

Post-Activation Potentiation

Underlying Physiology and Implications for Motor Performance

Matt Hodgson, David Docherty and Dan Robbins

School of Physical Education, University of Victoria, Victoria, Canada

Contents

Abstract	585
1. Post-Activation Potentiation (PAP): Underlying Physiological Mechanisms	586
1.1 Muscle Twitch Studies	586
1.2 Twitch Potentiation: Relevance to Human Motor Performance	587
1.3 H-Reflex Studies	587
1.4 H-Reflex Potentiation: Relevance to Human Motor Performance	589
1.5 Summary of Findings	590
2. PAP: Applied Movement Studies	590
2.1 Studies Supporting Short-Term Functional Effects	590
2.2 Studies Failing to Support Short-Term Functional Effects	593
2.3 Summary of Findings	593
3. Conclusions and Recommendations	594

Abstract

The response of muscle to volitional or electrically induced stimuli is affected by its contractile history. Fatigue is the most obvious effect of contractile history reflected by the inability of a muscle to generate an expected level of force. However, fatigue can coexist with post-activation potentiation (PAP), which serves to improve muscular performance, especially in endurance exercise and activities involving speed and power. The measured response of muscular performance following some form of contractile activity is the net balance between processes that cause fatigue and the simultaneous processes that result in potentiation. Optimal performance occurs when fatigue has subsided but the potentiated effect still exists. PAP has been demonstrated using electrically induced twitch contractions and attributed to phosphorylation of myosin regulatory light chains, which makes actin and myosin more sensitive to Ca^{2+} . The potentiated state has also been attributed to an increase in α -motoneuron excitability as reflected by changes in the H-reflex. However, the significance of PAP to functional performance has not been well established.

A number of recent studies have applied the principles of PAP to short-term motor performance as well as using it as a rationale for producing long-term neuromuscular changes through complex training. Complex training is a training strategy that involves the execution of a heavy resistance exercise (HRE) prior to performing an explosive movement with similar biomechanical characteristics, referred to as a complex pair. The complex pair is then repeated for a number of sets and postulated that over time will produce long-term changes in the ability of a muscle to generate power. The results of these studies are equivocal at this time and, in fact, no training studies have actually been undertaken. The discrepancies

among the results of the various studies is due in part to differences in methodology and design, with particular reference to the mode and intensity of the HRE, the length of the rest interval within and between the complex pairs, the type of explosive activity, the training history of the participants, and the nature of the dependent variables. In addition, few of the applied studies have actually included measures of twitch response or H-reflex to determine if the muscles of interest are potentiated. There is clearly more research required in order to clarify the functional significance of PAP and, in particular, the efficacy of complex training in producing long-term neuromuscular adaptations.

The response of skeletal muscle to volitional command or electrically induced stimuli is affected by its contractile history. Neuromuscular fatigue, which can briefly be defined as the decrease in force observed after a period of repeated muscle activation,^[1] is the most obvious effect of contractile history. In contrast to fatigue, which serves to impair force production, there is evidence that the contractile history of skeletal muscle may facilitate the volitional production of force – this phenomenon is known as post-activation potentiation (PAP).^[2] Although fatigue and potentiation have opposing effects on force production in skeletal muscle, these two mechanisms can coexist.^[1] Force output following contractile activity reflects the net balance between processes that enhance force development and those that diminish it.^[3] Identification of the possible physiological mechanisms mediating alterations in force production will promote the development of strategies that are effective in optimising such production.

The two most prevalent measures of neuromuscular output used to quantify the effect of previous activation history on subsequent force production have been: (i) muscle twitch force (for a detailed review see Sale^[2]); and (ii) H-reflex amplitude.^[4-9] In addition to examining the mechanisms that may account for PAP, there have been applied movement studies that have investigated the effect of contractile history (induced by means of a maximal or near-maximal preloading exercise) on subsequent dependent measures of mechanical power performance, such as vertical jump height and rate of force development (RFD) in an explosive movement.^[10-20]

The purposes of this article are: (i) to examine the possible physiological mechanisms underlying alterations in force production following volitional

muscle activation; (ii) to review the applied movement studies that have investigated the PAP phenomenon; and (iii) to discuss the functional implications of these findings to human motor performance.

1. Post-Activation Potentiation (PAP): Underlying Physiological Mechanisms

1.1 Muscle Twitch Studies

A twitch is a brief muscle contraction in response to a single presynaptic action potential or a single, synchronised volley of action potentials.^[21] The force of a twitch contraction is increased following: (i) a sustained maximal voluntary contraction (MVC);^[14,22,23] (ii) an evoked tetanic contraction;^[24] or (iii) repeated sub-fusion stimuli.^[25] In addition to enhancing peak twitch force, preceding forms of contractile conditioning (listed above) have also been shown to increase the RFD in a twitch response and decrease its time to peak force.^[2,26] This effect, known commonly as twitch potentiation (TP), is a well established and reproducible phenomenon, although its functional relevance to human motor performance is less clear.

