Sports Med (2016) 46:809–828
DOI 10.1007/s40279-015-0466-9

REVIEW ARTICLE

Understanding Vertical Jump Potentiation: A Deterministic Model

Timothy J. Suchomel[1] · Hugh S. Lamont[2] · Gavin L. Moir[1]

Published online: 28 December 2015

Abstract This review article discusses previous postactivation potentiation (PAP) literature and provides a deterministic model for vertical jump (i.e., squat jump, countermovement jump, and drop/depth jump) potentiation. There are a number of factors that must be considered when designing an effective strength–power potentiation complex (SPPC) focused on vertical jump potentiation. Sport scientists and practitioners must consider the characteristics of the subject being tested and the design of the SPPC itself. Subject characteristics that must be considered when designing an SPPC focused on vertical jump potentiation include the individual's relative strength, sex, muscle characteristics, neuromuscular characteristics, current fatigue state, and training background. Aspects of the SPPC that must be considered for vertical jump potentiation include the potentiating exercise, level and rate of muscle activation, volume load completed, the ballistic or non-ballistic nature of the potentiating exercise, and the rest interval(s) used following the potentiating exercise. Sport scientists and practitioners should design and seek SPPCs that are practical in nature regarding the equipment needed and the rest interval required for a potentiated performance. If practitioners would like to incorporate PAP as a training tool, they must take the athlete training time restrictions into account as a number of previous SPPCs have been shown to require long rest periods before potentiation can be realized. Thus, practitioners should seek SPPCs that may be effectively implemented in training and that do not require excessive rest intervals that may take away from valuable training time. Practitioners may decrease the necessary time needed to realize potentiation by improving their subject's relative strength.

Key Points

- Previous literature suggests that vertical jump potentiation may be due to two primary factors including the characteristics of the individual and the design of the strength–power potentiating complex.
- Subject characteristics that must be considered when seeking vertical jump potentiation are the individual's relative strength, sex, muscle characteristics, neuromuscular characteristics, current fatigue state, and training background.
- Aspects of the strength–power potentiating complexes that must be considered for vertical jump potentiation are the potentiating exercise, level and rate of muscle activation, volume load completed, the ballistic or non-ballistic nature of the potentiating exercise, and the rest interval(s) used following the potentiating exercise.

1 Introduction

Postactivation potentiation (PAP) is a topic that has become the subject of frequent investigation within strength and conditioning literature. PAP has been defined

✉ Timothy J. Suchomel
timothy.suchomel@gmail.com

[1] Department of Exercise Science, Koehler Field House, East Stroudsburg University, East Stroudsburg, PA 18301, USA

[2] Kinesiology, Recreation, and Sport Studies Department, Coastal Carolina University, Conway, SC, USA

as an acute enhancement of muscle performance as a result of contractile history and is considered the basis of complex training [1]. Topics that have been investigated within the PAP literature include underlying physiological mechanisms, various potentiating stimuli, the rest interval following a stimulus, characteristics of the subjects, and the electromyography or muscle activation differences following a stimulus. Through the use of PAP, researchers have attempted to identify stimuli that will acutely improve the subjects' performance (e.g., jumping, sprinting, agility, lifting, etc.). By identifying stimuli that may acutely improve performance, it may be possible to use PAP as a training stimulus. This review will focus on vertical jumping as the performance measure.

Previous research has indicated that the optimal conditions (i.e., type of exercise, exercise volume, exercise load, rest interval) for vertical jump potentiation are highly individualistic [2–6]. Thus, it appears that the characteristics of the subjects using various potentiation protocols may have a large effect on whether or not potentiation is realized. Specifically, previous research has indicated that the subject's relative strength level, sex, muscle characteristics, and training background may alter the effect of PAP on subsequent performances [7–11]. Although some characteristics may have a greater impact on vertical jump potentiation, it is important to take as many of the subject's characteristics into account as possible when considering the use of potentiation complexes within training or competition.

PAP is the basis of complex training. Complex training has been defined as a method of training that involves completing a resistance exercise before performing an exercise that is biomechanically similar [1, 10, 12]. It is believed that the use of complex training will allow participants to perform power exercises at a higher intensity [13–16], potentially leading to a greater chronic training stimulus if utilized repeatedly during specific blocks of training. Previous research has suggested that the enhanced training stimulus produced by complex training may result in superior performance gains longitudinally compared with normal training [14, 15, 17–19]. Protocols designed to produce a potentiated state have been termed strength–power potentiating complexes (SPPCs) [1, 7]. Specifically, SPPCs involve the performance of a high force or high power movement prior to a subsequent high power or high velocity movement (e.g., heavy back squats prior to drop jumps). An abundance of lower extremity SPPCs have been investigated with the intent to produce a potentiated state in which a subject can acutely improve their subsequent performance during various explosive movements such as jumping. However, it should be noted that different types of muscle actions during potentiation protocols may elicit varying effects on the subsequent explosive performances [8]. While some SPPCs have produced an enhanced jumping performance, others have not (Tables 1, 2, 3). There are a number of reasons as to why certain SPPCs may not produce an enhanced subsequent jumping performance, which makes designing an effective SPPC a trying task. In order to effectively design an SPPC, further understanding of jump potentiation is necessary.

Several underlying physiological mechanisms have been proposed to be components of the PAP phenomenon, including increased phosphorylation of myosin light chains [20–25], increased recruitment of higher order motor units [26–29], changes in the active muscle's pennation angle [8, 30], and increased muscle stiffness [14, 31, 32]. Although several different underlying physiological mechanisms exist, it is possible that they interact concurrently to produce a change in subsequent vertical jump performance. However, it is possible that the subject's characteristics and the design of the SPPC may alter the magnitude of the influence of a given underlying mechanism to a greater extent than another. For example, the use of heavier loads during an SPPC will likely promote the recruitment of higher order motor units as compared with lighter loads [33]. Ultimately, the combination of the subject's characteristics and SPPC will affect the underlying mechanisms of potentiation that will produce a positive or negative change in the force production characteristics of the vertical jump (Fig. 1). It is clear that further understanding of how the subject's characteristics and the design of the SPPC interact to produce a change in performance is needed.

One of the most common methods of assessing an athlete's performance is the monitoring of vertical jump performance (i.e., squat jump, countermovement jump, or drop/depth jump) [34]. The squat jump, countermovement jump, and drop/depth jump have been previously described by Bobbert and colleagues [35, 36]. Briefly, a squat jump is a vertical jump in which an individual starts from a relatively low position (i.e., flexed hips, knees, and ankles), holds the position for a short period of time to reduce or eliminate the influence of the stretch-shortening cycle before explosively pushing into the ground to reach a maximum height. A countermovement jump begins from a standing position from which the athlete lowers quickly to a self-selected position before immediately extending their hip, knee, and ankle joints to achieve a maximum jump height. Finally, a drop/depth jump is typically performed from a raised surface or position where the individual falls (i.e., drops) due to gravity to land on their feet before performing rapid absorptive flexion followed immediately by explosive extension to achieve maximum jump height. While the drop and depth jump were grouped due to their similarity, it should be noted that each exercise has unique characteristics with the drop jump including a stiff landing, decreased contact time, and reduced power and jump height, while the

Table 1 A summary of studies that have investigated the effects of various protocols on squat jump potentiation

Study	*N* (training status)	Intervention	Rest interval(s)	Results
Arabatzi et al. 2014 [38]	58 (TR)	3 × 3 s MVC squats	20 s, 4 min	↑ RFD as age increased in both males and females ↑ SJ performance only in men No effect on SJ performance in teen-male, boy, and female groups ↑ RFD in both adult and teen-male groups No change in RFD in children
Cilli et al. 2014 [39]	35 (TR)	Dynamic warm-up exercises while fixed to a cable-cross machine with 2, 4, 6, 8, and 10 % bodyweight resistance	NS	↑ SJ height after all % ages No difference in ↑ SJ height between % ages ↑ SJ peak force after 8 %
Kavanaugh et al. 2011 [40]	14 (RT)	3 × 30s static squat at 120–130° knee angle with or without WBV at 30 Hz and 3 mm amplitude	5 min	No difference in SJ height, peak force, PP, or RFD during SJ with 0 or 20 kg
Requena et al. 2011 [41]	14 (TR)	10 s MVC of knee extensors	5 min	Strong correlation between SJ height and twitch peak torque potentiation ($r = 0.64$)
Rittweger et al. 2000 [42]	37 (NS)	Exhaustive squat exercise with 40 % of body mass with and without WBV at 26 Hz with 6 mm amplitude	~10, 15, 20 s, 15 min	↓ SJ height at 10 and 15 s after WBV
Ronnestad, 2009 [43]	17 (RT, UT)	WBV protocols at 20, 35, and 50 Hz with 3 mm amplitude or no WBV	NS	↑ SJ peak average power after 50 Hz in both recreationally trained and untrained subjects No differences in SJ peak average power after WBV at 20 and 35 Hz
Seitz et al. 2014 [44]	18 (TR)	1 × 3 back squats at 90 % 1RM	15 s, 3, 6, 9, 12 min	↓ SJ power at 15 s for both strong and weak groups ↑ SJ power at 3, 6, 9, 12 min in strong group ↑ SJ power at 6, 9, 12 min in weak group
Smilios et al. 2005 [45]	10 (TR)	3 × 5 half-squats at 30 % 1RM (A) 3 × 5 half-squats at 60 % 1RM (B) 3 × 5 jump squats at 30 % 1RM (C) 3 × 5 jump squats at 60 % 1RM (D)	1, 5, 10 min after each set	↑ SJ height after 1st set with B
Suchomel et al. 2015 [46]	13 (TR)	1 × 2 ballistic concentric-only half-squats at 90 % 1RM	Immed, 1, 2, 3, 4, 5, 6, 7, 8, 9, 10 min	↑ SJ PP, but no differences between rest intervals No main effect differences in SJ peak force, net impulse, or RFD
Suchomel et al. 2015 [47]	15 (TR)	1 × 2 ballistic concentric-only half-squats at 90 % 1RM (A) 1 × 2 non-ballistic concentric-only half-squats at 90 % 1RM (B) Control (C)	2 min	Greater ↑ in SJ height, PP, and allometrically scaled PP during A compared with B and C No differences in SJ height, PP, and allometrically scaled PP between B and C
Suchomel et al. 2015 [48]	16 (TR)	1 × 2 ballistic concentric-only half-squats at 90 % 1RM (A) 1 × 2 non-ballistic concentric-only half-squats at 90 % 1RM (B)	Immed, 1, 2, 3, 4, 5, 6, 7, 8, 9, 10 min	Strong subjects ↑ SJ height and allometrically scaled PP earlier and to a greater extent compared with weak subjects during both A and B
Sygulla and Fountaine 2014 [49]	29 (TR)	1 × 3 back squats at 90 % 1RM	5 min	No difference in SJ height or PP
Weber et al. 2008 [50]	12 (TR)	1 × 5 back squats at 85 % 1RM	3 min	↑ Peak and mean jump height and force of 7 consecutive SJs
Young and Elliott 2001 [51]	14 (TR)	3 × 5 s MVC of plantar flexors and knee extensors	4 min	No difference in SJ performance

↑ increase or increased, ↓ decrease or decreased, *Immed* immediately following intervention, *MVC* maximal voluntary contraction, *NS* training status or rest interval not specified, *PP* peak power, *RFD* rate of force development, *RM* repetition maximum, *RT* subjects reported as recreationally trained, *SJ* squat jump, *TR* subjects who have trained at least twice per week for 1 year or athletes, *UT* untrained subjects who have not participated in any resistance training over the previous year, *WBV* whole-body vibration depth jump includes increased compliance and contact time, but a greater power output and jump height [37]. Due to its use as a common performance test, vertical jump performance (e.g., height, peak power, rate of force development, etc.) appears to be a criterion measurement to determine whether or not performance increased, decreased, or was unchanged following different training interventions. Potentiation literature has followed suit as a number of studies have investigated the effect of various potentiation protocols on subsequent squat jump (Table 1), countermovement jump (Table 2), and drop/depth jump performances (Table 3). While many of the studies reported an enhanced vertical jump performance, others did not. In order to design an effective SPPC, practitioners must understand the factors involved within the SPPC, but also understand how these factors interact with the characteristics of the subjects using the SPPC. Therefore, the purpose of this review is to discuss previous PAP literature and propose a deterministic model for vertical jump potentiation.

