REVIEW ARTICLE

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Factors Modulating Post-Activation Potentiation and its Effect on Performance of Subsequent Explosive Activities

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Abstract

Post-activation potentiation (PAP) is induced by a voluntary conditioning contraction (CC), performed typically at a maximal or near-maximal intensity, and has consistently been shown to increase both peak force and rate of force development during subsequent twitch contractions. The proposed mechanisms underlying PAP are associated with phosphorylation of myosin regulatory light chains, increased recruitment of higher order motor units, and a possible change in pennation angle. If PAP could be induced by a CC in humans, and utilized during a subsequent explosive activity (e.g. jump or sprint), it could potentially enhance mechanical power and thus performance and/or the training stimulus of that activity. However, the CC might also induce fatigue, and it is the balance between PAP and fatigue that will determine the net effect on performance of a subsequent explosive activity. The PAP-fatigue relationship is affected by several variables including CC volume and intensity, recovery period following the CC, type of CC, type of subsequent activity, and subject characteristics. These variables have not been standardized across past research, and as a result, evidence of the effects of CC on performance of subsequent explosive activities is equivocal. In order to better inform and direct future research on this topic, this article will highlight and discuss the key variables that may be responsible for the contrasting results observed in the current literature. Future research should aim to better understand the effect of different conditions on the interaction between PAP and fatigue, with an aim of establishing the specific application (if any) of PAP to sport.

1. Post-Activation Potentiation (PAP)

Post-activation potentiation (PAP) or post-tetanic potentiation (PTP) refers to the phenomena by which muscular performance characteristics are acutely enhanced as a result of their contractile history.[1,2] The difference between PAP and PTP is defined by the nature of the conditioning contraction. PTP is induced by an involuntary tetanic contraction, and PAP is induced by a voluntary contraction[3,4] performed typically at a maximal or near-maximal intensity. For simplicity, this article refers to all potentiation responses as PAP, and refers to the activity responsible for inducing PAP as a conditioning contraction (CC).

The presence of PAP in skeletal muscle has been recorded by many studies in both mammals and humans,[5-17] prompting a discussion amongst recent review articles over the mechanisms of PAP[1,3] and its application to sports performance.[1-3,18] If effectively utilized, PAP could be implemented into a power-training routine to enhance the training stimulus of a plyometric exercise.[2,18] Inducing PAP prior to competition might also prove better than conventional warm-up techniques at enhancing performance of explosive sports activities such as jumping, throwing and sprinting.[10] Because of inconsistencies within the literature, research remains inconclusive on the possible benefits of PAP to explosive sports performance and/or training. The inconsistencies of past research are most likely due to the complex interaction of factors that influence acute performance following a CC.[1-3,18] This review discusses these confounding factors in greater detail, with the purpose of helping to inform and direct future research efforts towards establishing the application (if any) of PAP to performance/training of explosive sports activities.

2. Mechanisms of PAP

It has been proposed that two principal mechanisms are responsible for PAP. One is the phosphorylation of myosin regulatory light chains (RLC),[1,3,4,11,12,19,20] and the other is an increase in the recruitment of higher order motor units.[1,10,20] There is also evidence to suggest that changes in pennation angle may contribute to PAP, and this possible mechanism is briefly introduced in this article.

2.1 Phosphorylation of Regulatory Light Chains

A myosin molecule is a hexamer composed of two heavy chains (figure 1).[21] The amino-termini of each heavy chain, classified as the myosin head, contain two RLCs,[9,21] and each RLC has a specific binding site for incorporation of a phosphate molecule. RLC phosphorylation is catalyzed by the enzyme myosin light chain kinase, which is activated when Ca^{2+} molecules, released from the sarcoplasmic reticulum during muscular contraction, bind to the calcium regulatory protein calmodulin.[1,5,13,21] RLC

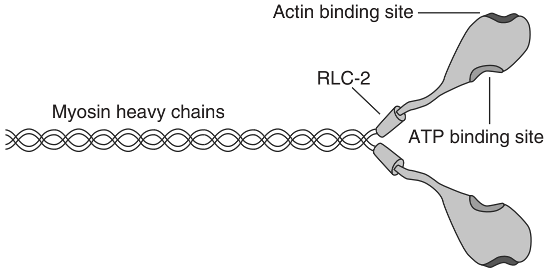

Fig. 1. One myosin molecule. Each myosin molecule is composed of two myosin heavy chains. Regulatory light chain (RLC)-2 represents a pair of RLCs positioned at the neck of a myosin head. Each RLC can incorporate a phosphate molecule, altering the structure of the myosin head. At each myosin head there is an actin and adenosine triphosphate (ATP) binding site.

phosphorylation is thought to potentiate subsequent contractions by altering the structure of the myosin head and moving it away from its thick filament backbone.[1,21] It has also been shown that RLC phosphorylation renders the actin-myosin interaction more sensitive to myoplasmic Ca^{2+}.[13] Consequently, RLC phosphorylation has its greatest effect at relatively low concentrations of Ca^{2+}, as is the case during twitch or low-frequency tetanic contractions.[1,3,4,22,23]

An acute increase in RLC phosphorylation, and a parallel potentiation of twitch tension following tetanic stimulation of specific efferent neural fibres, has been reported by many studies in skinned animal models[5,7,9,13] (figure 2). Relatively few studies have attempted to measure a similar response in human skeletal muscle. Stuart et al.[8] recorded a significantly elevated phosphate content of RLC in the vastus lateralis muscle ($p < 0.01$), and a significant potentiation of twitch tension of the knee extensors, following one 10-second isometric maximal voluntary contraction (MVC; $p < 0.05$). There was also a positive but non-significant correlation between the extent of twitch potentiation and the amount of phosphate incorporated into individual RLC units, and between potentiation and percentage of type II muscle fibres ($p > 0.05$).

Smith and Fry[24] also sampled muscle biopsies at the vastus lateralis, and analysed dynamic leg extension performance before and 7 minutes after a 10-second isometric MVC. The authors reported no significant change in RLC phosphorylation or leg extension performance for the entire sample ($p > 0.05$). The subjects were then split into those who responded to the MVC with a significant increase, and those who responded with a significant decrease in RLC phosphorylation ($p < 0.05$), but no significant differences in leg extension performance were found between the groups ($p > 0.05$). Methodological factors and differences in fibre-type distribution between animals and humans may explain why an observed increase in RLC phosphorylation following a CC is not as consistent in humans as animals. Nevertheless, the significance of RLC phosphorylation in human skeletal muscle remains unclear, and Stuart et al.[8] suggest that other factors may provide the major contribution to PAP.

2.2 Increased Recruitment of Higher Order Motor Units

Research on animals has shown that an induced tetanic isometric contraction (caused by stimulating specific afferent neural fibres, which in turn activate adjacent α-motoneurons via an afferent neural volley; figure 3) elevates the transmittance of excitation potentials across synaptic junctions at the spinal cord. This accommodating state can last for several minutes following the tetanic contraction,[10] and as a

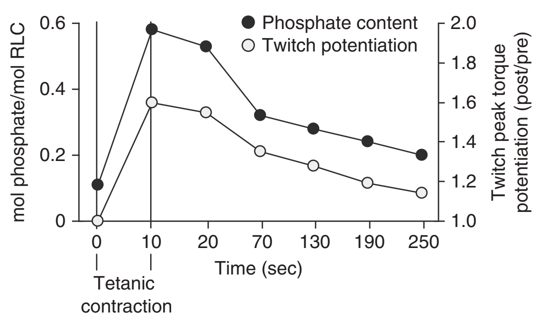

Fig. 2. The time-course of regulatory light chain (RLC) phosphorylation and twitch peak torque potentiation, following a 10-second pre-conditioning tetanus. Potentiation is represented as a ratio of the post-maximal voluntary contraction (MVC) peak torque value to the pre-MVC peak torque value (post/pre). These results indicate a possible relationship between RLC phosphorylation and twitch tension potentiation (reproduced from Moore and Stull,[7] with permission).