One proposed mechanism of TP is the phosphorylation of myosin regulatory light chains via myosin light chain kinase (MLCK), which theoretically renders actin-myosin interaction more sensitive to Ca²⁺ released from the sarcoplasmic reticulum.^[27] The activated MLCK phosphorylates a specific portion of the S-1 myosin head near its hinge region with the S-2 component. It is suggested that phosphate binding induces a conformational or structural alteration in this portion of the myosin molecule, leading to an increase in the rate by which myosin cross-bridges move from a non-force producing

state to a force producing state.^[26,27] Increased Ca^{2+} sensitivity exerts its greatest effect when myoplasmic Ca^{2+} levels are relatively low, as is the case during twitch and low-frequency tetanic contractions. In contrast, increased Ca^{2+} sensitivity has no observable effect at saturated Ca^{2+} levels, such as those associated with high-frequency tetanic contractions.^[3,28] Thus, with respect to the force-frequency relationship, TP increases the force and RFD of low-frequency tetanic isometric contractions; however, it does not increase peak force of high-frequency tetani, where only the RFD is enhanced.^[3]

With regard to TP induced via voluntary contraction, the magnitude of potentiation is dependent on both the intensity and duration of voluntary effort^[23] and muscle fibre type.^[22,29] The TP in human tibialis anterior (TA) and plantarflexor (PF) muscles following maximal voluntary isometric contractions (MVICs), were found to be maximal after MVICs of approximately 10 seconds in duration; after longer voluntary contractions, the potentiation was partially suppressed by fatigue.^[23] Moreover, it was shown that voluntary contractions that were <75% of MVC produced little or no potentiation. It appears that maximal (vs submaximal) voluntary contractions lasting approximately 10 seconds cause the greatest TP.^[23]

TP has also been found to be greater in fast, type 2 muscle fibres as these fibres demonstrate a greater phosphorylation of myosin regulatory light chains in response to previous contractile conditioning.^[27] In response to tetanic stimuli, the extent of TP was significantly greater in the human gastrocnemius muscle (which exhibits a higher percentage of type 2 fibres) compared with the soleus.^[29] Furthermore, in a recent study examining the correlation between fibre-type distribution and TP in human knee extensor muscles, individuals with shorter twitch contraction times and a higher percentage of type 2 fibres demonstrated greater TP.^[22]

1.2 Twitch Potentiation: Relevance to Human Motor Performance

Attempts to correlate TP with related measures of human performance are limited, and have failed to identify a functional role for this post-activation phenomenon. In a recent study investigating the effect of TP on dynamic knee extension perform-

ance, it was concluded that fatigue produced by the conditioning 10-second MVC suppressed any benefit that could be realised from the induced TP.^[14] More specifically, the authors found that peak velocity and power attained during performance of dynamic knee extensions was not increased 15 seconds post-MVC when TP was still at a high level. It is possible, however, that a longer recovery interval would have minimised the effects of fatigue, allowing the TP mechanism to subsequently enhance dynamic performance.^[14]

Although the application of TP and its mechanism(s) to human performance has yielded indeterminate results, there is evidence to suggest that strength and speed performance can theoretically be affected by TP.^[2] As previously noted, TP has been shown to increase the RFD of isometric force even at high stimulation frequencies >100Hz,^[3,28] analogous to those observed during voluntary ballistic muscle actions.^[30] It is theoretically possible, that TP, through subsequent increased RFD and acceleration, would increase peak velocity and power attained during the performance of dynamic muscle contractions.^[14] However, this hypothesis has yet to be confirmed and further research attempts using strategies to produce TP and its subsequent effects are required.

1.3 H-Reflex Studies

The H-reflex is another measurement tool utilised by researchers to study the effects of contractile history on neuromuscular response. The H-reflex is traditionally defined as a monosynaptic reflex (MSR) induced by an electrical stimulation of Group Ia afferents of the muscle nerve.^[21] Initially viewed as a purely MSR, modification of H-reflex amplitude via oligosynaptic pathways (e.g. Ib inhibitory affects from Golgi tendon organs and large cutaneous afferents) has demonstrated that only the rising edge of the H-reflex waveform is monosynaptic.^[31] Additional evidence indicating H-reflex modulation through mechanisms that influence levels of presynaptic inhibition has further disconfirmed its use as a direct measure of α -motoneuron excitability.^[32] It is also important to note that even though it is frequently employed as an estimate of spinal reflex processing, a number of methodological issues exist that can influence interpretation of the H-

reflex and, in some instances, undermine its validity as a measurement. Thus, rigorous experimental controls must be implemented to safeguard against a multitude of confounding factors that can affect the accurate interpretation of H-reflex measurements (for a detailed list see Zehr^[32]).