2 Literature Search Methodology

Original and review journal articles were retrieved from electronic searches of PubMed and Medline (EBSCO) databases. Additional searches of Google Scholar and relevant bibliographic hand searches with no limits of language of publication were also completed. The search strategy included the terms postactivation potentiation, strength–power potentiating complex, complex training, vertical jump, squat jump, countermovement jump, drop jump, and depth jump. The last month of the search was August 2015.

3 Deterministic Model

There are two main factors that must be considered when the goal is to potentiate a vertical jump: the characteristics of the subject who is being tested and the design of the SPPC itself. Each factor will be discussed in more detail in the following sections. Using concepts from previous research that have examined vertical jumping, muscle function, and factors of PAP [8, 114, 115], the following deterministic model for vertical jump potentiation is proposed (see Fig. 1).

4 Subject Characteristics

The first half of the deterministic model focuses on the characteristics of the subjects that may affect the ability to potentiate a type of vertical jump. Previous research has indicated that characteristics that may alter the effect of PAP on subsequent jump performances include the subject's absolute and relative strength, sex of the individual, their training background, and muscle characteristics [7–11].

4.1 Strength

Much of the existing potentiation literature has indicated that stronger subjects demonstrate a greater potential to use PAP more effectively to acutely enhance their performance as compared with their weaker counterparts [44, 48, 55, 81, 100, 116, 117]. Several studies indicated that individuals with greater relative strength levels may be able to dissipate fatigue faster when using SPPCs, allowing them to display an enhanced subsequent performance earlier as compared with weaker subjects [44, 48, 118]. Specifically, stronger and weaker subjects potentiated post-stimulus at 3 min compared with 5 min [44], immediately compared with 2 min [48], and 5 min compared with 15 min [118], respectively. Further research suggests that stronger subjects will develop fatigue resistance to high loads as an adaptation to repeated high load training [7]. Therefore, higher levels of relative strength may benefit an individual who is considering using SPPCs in their training programs. From a practical standpoint, practitioners should be aware that individuals with the ability to back squat at least twice their body mass have a greater potential to exhibit jump potentiation compared with weaker individuals [44, 47, 48, 119, 120]. Although there is evidence to counter the notion that greater relative strength levels relate to an individual's ability to potentiate [93, 111, 121], Miyamoto et al. [122] reported that an individual can enhance their ability to potentiate after getting stronger. Additional research has indicated that the ability to squat 1.7 times one's body mass [55] or 2.0 times one's body mass [44, 47, 48, 119, 120] will result in a greater likelihood of potentiation during subsequent jump performance(s) and a greater magnitude of potentiation. Therefore, it appears that lower relative strength levels may result in decreased potentiation and a longer duration for potentiation to exceed the level of fatigue. However, this may be altered as relative strength levels increase, resulting in greater potentiation and a more rapid decrease in fatigue.

4.2 Sex

When designing an SPPC for athletes, practitioners should consider if the protocol can be beneficial for both male and female participants. From a fiber composition standpoint, previous researchers have indicated that no statistical differences existed between males and females in fiber-type distribution of the vastus lateralis muscle [123]. However, other researchers have indicated that men possess a greater

Table 2 A summary of studies that have investigated the effects of various protocols on countermovement jump potentiation

Study	*N* (training status)	Intervention	Rest interval (s)	Results
Andrews et al. 2011 [52]	19 (TR)	3 × 3 back squats at 75 % 1RM 3 × 3 hang clean at 60 % 1RM	3 min	Hang clean protocol more effective at maintaining CMJ height across 3 sets compared with back squat protocol
Armstrong et al. 2010 [53]	90 (NS)	Various WBV protocols including different frequencies (30, 35, 40, 50 Hz) and amplitude (2–4 or 4–6 mm) for 1 min	1, 5, 10, 15, 20, 25, 30 min	No differences in CMJ height over time between groups, frequencies, and amplitudes ↑ CMJ height at 5 and 10 min for whole group
Batista et al. 2011 [54]	23 (TR)	1 or 3 5-s MVCs of leg press	4 min	No differences in CMJ height or take-off velocity existed between groups
Berning et al. 2010 [55]	21 (TR, UT)	Functional isometric squat with 150 % 1RM	4, 5 min	↑ CMJ height in trained subjects No difference in CMJ height in untrained subjects
Bogdanis et al. 2014 [56]	14 (TR)	3 × 3 s MVC half-squat (A) Equal impulse of: Concentric-only half-squats at 90 % 1RM (B) Eccentric half-squats at 70 % 1RM (C)	15 s, 2, 4, 6, 8, 10, 12, 15, 18, 21 min	↑ in CMJ performance as compared with baseline performance after A No change in CMJ performance after B or C compared with baseline values at any time point
Bomfim Lima et al. 2011 [57]	10 (TR)	2 × 5 DJs from 0.75 m	5, 10, 15 min	↑ CMJ height at 15 min compared with baseline and 5 min
Boullosa et al. 2013 [58]	12 (RT)	1 × 5 half-squats at 5RM (A) 1 × 5 half-squats at 5RM with 30 s cluster (B)	1, 3, 6, 9, 12 min	No main effects for CMJ parameters ↑ Peak power after B at 1 min ↑ Peak power after A at 9 min
Boullosa and Tuimil, 2009 [59]	12 (TR)	Université de Montréal Track Test Time limit at maximal aerobic speed	2, 7 min	↑ CMJ height after Université de Montréal Track Test at 2 min and 7 min ↑ CMJ height after time limit at maximal aerobic speed only at 2 min
Boyd et al. 2014 [60]	10 (TR)	1 × 1 functional isometric half-squat at 150 % 1RM 1 × 3 half-squats at 150 % 1RM	2, 5, 8, 11 min	No differences between protocols in peak force, power, displacement, velocity at any time point ↑ Peak force following squat protocols for combined condition CMJ data ↓ Peak power following squat protocols for combined condition CMJ data
Burkett et al. 2005 [29]	29 (TR)	1 × 5 CMJ at 75 % 1RM CMJ height 1 × 5 LCMJ (10 % bodyweight) onto box	2 min	↑ CMJ height after weighted CMJ
Burns et al. 2015 [61]	19 (RT) 18 (TR)	1 × 2-min static squat at 120° of knee flexion with or without WBV at 30 Hz with 13-mm amplitude	Immed	No difference in CMJ performance between conditions No condition × group interaction effects for any CMJ performance measure
Chaouachi et al. 2011 [62]	12 (TR)	1 × 10 half-squats at 70 % 1RM 1 × 5 half-squats at 70 % 1RM 1 × 5 half-squats at 85 % 1RM 1 × 3 half-squats at 85 % 1RM 1 × 3 half-squats at 90 % 1RM 1 × 1 half-squats at 90 % 1RM	1, 2, 3, 5, 10, 15 min	No differences between protocols in CMJ height, peak power, force, velocity, or mean power at any time point
Chattong et al. 2010 [63]	20 (TR)	CMJs onto box with 5, 10, 15, and 20 % bodyweight weighted vest (A) CMJs without weighted vest (B)	2 min	↑ CMJ height following both A and B No differences in CMJ height between A and B

Table 2 continued

Study	*N* (training status)	Intervention	Rest interval (s)	Results
Chen et al. 2013 [64]	10 (TR)	1 × 5 DJs 2 × 5 DJs	2, 6, 12 min	↑ CMJ height at 2 min compared with pretest, 6 min, and 12 min ↑ CMJ height at 6 min compared with 12 min No difference in CMJ height between protocols
Chiu and Salem, 2012 [65]	13 (TR)	3–4 × 2 snatch pulls at progressive barbell loads	3 min after each set wave	↑ CMJ height midway through the sets and following all the sets compared with baseline
Cilli et al. 2014 [39]	35 (TR)	Dynamic warm-up exercises while fixed to a cable-cross machine with 2, 4, 6, 8, and 10 % bodyweight resistance	NS	↑ CMJ height after all % ages ↑ CMJ height after 10 % compared with 6 and 8 % No difference in CMJ peak force at any % age
Clark et al. 2006 [66]	9 (TR)	1 × 6 LCMJs with 20 kg (A) 1 × 6 LCMJs with 40 kg (B)	4 min	↑ LCMJ height after B compared with A ↑ LCMJ peak power after B compared with A in 2nd and 3rd sets
Comyns et al. 2006 [5]	18 (TR)	1 × 5 back squats at 5RM	30 s, 2, 4, 6 min	No change in CMJ peak force ↓ CMJ flight time in entire group and women at 30 s and 6 min No sex differences
Cormie et al. 2006 [67]	9 (RT)	30-s WBV at 30 Hz with 2.5 mm amplitude	Immed, 5, 15, 30 min	↑ CMJ height Immed after WBV compared with sham treatment No differences in EMG of VL, VM, and BF between protocols
Crewther et al. 2011 [68]	9 (TR)	1 × 3 back squats at 3RM	15 s, 4, 8, 12, 16 min	↓ CMJ height at 15 s and 16 min ↑ CMJ height at 4, 8, 12 min ↑ Relative changes in CMJ height
Crum et al. 2012 [69]	20 (TR)	3 × 1 concentric-only quarter squats with 50 % 1RM (A) 3 × 1 concentric-only quarter squats with 65 % 1RM (B)	30 s, 3, 5, 10, 15 min	No differences in CMJ displacement, peak power output, peak force, or RFD between A and B
de Villarreal et al. 2007 [70]	12 (TR)	2 × 4 back squats at 80 % 1RM, 2 × 2 back squats at 85 % 1RM (A) 2 × 4 back squats at 80 % 1RM, 2 × 2 back squats at 90 % 1RM, and 2 × 1 back squats at 95 % 1RM (B) 3 × 5 back squats at 30 % 1RM (C) 3 × 5 CMJs with optimal load (D)	5 min, 6 h	↑ CMJ height after A and B at 5 min ↑ Loaded CMJ height after A and B at 5 min No difference in CMJ or LCMJ after C ↑ CMJ power after D ↑ LCMJ height at 5 min and 6 h after D
Dinsdale and Bissas, 2010 [71]	12 (TR)	1 × 3 hang clean at 90 % 1RM combined with different rest intervals Control	Immed, 1, 2, 3, 4, 5, or 6 min	No change in CMJ height or peak power after control, 1, 4, 5, or 6 min ↓ CMJ height after Immed, 2-, and 3-min rest period protocols
El Hage et al. 2011 [72]	17 (RT)	1 × 3 half-squats at 85 % 1RM (A) 1 × 5-s MVC half-squat at 90° knee angle with 100 % 1RM (B)	Immed, 2, 4 min	↓ CMJ performance Immed, 2, and 4 min after A compared with baseline ↓ CMJ performance Immed and 4 min after B compared with baseline No difference in CMJ performance 2 min after B compared with baseline
Esformes et al. 2013 [73]	27 (TR)	1 × 3 back squats at 3RM 1 × 3 quarter-squats at 3RM	5 min	↑ CMJ height, impulse, peak power, and flight time