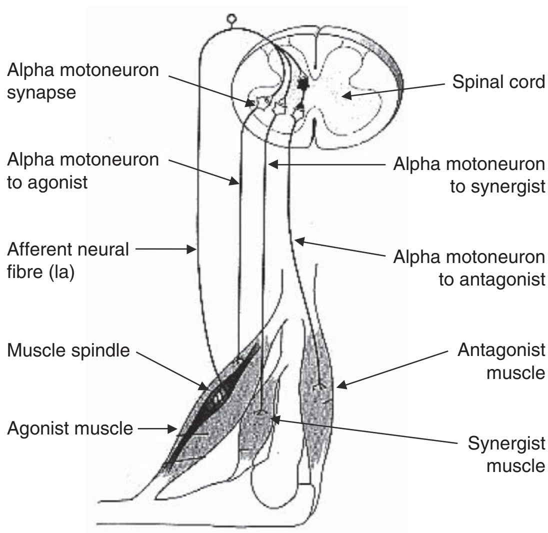

Fig. 3. The neural volleys of a Ia afferent fibre. An action potential generated at the Ia afferent neural fibre travels to the spinal cord, where it is transferred to the adjacent α-motoneuron of the agonist muscle. The action potential then travels directly to the agonist muscle, initiating the processes of muscular contraction.

result there is an increase in post-synaptic potentials, for the same pre-synaptic potential during subsequent activity.[25,26]

Luscher et al.[26] proposed a possible mechanism underlying the elevated transmittance of action potentials across synaptic junctions at the spinal cord. For each parent neural fibre (i.e. Ia fibre) numerous synapses project onto each α-motoneuron. Activation of an α-motoneuron works in an all-or-none fashion, whereby pre-synaptic transmitter release must coincide with the post-synaptic receptor sensibility. Transmitter failure at various synaptic junctions is a common occurrence during normal reflex or voluntary responses, due to an autonomously protected activation reserve.[26,27] An induced tetanic contraction is suggested to decrease the transmitter failure during subsequent activity, via one or a combination of several possible responses. These include an increase in the quantity of neurotransmitter released, an increase in the efficacy of the neurotransmitter, or a reduction in axonal branch-point failure along the afferent neural fibres.[28]

Hirst et al.[27] provided evidence to support a decreased monosynaptic transmitter failure during subsequent activity. They stimulated cat afferent neural fibres, and observed a 54% increase in excitatory post-synaptic potentials (EPSPs) for the same pre-synaptic stimulus, following a 20-second tetanic isometric contraction. Larger EPSPs represent greater depolarization of the α-motoneuron membrane, which would increase the likelihood of that α-motoneuron reaching the threshold required to initiate an action potential, and subsequently contract the muscle fibres of that motor unit.

Luscher et al.[26] also measured EPSPs at cat α-motoneurons, in response to electrical stimulation. They found a significant positive correlation between motoneuron input resistances and EPSP amplitude, for a standard stimulus ($r = 0.77$; $p < 0.01$; figure 4a), where input resistance was associated with the size of the α-motoneuron (with a smaller input resistance representing a larger motoneuron). This suggests that monosynaptic transmitter failure is greater at larger motoneurons (those responsible for activation of higher order or fast-twitch motor units). Conversely, when a twitch was stimulated following a 10-second tetanic contraction, Luscher et al.[26] found a significant negative correlation between EPSP potentiation and motoneuron input resistance ($r = -0.92$; $p < 0.001$; figure 4b). This demonstrates that a tetanic contraction decreased the transmitter failure occurring primarily at larger motoneurons, which resulted in a considerable PAP effect at these motoneurons. If a CC could induce an increase in higher order motoneuron recruitment in humans, this effect might theoretically increase fast-twitch fibre contribution to muscular contraction, and therefore enhance performance of a subsequent explosive activity.[10]

Previous studies have measured the H-wave in humans to investigate the effects of a CC on motoneuron recruitment.[10,29] The H-wave (H-reflex) is recorded at the muscle fibres using electromyography, and is the result of an afferent neural volley in response to single-pulse submaximal stimulation of the relevant nerve bundle (see figure 5 for more detail). An increase in

H-wave following a CC may therefore represent a decrease in transmitter failure at synaptic junctions, and a subsequent increase in higher order motoneuron recruitment. Gullich and Schmidtbleicher[10] stimulated the tibial nerve and measured changes in H-wave amplitude at the gastrocnemius before and after five 5-second isometric MVCs of the plantarflexors. They reported a depression in H-wave amplitude 1 minute after the MVCs (–24%; $p<0.05$), but a potentiation of H-wave amplitude 5–13 minutes after the MVCs (+20%; $p<0.01$). The H-wave, however, was not normalized to maximal M-wave (M-wave is the electrical counterpart of the activation of all motor units in the pool[30]). Therefore, other factors not relating to central activation, such as increased activity of the Na^{+}-K^{+} pump at the muscle fibres,[12,14,28] may be responsible for the results that Gullich and Schmidtbleicher[10] observed. Nevertheless, other studies have reported a potentiation in normalized H-wave amplitude 3–10 minutes post eight sets of dynamic MVCs,[29] and 5–11 minutes post a 10-second isometric MVC.[31] Collectively, these results suggest that PAP increases H-wave amplitude in humans (albeit after sufficient recovery), and this may be the result of increased higher order motoneuron recruitment at the spinal cord. Whether or not a CC can enhance motoneuron recruitment and performance during a subsequent voluntary contraction is yet to be determined.

The effect of isometric MVCs on subsequent voluntary motoneuron recruitment has been assessed using the interpolated twitch technique (ITT). The ITT can facilitate measurement of

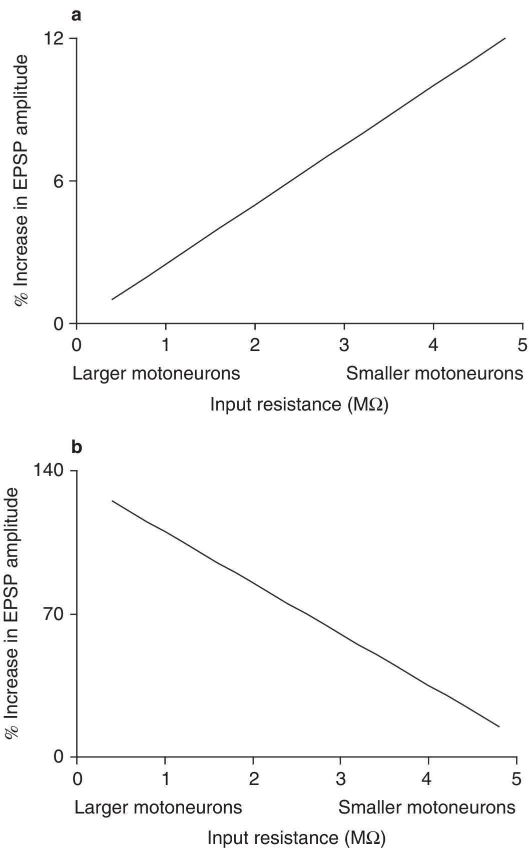

Fig. 4. (**a**) The relationship between input resistances of cat motoneurons, and amplitude of their excitatory post-synaptic potentials (EPSP) in response to twitch stimulation of the adjacent afferent neural fibres. (**b**) The relationship between input resistances of cat motoneurons, and the percentage increase (potentiation) in EPSP amplitude, in response to a twitch stimulation of the adjacent afferent neural fibres, following a 10-second tetanus. Although EPSP amplitude is greatest at smaller motoneurons (those with greater input resistances), representing greater transmitter failure at larger motoneurons (**a**), potentiation is greatest at larger motoneurons (those with smaller input resistances), demonstrating a decreased transmitter failure at these motoneurons (**b**).[22]

