Use of loaded conditioning activities to potentiate middle- and long-distance performance: a narrative review and practical applications

Running head: *Potentiation of middle- and long-distance performance*

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ABSTRACT

The warm-up is an integral component of a middle- and long-distance athlete's pre-performance routine. The use of a loaded conditioning activity (LCA), which elicits a post-activation potentiation (PAP) response to acutely enhance explosive power performance, is well-researched. A similar approach incorporated into the warm-up of a middle- or long-distance athlete potentially provides a novel strategy to augment performance. Mechanisms that underpin a PAP response, relating to acute adjustments within the neuromuscular system, should theoretically improve middle- and long-distance performance via improvements in sub-maximal force-generating ability. Attempts to enhance middle- and long-distance related outcomes using a LCA have been used in several recent studies. Results suggest benefits to performance may exist in well-trained middle- and long-distance athletes by including high-intensity resistance training (1-5 repetition maximum) or adding load to the sport skill itself during the latter part of warm-ups. Early stages of performance appear to benefit most, and it is likely that recovery (5-10 min) also plays an important role following a LCA. Future research should consider how priming activity, designed to enhance the $\dot{V}O_2$ kinetic response, and a LCA may interact to affect performance, and how different LCA's might benefit various modes and durations of middle- and long-distance exercise.

Key words: endurance, post-activation potentiation, warm-up, priming, pre-activation

INTRODUCTION

Middle- (2 – 10 min) and long-distance (> 10 min) performance is typically considered to be limited by physiological factors such as maximal oxygen uptake ($\dot{V}O_{2max}$), movement economy and fractional utilization of $\dot{V}O_{2max}$ (14, 62). However neuromuscular factors are also known to contribute (14, 71). To acutely optimize middle- and long-distance performance, it is well-established that an active warm-up should be included in an athlete's preparation routine (10). Research has tended to focus on 'priming' strategies, involving high-intensity intermittent or continuous exercise designed to induce specific cardiovascular and metabolic adjustments, which subsequently augment the oxygen uptake ($\dot{V}O_2$) kinetic response during the early stages of exercise, and thus performance outcomes (4, 18, 19, 50).

Conversely, for athletic performances that require high levels of power production, such as jumps and sprints, a plethora of research has been conducted investigating various preconditioning stimuli designed to potentiate the neuromuscular system, and enhance performance in these tasks (59, 78, 92). Although it is well-established that physiological parameters and performance can benefit following a period of strength training (ST) in middle- and long-distance athletes (6, 9), the possibility of using a loaded conditioning activity (LCA) to acutely enhance middle- and long-distance related outcomes has only been explored recently (5, 21, 79). A LCA involves utilizing a high-intensity resistance exercise or adding load to a movement akin to the sports skill itself, in order to elicit a short-term enhancement in neuromuscular function, known as post-activation potentiation (PAP). The aim of this narrative review is therefore to consider whether a LCA can provide an acute potentiation of middle- and long-distance performance from a theoretical and evidence-based perspective, and provide practical recommendations for coaches.

PRIMING ACTIVITY

Studies have typically shown that a warm-up which includes a bout of high-intensity exercise (60-85% of peak power output) lasting 3-6 min is sufficient to positively influence endurance performance (4, 41, 60). Several studies have also investigated the effects of high-intensity intermittent and single sprint approaches to enhancing performance or the $\dot{V}O_2$ response at the onset of exercise (11, 17, 48, 61, 90). When compared to a continuous warm-up of lower intensity, a priming protocol involving 5 x 10-s near-maximal sprints (50-s recovery) have been shown to enhance kayak 2 min time trial (TT) performance by a small (effect size (ES): 0.2) but statistically significant margin (11). Conversely the same protocol 5-min prior to a 3-km cycle TT had no effect on outcome, and was shown to attenuate performance if sprints were completed maximally (61). Utilizing a longer inter-repetition recovery duration (5-min), and rest period prior to the onset of exercise (15-min), maximal sprints (3 x 30-s) were shown to enhance the amplitude to which $\dot{V}O_2$ rose during peri-maximal-intensity cycle exercise by 11% (90). Similarly, the use of a single high-intensity run (200-m), performed 20-min prior to an 800-m TT, provided a significantly faster time (1.2-s) compared to a control trial, which utilized 6 x 50-m ‘strides’, typical of traditional warm-up for a middle-distance runner (48). Collectively these results demonstrate that a high-intensity bout of priming activity can positively influence $\dot{V}O_2$ kinetics and middle- and long-distance performance, providing the protocol does not lead to excessive fatigue caused by the interaction between exercise intensity and recovery duration.