Table 2 continued

Study	*N* (training status)	Intervention	Rest interval (s)	Results
Esformes et al. 2010 [74]	13 (TR)	3 × 3 half-squats at 3RM 3 × 24 plyometric bounds and hops	5 min	No difference in CMJ displacement, peak power, or peak vertical force Greater displacement following half-squats compared with plyometrics
Evetovich et al. 2015 [75]	27 (TR)	1 × 3 back squats at 3RM	5 min	↑ CMJ height, impulse, peak power, and flight time
Evetovich et al. 2015 [75]	20 (TR)	1 × 3 back squats at 85 % 1RM	8 min	No difference in responses between sexes ↑ CMJ height and horizontal jump distance
Faigenbaum et al. 2006 [76]	18 (TR)	Dynamic warm-up (A) Weighted vest dynamic warm-up with 2 % bodyweight (B) Weighted vest dynamic warm-up with 6 % bodyweight (C)	2 min	↑ CMJ height after A and B, but not after C
French et al. 2003 [77]	14 (TR)	3 × 3-s or 5-s MVC of knee extensors	Immed	No changes in CMJ performance
Fukutani et al. 2014 [78]	8 (TR)	Heavy: 1 × 3 back squats at 90 % 1RM Moderate: 1 × 3 back squats at 75 % 1RM	60 s	↑ CMJ height after both heavy and moderate conditions, but greater ↑ after heavy
Garcia-Pinillos et al. 2015 [79]	30 (TR)	4 × 3 × 400 m runs	2 min	↑ CMJ height after sets 1, 3, and 4, but not after set 2 ↑ CMJ peak power after all sets ↑ CMJ peak force after all sets
Gonzalez-Rave et al. 2009 [80]	24 (UT)	3 × 4 half-squats at 85 % 1RM (A) 3 × 4 half-squats at 85 % 1RM and 3 static stretches held for 15 s (B)	NS	No differences in CMJ height between A and B
Gourgoulis et al. 2003 [81]	20 (NS)	1 × 2 half-squats at 90 % 1RM	Immed	No difference in power ↑ CMJ height
Hanson et al. 2007 [82]	30 (TR)	1 × 8 back squats at 40 % 1RM 1 × 4 back squats at 80 % 1RM	5 min	No effect on CMJ performance
Hilfiker et al. 2007 [83]	13 (TR)	1 × 5 modified DJs from 60 cm	1 min	↑ CMJ power as compared with control
Hirayama, 2014 [84]	14 (TR)	1 × 1 at 20, 40, 60, 80 % 1RM and 6-s MVC half-squat	1 min after each set	↑ CMJ height after 60 %, 80 %, and MVC squats ↑ CMJ height after MVC squat vs 60 % and 80 % squats ↑ CMJ height after 80 % squat vs 60 % squat
Jensen and Ebben, 2003 [85]	21 (TR)	1 × 5 back squats at 5RM	10 s, 1, 2, 3, 4 min	↓ CMJ height at 10 s No effect at 1–4 min
Jones and Lees, 2003 [86]	8 (TR)	1 × 5 back squats at 85 % 1RM	Immed, 3, 10, 20 min	No main effects for CMJ performance or EMG activity
Khamoui et al. 2009 [87]	16 (TR)	1 × 2–5 back squats at 85 % 1RM	5 min	No effect on CMJ height or take-off velocity ↓ Force and impulse

Table 2 continued

Study	*N* (training status)	Intervention	Rest interval (s)	Results
Kilduff et al. 2011 [88]	9 (TR)	1 × 3 back squats at 87 % 1RM	Immed, 4, 8, 12, 16 min	↑ Peak power and jump height at 8 min than all other time intervals ↓ Peak power and jump height Immed after squats ↑ Peak vertical and horizontal force after squats compared with swim-specific warm-up
Kilduff et al. 2008 [89]	20 (TR)	3 × 3 back squats at 87 % 1RM	15 s, 4, 8, 12, 16, 20, 24 min	↓ Jump height 15 s ↑ Power output, RFD, and jump height at 8 min than all other time intervals
Kilduff et al. 2007 [6]	23 (TR)	1 × 3 back squats at 3RM	15 s, 4, 8, 12, 16, 20 min	↓ CMJ at 15 s ↑ CMJ at 8–12 min
Lamont et al. 2010 [90]	21 (RT)	1 × 30-s WBV at 30 Hz 3 × 10-s WBV at 30 Hz 1 × 30-s WBV at 50 Hz 3 × 10-s WBV at 50 Hz	2, 7.5, 17 min	No difference in CMJ height between protocols ↑ % change of CMJ height after 3 × 10 s at 50 Hz compared with 30 s at 30 Hz No difference in power or relative power between protocols
Latorre-Román et al. 2014 [91]	16 (TR)	4 × 3 × 400 m runs	2 min	↑ CMJ height after set 1, but not after other sets
Lowery et al. 2012 [92]	13 (TR)	1 × 5 back squats at 56 % 1RM 1 × 4 back squats at 70 % 1RM 1 × 3 back squats at 93 % 1RM	Immed, 0, 2, 4, 8, 12 min	No change in CMJ power after 56 % squats ↓ CMJ power Immed after 70 % and 93 % squats ↑ CMJ power 4 min after 70 % squats ↑CMJ power 4, 8 min after 93 % squats No difference in CMJ height and power between 70 % and 93 % squats
Mangus et al. 2006 [93]	11 (TR)	1 × 1 half-squat at 90 % 1RM half-squat (A) 1 × 1 quarter-squat at 90 % 1RM quarter-squat (B)	3 min	No difference in CMJ performance compared with control condition after A or B
McCann and Flanagan, 2010 [3]	16 (TR)	1 × 5 back squats at 5RM 1 × 5 hang clean at 5RM	4, 5 min	↑ CMJ height after subjects used optimal condition ↑ CMJ height after 4 min compared with baseline No main effect difference in CMJ height after 5 min No time effect differences in CMJ height No sex differences in CMJ height or peak force
Mitchell and Sale, 2011 [94]	11 (TR)	1 × 5 back squats at 5RM	4 min	↑ CMJ height and peak twitch
Moir et al. 2011 [95]	11 (TR)	1 × 3 back squats at 90 % 1RM 1 × 12 back squats at 37 % 1RM	2 min	No difference in CMJ height or vertical stiffness between protocols
Mola et al. 2014 [96]	22 (TR)	1 × 3 back squats at 3RM	15 s, 4, 8, 12, 16, 20 min	No difference in CMJ peak power or height between experimental and control No time effect existed for peak power and jump height

Table 2 continued

Study	N (training status)	Intervention	Rest interval (s)	Results
Naclerio et al. 2014 [97]	15 (TR)	1 × 3 back squats at 80 % 1RM with or without WBV at 40 Hz with 1.963-mm amplitude 3 × 3 back squats at 80 % 1RM with or without WBV at 40 Hz with 1.963-mm amplitude	1, 4 min	No main effects for condition × volume × rest period interaction for CMJ ↑ CMJ after 4 min compared with 1 min ↑ CMJ height for non-vibration at low volume, but not low volume
Needham et al. 2009 [98]	20 (TR)	Static stretching (A) Dynamic stretching (B) Dynamic stretching with dumbbell front squats with 20 % body mass (C)	3, 6 min	↑ CMJ height after C compared with A and B at 3 and 6 min
Reardon et al. 2014 [99]	11(RT)	3 × 10 back squats at 75 % 1RM 3 × 3 back squats at 90 % 1RM 1 × 1 back squat at 100 % 1RM	8, 20 min	No change in CMJ height, peak power, or average power for any protocol
Requena et al. 2011 [41]	14 (TR)	10-s MVC of knee extensors	5 min	Strong correlation CMJ height and twitch peak torque potentiation ($r = 0.61$)
Rixon et al. 2007 [100]	30 (TR, RT, UT)	3 × 3-s MVC squat (A) 1 × 3 half-squat at 3RM (B)	3 min	↑ CMJ height and power after A ↑ CMJ power compared with pretest
Robbins and Docherty, 2005 [101]	16 (RT)	3 × 7-s MVC squat	4 min	No effect on CMJ performance
Ronnestad, 2009 [43]	17 (RT, UT)	WBV protocols at 20, 35, and 50 Hz with 3-mm amplitude or no WBV	NS	↑ CMJ peak average power after 50 Hz in UT, but not RT No differences in CMJ peak average power after WBV at 20 and 35 Hz
Scott and Docherty, 2004 [102]	19 (TR)	1 × 5 back squats at 5RM	5 min	No acute or linear improvement in CMJ performance
Smilios et al. 2005 [45]	10 (TR)	3 × 5 half-squats at 30 % 1RM (A) 3 × 5 half-squats at 60 % 1RM (B) 3 × 5 jump squats at 30 % 1RM (C) 3 × 5 jump squats at 60 % 1RM (D)	1, 5, 10 min after each set	No change in CMJ height with A ↑ CMJ height after 1st and 2nd sets with B ↑ CMJ height after 1st and 2nd sets with C ↑ CMJ height after 2nd and 3rd sets with D
Sortiropoulos et al. 2010 [103]	26 (TR)	1 × 5 half-squats at 25 % 1RM, 1 × 5 half-squats at 35 % 1RM (A) 1 × 5 half-squats at 45 % 1RM, 1 × 5 half-squats at 65 % 1RM (B)	3 min	No difference between groups A and B in CMJ height or power
Stieg et al. 2011 [104]	17 (TR)	1 × 0, 3, 6, 9, or 12 DJs from individualized height	10 min	No main effect differences in condition, time, or relative ground reaction forces existed ↓ CMJ height after 9 DJs compared with 0, 3, and 6 DJs
Till and Cooke, 2009 [105]	12 (TR)	1 × 5 deadlifts at 5RM 1 × 5 tuck jumps 3 × 3s MVC knee extension at 90°	7, 8, 9 min	No difference in CMJ height or average CMJ height for any protocol
Tobin and Delahunt, 2014 [106]	20 (TR)	2 × 10 ankle hops, 3 × 5 70-cm hurdle jumps, and 5 DJs from 50 cm	1, 3, 5 min	↑ CMJ height and peak force at 1, 3, 5 min
Tsolakis and Bogdanis, 2011 [107]	23 (TR)	3 × 3-s MVC knee extensions (A) 3 × 5 tuck jumps (B)	Immed, 4, 8, 12 min	↑ CMJ power in men vs no change in women after A ↓ Peak leg power at 8 and 12 min after A ↓ CMJ power at 8 and 12 min after B

Table 2 continued

Study	*N* (training status)	Intervention	Rest interval (s)	Results
Turner et al. 2011 [108]	12 (RT)	30s WBV in half-squat at 0, 30, 35, 40 Hz with 8-mm amplitude	NS	No difference in CMJ height between any of the protocols ↑ CMJ height pre-post after WBV at 40 Hz
Veligekas et al. 2013 [109]	13 (TR)	3 × 3-s MVC squat at knee angle of either 91° or 139°	15 s, 3, 6, 9, 12 min	↑ Peak isometric force with 139° vs 91° MVC squats ↑ CMJ performance after 139° MVC squats at 3, 6, 9, 12 min No change in CMJ performance after 91° MVC squats
West et al. 2013 [110]	36 (TR)	3 × 3 back squats at 87 % 1RM	8 min	↑ CMJ peak power after both active and passive recovery ↑ Delta and % change in peak power after passive recovery as compared with active recovery
Witmer et al. 2010 [111]	24 (TR, RT)	1 × 3 back squats at 70 % 1RM	3, 6, 9, 12, 15, 18, 21, 24, 27, 30 min	No difference in CMJ height or stiffness compared with control for either sex No difference in responses between men and women
Young et al. 1998 [112]	10 (TR)	1 × 5 half-squat at 5RM	4 min	↑ LCMJ height