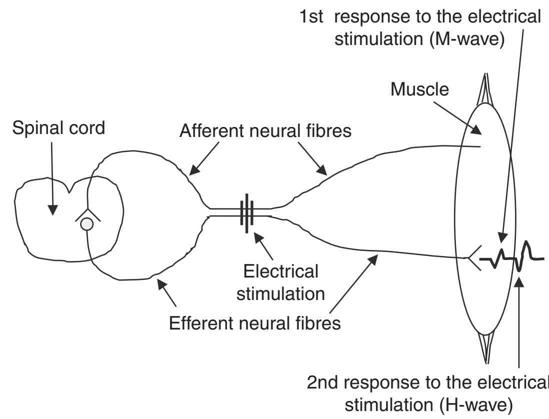

Fig. 5. Elicitation of an M- and H-wave. Stimulation of a nerve with a single submaximal electrical impulse evokes two electrical responses at the muscle. The first response (M-wave) is the result of an action potential travelling directly down the efferent neural fibres (α-motoneurons). The second response (H-wave) is the result of an action potential travelling along the afferent neural fibres to the spinal cord, where it is transmitted to adjacent efferent neural fibres, and down to the muscle.

motoneuron activation[32] by comparing maximal twitch amplitude at rest with that evoked when superimposed upon an MVC (for more detail of the ITT please refer to Folland and Williams[32] and Shield and Zhou[33]). Using the ITT, Behm et al.[34] reported a decrease in voluntary muscle activation following 10-second MVCs ($p < 0.05$). These results are in contrast to the proposed mechanism of PAP, but may demonstrate the dominance of central fatigue observed throughout this study (see section 4.2). Nevertheless, future research should consider using the ITT to investigate the mechanisms of PAP and their contribution to subsequent performance.

2.3 Changes in Pennation Angle

The pennation angle of a muscle (the angle formed by the fascicles and the inner aponeurosis) reflects the orientation of muscle fibres in relation to connective tissue/tendon.[35] The pennation angle will therefore affect force transmission to the tendons and bones.[35,36] The sum of the forces of all individual fibres being applied to the relevant tendon during muscular contraction is reduced by a factor of $\cos\theta$ (where $\theta =$ pennation angle).[36] Consequently, smaller pennation angles have a mechanical advantage with respect to force transmission to the tendon.[35,36] Using ultrasonography, Mahlfeld et al.[37] measured resting pennation angle of the vastus lateralis before and after three 3-second isometric MVCs. Pennation angle immediately after the MVCs (15.7°) had not changed from pre-MVC values (16.2°); however, 3–6 minutes after the MVCs, the pennation angle had significantly decreased (14.4°; $p < 0.05$). This change would only be equivalent to a 0.9% increase in force transmission to the tendons, but it is possible that this effect may contribute to PAP. Conditioning contractions, however, are also likely to increase connective tissue/tendon compliance,[38] and this may counter any increase in force transmission caused by a decrease in pennation angle. Nevertheless, the possibility that changes in muscle architecture contribute to PAP warrants further investigation.

3. PAP and Mechanical Power

Performance of explosive sports activities is largely determined by mechanical power.[10,39-43] Mechanical power can be defined as the rate at which force (F) is developed over a range of motion (d), in a specific period of time (t) [$P = F \times d/t$], or as force multiplied by velocity (v) [$P = F \times v$].[39,40,43] Accordingly, increasing the level of force at a given velocity will increase mechanical power, and this has been demonstrated in skinned rat/mouse models.[16,17,22] Similarly, decreasing the time over which a specific force is applied, without altering the distance over which that force is applied, will increase velocity, and consequently mechanical power. PAP could, therefore, increase force and/or velocity of the muscle contraction, which would enhance mechanical power and the associated sport performance.

To date, there is little evidence that PAP can increase maximal force. This is consistent with the observation that increased sensitivity of the myosin-actin interaction to Ca^{2+} has little or no effect in conditions of Ca^{2+} saturation, such as those caused by higher stimulation frequencies (>20 Hz for tetanic, or 200 Hz for voluntary contractions).[9,22] Stuart et al.[8] also found that a 10-second isometric MVC of the knee extensors was unable to increase maximum unloaded velocity of subsequent dynamic contractions. Although PAP appears to have little effect at the extremes of the force-velocity curve (figure 6), it has been shown to increase rate of force development (RFD) of tetanic contractions elicited at any frequency.[9] An increase in RFD causes a less concave force-velocity curve (figure 6), resulting in a greater velocity for a specific force, or vice versa.[3,44] Therefore, PAP may enhance the performance of activities that require submaximal force and velocity production.[3,11] Typically, athletes participating in explosive sports activities will not produce maximal force because the mass they are attempting to move is often relatively small (e.g. body mass), but they must still overcome that mass so will not achieve maximal unloaded velocity either.[40] Consequently, PAP could benefit the performance

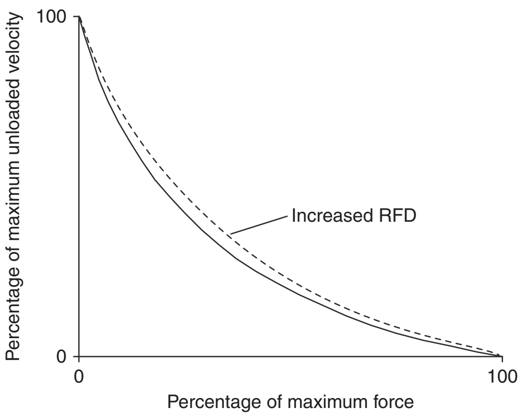

Fig. 6. The relationship between force and velocity. The dotted line represents a less concave force-velocity curve due to an increase in rate of force development (RFD) [reproduced from Sale,[3] with permission].

of explosive sports activities by increasing RFD and thus mechanical power.[3,11]

There is consensus over the existence of PAP, but if it is to be effectively utilized in performance and/or training, research must first confirm that PAP can be induced by an isometric or dynamic voluntary contraction, and then show that its benefits can be realized during a subsequent explosive sports activity. Unfortunately, measurement of both PAP and its effect on performance of a subsequent explosive sports activity in humans is inconsistent. Furthermore, little is known about the degree to which the proposed mechanisms underlying PAP may play a role in inducing an elevated neuromuscular response.

4. Acute Effects of PAP on Subsequent Activity

The performance of explosive sports activities relies predominantly on the activation of large muscle groups (e.g. ankle, knee, hip and/or arm and ab/adductors). Therefore, studies assessing the effect of PAP on smaller muscle groups have been excluded from the following sections. Furthermore, it has been shown[45,46] and is widely accepted that contractions of maximal or near maximal intensity (>80% of dynamic or isometric MVC) optimize PAP.[4] Therefore, studies assessing the effects of low-intensity contractions on subsequent performance have also been excluded from the following sections. Table I summarizes the studies that have investigated the effects of a voluntary CC on subsequent voluntary activity in humans.

