, respectively	2 × 3 × 10 m running sprint, 2 × 2 unloaded tuck jumps, 2 × 2 tuck jumps at 6.5 kg, 2 × 5 handstand push-ups, 2 × 3 × 10 s simulated butterfly kick and 2 × 3 medicine ball throw at 3 kg	Bodyweight to 6.5 kg weighted vest	↑ 1.7% 100 m time trial performance				

Values are means

Sets × repetitions × % 1RM = volume load (AU)

AU arbitrary units, *BOST* backward overhead squat throw, *CMJ* countermovement jump, *DJ* drop jump, *RFD* rate of force development, *RM* repetition maximum, *RPE* rate of perceived exertion, *RSI* reactive strength index, ↑ denotes significant increase reported, ↗ denotes non-significant increase reported, ↘ denotes non-significant decrease reported, ↔ denotes non-significant change where no further statistics were provided

[a] Estimation of percentage 1RM [39]

a resistance priming session. Research examining the potential of resistance priming strategies to improve performance across a broader range of sporting activities is needed.

4 Exercise Stimuli for Resistance Priming Strategies

4.1 Resistance Loading and Intensity

The resistance loading and exercise intensity of priming strategies appears to play a significant role in determining the performance response following resistance priming sessions (Table 3). Highly loaded resistance exercise or high-intensity exercise through an intent to perform movement at high velocity are effective priming stimuli for eliciting delayed potentiation. Four high-loaded (≥ 85% 1RM) protocols in three different studies [12, 14, 15] have been shown to significantly improve neuromuscular performance. Cook et al. [12] found significant improvements in 3RM squat strength, CMJ and sprinting performance 6 h following back squats loaded progressively up to 100% of 3RM (approximately 94% of 1RM) [39]. Villareal et al. [14] reported improvements in drop jump performance following two different sessions, each involving the half squat exercise at up to 85% and 95% of 1RM. Additionally, while no improvements were noted in CMJ peak power, Ekstrand [15] showed that BOST performance was enhanced 4–6 h following a session involving both back squats and power cleans at 85% of 1RM.

Significant improvements in performance have also been reported following some low and moderately loaded (30–65% 1RM) protocols [13, 14, 16, 27]. Raastad and Hallén [16] identified potentiation of jumping performance following a resistance exercise session where all exercises were performed ‘slowly and in a well-controlled’ manner. However, most investigations that have reported performance benefits following low or moderately loaded exercise have used ballistic exercise [13, 14, 27]. Mason et al. [27] showed delayed potentiation of bench throw performance following a band-resisted bench press exercise, in which participants performed the eccentric portion slowly before completing an explosive concentric phase to accelerate the bar maximally. Two other moderately loaded protocols (30–40% 1RM) reported potentiation of lower body performance measures following loaded jump exercises [13, 14], suggesting that resistance priming exercise of low and moderate resistance may be most beneficial when ballistic movements are performed. The effect of movement velocity was examined by Saez Saez de Villarreal et al. [14], who found 3 × 5 repetitions of the half squat exercise at 30% 1RM were ineffective after 6 h of recovery. In contrast, significant improvements in drop jump and loaded CMJ height were reported following a similar session of 3 × 5 repetitions of a loaded CMJ performed at ≈ 30–40% 1RM, highlighting that benefits from resistance priming involving low to moderately loaded resistance exercise may be maximised when performed at high velocity [14].

Currently, there is no evidence that low-loaded (< 30% 1RM) or unweighted priming activities can elicit neuromuscular potentiation in the 1–48 h following resistance priming. Whilst loaded jumping exercise protocols have been shown to improve performance in this timeframe [13, 14], similar unweighted jumping protocols [14, 35] appear to have no significant effect on subsequent performance. Although some non-significant improvements have been noted following this type of exercise [14, 35, 37, 38], high-loaded resistance exercise and low-loaded ballistic exercise appear most effective for use as resistance priming strategies. One study has shown that a priming session involving unloaded and low-loaded exercise was beneficial to afternoon swimming time trial performance when compared with a resting control (− 1.7 ± 0.7%) [38]. However, time trial performance was not significantly different compared with performance following a morning swimming session, which was also improved (− 1.6 ± 0.6%), suggesting that further benefits from this session may have occurred if higher-loaded resistance exercises were performed.