↑ increase or increased, ↓ decrease or decreased, *BF* biceps femoris, *CMJ* countermovement jump, *DJ* drop jump, *EMG* electromyography, *Immed* immediately following intervention, *LCMJ* loaded countermovement jump, *MVC* maximal voluntary contraction, *NS* training status or rest interval not specified, *RFD* rate of force development, *RM* repetition maximum, *RT* subjects reported as recreationally trained, *TR* subjects who have trained at least twice per week for 1 year or athletes, *UT* untrained subjects who have not participated in any resistance training over the previous year, *VL* vastus lateralis, *VM* vastus medialis, *WBV* whole-body vibration

percentage of type II fibers [124] and greater cross-sectional area of type II fibers compared with females [100, 124]. Because type II fibers are more likely to exhibit potentiation compared with type I fibers [24, 26, 124–129], it is possible that men are more likely to potentiate in response to an appropriate stimulus, but also display a greater degree of potentiation compared with women. However, the extant literature reveals mixed results. Some researchers have reported no statistical differences existed in lower body potentiation [3, 5, 85, 111], whereas other researchers have indicated that males and females display various potentiation differences, typically with men showing greater potentiation compared with women [107, 124, 130, 131]. It is unclear, however, whether or not these differences existed due to relative strength differences between men and women. Although the research that has investigated whether or not the sex of the subjects determines if potentiation may occur is inconclusive, there is little doubt that the vast majority of potentiation research has investigated SPPCs with male subjects. Thus, further research may be warranted to determine if the same potentiation protocols may be used effectively with male and female subjects.

4.3 Muscle Characteristics

An individual's muscle characteristics may dictate whether or not they will enhance their jump performance following a potentiating stimulus. Although the existing literature investigating the influence of other factors on potentiation contains mixed findings, this does not appear to be the case with the information regarding the muscle characteristics of individuals. All of the existing studies support the notions that type II (fast twitch) muscle fibers are better able to express potentiation than type I (slow twitch) muscle fibers and that individuals who possess a greater percentage of type II fibers are more likely to potentiate and potentiate to a greater extent than those who are type I dominant [24, 26, 124–129]. Because the characteristics of the target muscles appear to be an important aspect to consider when designing SPPCs, the difficult task becomes identifying individuals who are type II dominant. However, several studies have reported that stronger individuals tend to have a greater percentage of type II muscle fibers [132–134]. Therefore, assessing muscular strength and possibly gaining strength may be beneficial prior to using SPPCs in order to ensure the effectiveness of the protocol.

Table 3 A summary of studies that have investigated the effects of various protocols on drop/depth jump potentiation

Study	*N* (training status)	Intervention	Rest interval(s)	Results
Bergmann et al. 2013 [113]	12 (RT)	8 × 10 maximal bilateral hops with 30 s between sets	Immed, 30 s between sets	↑ DJ height after hops No difference in DJ contact time or ankle and knee angles between hops and control
Comyns et al. 2007 [12]	12 (TR)	1 × 3 back squats at 65 % 1RM (A) 1 × 3 back squats at 80 % 1RM (B) 1 × 3 back squats at 93 % 1RM (C)	4 min	↓ DJ contact time after C ↑ Vertical leg spring stiffness after C ↓ Flight time after A, B, and C ↓ Reactive strength index after B No change in peak force
de Villarreal et al. 2007 [70]	12 (TR)	2 × 4 back squats at 80 % 1RM, 2 × 2 back squats at 85 % 1RM (A) 2 × 4 back squats at 80 % 1RM, 2 × 2 back squats at 90 % 1RM, and 2 × 1 back squats at 95 % 1RM (B) 3 × 5 back squats at 30 % 1RM (C) 3 × 5 CMJs with optimal load (D)	5 min, 6 h	↑ DJ height after A and B at 5 min and 6 h No difference in DJ after C ↑ DJ height at 5 min and 6 h after D
French et al. 2003 [77]	14 (TR)	3 × 3-s or 5-s MVC of knee extensors	Immed	↑ DJ height, peak force, and acceleration impulse after 3-s MVCs No change in DJ after 5-s MVCs
Jones and Lees, 2003 [86]	8 (TR)	1 × 5 back squats at 85 % 1RM	Immed, 3, 10, 20 min	No main effects on DJ performance ↑ Biceps femoris activity during propulsive phase of DJ
Naclerio et al. 2014 [97]	15 (TR)	1 × 3 back squats at 80 % 1RM with or without WBV at 40 Hz with 1.963-mm amplitude 3 × 3 back squat s at 80 % 1RM with or without WBV at 40 Hz with 1.963-mm amplitude	1, 4 min	No main effects for condition × volume × rest period interaction for best DJ variables ↑ best DJ height after 4 min compared with 1 min ↑ Best DJ height during WBV in both low and high volume conditions
Young and Elliott, 2001 [51]	14 (TR)	3 × 5-s MVC of plantar flexors and knee extensors	4 min	No difference in DJ performance

↑ increase or increased, ↓ decrease or decreased, *CMJ* countermovement jump, *DJ* drop jump, *Immed* immediately following intervention, *MVC* maximal voluntary contraction, *RM* repetition maximum, *RT* subjects reported as recreationally trained, *TR* subjects who have trained at least twice per week for 1 year or athletes, *WBV* whole-body vibration

As previously mentioned, the pennation angle of an individual's active muscles may be considered as one of the primary mechanisms of PAP [8, 30]. The orientation of an individual's fibers within a muscle may affect the transmission of forces to tendons and bones [135, 136]. Mahlfeld et al. [30] indicated that the pennation angle of the vastus lateralis was statistically decreased 3–6 min following three, 3-s maximal voluntary contractions (MVC). A second study reported changes in pennation angle for the rectus femoris and vastus lateralis following moderate intensity (i.e., three sets of ten repetitions at 75 % 1RM), high intensity (i.e., three sets of three repetitions at 90 % 1RM), and 1RM squat protocols [99]. However, their results indicated that minimal potentiation was observed with little change in vertical jump height, peak power, or mean power reported. It should be noted, however, that a statistically significant moderate relationship ($r = -0.35$) was reported between mean vertical jump power and vastus lateralis pennation angle 8 min post-stimulus. A decreased pennation angle may allow for a greater mechanical advantage leading to enhanced force transmission to the tendon and bone [135, 136]. However, it is possible that potentiating exercise may result in an increase in connective tissue/tendon compliance that may counter the increases in the transmission of forces due to decreases in pennation angle [137]. There is little doubt that further research on this topic is required; however, one cannot discount the individual variability of resting pennation angle, change in pennation angle, and connective tissue/tendon compliance following a potentiating stimulus and how this may affect performance within an SPPC.

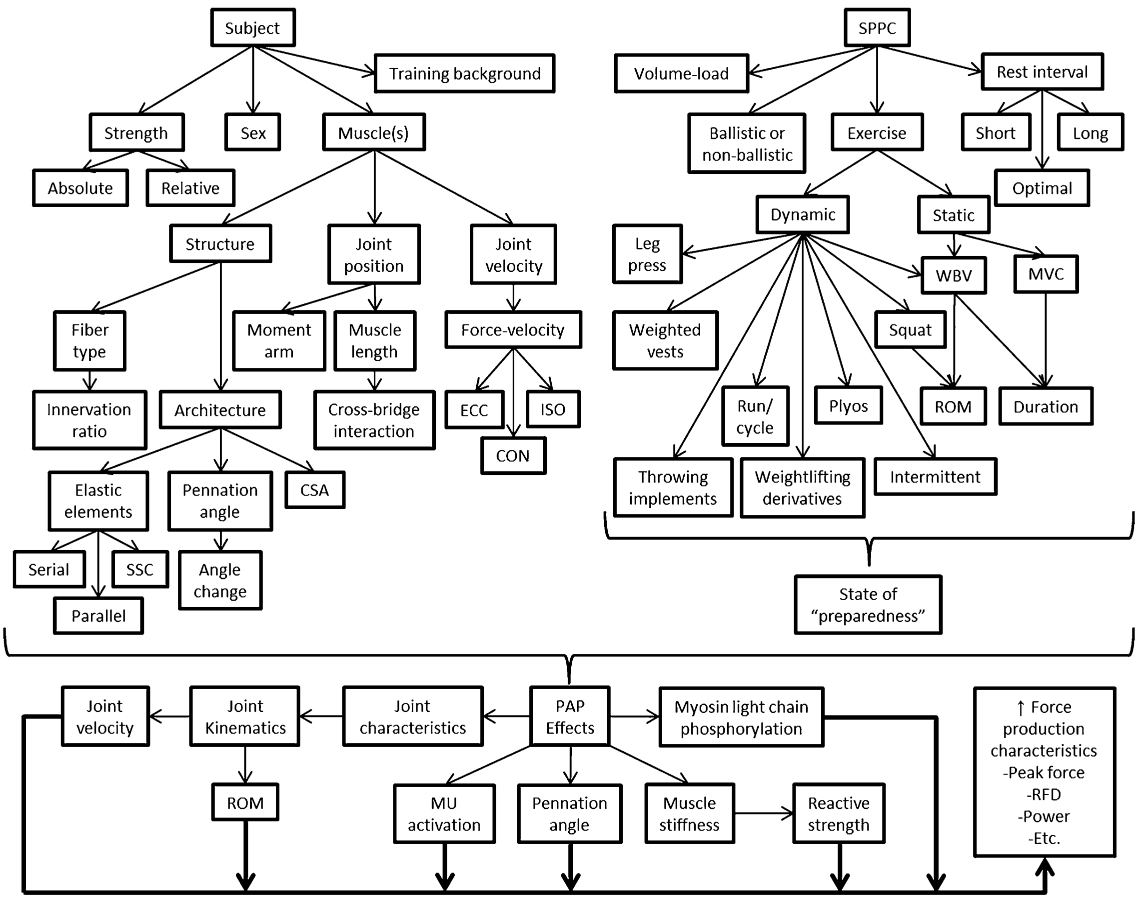

Fig. 1 Deterministic model for vertical jump potentiation. *CON* concentric muscle action, *CSA* cross-sectional area, *ECC* eccentric muscle action, *ISO* isometric muscle action, *MU* motor unit, *MVC* maximal voluntary contraction, *PAP* postactivation potentiation, *Plyos* plyometric exercise, *RFD* rate of force development, *ROM* range of motion, *SPPC* strength–power potentiation complex, *SSC* stretch-shortening cycle, *WBV* whole-body vibration

4.4 Neuromuscular Factors

One element of the PAP phenomenon which is often alluded to, but rarely shown in complex human performance-based models, is reflex potentiation (RP). Reflex potentiation can appear as a result of increased sensory discharge sensitivity within type Ia afferents, decreased sensory discharge failure at type Ia afferents, or a preferential lowering of higher order motor unit activation thresholds [8, 138]. Such characteristics have been shown in a number of studies utilizing single joint MVC, with or without the addition of electrical stimulation (twitch interpolation) [139–141]. Although the reflexive contribution to the gross PAP state appears to be small, inhibition in the form of postactivation depression within such reflex pathways may have a significant negative impact upon movements reliant upon a stretch-shortening cycle (e.g., countermovement jump, drop/depth jump) [22, 140–147]. Although it is currently unclear whether muscular responses observed during single joint tasks would be elicited during multi-joint tasks due to the task dependency of the mechanical behavior of both uniarticular and biarticular muscles [148], RP would appear to be an important transient neuromuscular phenomenon which needs to be considered within the proposed deterministic model of vertical jump potentiation. As action type and movement specificity appear to affect motor unit recruitment and discharge rates differently [139, 141, 145, 149, 150], RP may therefore be produced at different degrees of magnitude. Maximal voluntary contractions, heavy load dynamic contrast external resistance, loaded and unloaded ballistic jumps, neuromuscular electrical stimulation, and whole-body vibration (WBV) may provide the central and peripheral nervous systems with varying degrees of challenges and unique ratios of PAP to fatigue [22, 139, 140, 142, 145, 147, 149–151].