In agreement with the results produced by studies conducted on skinned mammalian models, research has consistently reported an enhanced twitch response following a CC in humans. Hamada et al.[12] elicited a twitch reflex at the femoral nerve prior to, 5 seconds after, and then every 30 seconds for 300 seconds after a 10-second isometric MVC of the knee extensors. Twitch P_t (peak torque) was significantly increased 5 seconds after the isometric MVC (+71%; $p < 0.01$); however, by 30 and 60 seconds after the isometric MVC, twitch P_t potentiation had decreased to +44% and +31%, respectively ($p < 0.01$). Potentiation continued to decrease at a more gradual rate for the remainder of the recovery period, but was still +12% 300 seconds after the isometric MVC ($p < 0.01$). Similar findings have been reported in other studies,[6,11,59] demonstrating that peak PAP is achieved immediately after a CC, but instantly begins to decrease. The decrease in PAP is rapid for the first minute, but then becomes more gradual resembling an exponential function (figure 7).

Although an isometric MVC has been found to consistently enhance subsequent twitch tension, evidence to show that PAP can be effectively utilized to enhance the performance of subsequent voluntary contractions is not as convincing. Gossen and Sale[11] assessed movement mechanics of both twitch and submaximal voluntary contractions following a 10-second isometric MVC. While the MVC enhanced twitch P_t ($p < 0.01$), knee extension peak velocity following the MVC was significantly lower than knee extension peak velocity executed in a control condition (326.7 vs 341.6°/sec; $p < 0.03$). These results suggest that although the 10-second MVC induced PAP, it also induced fatigue, and that the latter was more dominant during the voluntary contractions. It has been proposed, therefore, that it is the balance between PAP and fatigue that determines whether the subsequent

Table I. A summary of studies that have investigated the effects of a pre-conditioning contraction on a subsequent activity

Study	Subjects	Pre-conditioning contraction (condition)	Volume	Rest interval	Performance test	Performance changes
Batista et al.[47]	10 UT M	Isovelocity MVC, knee extension	10 (30 sec RI)	4 min 6 min 8 min 10 min	Isovelocity knee extensions at all rest intervals	6% ↑ P_t* at each rest interval
Behm et al.[34]	9 UT M	Isometric MVC, knee extension	1×10 sec 2×10 sec (1 min RI) 3×10 sec (1 min RI)	1, 5, 10, 15 min for all volumes	Isometric MVC knee extensions at all rest intervals	↔ ↔ 10-min post: 8.9% ↓ P_f* 15-min post: 7.5% ↓ P_f *
Chatzopoulos et al.[48]	15 UT M	Back-squat	10×1 rep 90% 1 RM (3 min RI)	3 min 5 min	30-m sprint 30-m sprint	↔ 3% ↓ 0–10-m sprint time*, 2% ↓ 0–30-m sprint time*
Chiu et al.[20]	24; 7 RT, 17 UT (12 M, 12 F)	Back-squat	90% 1 RM×5 (2 min RI)	5 min 6 min 7 min 5 min 6 min 7 min	CMJ: 30% 1 RM 50% 1 RM 70% 1 RM SJ: 30% 1 RM 50% 1 RM 70% 1 RM	RT: 1–3% ↑, UT: 1–4% ↓. RT > UT* RT: 1–3% ↑, UT: 1–4% ↓. RT > UT* RT: 1–3% ↑, UT: 1–4% ↓. RT = UT RT: 1–3% ↑, UT: 1–4% ↓. RT > UT* RT: 1–3% ↑, UT: 1–4% ↓. RT = UT RT: 1–3% ↑, UT: 1–4% ↓. RT = UT
Ebben et al.[49]	10 RT M	Dynamic bench-press	3–5 RM	0–5 sec	Medicine ball BPT	↔ GRF
French et al.[50]	14 RT (10 M, 4 F)	Isometric MVC, knee extension	3 sec×3 (3 min RI) 5 sec×3 (3 min RI)	0–5 sec	CMJ DJ 5 sec C-sprint Isovelocity KE CMJ DJ 5 sec C-sprint isovelocity KE	↔ 5.0% ↑ * (4.9% ↑ GRF*) ↔ 6.1% ↑ P_t * ↔ ↔ ↔ 3.0% ↓ P_t *
Gilbert et al.[51]	7 RT M	Back-squat	100% 1 RM×5 (5 min RI)	2 min 10 min 15 min 20 min 30 min	Isometric MVC at all rest intervals	5.8% ↓ RFD 5.8% ↓ RFD 10.0% ↑ RFD 13.0% ↑ RFD* ↔
Gossen and Sale[11]	10 UT (6 M, 4 F)	Isometric MVC, knee extension	10 sec	20 sec 40 sec	Dynamic KE Dynamic KE	↔ ↔

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Table I. Contd

Study	Subjects	Pre-conditioning contraction (condition)	Volume	Rest interval	Performance test	Performance changes
Gourgoulis et al.[15]	20 M (11 RT, 9 UT)	Back-squats	2 reps of: 20%, 40%, 60%, 80%, and 90% 1RM (5 min RI)	0–5 sec	CMJ	2.4% ↑ RT + UT* RT: 4.0% ↑ UT: 0.4% ↑
Gullich and Schmidtbleicher[10]	Study 1: 34 RT (22 M, 12 F) Study 2: 8 RT	Isometric MVC, leg press Isometric MVC, plantarflexion	3×5 sec (5 min RI) 5×5 (1 min RI)	3 min, then every 20 sec. 8 jumps measured 1 min, then every 2nd min for 13 min	CMJ and DJ Isometric MVC, plantarflexion	3.3% ↑ CMJ*. ↑ DJ* 13% ↓ RFD 1 min post*. RFD 3 min post. 19% ↑ RFD 5–13 min post*
Hanson et al.[52]	30 UT (24 M, 6 F)	Back-squats	4 reps of 80% 1 RM	5 min	CMJ	↔
Jenson and Ebben[53]	21 RT (11 M, 10 F)	Back-squats	5 RM	10 sec 1 min 2 min 3 min 4 min	CMJ CMJ CMJ CMJ CMJ	4–13% ↓* ↔ ↔ ↔ ↔
Kilduff et al.[54]	23 RT M	Dynamic back-squats Dynamic bench-press	1×3RM 1×3 RM	15 sec 4 min 8 min 12 min 16 min 20 min 15 sec 4 min 8 min 12 min 16 min 20 min	CMJ CMJ CMJ CMJ CMJ CMJ Barbell BPT Barbell BPT Barbell BPT Barbell BPT Barbell BPT Barbell BPT	2.9% ↓ P_p* ↔ 6.8% ↑ P_p* 8.0% ↑ P_p * ↔ ↔ 4.7% ↓ P_p * ↔ 2.8% ↑ P_p* 5.3% ↑ P_p* 0.8% ↑ P_p*
Magnus et al.[55]	10 UT M	Back-squats	90% 1 RM	3 min	CMJ	↔
Rahimi[45]	12 RT M	Back-squats	2×4 reps of 80% 1 RM (2 min RI)	4 min	40-m sprint	3% ↓ 0–40 m sprint time*
Rixon et al.[56]	30 UT (15 M, 15 F)	Dynamic back-squats Isometric MVC back-squats	3 RM 3×3 sec (2 min RI)	3 min 3 min	CMJ CMJ	2.9% ↑ JH *, 8.7% ↑ P_p * ↔ JH, 8.0% ↑ P_p *
Robbins and Docherty[57]	16 UT M	Isometric MVC back-squats	3×7 sec (8 min between each set)	4 min	CMJ after each set of isometric MVC	↔
Young et al.[58]	10 UT M	Back-squats	5 RM	4 min	LCMJ	2.8% ↑ *

BPT = bench press throw; **CMJ** = counter movement jump; **C-sprint** = cycle sprint; **DJ** = drop jump; **F** = females; **GRF** = ground reaction force; **JH** = jump height; **KE** = knee extensions; **LCMJ** = loaded counter movement jump; **M** = males; **MVC** = maximum voluntary contractions; $\mathbf{P_f}$ = peak force; $\mathbf{P_p}$ = peak power; $\mathbf{P_t}$ = peak torque; **RFD** = rate of force development; **RI** = rest interval; **RM** = repetition maximum; **RT** = resistance/athletically trained; **SJ** = squat jump; **UT** = un/recreationally trained; ↑ indicates increase; ↓ indicates decrease; ↔ indicates no differences; * $p < 0.05$.