The mechanisms which underpin an enhancement in $\dot{V}O_2$ kinetics and/or performance as a result of priming activity, are thought to relate to an improvement in the ability to deliver oxygen to active tissues (67) or activation of processes associated with oxidative metabolism (49). It has also been proposed that prior high-intensity exercise necessitates an increase in firing and/or recruitment of higher threshold motor units, which are subsequently accessible at the onset of exercise (49). This may allow a greater number of muscle fibres to share the load imposed by exercise and decrease the demand to recruit further motor units as exercise progresses. This hypothesis is supported by works which show increases in integrated electromyography (iEMG) at the onset of exercise (16) and during the latter half of intense exercise (85) following priming. Interestingly, Burnley and colleagues (16) observed the improvement in $\dot{V}O_2$ kinetics during the primary component closely matched the increase in iEMG which was observed. This evidence indicates that other forms of high-intensity exercise, such as a LCA, which is capable of activating a large pool of motor units (76), may offer an alternative means of enhancing middle- and long-distance performance.

POST-ACTIVATION POTENTIATION

Mechanistically PAP is defined as an increase in a twitch response that follows a brief maximal voluntary contraction (MVC) caused by the phosphorylation of myosin light chains (MLC) (47, 88). Contemporary definitions of PAP encompass a range of different types of muscular contraction and tend to attribute acute improvements in a wide range of athletic performance tasks following a preconditioning stimulus to PAP (59, 92). Moreover, evidence for MLC phosphorylation is somewhat weak in humans, therefore various authors have suggested that other mechanisms may also be responsible for a PAP response, including an increase in motor unit recruitment and changes in limb stiffness (59, 83). These mechanisms have been shown to facilitate a short-term improvement in neuromuscular performance that may also have utility for middle- and long-distance related outcomes.

The efficacy of a PAP inducing stimuli on performance in skills requiring power has been discussed in several recent reviews (38, 59, 92). Ballistic exercise protocols (3-5 repetitions of depth jumps, weighted jumps and weightlifting derivatives) and heavy resistance exercise (> 85% one repetition maximum (RM) or 3-RM) have consistently been shown to enhance (2-5%) vertical jump, sprint performance (≤ 100-m), repeated sprint ability and change of direction speed following a recovery duration of 5-10 min recovery. The effect of a PAP protocol on middle- and long-distance related outcomes has received far less attention. Given the paucity of literature, an examination of the mechanisms that underpin a PAP response could provide clues as to whether a benefit could exist.

Phosphorylation of myosin light chains

Although PAP can be elicited in both type I and type II fibres, athletes with a higher percentage of type II fibres, and therefore greater MLC, tend to experience higher levels of potentiation (88). Studies that have demonstrated positive outcomes from a LCA on explosive performance tasks have typically used athletes from intermittent high-intensity sports and/or participants with a background in strength-training (59, 78). Furthermore, there appears to be a clear link between strength status and the amplitude of a potentiation response (20, 37). This suggests that athletes who excel in endurance-based sports, who typically possess a high proportion of type I fibres (24), might be expected to elicit a lower PAP response compared to strength-trained athletes. Despite this supposition, endurance-trained athletes are capable of eliciting a greater twitch potentiation response compared to untrained individuals following a MVC (42). Endurance training has also been shown to enhance shortening velocity of type I fibres (30, 77), with a concomitant increase in MLC (77). This adaptation in the trained muscles of endurance-trained athletes has been attributed to an increased capacity for MLC phosphorylation, which therefore increases the potential of eliciting a PAP response (42).