Mechanistically, RP can be assessed by way of EMG, with both changes in reflex latency as well as frequency spectra characteristics following PAP [22, 140, 145, 146, 149, 152, 153]. Researchers have shown a lowering of the activation thresholds for sub-populations of higher order motor units during corrective reflexive tasks [8, 11, 33]. Such a phenomenon has led some researchers to suggest that increasing type Ia afferent spindle sensitivity prior to the performance of a lower extremity movement utilizing the stretch-shortening cycle could increase the resultant muscle activation within the same musculature [146, 149]. Such increased reflex activation in conjunction with the primary volitional activation could lead to greater force and rates of force development [22, 140, 144, 149, 150, 152]. The time course of RP, if present, appears to be correlated strongly with Hoffman reflex (H-reflex) up-regulation and/or depression following PAP activity [23, 27, 145, 146, 150]. The H-reflex is an externally induced reflex response from type Ia afferents in response to low–moderate intensity electrical stimulation [145, 146, 150]. As with fiber composition and training status, H-reflex patterns appear to be highly individualized with differences seen between endurance-trained versus strength/power-trained individuals [154–156]. In a previous review covering the PAP phenomenon, Tillin and Bishop [8] proposed that primary sites of PAP and concurrent fatigue were different based upon isometric versus dynamic-based interventions. The same authors proposed that MVC-based PAP interventions resulted primarily in peripheral-based PAP (at the site of the muscle) and central-based fatigue (within the brain and spinal cord). Heavy load and ballistic type movements were proposed to induce central-based PAP with peripheral fatigue. This would suggest that both modes of PAP could affect the central nervous system, but heavy load dynamic contrast external resistance and ballistic movements may have a greater relative impact upon RP [139, 144, 149, 151]. WBV has been proposed by some authors to bring about RP leading to improvements in countermovement jump height and power output [146, 147, 150, 157], while others suggest this is not the case [22, 142, 144]. An initial increase in type Ia afferent muscle spindle discharge has been shown followed by reduction and transient suppression following WBV exposure [22, 140, 144–146, 152, 153]. A supercompensatory rebound in Ia afferent activity could lead to increased alpha motor neuron discharge, decreased Ia afferent discharge failure, reduced sensitivity at the Renshaw cell (inter-neuron) level, or a reduction in the required descending drive from the primary motor cortex (M1) to maintain a similar force, or rate of force development level [140, 142, 145, 146, 150, 152].

Reflex potentiation coupled with reduced neural inhibition at the spinal cord level could result in greater alpha motor neuron firing frequency and motor unit synchronization [146, 149, 150]. Such transient effects in conjunction with increased phosphorylation of myosin regulatory light chains, localized muscle temperature, and inter- and intra-muscular coordination patterns would appear to account for the key neuromuscular factors behind the PAP phenomenon [22, 141–144, 150, 157]. As these factors appear to have different levels of susceptibility to facilitation and fatigue, and varying time courses of peak and plateaued effects, individualized 'trial and error' treatments may be warranted. In practice, utilizing SPPCs following or partly incorporated into 'dynamic warm-up' activities could transiently facilitate neural, myogenic, and metabolic/hemodynamic characteristics of PAP resulting in significant acute improvements in jump performance [22, 140–142, 144, 146, 147, 150, 157].

4.5 Training Background

The training background of subjects may also determine how they respond to various SPPCs. Several studies have examined the potentiation differences between athletes and non-athletes [116, 117, 158]. Chiu et al. [116] indicated that athletes improved their peak power to a greater extent than recreationally trained subjects during countermovement and concentric-only jump squats following five sets of one back squat repetition at 90 % 1RM. This may be due to the athletes developing resistance to high load fatigue as an adaptation to their training [7]. Similar results were found by Hamada et al. [158], who indicated that Canadian national team triathletes produced statistically greater peak torque during MVC in both the elbow extensors and plantar flexors as compared with sedentary subjects following maximal twitch contractions. A recent meta-analysis supports the findings of the above research, indicating that athletes displayed greater potentiation effects ($d = 0.81$) compared with trained subjects ($d = 0.29$) and untrained subjects ($d = 0.14$) [159]. Collectively, these studies indicate that potentiation favors athletes over non-athletes. Beyond performance measures, there is a paucity of research that has examined how various physical attributes differ between athletes and non-athletes in regard to potentiation. As shown here, the strength levels and muscle characteristics of an individual may dictate the ability of the subject to realize potentiation following a potentiating exercise. Thus, it should be noted that the training background of the subjects is just one of many factors that must be considered in regard to potentiation as indicated above (Fig. 1).

5 Strength–Power Potentiating Complex

The second portion of the proposed deterministic model focuses on the design of the SPPC. In order to design an effective SPPC, sport scientists and practitioners must consider all aspects that contribute to any variability that may affect an individual's ability to potentiate.

Specifically, sport scientists and practitioners should consider the choice of exercise(s) that is/are used as a potentiating stimulus, the volume load of the protocol, the muscle groups involved, the characteristics of the movement to be potentiated, the type of muscle action used during the stimulus and subsequent activity, the period of time between the conclusion of the warm-up and the subsequent performance, and the performance level of the athletes [9, 159–161]. The design of an SPPC ultimately produces a state of preparedness for subsequent activity. Preparedness may be defined as the summation of fitness and fatigue responses to a stimulus (fitness–fatigue relationship), where fitness includes the underlying mechanisms allowing performance and fatigue includes the factors that limit performance [162]. However, as displayed in Fig. 1, a number of factors within the SPPC itself can greatly affect whether or not the state of preparedness will lead to an enhancement or a decrement in performance. By taking into account as many aspects as possible, a sport scientist or practitioner may be able to more effectively design an SPPC.

5.1 Potentiating Exercise

Tables 1, 2 and 3 display the research that has examined the acute effects of many different types of exercise on subsequent squat jump, countermovement jump, or drop/depth jump performance. Although the exercise protocols may differ, the type of exercise typically falls within one of two categories: dynamic or static. Examples within the scientific literature that examined dynamic potentiating exercise include squatting movements, plyometrics, weightlifting movements, WBV, throwing implements, intermittent exercise, running and/or cycling, movements with weighted vests, leg press, and several miscellaneous exercises. In contrast, static potentiating exercise may include MVC, but also WBV. A recent review indicated that ballistic exercise as a potentiation stimulus may produce performance improvements of 2–5 % [163]; however, no further published information exists on any of the other outlined types of exercise. Practitioners designing SPPCs should consider how biomechanically similar the potentiating exercise and the subsequent exercise are in terms of the kinematic and kinetic variables associated with the movements and the muscle actions involved. For example, practitioners should choose a potentiating exercise in which the muscle actions and joint angles used are similar to those in the subsequent exercise [47].

5.2 Ballistic versus Non-Ballistic Movements

The nature in which the potentiating exercise is performed may alter the PAP effects displayed in subsequent performances. Previous research has indicated that ballistic movements produce greater muscle activation as compared with similar movements that are non-ballistic [164]. Further research has indicated that an exercise performed in a ballistic manner may produce greater power outputs than the same exercise performed in a non-ballistic manner [165]. Three studies have examined the potentiation differences between a ballistic exercise (i.e., hang clean or power clean) and a non-ballistic exercise (i.e., back squat) [3, 52, 166]. Although one study indicated that there were no differences in the potentiation effects between the hang clean and back squat [3], the remaining studies indicated that the hang clean [52]and power clean [166] produced statistically greater potentiation effects than the back squat. It should be noted that neither of these studies used the same absolute load between the exercises, which may effectively alter the necessary forces and rate of force production needed to complete the exercise, the individual’s level of fatigue, and exercise mechanics (e.g., muscle actions and joint angles). This in turn may lead to different degrees of potentiation. Recent research examined the differences in potentiation following the same potentiating exercise performed in either a ballistic or non-ballistic manner using the same absolute load [47, 48]. Collectively, the results indicated that ballistic concentric-only half-squats enhanced subsequent squat jump height, absolute peak power, and allometrically scaled peak power to a greater extent compared with concentric-only half-squats performed in a non-ballistic manner. For further information regarding the use of ballistic exercise within SPPCs, readers are directed to a recent review by Maloney and colleagues [163].

5.3 Volume Load

Previous researchers have indicated that the type, volume, intensity, and the duration of exercise and recovery may determine whether fatigue or potentiation is dominant over the other at various rest intervals [159, 167]. Thus, an aspect of each potentiation protocol that cannot be overlooked is the volume load completed prior to the subsequent vertical jump(s). Using the theoretical model of the interaction between fatigue and potentiation provided by Sale [11], Tillin and Bishop [8] expanded the model and indicated that two windows may exist to realize potentiation effects with regard to the volume load of the potentiating stimulus. If the volume load of the potentiating stimulus is low, but has sufficient intensity, it is likely that a decreased amount of fatigue will result and potentiation may be realized earlier (i.e., window 1). In contrast, if the volume load is high, greater fatigue may be present and a longer rest interval may be required to realize potentiation (i.e., window 2). Previous research has indicated that multiple sets of exercise produced a statistically greater effect size than a single set [159].

However, it should be noted that the volume load completed by the subjects must be large enough to stimulate the underlying mechanisms of PAP, but volume loads that are too large may result in excessive fatigue that may mask the potential benefits of PAP [168].

5.4 Rest Interval

Following a potentiation protocol, a state of both fatigue and potentiation is present [10, 11, 168, 169]. The interaction between fatigue and potentiation may be modeled acutely on the fitness–fatigue paradigm [170], where the subsequent performance(s) is/are the result of the interaction of fatigue and fitness after-effects that result following the potentiating exercise. In this case, the potentiating exercise raises the ‘preparedness’ (i.e., the difference between fitness and fatigue) of the subject for the subsequent performance(s) [7]. The rest interval length used within the SPPC may determine whether or not an enhanced performance is realized. Previous research has indicated that fatigue may dominate over potentiation in the early stages of recovery following the potentiating exercise [8]. Thus, if the rest interval is too short, fatigue may mask the benefits of potentiation [50, 171]. Conversely, if the rest interval is too long, the optimal potentiation effects may dissipate, which may lead to no changes in performance. In this regard, several studies indicated that fatigue dissipates faster than preparedness [128, 172, 173].

Previous research has indicated that potentiation effects may last from 2 to 20 min post-stimulus [100, 116, 125, 174]. Wilson and colleagues [159] indicated that the potentiation effects that existed between 3–7 min ($d = 0.54$) and 7–10 min were statistically greater than those that existed at rest intervals longer than 10 min ($d = 0.02$). A second meta-analysis supports these findings and indicated that a negative medium and a small effect size existed at rest intervals of 0–3 min and those >16 min, respectively [175]. In addition, positive medium and small effect sizes existed at rest intervals of 8–12 min and 4–7 min, respectively. Because the type, intensity, and duration of exercise may determine if fatigue or potentiation is dominant over the other [167], it is likely that each potentiation complex has an optimal rest interval where the greatest potentiation effects occur. However, practitioners should note that individualized rest periods may be needed in order to provide the optimal training stimulus [2–6, 48].