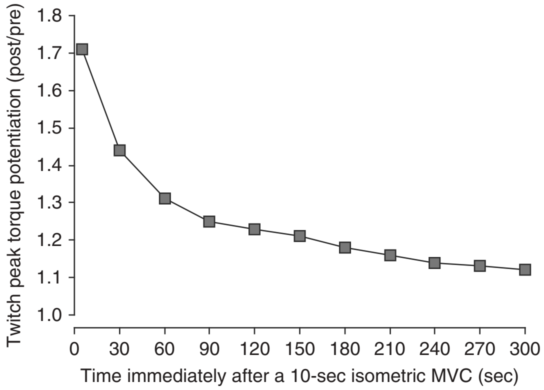

Fig. 7. The time-course of twitch peak torque potentiation immediately after a 10-second isometric maximal voluntary contraction (MVC).[12] Potentiation is represented as a ratio of the post-MVC peak torque value to the pre-MVC peak torque value (post/pre).

contractile response is enhanced, diminished or unchanged.[2]

4.1 PAP versus Fatigue

The balance between PAP and fatigue and its effect on subsequent explosive contractions has been observed by several studies. Immediately after a CC, Gullich and Schmidtbleicher[10] and Gilbert et al.[51] reported a decrease or no change in isometric RFD, but following a sufficient recovery (4.5–12.5 minutes[10] and 15 minutes[51]) isometric RFD was significantly increased (+10–24%; $p<0.05$). The same pattern of no change/decrease followed by an increase in counter-movement jump (CMJ) peak power (+7–8%; $p<0.05$)[54] and 30-m sprint performance (2–3%; $p<0.05$)[48] 8–12 minutes and 5 minutes, respectively, following a CC have also been reported. Collectively, these results suggest that although twitch studies have reported maximal PAP immediately after a CC (described in section 4; see figure 7), fatigue is also present early on. Furthermore, fatigue seems more dominant in the early stages of recovery and, consequently, performance of subsequent voluntary activity is diminished or unchanged. However, fatigue subsides at a faster rate than PAP, and potentiation of performance can be realized at some point during the recovery period. Figure 8 illustrates the PAP-fatigue relationship and shows how the net affect on subsequent voluntary contractions might be very different to the effect of a MVC on subsequent twitch contractions (represented in figure 7).

There is also evidence that a recovery period may not be required to benefit from PAP, or that even with a recovery period performance of a subsequent voluntary activity may remain unchanged/diminished. French et al.[50] did not utilize a recovery period, but still observed a significant increase in both drop jump (DJ) height and isovelocity knee extension P_t (+5.0% and +6.1%, respectively; $p<0.05$), immediately after three sets of 3-second isometric MVC knee extensions. Likewise, Gourgoulis et al.,[15] reported a significant increase in CMJ height (+2.4%; $p<0.05$) immediately after two back-squats performed with 90% of one repetition maximum (1RM). Conversely, Chiu et al.[20] were unable to detect a significant improvement in peak power of three CMJs or three loaded squat jumps (SJ) [$p>0.05$], even though they were performed after a recovery period of 5, 6 and 7 minutes, respectively, following five sets of one back-squat, with 90% 1RM. The three CMJs (5, 6 and 7 minutes post-activation), were executed with different

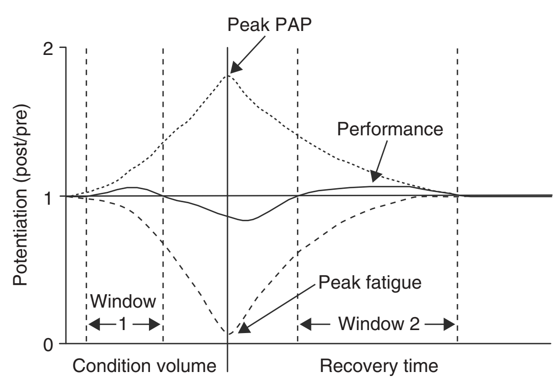

Fig. 8. A model of the hypothetical relationship between post-activation potentiation (PAP) and fatigue following a pre-conditioning contraction protocol (condition).[3] When the condition volume is low, PAP is more dominant than fatigue, and a potentiation in subsequent explosive performance (post/pre) can be realized immediately (window 1). As the condition volume increases, fatigue becomes dominant, negatively affecting subsequent performance. Following the condition, fatigue dissipates at a faster rate than PAP, and a potentiation of subsequent explosive performance can be realized at some point during the recovery period (window 2).

loads (30%, 50% and 70% of 1RM, respectively), which may have affected peak power output, and makes it difficult to compare differences in performance over the time-course. However, these results were supported by those of Mangus et al.,[55] who reported no change in CMJ height 3 minutes after one back-squat with 90% 1RM. Finally, Behm et al.[34] observed no change in isometric peak force immediately after three 10-second MVCs; however, after a 10- to 15-minute recovery period, maximal force had decreased (7–9%; $p<0.05$). These contradictory findings suggest that the PAP-fatigue relationship and its effects on subsequent voluntary activity are multi-faceted.

In summary, it has been suggested that following a CC an optimal recovery time is required to diminish fatigue and realize PAP; however, evidence is inconsistent in support of this theory. There are a number of possible explanations for the contrasting results produced by the aforementioned studies. The relationship between PAP and fatigue, and the overall effect of contractile history on subsequent performance, is influenced by a combination of factors.[2] These include: volume of the CC (e.g. sets, repetitions and rest interval between numerous sets); intensity of the CC (although there is consensus that maximal-intensity contractions optimize PAP), the type of CC performed (e.g. dynamic or isometric); subject characteristics (e.g. muscular strength, fibre-type distribution, training status or power-strength ratio), and the type of activity performed after the CC.[1,2] Figure 9 illustrates the interaction of these complex factors and the following sections discuss them in more detail.

4.2 Conditioning Contraction Volume

The effect of the CC volume on the interaction between PAP and fatigue is highlighted by one particular study. Hamada et al.[14] used a fatiguing protocol of 16 5-second isometric MVC knee extensions, with each MVC separated by a 3-second rest interval. A twitch response was stimulated at the femoral nerve pre-MVCs, between each MVC, 1 minute after the MVCs, and then every second minute after the MVCs, for 13 minutes. Twitch P_t gradually augmented over the first three MVCs, peaking at a 127% increase from baseline values ($p<0.05$). This demonstrates that PAP was more dominant than fatigue, after the first three MVCs when the MVC volume was small. For the remainder of the fatigue protocol, however, twitch P_t progressively decreased, and by the sixteenth MVC measured 32% below baseline-values ($p<0.05$). This demonstrates that as the volume of MVCs continued to increase, so did the dominance of fatigue. Following the fatigue protocol twitch P_t gradually increased, and exceeded baseline values after 30–120 seconds of recovery (+32%; $p<0.05$). This demonstrates that fatigue dissipated at a faster rate than PAP and, consequently, there was a potentiation in twitch P_t during the recovery