In regard to H-reflex modulation following volitional activation, two main effects have been found: (i) post-activation depression (PAD); and (ii) PAP or reflex potentiation (RP). PAD of H-reflexes post-voluntary contraction has been consistently documented.^[4,6,8,33] PAD is presumed to be caused by mechanisms acting at a presynaptic level, most likely related to the phenomenon of a reduced transmitter release from previously activated fibres.^[7] PAD develops immediately upon muscle relaxation and, depending on the nature of the preceding contractile activity, its time course can be relatively brief, lasting 10–60 seconds,^[4,5,33] or can persist for several minutes.^[6,8]

H-reflex potentiation induced via high-frequency electrical stimulation of the Ia afferents of the homonymous muscle, known more commonly as post-tetanic potentiation (PTP), has been previously observed in the human soleus muscle.^[9,34,35] Following tetanical stimulation of the test muscle nerve, RP develops after several seconds and can last anywhere from 1 to 16 minutes depending on the subject and the specific parameters of the tetanic stimulation employed.^[9,34,35] Stimulation frequencies >100Hz are required to produce PTP of the H-reflex in humans,^[9,34,35] whereas lower frequencies of electrical stimulation have been shown to be ineffective in eliciting RP.^[34] The PTP mechanism has been attributed to the effects of a residual elevation in presynaptic Ca^{2+} , which causes a corresponding increase in the probability of neurotransmitter release from the presynaptic membrane terminal.^[36]

H-reflex potentiation post-volitional activation has received considerably less attention than either PAD or PTP. It is theorised that if some attributes of tetanic electrical stimulation, such as the sustained recruitment of high-threshold motor units, are reflected in the volitional conditioning stimulus, the potentiation of the reflex could occur in response to previous voluntary activation.^[8] Studies that have demonstrated this effect are limited.^[6,8] Following a cyclical concentric-eccentric triceps surae exercise

(eight sets of ten repetitions) every subject was found to demonstrate an initial depression of the lateral gastrocnemius (LG) and soleus (SOL) H-reflex immediately post-conditioning.^[8] The duration of this depression lasted 10–60 seconds, which is consistent with previous reports of PAD following volitional activation.^[4,33] After the period of depression, a significant potentiation of H-reflex amplitude of the LG muscle was reported. A non-statistically significant potentiation of the soleus H-reflex was also documented.^[8] It is important to note that while group mean values demonstrated a significant potentiation of H-reflex amplitude, this effect was found in only five of ten subjects. Moreover, the data reported by Trimble and Harp^[8] revealed marked inter-subject variability regarding the time course of PAD and the onset and duration of potentiation. This observation is consistent with previous literature regarding the temporal profiles of H-reflex modulation post-conditioning, regardless of whether the preceding contractile activity was induced via electrical stimulation or volitional activation.^[4,6,9,34]

In a similar study conducted by Güllich and Schmidbleicher,^[6] H-reflex amplitude was measured in the LG and SOL muscles before and after performance of a series of isometric maximum voluntary plantarflexions (five repetitions of a 5-second MVC with a 1-minute recovery interval between contractions). Subjects were differentiated by their level of training status as either elite speed-strength athletes, or untrained physical education students. Consistent with the findings of Trimble and Harp,^[8] the immediate post-conditioning H-wave amplitude was significantly depressed for all subjects. Following the initial depression, H-reflex amplitude was significantly potentiated in the LG muscle of the trained speed-strength athletes, however, this was not the case for the untrained physical education students. This perhaps indicates an adaptation inherent to spinal reflex processing found only in highly trained subjects. Also, in accordance with previous findings,^[4,6,8,9,34] the time course and peaks of PAD and potentiation varied to a great extent between subjects. The approximate time for the onset and period of RP among speed-strength athletes was between 4 and 11 minutes,^[6] which is consistent with the data from Trimble and Harp.^[8] It is important to note, however, that the authors of this study

failed to include a comprehensive methodology with regard to H-reflex measurements. As previously discussed, there are number of methodological issues pertaining to the use of the H-reflex in exercise studies.^[32] In order to accurately interpret modulation of H-wave amplitude across conditions, rigorous controls must be implemented.^[32] For instance, Güllich and Schmidbleicher^[6] failed to indicate their method for establishing stimulus constancy, or whether subjects were exposed to factors associated with sensory feedback related to variable aspects of posture and voluntary movement, which have been shown to induce considerable modulation of H-reflexes in many muscles.^[32] Therefore, any conclusions the authors inferred from their H-reflex data must be approached with caution.

In contrast to the studies cited above, Enoka et al.^[4] reported only H-reflex depression following a 5-second maximal effort plantarflexion. A significant limitation to this study, however, was that the duration of the H-reflex recording period post-conditioning was limited to 1 minute. Although the findings are consistent with the time course of PAD following voluntary activation, the onset of potentiation in the studies previously discussed did not evolve until at least 3 minutes post-activation.^[8] Therefore, had a longer recording period post-conditioning (e.g. 10 minutes) been employed, a potentiating effect may have been observed by Enoka and colleagues.