6 Conclusions and Practical Applications

The deterministic model proposed within this review may aid sport scientists and practitioners who hope to develop effective SPPCs for various populations. There are a number of factors that must be considered when designing an effective SPPC. Not only do sport scientists and practitioners have to consider the potentiating exercise and the subsequent exercise, but they must also consider the characteristics of the individuals who will use the SPPCs in training and/or competition. The subject characteristics that must be considered when seeking vertical jump potentiation are the individual’s absolute and relative strength, sex, muscle characteristics, neuromuscular characteristics, and training background. In addition, the aspects of the SPPC that must be considered for vertical jump potentiation are the potentiating exercise, volume load completed, the ballistic or non-ballistic nature of the potentiating exercise, and the rest interval(s) used following the potentiating exercise. The extent to which some of these factors affect one another may still be up for debate; however, the use of SPPC with certain subjects and the design of certain SPPC may be questioned given the findings of previous research. For example, using a specific SPPC with weaker subjects may not be ideal as the likelihood of producing an enhanced training response is less than that of stronger subjects who use the same protocols. Furthermore, during the development of an SPPC to elicit an enhanced countermovement jump performance, the practitioner should consider the inclusion of an eccentric muscle action, but should also consider the load and joint angles used with the potentiating exercise.

The design of SPPCs should be practical in nature with regard to the equipment needed and the rest interval required for the potentiation of a subsequent performance. A number of protocols within Tables 1–3 used WBV to enhance vertical jump performance; however, sport scientists and practitioners should question how economical the use of WBV on machines is in a practical setting. With regard to team sports using WBV, it is unlikely that an athletic department will allocate the necessary funds to purchase a sufficient number of WBV platforms to be used in training while free weights are already present. Practitioners must also consider the rest interval needed to realize potentiation using certain protocols. For example, meta-analyses have indicated that the optimal period to realize potentiation is 7–12 min post-stimulus [159, 175]. Even if the practitioners were to use the earliest rest interval of 7 min, it should be questioned whether an SPPC that requires individuals to wait 7 min before a subsequent performance occurs is actually practical. With athlete-training-time restrictions, such as the accountable hours enforced by the National Collegiate Athletic Association, practitioners who would like to incorporate PAP as a training tool must seek SPPCs that may be effectively implemented in training and that do not require excessive rest intervals that may take away from valuable training time. It should be noted that practitioners may decrease the necessary time needed to realize potentiation by improving their subject's relative strength [44, 47, 48, 118, 122]. This may allow for the use of SPPCs within athletic events when time may be a limiting factor (e.g., track and field heats and attempts).

Compliance with Ethical Standards

No sources of funding were used to assist in the preparation of this article.

Conflicts of interest Timothy Suchomel, Hugh Lamont, and Gavin Moir declare that they have no conflicts of interest relevant to the content of this review.

References

1. Robbins DW. Postactivation potentiation and its practical applicability: a brief review. J Strength Cond Res. 2005;19(2):453–8.
2. Bevan HR, Cunningham DJ, Tooley EP, et al. Influence of postactivation potentiation on sprinting performance in professional rugby players. J Strength Cond Res. 2010;24(3):701–5.
3. McCann MR, Flanagan SP. The effects of exercise selection and rest interval on postactivation potentiation of vertical jump performance. J Strength Cond Res. 2010;24(5):1285–91.
4. Linder EE, Prins JH, Murata NM, et al. Effects of preload 4 repetition maximum on 100-m sprint times in collegiate women. J Strength Cond Res. 2010;24(5):1184–90.
5. Comyns TM, Harrison AJ, Hennessy LK, et al. The optimal complex training rest interval for athletes from anaerobic sports. J Strength Cond Res. 2006;20(3):471–6.
6. Kilduff LP, Bevan HR, Kingsley MI, et al. Postactivation potentiation in professional rugby players: optimal recovery. J Strength Cond Res. 2007;21(4):1134–8.
7. Stone MH, Sands WA, Pierce KC, et al. Power and power potentiation among strength-power athletes: preliminary study. Int J Sports Physiol Perform. 2008;3(1):55–67.
8. Tillin NA, Bishop D. Factors modulating post-activation potentiation and its effect on performance of subsequent explosive activities. Sports Med. 2009;39(2):147–66.
9. Docherty D, Hodgson MJ. The application of postactivation potentiation to elite sport. Int J Sports Physiol Perform. 2007;2(4):439–44.
10. Hodgson M, Docherty D, Robbins D. Post-activation potentiation: underlying physiology and implications for motor performance. Sports Med. 2005;35(7):585–95.
11. Sale DG. Postactivation potentiation: role in human performance. Exerc Sport Sci Rev. 2002;30(3):138–43.
12. Comyns TM, Harrison AJ, Hennessy L, et al. Identifying the optimal resistive load for complex training in male rugby players. Sports Biomech. 2007;6(1):59–70.
13. Verkhoshansky Y. Speed-strength preparation and development of strength endurance of athletes in various specializations. Sov Sports Rev. 1986;22:120–4.
14. Chu DA. Explosive power and strength: complex training for maximum results. Champaign: Human Kinetics; 1996.
15. Docherty D, Robbins D, Hodgson M. Complex training revisited: A review of its current status as a viable training approach. Strength Cond J. 2004;26(6):52–7.
16. Ebben WP, Jensen RL, Blackard DO. Electromyographic and kinetic analysis of complex training variables. J Strength Cond Res. 2000;14(4):451–6.
17. Ebben WP, Watts PB. A review of combined weight training and plyometric training modes: complex training. Strength Cond J. 1998;20(5):18–27.
18. Ebben WP, Blackard DO. Complex training with combined explosive weight training and plyometric exercises. Olympic coach. 1997;7(4):11–2.
19. Ebben WP. Complex training: a brief review. J Sports Sci Med. 2002;1(2):42–6.
20. Rassier DE, Herzog W. The effects of training on fatigue and twitch potentiation in human skeletal muscle. Eur J Sport Sci. 2001;1(3):1–8.
21. Palmer BM, Moore RL. Myosin light chain phosphorylation and tension potentiation in mouse skeletal muscle. Am J Physiol Cell Physiol. 1989;257(5):C1012–9.
22. Cochrane DJ, Stannard SR, Firth EC, et al. Acute whole-body vibration elicits post-activation potentiation. Eur J Appl Physiol. 2010;108(2):311–9.
23. Hodgson M, Docherty D, Zehr EP. Postactivation potentiation of force is independent of h-reflex excitability. Int J Sports Physiol Perform. 2008;3(2):219–31.
24. Vandenboom R, Grange RW, Houston ME. Myosin phosphorylation enhances rate of force development in fast-twitch skeletal muscle. Am J Physiol. 1995;268(3 Pt 1):C596–603.
25. Ryder JW, Lau KS, Kamm KE, et al. Enhanced skeletal muscle contraction with myosin light chain phosphorylation by a calmodulin-sensing kinase. J Biol Chem. 2007;282(28):20447–54.
26. Hamada T, Sale DG, MacDougall JD, et al. Postactivation potentiation, fiber type, and twitch contraction time in human knee extensor muscles. J Appl Physiol. 2000;88(6):2131–7.
27. Trimble MH, Harp SS. Postexercise potentiation of the H-reflex in humans. Med Sci Sports Exerc. 1998;30(6):933–41.
28. Suzuki S, Kaiya K, Watanabe S, et al. Contraction-induced potentiation of human motor unit discharge and surface EMG activity. Med Sci Sports Exerc. 1988;20(4):391–5.
29. Burkett LN, Phillips WT, Ziuraitis J. The best warm-up for the vertical jump in college-age athletic men. J Strength Cond Res. 2005;19(3):673–6.
30. Mahlfeld K, Franke J, Awiszus F. Postcontraction changes of muscle architecture in human quadriceps muscle. Muscle Nerve. 2004;29(4):597–600.
31. Shorten MR. Muscle elasticity and human performance. Med Sport Sci. 1987;25(1):18.
32. Hutton RS, Atwater SW. Acute and chronic adaptations of muscle proprioceptors in response to increased use. Sports Med. 1992;14(6):406–21.
33. Henneman E, Somjen G, Carpenter DO. Excitability and inhibitibility of motoneurons of different sizes. J Neurophysiol. 1965;28(3):599–620.
34. Taylor KL. Fatigue monitoring in high performance sport: a survey of current trends. J Aust Strength Cond. 2012;20(1):12–23.
35. Bobbert MF, Huijing PA, Van Ingen Schenau GJ. Drop jumping. I. The influence of jumping technique on the biomechanics of jumping. Med Sci Sports Exerc. 1987;19(4):332–8.
36. Bobbert MF, Huijing PA, Van Ingen Schenau GJ. Drop Jumping. II. The influence of dropping height on the biomechanics of drop jumping. Med Sci Sports Exerc. 1987;19(4):339–46.
37. Verkhoshansky YV, Siff MC. Supertraining: Verkhoshansky; 2009. p. 456–9, 563–577.
38. Arabatzi F, Patikas D, Zafeiridis A, et al. The post-activation potentiation effect on squat jump performance: age and sex effect. Pediatr Exerc Sci. 2014;26(2):187–94.
39. Cilli M, Gelen E, Yildiz S, et al. Acute effects of a resisted dynamic warm-up protocol on jumping performance. Biol Sport. 2014;31:277–82.