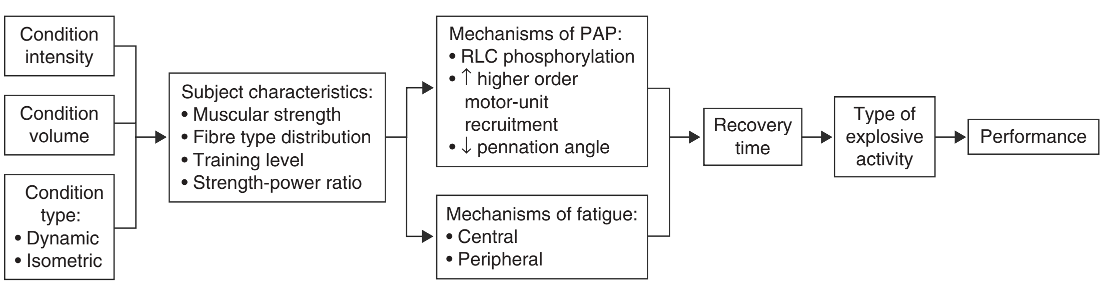

Fig. 9. The complex factors influencing performance of a voluntary explosive activity following a conditioning contraction (condition). Condition intensity, volume and type will affect individuals differently, depending on their subject characteristics. Collectively, these factors will influence the extent to which the mechanisms of post-activation potentiation (PAP) and fatigue are affected. The interaction between the mechanisms of PAP and fatigue will determine whether subsequent performance is potentiated, and the recovery period required to realize potentiation. Regardless of the previous interactions, however, the response of some explosive activities to the condition may be different to the response of other explosive activities. **RLC** = regulatory light chain.

period. An adaptation of these results is presented in figure 10. These findings were supported in another study.[6] They recorded twitch tension in the dorsiflexors before and immediately after five isometric dorsiflexion MVC protocols, where each protocol differed in MVC duration (volume). Accordingly, each protocol induced a different level of PAP, with a 10-second isometric MVC eliciting the greatest potentiation (twitch P_t: after a 1-second MVC = +43%; after a 3-second MVC = +130%; after a 10-second MVC = +142%; after a 30-second MVC = +65%; after a 60-second MVC = +14%). Again, the important question is whether or not a similar effect will occur during performance of voluntary explosive activities?

French et al.[50] assessed the effect of different CC volumes on performance of subsequent voluntary explosive activities. They measured a significant increase in isovelocity knee-extension P_t immediately after three 3-second isometric MVCs (+6.1%; $p < 0.05$), but reported a significant decrease in isokinetic knee-extension P_t immediately after three 5-second isometric MVCs (3%; $p < 0.05$). In contrast, Behm et al.[34] measured isometric MVC peak force after one, two and three sets of 10-second isometric MVCs, and the only effect reported was an 8–9% decrease in peak force 10–15 minutes after three sets of MVCs. As discussed in section 3, PAP is not expected to enhance isometric peak force (which represents maximal force), so Behm et al.[34] may have observed potentiation had they measured voluntary RFD or dynamic performance. Additionally, the smallest CC volume used by Behm et al.[34] (10-second isometric MVC) is arguably larger than the smallest CC volume used by French et al.[50] (three 3-second isometric MVCs separated by 3 minutes), and may therefore have induced a greater degree of fatigue. Furthermore, due to the various other measurements taken by Behm et al.[34] during the recovery period (including high-frequency tetanic contractions, twitches, 30% isometric MVC and ITT), fatigue may have continued to accumulate, thus reducing any opportunity to realize PAP.

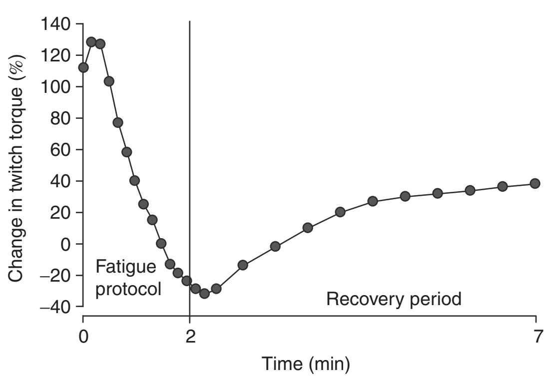

Fig. 10. The time-course of knee extensor twitch torque during a fatigue protocol and throughout a subsequent 5-minute recovery period. The fatigue protocol consisted of 16 5-second MVCs separated by 3 seconds of recovery. A twitch contraction was recorded pre-fatigue protocol, between each MVC, 5 seconds post-fatigue protocol, and then every 30 seconds throughout the recovery period. Twitch torque is given as percentages of pre-fatigue values.[14]

The results of the four aforementioned studies[6,14,34,50] demonstrate the influence of CC volume on the PAP-fatigue relationship. They also present the possibility that PAP develops quicker than fatigue and may therefore be utilized immediately after a relatively low CC volume (window 1 in figure 8). In contrast, as the CC volume increases so does fatigue and its dominance in the PAP-fatigue relationship, and therefore a recovery period may be required before PAP is realized (window 2 in figure 8). The specific recovery period required for different CC volumes is yet to be determined and it is difficult to compare the results of individual studies because methodologies have not been standardized. If future research intends to infer the ideal warm-up and/or training protocol for optimizing PAP, CC volume and recovery between the CC and subsequent activity should be assessed together.

4.3 Conditioning Contraction Type

Although, to varying degrees, any type of contraction is likely to activate the mechanisms of PAP,[4] the degree of potentiation achieved is likely to be related to contraction type. Consequently, the use of different types of CC has probably contributed to the inconsistent results that have already been discussed. As past research has typically used either isometric or dynamic CC, this article will only discuss the differences between these two types of contractions.

Several studies have investigated the effects of isometric MVCs on subsequent explosive activity, and whilst two reported an increase,[10,50] others reported no change in performance.[11,34,57] Past studies have also used dynamic maximal/near maximal voluntary contractions to induce PAP, and again, some recorded potentiation of a subsequent explosive activity[15,45-48,54,58] and others did not.[20,49,52,53,55] These conflicting results (see table I for results) present no clear relationship between contraction type (isometric vs dynamic) and PAP-response, and only one study (to our knowledge) has directly compared isometric and dynamic CC with respect to their effects on performance of a subsequent explosive activity.[56] This study reported that while a significant increase in CMJ height (2.9%; $p < 0.01$) and peak power (8.7%; $p < 0.001$) was observed 3 minutes after three 3-second isometric MVC back-squats, no change in CMJ height ($p > 0.05$) but a significant increase in CMJ peak power (8.0%; $p < 0.001$) was measured 3 minutes after a 3RM dynamic back-squat set. The authors concluded that their isometric condition induced a greater PAP-response than their dynamic condition. The two conditions, however, were not matched with respect to volume or frequency, and as a result, it is difficult to make a direct comparison between their effects.

Theoretically, different types of contraction would have different effects on neuromuscular fatigue.[60,61] Babault et al.[60] assessed neuromuscular fatigue during a dynamic contraction fatiguing protocol and an isometric contraction fatiguing protocol, where the two protocols were matched in terms of P_t decrement. The authors reported that early fatigue during the dynamic protocol was preferentially peripheral in origin (peripheral fatigue defined as a decrease in force generating capacity due to action potential failure, excitation-contraction coupling failure, or impairment of cross-bridge cycling in the presence of unchanged or increased neural drive[61]), while central fatigue (defined as a reduction in neural drive to muscle[61]) developed towards the end of the dynamic fatiguing protocol. The isometric protocol, however, produced the opposite profile, whereby fatigue was firstly central and then peripheral in origin.