1.4 H-Reflex Potentiation: Relevance to Human Motor Performance

The theoretical link between a potentiated H-reflex and a corresponding enhancement of volitional force production can be described as follows: H-reflex amplitude is a function of the number and size of the recruited motor units.^[37] Variation of H-wave amplitude relative to a constant stimulation intensity and constant efferent motor response (M-wave), is an indication of some form of synaptic modification occurring in the spinal cord, which can be explained, assuming suitable methodological constraints are in place, by at least three possibilities: (i) alteration in the excitability of the motoneurons; (ii) variation in the amount of neurotransmitter released by the afferent terminals; or (iii) variation in the intrinsic properties of the motoneurons.^[38] Thus, an increase

in reflex amplitude relative to a constant stimulation intensity implies an equivalent increase in synaptic efficacy between Ia afferent terminals and the post-synaptic membranes of the α -motoneurons of the homonymous muscle. Recruitment of MUs by Ia afferent inputs (as in the H-reflex) proceeds in an orderly fashion from smallest to largest according to the size principle.^[32,39] Therefore, if H-reflex amplitude is increased post-conditioning, it is assumed that in accordance with the size principle, the next motor units to be reflexly recruited would be the larger, high-threshold, fast MUs. In addition to muscle cross-sectional area and the proportion of fast-twitch muscle fibres, the effectiveness of voluntary neuromuscular activation (i.e. the ability to activate as many high-threshold fast MUs as possible and have them discharge at a high frequency) is viewed as a main determinant of the maximal RFD and peak force production.^[6] In the presence of a potentiated reflex response following contractile activity, an individual may, in theory, increase the effectiveness of voluntary activation by optimising the reflex contribution to neural drive.

To test this hypothesis, Güllich and Schmidbleicher^[6] had the speed-strength athletes, who demonstrated a significant H-reflex potentiation post-conditioning, complete a second experiment in which they performed explosive isometric plantarflexions both before and at specified time intervals (between 5 seconds and 10 minutes) following the conditioning protocol. Subject positioning was identical to that used for the H-reflex recordings. Consistent with the temporal profile of H-reflex amplitude, subjects had a significantly depressed rate of explosive force development immediately post-conditioning, followed by a gradual return to control values and subsequent significant potentiation of explosive force development, which occurred between 4 and 11 minutes depending on the subject. Through regression analysis, a comparison of the temporal profiles of H-reflex amplitude and explosive isometric force development post-activation revealed a significant Pearson correlation coefficient ($r = 0.97$). These findings led the authors to conclude that a short-term potentiation of explosive force development can be induced via a preceding MVC, and that the increase in force production is related primarily to neuronal factors. Once again, however, due to the

methodological limitations inherent to this study, the above conclusion remains to be adequately confirmed.

1.5 Summary of Findings

With reference to PAP, the existing literature has classically ascribed this phenomenon to physiological events localised within the muscle, such as the phosphorylation of myosin light chains.^[2] However, in lieu of findings regarding H-reflex potentiation following contractile activity, PAP also appears to occur at the spinal level, through an increased synaptic efficacy between Ia afferent terminals and α -motoneurons of the homonymous muscle.^[6,8,9,34,35] It is also possible that PAP is the result of both myogenic and neurogenic mechanisms.^[40] Furthermore, although theoretically possible,^[2] there is no evidence to date that supports a direct functional benefit of twitch potentiation. It would, therefore, appear instructive to establish experimental protocols that provide a valid index of force production with other concurrent measures of neuromuscular output (i.e. twitch force and H-reflex), which may reveal the locus or loci of mechanisms mediating potential alterations in volitional force production post-contractile conditioning.

2. PAP: Applied Movement Studies

The phenomenon of PAP would appear to be well supported by increases in the twitch contractile properties of muscle (TP) and, to a lesser extent, in H-reflex amplitude following some form of premaximal or near-maximal contraction.^[2,6,8] Only two of these studies examining either the twitch characteristics of muscle or the H-reflex also examined the effects on voluntary force generation of muscle, usually by some form of rapid voluntary contraction.^[6,14] Recently, a number of studies have applied the concept of PAP to measures of explosive force production or measures of motor performance.^[10-20] Such studies have generally examined the short-term effects of a heavy preload exercise, either isometric or isoinertial, on subsequent ballistic movements. Many of these studies have been used to examine the concept of 'complex training' that incorporates the principles of PAP in order to induce long-term neuromuscular adaptations, such as an

increase in the RFD of dynamic muscle performance. Complex training involves the execution of a heavy resistance exercise (HRE) prior to performing an explosive movement, such as a plyometric exercise, with similar biomechanical characteristics in the belief that the HRE will induce PAP and consequently increase the performance of the plyometric exercise. When repeated over a training cycle, it is postulated that complex training will produce long-term changes in the ability of the muscle to generate power. An example of a HRE and plyometric exercise often used in short-term studies and complex training programmes would be five repetitions of a back squat followed by 4–6 vertical counter-movement jumps (CMJs), referred to as a complex pair.^[15] It has also been suggested that performing a heavy pre-load exercise to potentiate the muscle may also be beneficial in enhancing short-term performance and possibly could be integrated into the warm-up prior to competition that requires explosive power.^[6]

Although the evidence for PAP has been established using electrically induced twitch contractions and in changes in the H-reflex, the effect on short-term explosive movement would appear equivocal at this time. In addition, despite its current popularity among coaches and athletes, no studies have yet examined the long-term neuromuscular adaptations or performance changes produced by complex training strategies. The remainder of this review will present the studies that have examined the application of the principles of PAP to measures of short-term explosive motor performance often used to investigate the validity of the complex training approach. Only studies that have been published with complete design and methodological descriptions have been included in the review and are summarised in table I.