40. Kavanaugh AA, Ramsey MW, Sands WA, et al. Acute whole-body vibration does not affect static jump performance. Eur J Sport Sci. 2011;11(1):19–25.
41. Requena B, Saez-Saez de Villarreal E, Gapeyeva H, et al. Relationship between postactivation potentiation of knee extensor muscles, sprinting and vertical jumping performance in professional soccer players. J Strength Cond Res. 2011;25(2):367–73.
42. Rittweger J, Beller G, Felsenberg D. Acute physiological effects of exhaustive whole-body vibration exercise in man. Clin Physiol. 2000;20(2):134–42.
43. Ronnestad BR. Acute effects of various whole-body vibration frequencies on lower-body power in trained and untrained subjects. J Strength Cond Res. 2009;23(4):1309–15.
44. Seitz LB, de Villarreal ESS, Haff GG. The temporal profile of postactivation potentiation is related to strength level. J Strength Cond Res. 2014;28:706–15.
45. Smilios I, Pilianidis T, Sotiropoulos K, et al. Short-term effects of selected exercise and load in contrast training on vertical jump performance. J Strength Cond Res. 2005;19(1):135–9.
46. Suchomel TJ, Sato K, DeWeese BH, et al. Relationships between potentiation effects following ballistic half-squats and bilateral symmetry. Int J Sports Physiol Perform. 2015. doi:10.1123/ijspp.2015-0321.
47. Suchomel TJ, Sato K, DeWeese BH, et al. Potentiation effects of half-squats performed in a ballistic or non-ballistic manner. J Strength Cond Res. 2015. doi:10.1519/JSC.0000000000001251.
48. Suchomel TJ, Sato K, DeWeese BH, et al. Potentiation following ballistic and non-ballistic complexes: The effect of strength level. J Strength Cond Res. 2015. doi:10.1519/JSC.0000000000001288.
49. Sygulla KS, Fountaine CJ. Acute post-activation potentiation effects in NCAA division II female athletes. Int J Exerc Sci. 2014;7(3):212–9.
50. Weber KR, Brown LE, Coburn JW, et al. Acute effects of heavy-load squats on consecutive squat jump performance. J Strength Cond Res. 2008;22(3):726–30.
51. Young W, Elliott S. Acute effects of static stretching, proprioceptive neuromuscular facilitation stretching, and maximum voluntary contractions on explosive force production and jumping performance. Res Q Exerc Sport. 2001;72(3):273–9.
52. Andrews TR, Mackey T, Inkrott TA, et al. Effect of hang cleans or squats paired with countermovement vertical jumps on vertical displacement. J Strength Cond Res. 2011;25(9):2448–52.
53. Armstrong WJ, Grinnell DC, Warren GS. The acute effect of whole-body vibration on the vertical jump height. J Strength Cond Res. 2010;24(10):2835–9.
54. Batista MA, Roschel H, Barroso R, et al. Influence of strength training background on postactivation potentiation response. J Strength Cond Res. 2011;25(9):2496–502.
55. Berning JM, Adams KJ, DeBeliso M, et al. Effect of functional isometric squats on vertical jump in trained and untrained men. J Strength Cond Res. 2010;24(9):2285–9.
56. Bogdanis GC, Tsoukos A, Veligekas P, et al. Effects of muscle action type with equal impulse of conditioning activity on postactivation potentiation. J Strength Cond Res. 2014;28(9):2521–8.
57. Bomfim Lima J, Marin D, Barquilha G, et al. Acute effects of drop jump potentiation protocol on sprint and countermovement vertical jump performance. Hum Mov. 2011;12(4):324–30.
58. Boullosa DA, Abreu L, Beltrame LG, et al. The acute effect of different half squat set configurations on jump potentiation. J Strength Cond Res. 2013;27(8):2059–66.
59. Boullosa DA, Tuimil JL. Postactivation potentiation in distance runners after two different field running protocols. J Strength Cond Res. 2009;23(5):1560–5.
60. Boyd DA, Donald N, Balshaw TG. A comparison of acute countermovement jump responses following functional isometric and dynamic half squats. J Strength Cond Res. 2014;28(12):3363–74.
61. Burns JD, Miller PC, Hall EE. Acute effects of whole body vibration on functional capabilities of skeletal muscle. Retos. 2015;27:180–3.
62. Chaouachi A, Poulos N, Abed F, et al. Volume, intensity, and timing of muscle power potentiation are variable. Appl Physiol Nutr Metab. 2011;36(5):736–47.
63. Chattong C, Brown LE, Coburn JW, et al. Effect of a dynamic loaded warm-up on vertical jump performance. J Strength Cond Res. 2010;24(7):1751–4.
64. Chen ZR, Wang YH, Peng HT, et al. The acute effect of drop jump protocols with different volumes and recovery time on countermovement jump performance. J Strength Cond Res. 2013;27(1):154–8.
65. Chiu LZF, Salem GJ. Potentiation of vertical jump performance during a snatch pull exercise session. J Appl Biomech. 2012;28:627–35.
66. Clark RA, Bryant AL, Reaburn P. The acute effects of a single set of contrast preloading on a loaded countermovement jump training session. J Strength Cond Res. 2006;20(1):162–6.
67. Cormie P, Deane RS, Triplett NT, et al. Acute effects of whole-body vibration on muscle activity, strength, and power. J Strength Cond Res. 2006;20(2):257–61.
68. Crewther BT, Kilduff LP, Cook CJ, et al. The acute potentiating effects of back squats on athlete performance. J Strength Cond Res. 2011;25(12):3319–25.
69. Crum AJ, Kawamori N, Stone MH, et al. The acute effects of moderately loaded concentric-only quarter squats on vertical jump performance. J Strength Cond Res. 2012;26(4):914–25.
70. de Villarreal ESS, Gonzalez-Badillo JJ, Izquierdo M. Optimal warm-up stimuli of muscle activation to enhance short and long-term acute jumping performance. Eur J Appl Physiol. 2007;100(4):393–401.
71. Dinsdale A, Bissas A. Completing a prior set of hang cleans does not improve the performance in the vertical jump irrespective of the length of the recovery period [Abstract]. J Strength Cond Res. 2010;24:1. doi:10.1097/01.JSC.0000367096.11499.1c.
72. El Hage R, Zakhem E, Moussa E, et al. Acute effects of heavy-load squats on consecutive vertical jump performance. Sci Sports. 2011;26(1):44–7.
73. Esformes JI, Bampouras TM. Effect of back squat depth on lower body post-activation potentiation. J Strength Cond Res. 2013;27(11):2997–3000.
74. Esformes JI, Cameron N, Bampouras TM. Postactivation potentiation following different modes of exercise. J Strength Cond Res. 2010;24(7):1911–6.
75. Evetovich TK, Conley DS, McCawley PF. Post-activation potentiation enhances upper and lower body athletic performance in collegiate men and women athletes. J Strength Cond Res. 2015;29(2):336–42.
76. Faigenbaum AD, McFarland JE, Schwerdtman JA, et al. Dynamic warm-up protocols, with and without a weighted vest, and fitness performance in high school female athletes. J Athl Train. 2006;41(4):357–63.
77. French DN, Kraemer WJ, Cooke CB. Changes in dynamic exercise performance following a sequence of preconditioning isometric muscle actions. J Strength Cond Res. 2003;17(4):678–85.
78. Fukutani A, Takei S, Hirata K, et al. Influence of the intensity of squat exercises on the subsequent jump performance. J Strength Cond Res. 2014;28(8):2236–43.
79. Garcia-Pinillos F, Soto-Hermoso VM, Latorre-Roman PA. Acute effects of extended interval training on countermovement

jump and handgrip strength performance in endurance athletes: Postactivation potentiation. J Strength Cond Res. 2015;29(1):11–21.
80. Gonzalez-Rave JM, Machado L, Navarro-Valdivielso F, et al. Acute effects of heavy-load exercises, stretching exercises, and heavy-load plus stretching exercises on squat jump and countermovement jump performance. J Strength Cond Res. 2009;23(2):472–9.
81. Gourgoulis V, Aggeloussis N, Kasimatis P, et al. Effect of a submaximal half-squats warm-up program on vertical jumping ability. J Strength Cond Res. 2003;17(2):342–4.
82. Hanson ED, Leigh S, Mynark RG. Acute effects of heavy- and light-load squat exercise on the kinetic measures of vertical jumping. J Strength Cond Res. 2007;21(4):1012–7.
83. Hilfiker R, Hubner K, Lorenz T, et al. Effects of drop jumps added to the warm-up of elite sport athletes with a high capacity for explosive force development. J Strength Cond Res. 2007;21(2):550–5.
84. Hirayama K. Acute effects of an ascending intensity squat protocol on vertical jump performance. J Strength Cond Res. 2014;28(5):1284–8.
85. Jensen RL, Ebben WP. Kinetic analysis of complex training rest interval effect on vertical jump performance. J Strength Cond Res. 2003;17(2):345–9.
86. Jones P, Lees A. A biomechanical analysis of the acute effects of complex training using lower limb exercises. J Strength Cond Res. 2003;17(4):694–700.
87. Khamoui AV, Brown LE, Coburn JW, et al. Effect of potentiating exercise volume on vertical jump parameters in recreationally trained men. J Strength Cond Res. 2009;23(5):1465–9.
88. Kilduff LP, Cunningham DJ, Owen NJ, et al. Effect of postactivation potentiation on swimming starts in international sprint swimmers. J Strength Cond Res. 2011;25(9):2418–23.
89. Kilduff LP, Owen N, Bevan H, et al. Influence of recovery time on post-activation potentiation in professional rugby players. J Sports Sci. 2008;26(8):795–802.
90. Lamont HS, Cramer JT, Bemben DA, et al. The acute effect of whole-body low-frequency vibration on countermovement vertical jump performance in college-aged men. J Strength Cond Res. 2010;24(12):3433–42.
91. Latorre-Román PA, García-Pinillos F, Martínez-López EJ, et al. Concurrent fatigue and postactivation potentiation during extended interval training in long-distance runners. Mot Rev Educ Fís. 2014;20(4):423–30.
92. Lowery RP, Duncan NM, Loenneke JP, et al. The effects of potentiating stimuli intensity under varying rest periods on vertical jump performance and power. J Strength Cond Res. 2012;26(12):3320–5.
93. Mangus BC, Takahashi M, Mercer JA, et al. Investigation of vertical jump performance after completing heavy squat exercises. J Strength Cond Res. 2006;20(3):597–600.
94. Mitchell CJ, Sale DG. Enhancement of jump performance after a 5-RM squat is associated with postactivation potentiation. Eur J Appl Physiol. 2011;111(8):1957–63.
95. Moir GL, Mergy D, Witmer C, et al. The acute effects of manipulating volume and load of back squats on countermovement vertical jump performance. J Strength Cond Res. 2011;25(6):1486–91.
96. Mola JN, Bruce-Low SS, Burnet SJ. Optimal recovery time for postactivation potentiation in professional soccer players. J Strength Cond Res. 2014;28(6):1529–37.
97. Naclerio F, Faigenbaum AD, Larumbe-Zabala E, et al. Effectiveness of different postactivation potentiation protocols with and without whole body vibration on jumping performance in college athletes. J Strength Cond Res. 2014;28(1):232–9.
98. Needham RA, Morse CI, Degens H. The acute effect of different warm-up protocols on anaerobic performance in elite youth soccer players. J Strength Cond Res. 2009;23(9):2614–20.
99. Reardon D, Hoffman JR, Mangine GT, et al. Do acute changes in muscle architecture affect post-activation potentiation? J Sports Sci Med. 2014;13:483–92.
100. Rixon KP, Lamont HS, Bemben MG. Influence of type of muscle contraction, gender, and lifting experience on postactivation potentiation performance. J Strength Cond Res. 2007;21(2):500–5.
101. Robbins DW, Docherty D. Effect of loading on enhancement of power performance over three consecutive trials. J Strength Cond Res. 2005;19(4):898–902.
102. Scott SL, Docherty D. Acute effects of heavy preloading on vertical and horizontal jump performance. J Strength Cond Res. 2004;18(2):201–5.
103. Sotiropoulos K, Smilios I, Christou M, et al. Effects of warm-up on vertical jump performance and muscle electrical activity using half-squats at low and moderate intensity. J Sports Sci Med. 2010;9(2):326–31.
104. Stieg JL, Faulkinbury KJ, Tran TT, et al. Acute effects of depth jump volume on vertical jump performance in collegiate women soccer players. Kinesiology. 2011;43(1):25–30.
105. Till KA, Cooke C. The effects of postactivation potentiation on sprint and jump performance of male academy soccer players. J Strength Cond Res. 2009;23(7):1960–7.
106. Tobin DP, Delahunt E. The acute effect of a plyometric stimulus on jump performance in professional rugby players. J Strength Cond Res. 2014;28(2):367–72.
107. Tsolakis C, Bogdanis GC. Influence of type of muscle contraction and gender on postactivation potentiation of upper and lower limb explosive performance in elite fencers. J Sports Sci Med. 2011;10(3):577–83.
108. Turner AP, Sanderson MF, Attwood LA. The acute effect of different frequencies of whole-body vibration on countermovement jump performance. J Strength Cond Res. 2011;25(6):1592–7.
109. Veligekas P, Bogdanis GC, Tsoukos A, et al. Effect of maximum isometric contractions with different knee angles on postactivation potentiation in power athletes. Med Sci Sports Exerc. 2013;45(5):S507.
110. West D, Cunningham D, Bevan H, et al. Influence of active recovery on professional rugby union player's ability to harness postactivation potentiation. J Sports Med Phys Fitness. 2013;53(2):203–8.
111. Witmer CA, Davis SE, Moir GL. The acute effects of back squats on vertical jump performance in men and women. J Sports Sci Med. 2010;9(2):206–13.
112. Young WB, Jenner A, Griffiths K. Acute enhancement of power performance from heavy load squats. J Strength Cond Res. 1998;12(2):82–4.
113. Bergmann J, Kramer A, Gruber M. Repetitive hops induce postactivation potentiation in triceps surae as well as an increase in the jump height of subsequent maximal drop jumps. PloS One. 2013;8(10):e77705.
114. Ham DJ, Knez WL, Young WB. A deterministic model of the vertical jump: Implications for training. J Strength Cond Res. 2007;21(3):967–72.
115. Baltzopoulos V, Gleeson NP. Skeletal muscle function. In: Eston RG, Reilly T, editors. Kinanthropometry and exercise physiology laboratory manual: tests, procedures and data. London: Routledge; 2001. p. 7–35.
116. Chiu LZF, Fry AC, Weiss LW, et al. Postactivation potentiation response in athletic and recreationally trained individuals. J Strength Cond Res. 2003;17(4):671–7.