Current investigations suggest that resistance priming exercise ranging between 30% and 95% 1RM may elicit neuromuscular performance improvements for up to 48 h (Table 3). High resistance loading (≥ 85% 1RM) appears beneficial to performance in this timeframe, while loading between 30% and 40% 1RM is also effective when performing ballistic exercise. Despite this, further investigation into the effectiveness of moderate-loaded, low-loaded and unloaded exercise may be beneficial given the potential for limited resources and reluctance of coaches and athletes to

Table 3 Exercises performed at various resistance loading have been shown to be effective resistance priming stimuli [12–16, 27, 28]

Resistance loading	Exercise	Performance improvements
80–95% 1RM	Half squat Back squat Power clean Bench press	Jumping Sprinting Upper- and lower-body strength Full-body power
50–70% 1RM	Back squat Front squat Leg extension	Jumping
30–40% 1RM	Jump squat	Jumping Isometric RFD Drop jump RSI
Band resisted loading	Bench press	Upper-body power

RFD rate of force development, *RM* repetition maximum, *RSI* reactive strength index perform high-load resistance exercise in this pre-competition period. Furthermore, the performance response following resistance exercise at 50–80% of 1RM has not been examined extensively, despite conceivably also being an effective resistance priming stimulus (Table 3). Finally, future investigations should report the strength level of the participants and relative resistance loading (% of 1RM) of priming protocols so these factors can be considered when assessing the effectiveness of resistance priming on performance.

4.2 Resistance Exercise Volume

Relatively low volumes of resistance exercise in three high-load protocols (≥ 85% 1RM) improved performance at 6 h following priming [12, 14] (Table 2). In addition, external resistance was progressively loaded in these sessions where only 3–6 repetitions were completed at ≥ 85% 1RM in each of these protocols. In contrast, the relatively high-volume and high resistance load (85% 1RM) priming session used by Ekstrand et al. [15] was ineffective in improving vertical jump performance. The exercise protocol involved the back squat 'to fatigue' at 85% 1RM, approximately 6–7RM loading [39], followed by multiple sets of 4 repetitions of the power clean. While the total volume of the main exercise protocol was not provided in this investigation, this is likely to be an excessive stimulus to maximise any delayed potentiation effects on performance. Furthermore, the additional stimulus of the warm-up protocol, which included 4 × 6 power cleans at 35% 1RM and then 1 × 6 repetitions of the back squat at 85% 1RM, would be considerable and likely to be fatiguing rather than potentiating to performance. Given the improvements in vertical jump measures in previous investigations [12–14], the seemingly high training volume used by Ekstrand et al. [15] appears to be suboptimal for delayed potentiation to occur. Collectively, the available data suggest that when high resistance loading is used during priming, performance may be maximised when resistance is progressively loaded over multiple sets and only a low volume of repetitions (≤ 6 total repetitions) are performed at high resistance (≥ 85% 1RM) (Table 4).

When low- to moderate-loaded resistance exercise is performed in a ballistic manner, 15–20 repetitions of exercise completed over a number of sets has been shown to improve performance [13, 14]. Additionally, Raastad and Hallén [16] showed that even higher volumes of exercise (36 repetitions) were effective at improving CMJ performance after 33 h when moderate resistance loading (70% of 3RM) was performed in a slow and controlled manner. This demonstrates that the intent to which an exercise is performed at high- or low-velocity also interacts with the volume of exercise to determine the total stimulus and subsequent performance response.