2.1 Studies Supporting Short-Term Functional Effects

In addition to examining the effects of contractile history on the H-reflex and the RFD of rapid isometric contractions, Güllich and Schmitzleicher^[6] also investigated its effects on explosive dynamic muscular performance. They found that 3–5 repetitions at 90–100% of MVIC contractions in a bench-press position increased the RFD in guided barbell push

Table I. Summary of studies examining the short-term effects of heavy resistance exercise (HRE) on subsequent dynamic muscular performance

Study	No. and sex of subjects	Training status	Pre-load exercise	Dependent measure(s)	Results
Baker ^[10]	16 M	Rugby league players; different playing levels; 1y exp. in CT	6 reps of bench press at 65% 1RM	Highest average PO during 5 reps of concentric-only bench-press throw	4.5% ↑ in post PO
Chiu et al. ^[11]	12 M, 12 F	6mo exp. in squat exercise; M able to squat 1.5 × BW; F 1.0 × BW	5 sets of reps at 90% 1RM; 2 min rest between sets	Percentage potentiation for average and peak power for loaded jumps at 30%, 50% and 70% 1RM squat-loads during RJ and CJ	Initially no sig. effect. When divided into ATH and RT groups found sig. effect for CJ but not RJ for ATH
Duthie et al. ^[12]	11 F	Resistance trained (5 h/wk); hockey and softball players	3 sets of 3RM half-squat load	Mean of 4 reps of loaded (30% 1RM half-squat) squat jumps for jump height, peak power and max. force	Initially no sig. effect. Sig. correlation between absolute strength and peak power and max. force. Divided into high- and low-strength groups. High-strength group showed 2% ↑ in max. force
French et al. ^[13]	10 M, 4 F	Track-and-field athletes with at least 2y resistance exercise exp.	3 × 3 sec MVIC of knee extension or 3 × 5 sec MVICs of knee extension	Max. jump height of 5 CMJ and 5 DJ, GRF, 5-sec cycle sprint; isokinetic knee extension torque at 250°/sec; EMG of VM	3 × 3 sec condition produced 5.03% ↑ in CMJ height; 4.94% ↑ max. force and 9.49% ↑ in acceleration impulse; 6.12% ↑ in knee extension torque. No change in CMJ or 5-sec sprint cycle. No change for 3 × 5 sec MVIC condition or in any EMG activity
Gossen and Sale ^[14]	6 M, 4 F	Moderately active	10-sec MVICs of single knee extension	Dynamic knee extension at 15%, 30%, 45% and 60% of MVIC in random order for peak torque, power, velocity and total work	No sig. difference in any of the values – results failed to support hypothesis
Gourgoulis et al. ^[15]	14 F	Intercollegiate basketball players	5 sets of half-squats with 2 reps at 20%, 40%, 60%, 80% and 90% 1RM	Mean of 2 CMJ on Kistler platform for vertical height and velocity, power output	2.9% ↑ in mean vertical height. Divided into 2 groups (<160kg 1RM squat and >160kg squat). Stronger group ↑ 4.0% compared with 0.42% in less strong group
Gülich and Schmidbleicher ^[6]	45–46 M and F	Speed-strength athletes at national and international level competition	3–5 MVICs in bench-press position; 3–5 MVICs in unilateral leg-press position	Mean of 5 force/time curves for guided barbell pushes; mean of 8 CMJ	↑ in explosive force in upper body; 1.4cm ↑ in CMJ height (no statistics reported)
Hrysomallis and Kidgell ^[16]	12 M	Average of 3.1y resistance training	1 set of 5RM load bench-press	3 max. efforts of explosive push-ups on force platform for impulse, mean RFD, peak force and average force divided by BW	No sig. effect for any of the dependent measures

Continued next page

Table I. Contd

Study	No. and sex of subjects	Training status	Pre-load exercise	Dependent measure(s)	Results
Jensen and Ebbert ^[17]	11 M, 10 F	NCAA athletes involved in anaerobic sports, trained in squats and plyometrics	5RM load	6 reps of single CMJ on force platform for GRF and jump height at different rest intervals following HRE (10 sec, 1, 2, 3 and 4 min)	No sig. effect for any measure in any rest condition even when divided into high- and low-strength groups
Jones and Lees ^[18]	8 F	Experienced in resistance training and plyometrics (able to squat 1.5 × BW)	5 reps at 85% 1RM parallel squats	EMG and kinetic measures during 4 blocks of 6 jumps (3 CMJ; 3 DJ) for GRF, rebound height and power output.	No sig. differences for any measure of EMG or kinetic performance
Scott and Docherty ^[19]	19 M	Physically active and able to squat 1.5 × BW	5RM half-squat load	Mean of 4 CMJ and 4 HJ for 4 testing sessions	No sig. effect for the mean or max. value for CMJ or HJ even after 4 training sessions
Young et al. ^[20]	10 M	1y exp. in half-squat exercise	5RM half-squats	Mean of 5 loaded CMJ (1 set)	1cm ↑ in vertical jump