Following a peri-maximal voluntary contraction, fatigue and potentiation can coexist within a muscle (58), with the magnitude of both a consequence of the nature of the contraction and the characteristics of the individual. Due to a superior resistance to fatigue in endurance-trained athletes, potentiation effects have also been shown to prevail for longer during an intermittent fatiguing task, compared to power-trained athletes (66). Potentially therefore, despite possessing a relatively low percentage of type II fibres (and thus MLC), middle- and long-distance athletes could have the capability to amplify a PAP response in trained muscles, which may also be sufficiently long-lasting to benefit performance. In addition, it is also recognised that a PAP state provides the largest benefits during dynamic activities requiring low frequency force outputs (39, 87). These frequencies approximate the firing rates required to sustain repeated submaximal contractions (25, 42), which implies PAP could potentially be used to augment middle- and long-distance performance.

Motor unit recruitment

A LCA such as an MVC or a series of explosive dynamic contractions, require the activation of high threshold motor units (76). During such contractions, high frequency electrical impulses provide the input required to release large quantities of neurotransmitter at the neuromuscular junction, thus ensuring the activation of large motor units. Additionally, during a conditioning activity where a muscle is stretched rapidly, such as a plyometric exercise, Ia afferent fibres respond via the muscle spindle apparatus by transmitting high frequency impulses to the spinal cord (51). This elicits a stretch reflex response whereby for each parent

Ia fibre, multiple synapses project action potentials to adjacent efferent α-motoneurons (1). This in turn elevates output from the motoneuron pool, which can be detected as the second response to an artificially evoked contraction on an electromyography trace, known as H-wave (1). It has been shown that an induced tetanic contraction is capable of acutely elevating the transmittance of excitation potentials via the Ia afferent at the spinal cord and reduces the threshold for activation in higher order motor units (45, 57). This potentially allows a greater level of force to be developed for the same electrical input during activities that have a high reliance on the stretch-shortening cycle. Moreover, an increase in H-wave amplitude has been observed following MVCs in the plantarflexors (40, 86) and knee extensors (34) during the 5-11 minute period post-LCA. Although the evidence for enhanced motor unit recruitment following a LCA is mainly derived from studies in animal models or using artificial stimulation, it is possible that PAP could exert a beneficial effect during dynamic activities of various durations via this mechanism (75, 83).

It is well-established that during sub-maximal exercise, both PAP and fatigue are present within the muscle, and consequently PAP is thought to provide a mechanism to counteract the effects of peripheral fatigue during prolonged exercise (13, 73). When this effect becomes depressed during the latter stages of exercise due to impaired excitation-contraction coupling, it has been postulated that an augmentation of the PAP response may enable force to be maintained for longer (39, 72). Similarly, as middle- and long-distance events require relatively low motor unit firing frequencies, even a small enhancement in the force delivered by the motor units should improve performance (75). Moreover, for a given intensity of sub-maximal exercise, a state of potentiation, which provides a more accessible pool of motoneurons, should result in motor units decreasing their firing frequency, thus delaying the onset of fatigue (42, 75). A reduction in motor unit firing frequency has been shown during the early part of sustained isometric contractions without any compensatory activation of other motor units (25). It was suggested that a PAP response may partly explain this finding (25).

Stiffness

Stiffness refers to the ability of a body, limb or joint to resist the application of a force (15). An increase in musculotendinous stiffness would theoretically reduce energy cost of exercise, as a stiffer structure enables muscles to achieve quasi-isometric states more rapidly. This in turn influences both the magnitude and rate of shortening velocity in muscle fascicles reducing the amount of muscular work performed (32, 33). Improved musculotendinous stiffness also enables a greater contribution of mechanical work to be derived from storage and return of elastic strain energy in the Achilles tendon (74). A relationship between musculotendinous stiffness and running economy has previously been reported (2, 28), and increases in tendon stiffness following a period of heavy resistance training have been shown to correlate (r^2 = 0.43, p=0.02) with improvements in running economy (31). Moreover, as running speed increases, tendon elastic strain energy provides a greater contribution to the work performed by the muscle-tendon unit at the ankle plantar-flexors (54), Therefore it is likely that for a well-trained middle-distance runner who operates at relatively high speeds, an enhancement in this quality would improve performance.

Higher stiffness is also related to greater concentric-dominant muscular capacity (91), which may be relevant for sports such as cycling, cross-country skiing, and swimming. Indeed, higher levels of musculotendinous stiffness have been shown to correlate with cycling speed (89), and double poling velocity in cross-country skiing (56), thus an acute improvement in this physiological attribute may provide a mechanism to enhance performance for middle- and long-distance athletes. It has also been suggested that an acute enhancement in limb stiffness may offer an additional explanation for the improvements observed in explosive activities following a LCA (59).