Relatively low volumes appear to be most beneficial for delayed potentiation of performance following high-resistance (≥ 85% 1RM) exercise [12, 14]. Additionally, higher volumes of low- to moderate-resistance loading (30–65% 1RM) may improve performance in this timeframe [13, 14, 16]. However, further research is needed to provide a more definitive range of exercise volumes that may be effective to improve performance in this timeframe. The use of a volume load calculation [number of sets × number of repetitions × % 1RM = arbitrary units (AU)] [40] may be useful to prescribe resistance priming sessions (Table 4). Additionally, this calculation highlights the relatively low total stimulus of this type of session for the athlete, with effective resistance priming sessions commonly ranging between 450 and 1190 AU [12–14] (Table 4). In contrast, general strength–power training sessions performed in practice typically involve multiple exercises, sets and repetitions with total volume load well exceeding 3000 AU (Table 5).

4.3 Exercise Types

The total stimulus of the resistance priming session may also be influenced, to some extent, by the type and number of exercises used. Some investigations have reported performance benefits following sessions involving only one exercise [13, 14], whilst others have demonstrated potentiation following multiple exercises [12, 15, 26], where up to three different exercises of the same muscle group have

Table 4 Various resistance exercise volumes effective in enhancing strength-power performance after 1–48 h of recovery [12–14, 16]

Exercise volume (total repetitions)	Resistance loading and intensity	Sets × repetitions × % 1RM (AU)
20 + repetitions	65% 1RM Slow and controlled velocity	2340
15–20 repetitions	30–40% 1RM High-velocity, ballistic exercise	450–800
9–14 repetitions (3–6 repetitions at ≥ 85% 1RM)	80–95% 1RM Loading requires high intent	760–1190

AU arbitrary units, *RM* repetition maximum

Table 5 Objectives and training prescription variables for various resistance exercise sessions [41, 42]

Session characteristics	General strength-power	PAP	Resistance priming
Acute objectives	Maximal recruitment of motor units, produce force at high velocity, targeting various specific athletic movements	Acute potentiation (< 20 min) of neuromuscular system without inducing excessive fatigue	Delayed potentiation (1–48 h) of neuromuscular system without inducing excessive fatigue
Long-term objectives	Increase muscle fibre size, increase maximal strength, increase rate of force development, increase movement competency	Stimulus may have a micro-dosing effect for maximal strength–power adaptations or maintenance	Stimulus may have a micro-dosing effect for maximal strength–power adaptations or maintenance
Training variables			
Volume	Moderate–high	Low	Low
Resistance loading	Low–high	Low–high	Low–high
Rest	Long rest periods ≈ 3 min	Long rest periods ≈ 3 min	Long rest periods ≈ 3 min
Movement velocity	Low–high dictated by loading	Low–high dictated by loading	Low–high dictated by loading
Intent of velocity	High	High	High
Example session (lower-body volume load)	Hang clean pull 2 × 3 at 85% 1RM Power clean 2 × 2 at 90% 1RM Back squat 4 × 3 at 85% 1RM Step up 3 × 6 at 60% 1RM Lateral lunge 3 × 6 at 60% 1RM (4080 AU)	Back squat 3 × 3 at 85% 1RM (765 AU)	Half squat 3 × 2 at 85–90% 1RM Bench press 3 × 2 at 85–90% 1RM (510–540 AU) *OR* Jump squat 3 × 5 at 30–40% 1RM (480–600 AU)

Number of sets × number of repetitions × %1RM = AU

AU arbitrary units, *PAP* post-activation potentiation, *RM* repetition maximum

had a beneficial effect on subsequent performance [16]. The back squat exercise has commonly been used as a stimulus for eliciting a delayed potentiation response [12, 14–16, 27] while the jump squat, which involves the same movement completed ballistically, has also been effective [13, 14]. Other sessions that have resulted in increased performance included exercises such as the power clean [15], clean pull [26], snatch pull [26] and leg extension [16]. Despite the variety of exercises that have been shown to be useful for this type of session, the majority of the research shows squat-type movements (including loaded jumps) to be the most effective stimulus for eliciting lower-body neuromuscular potentiation in a 48-h timeframe [12–16]. Consideration of the performance benefits of resistance priming suggests that the delayed potentiation effect appears to be specific to the movement of the priming exercise (Table 3).