ATH = athletically trained group; **BW** = bodyweight; **CJ** = concentric-only jump; **CMJ** = counter-movement jumps; **CT** = complex training; **DJ** = drop jumps; **EMG** = electromyogram; **exp.** = experience; **F** = females; **GRF** = ground reaction force; **HJ** = horizontal jumps; **M** = males; **max.** = maximum; **MVIC** = maximal voluntary isometric contraction; **NCAA** = National Collegiate Athletic Association; **PO** = power output; **reps** = repetitions; **RFD** = rate of force development; **RJ** = rebound jump; **RM** = repetition maximum; **RT** = recreationally trained group; **sig.** = significant; **VM** = vastus medialis; ↑ indicates increase.

ups. Performance of 3–5 repetitions at 90–100% 1MVIC in a single leg-press position resulted in a 1.4cm increase in the mean of eight CMJs. A five repetition maximum (5RM) half squat was also found to produce a 1cm increase in the height of one set of loaded CMJs.^[20] More recently, the effects of five sets of half squats with two repetitions at differing loads (20%, 40%, 60%, 80% and 90% 1RM) on subsequent measures of power output during two CMJs were examined.^[15] An overall improvement of 2.39% in mean jump height occurred but the increase failed to attain statistical significance. The group was then divided into two groups based on their 1RM squat performance. A significant 4.0% increase in CMJ height was found for the group that squatted over 160kg, whereas the group with <160kg squat performance failed to demonstrate any enhanced performance. No changes were found in the other dependent measures (vertical velocity and power output) that were included to explain the differences in performance.

Chiu et al.^[11] also used a heavy squat load (90% 1RM) to examine the effects of contractile history on vertical jump performance with a pre-stretch action (rebound jump) and without a pre-stretch component (concentric-only jump). They also used several different loads during the performance jumps (30%, 50% and 70% 1RM squat). The average percentage of potentiation was calculated for average and peak power for each jump. Initial analysis failed to identify any significant effect. The group was then divided into athletically (ATH) and recreationally (RT) trained groups. Significant increases in power output were found for the ATH but only in the concentric-only jump. The results of this study were confounded by the statistical analysis that compared the post test values for both groups. The performance of RT had actually declined 1–4%, reflecting possible fatigue following the pre-load, compared with the ATH, that showed a 1–3% improvement in performance, reflecting a possible small potentiated effect, so the direct effects of potentiation on ATH were not determined.

The effects of a HRE on subsequent upper-body power performance has also been investigated.^[10] Athletes with at least 1 year of complex training served as participants for the study and performed a preload exercise consisting of six repetitions of a

bench press at 65% 1RM. The dependent measure involved five repetitions of an explosive bench-press style throw with an absolute resistance of 50kg in which the highest power output for the concentric phase was recorded. A 4.5% improvement was found for power output.

The practical application of PAP to athletic performance was recently investigated using MVICs and measures of dynamic exercise performance.^[13] Three sets of single maximal-effort knee extensions, using either 3- or 5-second muscle actions, were performed prior to doing vertical jumps, a 5-second cycle sprint, or isokinetic knee extensions. The results indicated a significant improvement in jump height, maximum ground force, acceleration impulse for drop jumps, and an increase in isokinetic torque following the 3-second MVICs but not the 5-second MVICs. In contrast, analysis of the CMJ data indicated no significant difference in mean jump height for any of the experimental conditions. It would appear that PAP is modulated by the volume of the preconditioning isometric stimulus and the measured outcome is dependent on the nature of the subsequent exercise (drop jumps or CMJ).

Duthie et al.^[12] replicated a training paradigm often used in complex training that involved participants performing three sets of a complex pair of exercises. The exercises consisted of a 3RM squat load followed by four repetitions of a loaded CMJ using 30% 1RM squat load. Jump height, peak power, and maximum force for each set of loaded CMJs were recorded. Initially no improvement in performance was found, and in fact there was a decrease in performance. A significant correlation was found between absolute strength and changes in peak power and maximum force. Participants were subsequently divided into two groups based on the median of the predicted 1RM squat load. A 2% increase in maximum force was found for the group identified with greater absolute strength.

2.2 Studies Failing to Support Short-Term Functional Effects

In contrast to studies that have found some enhancement in explosive performance following HRE, a number of studies have not found any functional performance affect. A set of 5RM squats did not produce any significant effect on subsequent

jump height or ground reaction forces as measured on a force plate.^[17] The length of rest interval (10 seconds, 1, 2, 3 and 4 minutes) also failed to affect the ability to elicit any enhanced performance. Furthermore, no significant effect was found when the male and female participants were separated into high- and low-strength groups, despite a 6–8cm increase in mean jump height performance. The effect of five repetitions at 85% 1RM parallel squats on kinetic measures (ground reaction force and power output) and electromyogram (EMG) recordings during six jumps (three CMJs and three drop jumps) were investigated by Jones and Lees.^[18] Small differences were found in the kinetic measures as well as EMG output, but again failed to attain statistical significance. The authors concluded their results did not support the hypothesis that HRE increases neural activation. The effects of a 5RM squat on CMJ and horizontal jumps has also been examined over four subsequent training sessions.^[19] No enhanced performance effect was found for either CMJ or horizontal jumps despite the repeated exposure to the loading protocols. Additionally, in contrast to the findings of Baker,^[10] one set of 5RM bench-press load failed to invoke any improved performance in explosive push ups performed on a force platform^[16] as reflected by measures of impulse, RFD, relative peak and average force.