Following a LCA used to induce PAP, both the muscular properties and the tensile mechanisms of a musculotendinous unit are likely to be affected (35). A previous review concluded that there was moderate evidence for decreased Achilles tendon stiffness (measured via ultrasound) after MVC, however activities involving a stretch-shortening cycle (SSC), such as running and hopping, have minimal effect (69). A subsequent investigation observed a PAP response without alteration in tendon stiffness following a single 6-s MVC (35), demonstrating fatigue may be an important factor modulating short-term changes in stiffness. It seems therefore that the direction and extent of alterations in stiffness following a LCA are influenced by the mode and dosage of exercise employed (69). Tendons in particular appear to be more resistant to fatigue during conditioning activities that utilize the SSC. This has implications when examining the efficacy of such strategies upon middle- and long-distance disciplines that rely heavily upon musculotendinous stiffness.

Assessing changes in tendon structures provides one perspective on stiffness, however changes in vertical or limb stiffness may be the consequence of morphological alterations in other tissues or segments. Leg stiffness and ground contact time during a drop jump task performed on a sledge was shown to be positively affected following a set of back squats at 93% of 1RM in elite rugby players (22). Similarly, Moir et al. (65) found improvements in vertical stiffness during a counter-movement jump following three back squat repetitions at 90% 1RM in female volleyball players. In contrast to the aforementioned studies, these results indicate that a LCA may provide a suitable stimulus to acutely enhance leg and vertical stiffness during activities that require the SSC, such as distance running. Moreover, leg stiffness has been shown to decrease with fatigue in runners (44), therefore an increase in stiffness at the onset of exercise may offset this reduction.

EXPERIMENTAL EVIDENCE

The foregoing discussion suggests that the inclusion of a LCA within the warm-up routine of middle- and long-distance athletes could augment subsequent performance outcomes. Only four studies have attempted to examine this conjecture experimentally (Table 1), yielding mixed results. Two studies have investigated the effect of heavy resistance exercise on middle- (29) and long-distance (79) performance. Silva and colleagues (79) found an improvement (-6.1%, p=0.02, ES=0.38) in 20-km TT performance in well-trained cyclists following 4-sets of 5-RM on a leg press. The authors attributed the improvement to an increase (5.8%) in mean power during the first 2-km of the test, as little difference was observed across other split times. Similarly, Feros and co-workers (29) utilized 5 x 5-s isometric contractions on a rowing ergometer to successfully enhance the first 500-m of a 1-km TT performance in elite international rowers (-1.9%, p=0.009, ES=0.62), however an improvement in 1-km TT performance was not noted compared to the control trial. Both studies found no change in perceived exertion between trials, which is thought to regulate effort during endurance performance (80). This suggests that potentiation in the neuromuscular system allowed a greater amount of power to be developed during the first few minutes of exercise for the same level of effort. It therefore appears that a LCA could be beneficial for the early stages of a middle- or long-distance TT effort, however it is unclear whether potentiating starting speed facilitates an improvement in overall performance.

Table 1 about here

Barnes et al. (5) used six sprints wearing a weighted vest (20% body mass) to achieve beneficial effects to running economy (-6.0%, ES=1.40) and peak running speed (2.9%, ES=0.35) in a group of well-trained distance runners. The authors observed a very high correlation (r=-0.88) between changes in peak speed and changes in leg stiffness. Evidence for individual responses to the LCA were also present. The acute improvements achieved in running economy in this study are of a similar magnitude to those achieved following a 8-14 week explosive ST intervention (8, 64, 71), and are likely to be sufficient to provide a performance benefit (46). Recently, Chorley and Lamb (21) used a similar protocol in a group of highly-trained cyclists. Prior to a 4-km time-trial, participants performed three 10-s loaded sprints (70% peak power output) at a low cadence (60-rpm). The results showed a small (ES=0.2-0.3) and non-significant (p>0.05) change in completion times, mean power output and mean peak force, however the authors suggested that the improvements were meaningful in the context of smallest worthwhile effect values (21). A statistically significant increase in $\dot{V}O_2$ during the first 1.5-km (6.8%, ES=0.97) perhaps indicates an enhancement in rate adjustment of the oxidative system, or again, a potentiation effect benefited the initial stages of exercise.