Upper-body exercise also appears to elicit potentiation in this period, although investigations examining these effects are limited compared with those that have used lower-body resistance priming (Table 3). Studies have demonstrated that resistance priming sessions involving the bench press exercise were effective in potentiating upper-body strength and power performance of ‘pushing’ movements [12, 27]. Cook et al. [12] showed significant improvement in 3RM bench press strength 6 h following morning resistance priming, which included 3 × 3 repetitions of the bench press at 3RM loading. Mason et al. [27] also demonstrated delayed potentiation of bench throw peak force and peak power 1 h 45 min following a session involving 4 × 3 repetitions of a band-resistance bench press exercise at a total resistance of 46.7 kg at full extension. Given these performance improvements in upper-body pushing-type movements, it is possible that different upper-body movements may also similarly enhance neuromuscular performance in this timeframe. For instance, ‘pulling’ type exercises may be beneficial to relevant movement activities such as swimming, tackling, rowing and paddling. However, no studies have explored the effectiveness of these various upper-body priming activities and, as such, there appears to be considerable scope for further research. Findings from one study suggest that upper-body resistance priming may also elicit delayed potentiation of lower-body performance [28], although there is little further evidence supporting this. In addition, these benefits do not appear to compare with those observed following lower-body neuromuscular priming [12–14], suggesting that the priming activity must be specific to the neuromuscular pathway of the subsequent performance in order to maximise potentiation of performance.

4.4 Time Course of Delayed Potentiation

A number of neuromuscular performance measures have been shown to be potentiated at various times up to 48 h following resistance priming exercise [12–16, 27]. Numerous studies have reported performance benefits at 6 h of recovery [12, 14, 15], suggesting that resistance priming exercise performed 6 h before competing may be effective and practically applicable for afternoon or evening competition. It is also conceivable that potentiation may occur after shorter recovery times of between 1 and 5 h [15, 27, 28]. However, performance benefits in this period are inconsistent, with studies showing that resistance priming does not improve jumping performance within 5 h of recovery despite potentiation in other measures [15, 27, 28] (Table 2).

Other studies have also indicated that delayed potentiation may last up to 48 h [13, 16]. Raastad and Hallén [16] noted that CMJ height peaked at 33 h post resistance exercise, whilst findings from Tsoukos et al. [13], who examined performance at 24 and 48 h, showed that potentiation was maximised at 24 h before dissipating; however, small benefits were still present after 48 h [13]. These findings suggest that while benefits following resistance priming may last for up to 48 h, they are most effective up to 33 h. As such, current evidence suggests that resistance priming strategies are most beneficial when performed 6–33 h prior to competition. It is conceivable that delayed potentiation may be achieved outside this period; however, there is limited research that has examined performance outside this period following resistance priming exercise. Furthermore, current studies have not examined performance at more than two timepoints in the same investigation, making it difficult to predict the time course of potentiation following a single resistance priming session.

Though the neuromuscular performance response following resistance priming exercise sessions is similar to that demonstrated in PAP, the benefits have been shown to occur after longer recovery periods. Whilst it is accepted that general resistance training results in an acute period of fatigue prior to long-term adaptation, acute potentiation effects of exercise appear to co-exist with fatigue [43], perhaps longer than the PAP literature might suggest. As such, when resistance exercise is performed at low volume but high intensity, it appears that short-term potentiation of the neuromuscular system may occur without substantial fatiguing effects, resulting in an increase in performance (Fig. 1).