2.3 Summary of Findings

Presently, the literature is equivocal regarding the short-term effects of HRE on subsequent performance of activities requiring explosive force. It is difficult to compare the studies because of differences in methodology and design, with particular reference to the mode and intensity of the HRE, the length of the rest interval within and between the 'complex pairs', the type of explosive movement, and the nature of the dependent measures. It is clear that fatigue and potentiation can co-exist^[1] and there is probably an optimal time when the muscle has recovered but is still potentiated. However, the optimal recovery time appears to be variable among individuals^[6] and possibly masks any potentiated effect in group design studies. It would also appear some individuals respond better than others in regard to being able to benefit from a heavy pre-load activity.^[8] It may be that the individuals that are

better able to utilise the PAP effect are stronger compared with their peers.^[12,20] However, these studies have been retrospective and the effect of strength on PAP needs to be established through longitudinal studies that increase strength and then determine its effects on subsequent PAP. It is possible the stronger individuals are better able to benefit from PAP because they may possess a greater proportion of type 2 fibres compared with their less strong peers. Individuals that were identified as the highest PAP responders were found to have a higher percentage of type 2 fibres and greater type 2 fibre area than a group identified as the lowest PAP responders as reflected by the twitch contractile studies.^[22] However, the relationship between fibre type and the ability to utilise potentiation for subsequent explosive movement has not yet been established. The studies that have clearly demonstrated PAP have used electrically stimulated twitch contractile characteristics or an electrically evoked H-reflex. It is possible that the effects of PAP are more easily elicited using electrical stimulation compared with voluntary muscular actions and are less likely to induce a direct functional benefit.

3. Conclusions and Recommendations

Only two studies have included concurrent measures of neuromuscular output when examining the effects of contractile history on subsequent explosive muscular performance.^[6,14] Other short-term studies have simply assumed that the muscle was in fact potentiated and, therefore, should produce enhanced performance. It would seem beneficial to include measures of neuromuscular output (e.g. twitch force and H-reflex) with performance measures to ensure some form of potentiation has in fact occurred, and in order to localise the underlying physiology of PAP.

Most short-term studies examining the effects of HRE on subsequent explosive movements have been conducted with the intent to support or refute the efficacy of complex training protocols. There is an absence of studies that have actually investigated the efficacy of complex training on long-term neuromuscular adaptations or performance. The short-term studies are equivocal in their support of the short-term response implied in complex training protocols. Even if support was unequivocal, it re-

mains to be determined whether the magnitude of the effect would be sufficient to produce long-term changes in performance, especially when compared with other HRE and plyometric training protocols. Finally, most coaches and athletes train to enhance performance in selected sports or athletic events that involve numerous complex movement patterns. Should complex training be found to be an effective training strategy for improving explosive power in selected movements, the actual transfer to enhancing performance in the actual sport or athletic event would still need to be established.

It is clear from this review that PAP can be elicited following some form of maximal or near maximal contractile history but its functional application to motor performance and training can only be determined through continued research.

Acknowledgements

No sources of funding were used to assist in the preparation of this review. The authors have no conflicts of interest that are directly relevant to the content of this review.

References

1. Rassier DE, MacIntosh BR. Coexistence of potentiation and fatigue in skeletal muscle. *Braz J Med Biol Res* 2000; 33 (5): 499-508
2. Sale DG. Postactivation potentiation: role in human performance. *Exerc Sport Sci Rev* 2002; 30 (3): 138-43
3. Vandenberg R, Grange RW, Houston ME. Threshold for force potentiation associated with skeletal myosin phosphorylation. *Am J Physiol* 1993; 265 (6 Pt 1): C1456-62
4. Enoka RM, Hutton RS, Eldred E. Changes in excitability of tendon tap and Hoffmann reflexes following voluntary contractions. *Electroencephalogr Clin Neurophysiol* 1980; 48 (6): 664-72
5. Gollhofer A, Schopp A, Rapp W, et al. Changes in reflex excitability following isometric contraction in humans. *Eur J Appl Physiol Occup Physiol* 1998; 77 (1-2): 89-97
6. Gülllich A, Schmidtbleicher D. MVC-induced short-term potentiation of explosive force. *N Stud Athlet* 1996; 11 (4): 67-81
7. Hultborn H, Illert M, Nielsen J, et al. On the mechanism of the post-activation depression of the H-reflex in human subjects. *Exp Brain Res* 1996; 108 (3): 450-62
8. Trimble MH, Harp SS. Postexercise potentiation of the H-reflex in humans. *Med Sci Sports Exerc* 1998; 30 (6): 933-41
9. van Bostel A. Differential effects of low-frequency depression, vibration-induced inhibition, and posttetanic potentiation on H-reflexes and tendon jerks in the human soleus muscle. *J Neurophysiol* 1986; 55 (3): 551-68
10. Baker D. The effect of alternating heavy and light resistances on power output during upper-body complex power training. *J Strength Cond Res* 2003; 17 (3): 493-7
11. Chiu LZ, Fry AC, Weiss LW, et al. Postactivation potentiation response in athletic and recreationally trained individuals. *J Strength Cond Res* 2003; 17 (4): 671-7
12. Duthie GM, Young WB, Aitken DA. The acute effects of heavy loads on jump squat performance: an evaluation of the com-