117. Koch AJ, O'Bryant HS, Stone ME, et al. Effect of warm-up on the standing broad jump in trained and untrained men and women. J Strength Cond Res. 2003;17(4):710–4.
118. Jo E, Judelson DA, Brown LE, et al. Influence of recovery duration after a potentiating stimulus on muscular power in recreationally trained individuals. J Strength Cond Res. 2010;24(2):343–7.
119. Bullock N, Comfort P. An investigation into the acute effects of depth jumps on maximal strength performance. J Strength Cond Res. 2011;25(11):3137–41.
120. Ruben RM, Molinari MA, Bibbee CA, et al. The acute effects of an ascending squat protocol on performance during horizontal plyometric jumps. J Strength Cond Res. 2010;24(2):358–69.
121. Terzis G, Karampatsos G, Kyriazis T, et al. Acute effects of countermovement jumping and sprinting on shot put performance. J Strength Cond Res. 2012;26(3):684–90.
122. Miyamoto N, Wakahara T, Ema R, et al. Further potentiation of dynamic muscle strength after resistance training. Med Sci Sports Exerc. 2013;45(7):1323–30.
123. Staron RS, Hagerman FC, Hikida RS, et al. Fiber type composition of the vastus lateralis muscle of young men and women. J Histochem Cytochem. 2000;48(5):623–9.
124. Terzis G, Spengos K, Karampatsos G, et al. Acute effect of drop jumping on throwing performance. J Strength Cond Res. 2009;23(9):2592–7.
125. Gullich A, Schmidtbleicher D. MVC-induced short-term potentiation of explosive force. New Stud Athletics. 1996;11(4):67–81.
126. O'Leary DD, Hope K, Sale DG. Posttetanic potentiation of human dorsiflexors. J Appl Physiol. 1997;83(6):2131–8.
127. Vandenboom R, Grange RW, Houston ME. Threshold for force potentiation associated with skeletal myosin phosphorylation. Am J Physiol. 1993;265(6 Pt 1):C1456–62.
128. Vandervoort AA, Quinlan J, McComas AJ. Twitch potentiation after voluntary contraction. Exp Neurol. 1983;81(1):141–52.
129. Hamada T, Sale DG, MacDougall JD, et al. Interaction of fibre type, potentiation and fatigue in human knee extensor muscles. Acta Physiol Scand. 2003;178(2):165–73.
130. Radcliffe JC, Radcliffe JL. Effects of different warm-up protocols on peak power output during a single response jump task [Abstract]. Med Sci Sports Exerc. 1996;28:S189.
131. O'Leary DD, Hope K, Sale DG. Influence of gender on posttetanic potentiation in human dorsiflexors. Can J Physiol Pharmacol. 1998;76(7–8):772–9.
132. Thorstensson A, Grimby G, Karlsson J. Force-velocity relations and fiber composition in human knee extensor muscles. J Appl Physiol. 1976;40(1):12–6.
133. Aagaard P, Andersen JL. Correlation between contractile strength and myosin heavy chain isoform composition in human skeletal muscle. Med Sci Sports Exerc. 1998;30(8):1217–22.
134. Maughan RJ, Watson JS, Weir J. Strength and cross-sectional area of human skeletal muscle. J Physiol. 1983;338(1):37–49.
135. Folland JP, Williams AG. The adaptations to strength training : morphological and neurological contributions to increased strength. Sports Med. 2007;37(2):145–68.
136. Fukunaga T, Ichinose Y, Ito M, et al. Determination of fascicle length and pennation in a contracting human muscle in vivo. J Appl Physiol. 1997;82(1):354–8.
137. Kubo K, Kanehisa H, Kawakami Y, et al. Effects of repeated muscle contractions on the tendon structures in humans. Eur J Appl Physiol. 2001;84(1–2):162–6.
138. Zehr EP. Training-induced adaptive plasticity in human somatosensory reflex pathways. J Appl Physiol. 2006;101(6):1783–94.
139. Duclay J, Martin A. Evoked H-reflex and V-wave responses during maximal isometric, concentric, and eccentric muscle contraction. J Neurophysiol. 2005;94(5):3555–62.
140. Nishihira Y, Iwasaki T, Hatta A, et al. Effect of whole body vibration stimulus and voluntary contraction on motoneuron pool. Adv Exerc Sport Physiol. 2002;8(4):83–6.
141. Baudry S, Klass M, Duchateau J. Postactivation potentiation influences differently the nonlinear summation of contractions in young and elderly adults. J Appl Physiol. 2005;98(4):1243–50.
142. Wilcock IM, Whatman C, Harris N, et al. Vibration training: could it enhance the strength, power, or speed of athletes? J Strength Cond Res. 2009;23(2):593–603.
143. Kemertzis MA, Lythgo ND, Morgan DL, et al. Ankle flexors produce peak torque at longer muscle lengths after whole-body vibration. Med Sci Sports Exerc. 2008;40(11):1977–83.
144. Fernandes IA, Kawchuk G, Bhambhani Y, et al. Does whole-body vibration acutely improve power performance via increased short latency stretch reflex response? J Sci Med Sport. 2013;16(4):360–4.
145. Ritzmann R, Gollhofer A, Kramer A. The influence of vibration type, frequency, body position and additional load on the neuromuscular activity during whole body vibration. Eur J Appl Physiol. 2013;113(1):1–11.
146. Ritzmann R, Kramer A, Gollhofer A, et al. The effect of whole body vibration on the H-reflex, the stretch reflex, and the short-latency response during hopping. Scand J Med Sci Sports. 2013;23(3):331–9.
147. Wang H-H, Chen W-H, Liu C, et al. Whole-body vibration combined with extra-load training for enhancing the strength and speed of track and field athletes. J Strength Cond Res. 2014;28(9):2470–7.
148. Zajac FE. Muscle coordination of movement: a perspective. J Biomech. 1993;26:109–24.
149. Gruber M, Gruber SBH, Taube W, et al. Differential effects of ballistic versus sensorimotor training on rate of force development and neural activation in humans. J Strength Cond Res. 2007;21(1):274–82.
150. Cochrane DJ. The potential neural mechanisms of acute indirect vibration. J Sports Sci Med. 2011;10(1):19–30.
151. Kurokawa S, Fukunaga T, Nagano A, et al. Interaction between fascicles and tendinous structures during counter movement jumping investigated in vivo. J Appl Physiol. 2003;95(6):2306–14.
152. Eckhardt H, Wollny R, Müller H, et al. Enhanced myofiber recruitment during exhaustive squatting performed as whole-body vibration exercise. J Strength Cond Res. 2011;25(4):1120–5.
153. Fratini A, Cesarelli M, Bifulco P, et al. Relevance of motion artifact in electromyography recordings during vibration treatment. J Electromyogr Kinesiol. 2009;19(4):710–8.
154. Maffiuletti NA, Martin A, Babault N, et al. Electrical and mechanical Hmax-to-Mmax ratio in power-and endurance-trained athletes. J Appl Physiol. 2001;90(1):3–9.
155. Earles DR, Dierking JT, Robertson CT, et al. Pre-and post-synaptic control of motoneuron excitability in athletes. Med Sci Sports Exerc. 2002;34(11):1766–72.
156. Koceja DM, Davison E, Robertson CT. Neuromuscular characteristics of endurance-and power-trained athletes. Res Quart Exerc Sport. 2004;75(1):23–30.
157. Armstrong WJ, Grinnell DC, Warren GS. The acute effect of whole-body vibration on the vertical jump height. J Strength Cond Res. 2010;24(10):2835–9.
158. Hamada T, Sale DG, MacDougall JD. Postactivation potentiation in endurance-trained male athletes. Med Sci Sports Exerc. 2000;32(2):403–11.
159. Wilson JM, Duncan NM, Marin PJ, et al. Meta-analysis of postactivation potentiation and power: effects of conditioning activity, volume, gender, rest periods, and training status. J Strength Cond Res. 2013;27(3):854–9.
160. Young WB. Neural activation and performance in power events. Mod Athl Coach. 1992;30:29–31.

161. Koziris LP. Postactivation potentiation: Sometimes more fatigue than potentiation. Strength Cond J. 2012;34(6):75–6.
162. Stone MH, Stone M, Sands WA. Principles and Practice of Resistance Training. Champaign: Human Kinetics; 2007.
163. Maloney SJ, Turner AN, Fletcher IM. Ballistic exercise as a pre-activation stimulus: a review of the literature and practical applications. Sports Med. 2014;44(10):1347–59.
164. Newton RU, Kraemer WJ, Häkkinen K, et al. Kinematics, kinetics, and muscle activation during explosive upper body movements. J Appl Biomech. 1996;12:31–43.
165. Lake JP, Lauder MA, Smith NA, et al. A comparison of ballistic and non-ballistic lower-body resistance exercise and the methods used to identify their positive lifting phases. J Appl Biomech. 2012;28(4):431–7.
166. Seitz LB, Trajano GS, Haff GG. The back squat and the power clean: elicitation of different degrees of potentiation. Int J Sports Physiol Perform. 2014;9(4):643–9.
167. Masiulis N, Skurvydas A, Kamandulis S, et al. Post-activation potentiation and fatigue of quadriceps muscle after continuous isometric contractions at maximal and submaximal intensities. Ugdym Kūno Kult Sportas. 2007;4(67):56–63.
168. Rassier DE, Macintosh BR. Coexistence of potentiation and fatigue in skeletal muscle. Braz J Med Biol Res. 2000;33(5): 499–508.
169. Fowles JR, Green HJ. Coexistence of potentiation and low-frequency fatigue during voluntary exercise in human skeletal muscle. Can J Physiol Pharmacol. 2003;81(12):1092–100.
170. Zatsiorsky V. Science and practice of strength training. Champaign: Human Kinetics; 1995.
171. Gossen ER, Sale DG. Effect of postactivation potentiation on dynamic knee extension performance. Eur J Appl Physiol. 2000;83(6):524–30.
172. Requena B, Gapeyeva H, Garcia I, et al. Twitch potentiation after voluntary versus electrically induced isometric contractions in human knee extensor muscles. Eur J Appl Physiol. 2008;104(3):463–72.
173. Houston ME, Grange RW. Myosin phosphorylation, twitch potentiation, and fatigue in human skeletal muscle. Can J Physiol Pharmacol. 1990;68(7):908–13.
174. Gilbert G, Lees A, Graham-Smith P. Temporal profile of post-tetanic potentiation of muscle force characteristics after repeated maximal exercise. J Sports Sci. 2001;19:6.
175. Gouvêa AL, Fernandes IA, César EP, et al. The effects of rest intervals on jumping performance: a meta-analysis on post-activation potentiation studies. J Sports Sci. 2013;31(5):459–67.