It is possible that resistance priming sessions elicit a greater neuromuscular stimulus than protocols that have elicited PAP [14]. This increased stimulus may prolong the time course of fatigue and recovery, explaining this delayed potentiation effect. However, the exercise stimuli used in PAP and resistance priming investigations appear similar. Considering previous investigations have identified that neuromuscular benefits of PAP dissipate well within 30 min of recovery [10, 17–20, 22, 24], it appears two windows of neuromuscular potentiation may exist (Fig. 2). Findings from Saez Saez de Villarreal et al. [14] support this, with potentiation noted both 5 min and 6 h following some resistance exercise protocols. However, it is unclear whether performance remained potentiated across this entire period or if it occurred in separate windows (Fig. 3). Further investigation into the effects of resistance priming after 1–5 h may help to identify this time course of potentiation following resistance priming.

4.5 Additional Factors

Other factors such as individual characteristics may also influence the resistance priming response. Given its influence on PAP [10], the strength level of the individual may also influence delayed potentiation and its time course, where stronger individuals may elicit greater and earlier potentiation following resistance priming [10]. All investigations that have reported participant strength level and significant resistance priming benefits have used highly trained participants (Table 2). The lowest mean 1RM squat strength of male participants in studies that have shown benefits of resistance priming was 158 kg reported by Saez

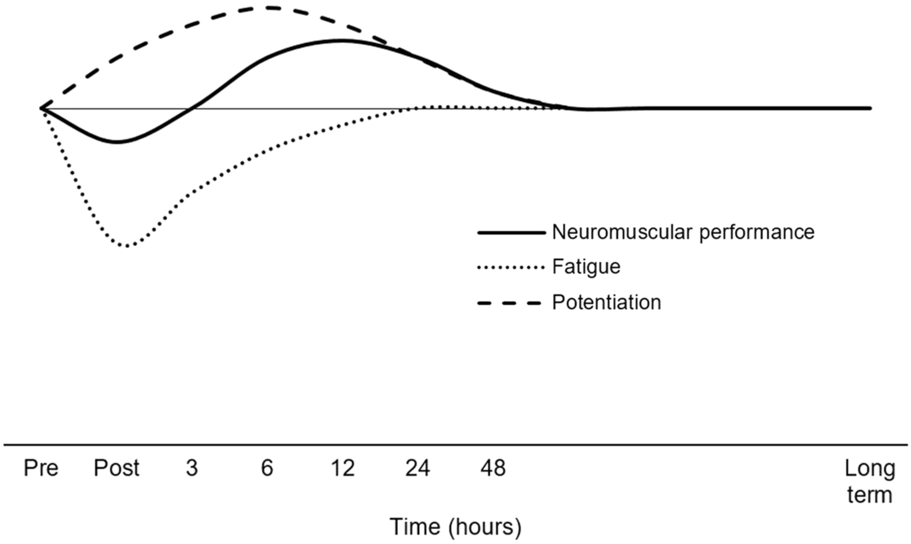

Fig. 1 The hypothetical interaction between fatigue, potentiation and performance describing the delayed potentiation response following resistance priming according to Banister's fitness-fatigue model [44]