- plex and contrast methods of power development. *J Strength Cond Res* 2002; 16 (4): 530-8
13. 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
 14. Gossen ER, Sale DG. Effect of postactivation potentiation on dynamic knee extension performance. *Eur J Appl Physiol* 2000; 83 (6): 524-30
 15. 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
 16. Hrysomallis C, Kidgell D. Effect of heavy dynamic resistive exercise on acute upper-body power. *J Strength Cond Res* 2001; 15 (4): 426-30
 17. 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
 18. 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
 19. Scott S, Docherty D. Acute effects of heavy pre-loading on vertical and horizontal jump performance. *J Strength Cond Res* 2004 May; 18 (2): 201-5
 20. Young WB, Jenner A, Griffiths K. Acute enhancement of power performance from heavy load squats. *J Strength Cond Res* 1998; 12 (2): 82-8
 21. Latash ML. Neurophysiological basis of movement. Champaign (IL): Human Kinetics, 1998
 22. 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
 23. Vandervoort AA, Quinlan J, McComas AJ. Twitch potentiation after voluntary contraction. *Exp Neurol* 1983; 81 (1): 141-52
 24. O'Leary DD, Hope K, Sale DG. Posttetanic potentiation of human dorsiflexors. *J Appl Physiol* 1997; 83 (6): 2131-8
 25. MacIntosh BR, Willis JC. Force-frequency relationship and potentiation in mammalian skeletal muscle. *J Appl Physiol* 2000; 88 (6): 2088-96
 26. Grange RW, Vandenboom R, Houston ME. Physiological significance of myosin phosphorylation in skeletal muscle. *Can J Appl Physiol* 1993; 18 (3): 229-42
 27. Sweeney HL, Bowman BF, Stull JT. Myosin light chain phosphorylation in vertebrate striated muscle: regulation and function. *Am J Physiol* 1993; 264 (5 Pt 1): C1085-95
 28. Abbate F, Sargeant AJ, Verdijk PW, et al. Effects of high-frequency initial pulses and posttetanic potentiation on power output of skeletal muscle. *J Appl Physiol* 2000; 88 (1): 35-40
 29. Vandervoort AA, McComas AJ. A comparison of the contractile properties of the human gastrocnemius and soleus muscles. *Eur J Appl Physiol Occup Physiol* 1983; 51 (3): 435-40
 30. van Cutsem M, Duchateau J, Hainaut K. Changes in single motor unit behaviour contribute to the increase in contraction speed after dynamic training in humans. *J Physiol* 1998; 513 (Pt 1): 295-305
 31. Burke D, Gandevia SC, McKeon B. Monosynaptic and oligosynaptic contributions to human ankle jerk and H-reflex. *J Neurophysiol* 1984; 52 (3): 435-48
 32. Zehr PE. Considerations for use of the Hoffmann reflex in exercise studies. *Eur J Appl Physiol* 2002; 86 (6): 455-68
 33. Crone C, Nielsen J. Methodological implications of the post activation depression of the soleus H-reflex in man. *Exp Brain Res* 1989; 78 (1): 28-32
 34. Corrie WS, Hardin WB. Post-tetanic potentiation of H reflex in man; quantitative study. *Arch Neurol* 1964; 11: 317-23
 35. Kitago T, Mazzocchio R, Liuzzi G, et al. Modulation of H-reflex excitability by tetanic stimulation. *Clin Neurophysiol* 2004 Apr; 115 (4): 858-61
 36. Zucker RS, Regehr WG. Short-term synaptic plasticity. *Annu Rev Physiol* 2002; 64: 355-405
 37. Hugon M. Methodology of the Hoffmann reflex in man. In: Desmedt JE, editor. *New developments in electromyography and clinical neurophysiology*. Basel: Karger, 1973, 3277-93
 38. Misiaszek JE. The H-reflex as a tool in neurophysiology: its limitations and uses in understanding nervous system function. *Muscle Nerve* 2003; 28 (2): 144-60
 39. Henneman E, Somjen G, Carpenter DO. Excitability and inhibibility of motoneurons of different sizes. *J Neurophysiol* 1965; 28 (3): 599-620
 40. Tubman LA, MacIntosh BR, Maki WA. Myosin light chain phosphorylation and posttetanic potentiation in fatigued skeletal muscle. *Eur J Appl Physiol* 1996; 431: 882-7

Correspondence and offprints: Dr *David Docherty*, School of Physical Education, University of Victoria, Victoria, BC V8W 3P1, Canada.
E-mail: docherty@uvic.ca