Babault et al.[60] proposed that the difference in fatigue development between isometric and concentric contractions might be associated with muscle metabolite accumulation, which is suggested to activate and/or sensitize groups of small diameter (III and IV) afferent neural fibres.[60,62,63] This would in turn cause central fatigue by inhibiting α-motoneuron activation, and/or reducing the supraspinal descending drive,[60,63] and/or decreasing motoneuron firing rate.[64] The intermittent nature of dynamic contractions may favour blood flow, subsequently aiding the removal of metabolic by-products. Accordingly, metabolite accumulation would be greater during isometric contractions, resulting in greater central fatigue. Conversely, lactate accumulation has been reported to alleviate peripheral fatigue.[65] This might account for the slower development of peripheral fatigue during isometric contractions when compared with dynamic contractions.[60]

If isometric and dynamic contractions can induce different fatigue responses, then it is fair to assume that they might also have different effects on the mechanisms of PAP. For example, the eccentric motion of dynamic contractions (but not isometric contractions) increases muscle spindle firing, activating group Ia neural fibres.[63] In turn, this might enhance the afferent neural volley at the spinal cord. Consequently, decreased transmission failure from Ia neural fibres to adjacent α-motor units, resulting in increased higher order motor unit activation during subsequent activity, might be greater after dynamic contractions. On the other hand, isometric contractions activate a greater number of motor units than dynamic contractions.[66] Consequently, more muscle fibres might be involved during an isometric contraction, and this might result in a greater percentage of RLC phosphorylation, and greater changes in muscle architecture.

In summary, preliminary evidence suggests that isometric CCs may induce greater central fatigue, but are more likely to activate the peripheral mechanisms of PAP. In contrast, dynamic

CCs may induce greater peripheral fatigue, but are possibly more likely to activate the central mechanisms of PAP (table II). The manner in which these mechanisms interact has not yet been determined, but it is fair to assume that isometric and dynamic contractions will have different effects on subsequent explosive activities. The differences between isometric and dynamic contractions will also influence the volume and recovery period required to potentiate subsequent explosive activity. Future research should investigate the effects of contraction type on the mechanisms of PAP and fatigue, whilst standardizing CC volume and recovery period. It is also not known whether a CC of any type is more beneficial than conventional warm-up methods,[18] and although one study suggested that it is,[46] their results were specific to the individuals and protocols assessed. Future research should compare the potentiating effects of CC to conventional warm-up techniques.

4.4. Subject Characteristics

The subject characteristics that have been suggested to affect an individual's PAP-fatigue response include muscular strength, fibre-type distribution, training level and power-strength ratio. These factors are discussed in more detail in the following sections.

4.4.1 Muscular Strength

There is evidence to suggest that an individual's muscular strength might partly determine their PAP response following a CC. Gourgoulis et al.[15] observed a 4% increase in CMJ height ($p < 0.05$) following five sets of back-squats in those subjects able to squat a load of >160 kg. Conversely, those subjects unable to squat loads of >160 kg, only recorded a 0.4% increase in CMJ height ($p > 0.05$). Similarly, Kilduff et al.[54] reported a correlation between muscular strength (absolute and relative) and CMJ peak power potentiation 12 minutes after a 3RM back-squat set ($r = 0.63$; $p < 0.01$). A possible explanation for these findings might be associated with subject fibre-type distribution. The positive linear relationship between muscular strength and percentage of type II muscle fibres is well documented ($r = 0.5$–0.93; $p < 0.05$),[67-69] and type II muscle fibres display the greatest increase in RLC phosphorylation following a CC.[7] Furthermore, subjects with a higher percentage of type II muscle fibres would presumably have a greater number of higher order motor units in reserve, which could be activated via decreased transmitter failure, following a CC. The combined effect of a greater RLC phosphorylation and a greater increase in higher-order motor unit recruitment would theoretically predispose individuals with a higher percentage of type II muscle fibres to a greater PAP response. Consequently, it could be speculated that the stronger subjects in the two studies discussed above[15,54] had a higher percentage of fast-twitch muscle fibres, and thus achieved a greater PAP response.

Table II. An illustration of the hypothetical effects of isometric and dynamic conditioning contractions on the central and peripheral mechanisms of post-activation potentiation (PAP) and fatigue

Type of conditioning contraction	The mechanisms of PAP predominantly induced	The mechanisms of fatigue predominantly induced
Isometric	Peripheral	Central
Dynamic	Central	Peripheral

4.4.2 Fibre-Type Distribution

Hamada et al.[14] provided evidence to support a relationship between fibre-type distribution and PAP. They separated their subjects into two groups: one with predominantly fast-twitch (type II) muscle fibres (T-II; $n = 4$), and a second, with predominantly slow-twitch (type I) muscle fibres (T-I; $n = 4$). They reported a greater P_t response in the T-II group during a 3-second isometric MVC (250.0 vs 171.0 $N \cdot m$; $p < 0.01$). Furthermore, in response to a fatigue protocol of 16 5-second isometric MVCs of the knee extensors, the T-II group showed significantly greater twitch tension potentiation during the early stages of the fatigue protocol (+127% vs +40% increase in P_t after the third MVC; $p < 0.05$). However, the T-II group also had a greater decrease in both twitch P_t and MVC P_t during the later stages of the fatigue protocol ($p < 0.05$). Therefore, although subjects with a greater percentage of type II muscle fibres elicited a greater PAP response, they also elicited a greater fatigue response following a high-volume CC protocol.

There are a number of possible reasons why Hamada et al.[14] observed a greater fatigue response in the T-II group. As stated, Hamada et al.[14] reported a greater P_t production in the T-II group during the early stages of the fatigue protocol. Therefore, according to the force-fatigue relationship,[70] a greater fatigue response in the T-II group would be expected. Additionally, a negative correlation has been reported between initial glycolytic rate and fatigue during intermittent exercise.[71] The specific task employed by Hamada et al.[14] (16 5-second isometric MVCs, with 3 seconds of rest between MVCs) would rely predominantly on a high anaerobic adenosine triphosphate (ATP) turnover rate, especially in subjects with a higher percentage of type II muscle fibres.[72,73] Therefore, although subjects with a higher percentage of type II muscle fibres are expected to produce a larger MVC P_t, due to a higher initial anaerobic ATP turnover rate, they are also likely to show greater P_t decrements, due to a greater utilization of anaerobic energy stores and the production of metabolites associated with fatigue.[74,75]

4.4.3 Training Level

An individual's training level may also influence PAP and fatigue responses following a CC. Chiu et al.[20] separated a sample of 24 subjects into athletes who were training and participating in a sport at national and/or international level (RT; n = 7), and those who participated in recreational resistance training (UT; n = 17). Five sets of one back-squat with 90% 1RM and 5–7 minutes of subsequent recovery induced a 1–3% increase in CMJ and SJ height in the RT group. In contrast, the UT group reacted to the same condition with a 1–4% decrease in CMJ and SJ height. Chiu et al.[20] suggested that those subjects training at higher levels of resistance would develop fatigue resistance as an adaptation of their intensive training regimens, and were more likely to realize PAP. Chiu et al.,[20] however, did not measure fibre-type distribution, so it is possible that a greater percentage of fast-twitch muscle fibres in the RT group also contributed to the effects observed in this study.

4.4.4 Power-Strength Ratio

There is also evidence to suggest that a subject's power-strength ratio will influence their PAP response to a CC. Schneiker et al.[76] reported a significant negative correlation between power-strength ratio and potentiation of peak power during loaded CMJ, executed 2–4 minutes after one set of 6RM back-squats ($r^2 = 0.65$; $p < 0.05$). Furthermore, when the sample of strength-trained subjects were separated into those with a power-strength ratio of <19 W/kg (group 1) and those with a power-strength ratio of >19 W/kg (group 2), group 1 had a significant negative correlation between power-strength ratio and peak power potentiation ($r^2 = 0.91$; $p < 0.05$). In contrast, group 2 showed no relationship between power-strength ratio and peak power potentiation ($p > 0.05$). These results suggest that those subjects less able to effectively convert their strength into power are more likely to benefit from PAP than those that can. In addition, it appears that there may be a power-strength ratio threshold above which subjects do not benefit from PAP.