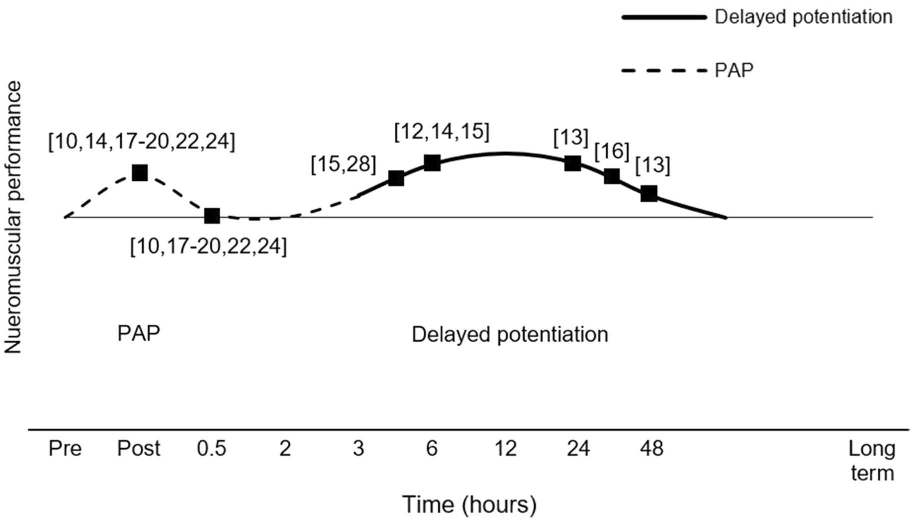

Fig. 2 Post-activation potentiation investigations demonstrate that neuromuscular performance benefits dissipate within 30 min whilst most evidence supporting resistance priming shows delayed potentiation effects occur between 6 and 48 h, suggesting two windows of potentiation may be present. Studies showing potentiation responses appear in brackets. *PAP* post-activation potentiation

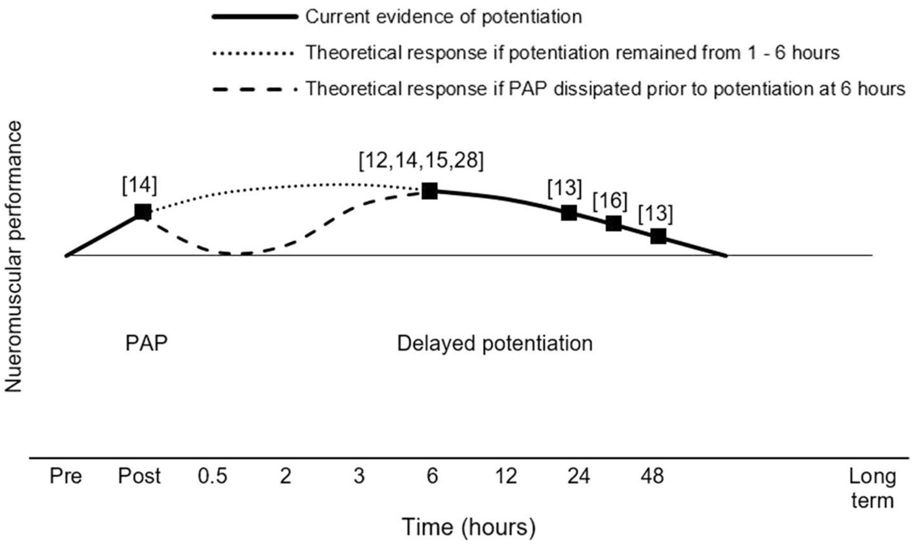

Fig. 3 Theoretical response of potentiation occurring in one window or two windows. Findings from Saez Saez de Villarreal et al. [14] showed potentiation at 5 min and 6 h of recovery following resistance priming exercise; however, it is unknown whether performance may have remained improved over this period. *PAP* post-activation potentiation

Saez de Villarreal et al. [14], whilst the lowest relative 1RM was estimated to be 1.9 × bodyweight [12, 39]. The sex of the athlete has also been considered as a moderating factor; male individuals appear to elicit a greater PAP response than females [45]. However, this effect may be due to differences in strength levels [10, 45]. Differences in strength level and sex may influence the effectiveness of resistance priming strategies but this is yet to be investigated. Individuals with a higher proportion of fast twitch muscle fibres have also been shown to exhibit greater PAP [9, 46] and, as such, further investigation into the influence of factors such as muscle fibre composition and strength level may help to identify individuals who are likely to respond positively to resistance priming. Another important consideration for applying resistance priming is the state of athlete preparedness. Potentiation strategies (PAP or resistance priming) may not be effective if an athlete is fatigued from a prior training stimulus. Some general resistance training sessions may be detrimental to neuromuscular performance for 48 h or longer [35, 36, 47]. During this period of recovery, it is not known whether performing a resistance priming session may still be of benefit to performance.

5 Mechanisms of Delayed Potentiation

It has previously been suggested that neuromuscular mechanisms are unlikely to influence performance in a 1–48 h timeframe following resistance priming [12]. However, considering the performance benefits that a number of researchers have identified, it is reasonable to suggest that some changes might occur directly in the neuromuscular system. Benefits to RSI [13] and drop jump height [14] found between 6 and 48 h after resistance priming suggest that improvements are likely to originate from neuromuscular changes. Saez Saez de Villarreal et al. [14] discuss the potential for high-frequency motor neuron activation as well as the role of muscle temperature, both of which have been associated with neuromuscular performance in the acute period following resistance exercise [11, 48, 49]. However, whilst it has not been directly examined whether these effects may remain influential across a period of 48 h, it appears unlikely that this would be the case given the time course of their respective benefits. Mechanical stiffness has also been proposed as a potential mechanism [13] due to the relationship between joint stiffness and neuromuscular performance [50]. Other peripheral mechanisms that occur during PAP, affecting the contractile properties of the muscle itself, such as increased fibre sensitivity to calcium ions (Ca^{2+}) [9, 11, 51], may also explain the delayed potentiation phenomenon but have not been examined following this type of strategy.

One mechanism that potentially contributes to delayed potentiation may be associated with diurnal changes in performance between morning and afternoon. Cook et al. [12] proposed that morning exercise, including resistance exercise, may help to offset the diurnal decline in performance between morning and afternoon. Hormonal status of athletes has previously been related to variance in physical performance and readiness to perform [21, 52–54]. Increases in free testosterone, or the free testosterone:cortisol ratio, have been related to increases in strength and sprint performance [53], and as such may contribute directly to performance or provide a marker of the athlete's readiness to perform. If strategies such as resistance priming help to offset negative changes in hormonal status, this may in part explain benefits in physical performance seen in this time period.

Russell et al. [28] examined the acute response following a morning upper-body resistance priming session in 15 professional rugby union players. Salivary testosterone was significantly greater (17%, $p < 0.01$) 5 h following the morning priming session than in the control trial, which coincided with some increases in performance. The first two sprints of a 6-repetition 40 m sprint test were significantly faster (2.0–2.3%, $p < 0.05$) following the upper-body priming session than in the control trial; however, no change in total sprint times or CMJ performance was noted. Given the significant improvement in CMJ measures previously reported by Cook et al. [12] following both lower- and upper-body resistance priming, it appears that the priming stimulus must be specific to the movement of the subsequent performance in order to maximise benefits. Despite this, the improvements in sprint times reported by Russell et al. [28] suggest that upper-body resistance priming may still influence afternoon performance. As these increases also coincided with increases in the salivary testosterone concentration, it is possible that changes in hormonal status influence the performance response following resistance priming sessions. The studies by Cook et al. [12] and Russell et al. [28] have also assessed the use of running and cycling priming exercise, indicating that other forms of morning exercise may also be beneficial to some performance measures in the afternoon, perhaps due to these hormonal mechanisms. However, it was shown that resistance-based exercise was more beneficial than other strategies in hormonal and physical performance measures [12, 28].

Whilst hormonal mechanisms may play some role in the delayed potentiation effect following resistance priming, given the similarities in the investigations by Cook et al. [12] and Russell et al. [28], the same benefits to lower-body performance might be expected if only hormonal mechanisms were responsible. Furthermore, if hormonal status was the primary mechanism for performance benefits following resistance priming, it is unclear how these might contribute to the performance improvement identified after 24–48 h of recovery [13, 16]. It is therefore possible that both neuromuscular and hormonal mechanisms contribute to the performance benefits following resistance priming sessions; however, this is yet to be examined directly.