In summary, several subject characteristics have been suggested to affect an individual's PAP-fatigue response, and this may partly explain the inconsistencies of past research. Evidence suggests that individuals most likely to benefit from PAP include those with a greater muscular strength, a larger percentage of type two fibres (although fatigue may also be greater in these individuals), a higher level of resistance training, and a smaller power-strength ratio. Further research, however, is required to validate these findings as well as determine the possible effects of other subject characteristics such as muscle and/or lever lengths. For coaches considering the implementation of CC prior to explosive activities (in training or performance), it may be pertinent to first assess each athlete's susceptibility to PAP during the off-season period.

4.5 Type of Subsequent Activity

An additional explanation for the inconsistent results of past research is the different types of subsequent explosive activities used to determine the acute effects of PAP. The types of subsequent explosive activities employed by previous studies have included isometric MVCs,[10,34,51] isolated dynamic contractions (e.g. isovelocity knee extensions),[11,47,50] and compound ballistic activities (e.g. CMJ and DJ).[10,15,46,49,52-58] It is possible that a specific CC will not have the same effect on different explosive activities.

With regard to differences between isometric and dynamic explosive contractions, previous studies have reported moderate to strong correlations between isometric and dynamic RFD ($r = 0.65–0.75$),[77] and moderate to strong correlations between isometric and dynamic peak force ($r = 0.66–0.77$).[77,78] These results indicate a clear relationship between tests measuring isometric and dynamic strength and power. There are, however, a number of differences in the neural and mechanical processes involved in isometric and dynamic activities. For example, the motor unit recruitment and rate coding for an isometric contraction will probably be regulated by the size principle,[79] whereby motor units are recruited in a hierarchical order of small, followed by higher order units. On the other hand, dynamic contractions might display a specific pattern of motor unit recruitment relevant to joint angle and position through the range of motion.[80] Additionally, the eccentric movement involved in dynamic contractions, but not isometric contractions, would result in a greater afferent (group Ia neural fibres) input from muscle spindles.[61,81] As a result, the α-motoneuron activation responses for isometric and dynamic contractions would be different.[82] Furthermore, utilization of elastic strain energy (stretch-shortening cycle), stored in the muscles during an eccentric contraction, provides a significant contribution to overall performance of dynamic movements.[83-85] The stretch-shortening cycle, however, is not utilized during an isometric contraction and, consequently, isometric contractions may not reflect the muscles capabilities for dynamic situations.[82] Finally, PAP is greatest whilst the muscle is shortening[86] and extends to higher stimulation frequencies in concentric when compared with isometric contractions.[22] This suggests that PAP may have a performance-enhancing effect beyond what would be expected based on isometric contractions.

It is also likely that whilst a specific CC might enhance performance of a particular dynamic activity, it might decrease or have no effect on the performance of a different dynamic activity. French et al.[50] analysed isovelocity knee extension, CMJ, DJ and 5-second cycle sprint performance before and immediately after three 3-second MVC knee extensions. They reported significant improvements in DJ height, DJ RFD and knee extension P_t (+5.0%, +9.5% and +6.1%, respectively; $p < 0.05$) after the MVCs, but found no significant effect in any of the other activities ($p > 0.05$). French et al.[50] used time-motion analysis to explain their results. They reported that the DJ and knee extension MVC had a muscle activation period of ≤0.25 seconds. In contrast, the CMJ and 5-second cycle sprint had a muscle activation period of ≥0.25 seconds. Explosive muscle actions have previously been defined as those that have an activation period of ≤0.25 seconds.[77] French et al.[50] therefore concluded that PAP was only effective in tasks defined as explosive muscle actions. The conclusions of French et al.,[50] however, should be interpreted with caution. Some studies have recorded a potentiation effect in CMJ performance, as well as other activities that otherwise might not fall under the above definition of explosive muscle action.[10,15,46,51,54,56,58] In addition, French et al.[50] only measured exercise performance immediately after the CC, and a rest interval may have been needed for a potentiation effect to be realised. Finally, the CC exercise was an isolation exercise targeting the knee extensors alone. The DJ may load the knee extensors to a greater extent than the CMJ and 5-second cycle sprint, which would explain the increase in DJ height/RFD. The CMJ and 5-second cycle sprint, however, may rely on the contribution of various other large muscle groups, which due to the kinematics of the CC, had not been potentiated.

These results therefore highlight the importance of closely matching the kinematics of the CC to those of the subsequent explosive activity. By doing so, an individual is more likely to activate the higher order motor units, phosphorylate the RLC and change the architecture of those muscle fibres specifically associated with the subsequent activity.

The aim of recent research has been to establish the application of PAP to specific explosive sports activities. Explosive sports activities are dynamic in nature so, for the reasons discussed above, isometric responses to a CC should not be used to infer effects of the same CC on subsequent sports activities. If researchers are investigating the application of PAP to a training scenario, the reported effects of a CC on subsequent ballistic activities (e.g. CMJ and DJ) may be useful, as ballistic exercises are used in power-training programmes. On the other hand, whilst PAP may sometimes be effective in enhancing performance of a ballistic exercise, it may not have the same ergogenic effect on performance of a specific explosive sports activity (e.g. sprinting, long jump). If PAP is to be utilized in competition, research must first determine its effects beyond those reported for ballistic training exercises. Two recent studies have shown that PAP can enhance performance of a specific explosive sports activity, reporting a decrease in sprint time (–3% over 10 m,[48] –2% over 30 m,[48] and –3% over 40 m;[45] $p < 0.05$) 4–5 minutes after the execution of near maximal (>80% 1RM) back-squats. Nevertheless, further research is required to establish the application of PAP to many different explosive sports activities. Furthermore, even if PAP is consistently shown to enhance performance of different explosive sports activities, several practical implications would need to be addressed to effectively apply PAP to a competitive scenario (such as the need for possible equipment in the warm-up area and the requirement to compete within the optimal recovery period following activation). As a result of these impracticalities, the application of PAP to performance has been challenged,[18] but with reported increases in performance by >3%, further investigation is warranted.

5. Conclusion

It may be possible to effectively utilize PAP to enhance mechanical power and therefore performance and/or the training stimulus of an explosive sports activity. Evidence over the practical application of PAP to explosive activities is, however, inconclusive. The inconsistent results of past research appear to be due to the complex interaction of several factors that determine the degree to which the different mechanisms of PAP and fatigue are affected. Greater CC volumes and intensities are expected to induce greater levels of both PAP and fatigue. However, the rates at which PAP and fatigue develop and dissipate may differ, resulting in two windows of opportunity to potentiate performance; immediately after a low-volume CC, or after a specific recovery period following a high-volume CC. The type of CC may also have different effects on the mechanisms of PAP and fatigue. For example, isometric MVCs may induce central fatigue, but peripheral PAP, whilst dynamic MVCs may induce the opposite response. The interaction of these different mechanisms would, in turn, determine the optimal CC volume and recovery time required to potentiate (if at all) subsequent performance. Regardless of the above factors, an individual training at a higher level, with a greater muscular strength, a greater fast-twitch fibre distribution and a lower power-strength ratio may be more likely to benefit from PAP than an individual without these characteristics. When interpreting results, consideration should also be given to the specific application of PAP in sport. If the intention is to utilize PAP in competition, only the results of studies reporting the effects of a CC on performance of a specific explosive sports activity should be considered. Although standardization of these various factors provides future research with an extremely arduous task, the results of studies showing 2–10% increases in performance suggests further investigation of PAP may be worthwhile. It may be pertinent, however, for research to first establish how the mechanisms of PAP and fatigue interact under different conditions before applying PAP to sport.

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