6 Application of Resistance Priming

Low-volume, high-intensity resistance exercise sessions have been shown to improve various measures of neuromuscular performance in the subsequent 48 h. The presence of this delayed potentiation effect suggests that resistance priming strategies performed in the 48-h pre-competition period may be effective in maximising performance in some sporting competitions. Limited research has investigated the effectiveness of this performance strategy and, while there is evidence that neuromuscular benefits may occur following resistance priming, further work is required to better understand its effects on sporting performance and its many complexities.

While squat-based movements, including partial squats and loaded jumps, have commonly been explored and appear effective for resistance priming, other similar movements may also be applied with similar benefits. The only upper-body resistance priming exercise to be examined thus far is the bench press, which was shown to improve upper-body strength and power measures in upper-body pushing movements after 1–6 h of recovery [12, 27]. As such, resistance priming exercises involving other upper-body movements such as a row or pull up may also potentiate strength and power performance of similar movements such as rowing and paddling, but this is yet to be examined.

Table 6 Example week of strength–power training integrating upper- and lower-body resistance priming the day before competition

Monday	Tuesday	Wednesday	Thursday	Friday	Saturday	Sunday
	Session 1 *Lower body* Power clean Back squat Step up Lateral lunge	*Session 2* *Upper body* Bench press Bench pull Dumbbell incline press Chin up		*Session 3* *Priming* Half squat Bench press Bench pull	*Competition*	

High-load (85% 1RM) resistance exercise appears to improve performance when performed in low volume (3–6 repetitions). Alternatively, low-load (30–40% 1RM) ballistic exercises have also been shown to be beneficial when completed in higher volumes (15–20 repetitions). It is conceivable that a range of resistance loadings between 40% and 85% 1RM may be effective in resistance priming strategies [16]. However, this is an area that requires additional research. Similarly, while current evidence suggests benefits may be maximised after 6–33 h, a shorter recovery period (i.e. 1–5 h) may also be beneficial to performance. Future research examining the effectiveness of low-load and unloaded priming activities, as well as the time course of performance response, would be of particular importance to practitioners and investigators.

In many sports, competitions often take place in the afternoon or evening. Considering this, preparation periods for athletes between waking and competition commonly range between 6 and 14 h, providing an opportunity to perform resistance priming sessions on the day of, or the day before, competition. For an afternoon sporting competition, resistance priming strategies may be effective when performed either in the morning of competition [12, 14, 15, 27, 28] or the day before, 24–33 h prior to competition [13, 16] (Table 6). The benefits of applying this strategy prior to morning performance have yet to be investigated; however, potentiation may still conceivably be present within this 1- to 48-h timeframe before morning competitions. Given the scope for its application in practice and the benefits to neuromuscular performance, resistance priming may be an applicable strategy for athletes to maximise performance in strength–power activities.

7 Conclusion and Recommendations for Future Research

Resistance priming exercise has been shown to improve various measures of neuromuscular performance within 48 h and, therefore, performing this type of session prior to competition may be an effective performance strategy for strength–power athletes [12–15, 27, 28]. Although this strategy has been shown to improve performance at various times between 1 and 48 h, the time course of performance response following resistance priming is not well-understood. Similarly, whilst some parameters of resistance loading and exercise volume have been identified to be effective for this type of session, the effects of these variables have not been thoroughly examined; as such, optimal training stimuli for resistance priming exercise is unclear. Future research should explore the effects of exercise volume and loading, as well as the time course of performance response. Lastly, further investigation examining the effects of resistance priming exercise on specific measures of sporting performance would be particularly beneficial for practitioners to assess the value of applying this strategy in various sporting environments.

Compliance with Ethical Standards

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Conflict of interest Peter Harrison, Lachlan James, Mike McGuigan, David Jenkins and Vincent Kelly declare that they have no conflicts of interest relevant to the content of this review.

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