PRACTICAL APPLICATIONS AND MODULATING FACTORS

A PAP response is modulated by a number of variables that each require consideration to ensure a performance benefit is optimized. These factors have been reviewed extensively for short-duration athletic performance (59, 78), however recommendations should be examined for appropriateness in the context of middle- and long-distance performance. Based upon the available evidence, Figure 1 provides a suggested warm-up protocol that middle- and long-distance athletes could adopt to enhance their performance. There is convincing evidence that following an initial low intensity warm-up, pre-performance preparation should include a higher intensity priming component (e.g. 3-6 min at 60-85% peak power output) to facilitate the $\dot{V}O_2$ kinetic response during the early stages of exercise (4, 41, 60). Following a 5-10 min passive recovery from this aerobic phase of warm-up, a performance advantage is likely to be gained by including either near maximal intermittent sprints (4-6 x ~10-s) or a LCA designed to elicit a PAP response. Based upon the experimental evidence to date, it is likely that a PAP response will only be realised under a specific set of circumstances.

Figure 1 about here

Participant characteristics

As discussed, type II muscle fibres have a greater affinity for a PAP response (42), thus endurance-trained individuals, who typically possess a low percentage of type II fibres (24, 81), are less likely to benefit from a LCA compared to strength-trained athletes. It is likely therefore, that middle-distance competitors, who possess a more even split of fibre phenotypes (23) might benefit from a warm-up that includes a LCA more-so than a long-distance athlete. It is also possible that older endurance athletes have a lower capacity to generate a PAP response as age-related reductions in muscle mass have been attributed to smaller type II fibre size (68).

As expected, strength-trained athletes tend to exhibit a larger PAP response (ES=0.53) than athletes with no ST experience (ES=0.07) irrespective of strength-level (78). It has been reported that well-trained rowers and swimmers regularly utilize ST as part of their training routine (3, 55), and highly-trained distance runners include ST modalities more so than recreational runners (12). The well-trained runners, cyclists and rowers in the studies that observed an improvement in performance following a LCA had ST experience (5, 29, 79), therefore it appears that possessing a background in ST may be important to ensure a LCA is beneficial. Furthermore, highly-trained endurance athletes are capable of eliciting an amplified PAP response, the extent of which appears closely related to the training status of the limb exposed to the LCA (42, 66). It seems that training status *per se*, may therefore be as important as ST experience when considering the type of athlete who may benefit from a LCA. This could be attributed to an athletes skill level on a LCA, as better inter-muscular co-ordination on a task is likely to enable higher threshold motor units to be activated (7). In this regard, it may therefore be possible that a learning-effect exists, whereby middle- and long-distance athletes with less ST experience are able to benefit from a LCA following a number of exposures to a PAP-type protocol. Further investigation is required to confirm this conjecture.

Loaded conditioning activity

A recent meta-analysis indicated that plyometric and high-load resistance training provide a similar PAP response (ES: 0.41 and 0.47 respectively), whereas moderate load exercises and isometric contractions produce a negligible effect (ES: <0.2) on tasks requiring short bursts of explosive power (78). Results from the studies on middle- and long-distance performance (Table 1) corroborate this finding. Silva et al. (79) observed an improvement (-6.1%, ES: 0.38) in 20-km cycling performance following 5-RM leg pressing, and 1-km rowing performance was unaltered by a series of 5 x 5-s isometric contractions (29). No studies to date have attempted to use a traditional plyometric exercise to elicit a PAP response in endurance athletes. However Barnes and colleagues (5) added load (20% body mass) to sprints (6 x 10-s) and achieved improvements in running economy (-6.0%, ES: 1.40), peak running speed (2.9%, ES: 0.35) and %$\dot{V}O_{2max}$ (-7.2%, ES=0.68).

When attempting to exploit PAP to enhance performance, a sufficiently high-intensity LCA is required to induce potentiation, however this also produces a high-level of fatigue. A recent review provides evidence for impairments in endurance-related performance for up to 72-h following a single bout of resistance training (27). Obviously performing multiple exercises and/or high load volumes will generate a level of neuromuscular fatigue that is likely to adversely affect a bout of endurance exercise performed immediately after. However, several studies have observed high levels of fatigue generated from a prescription that is not excessively different to the studies reviewed (26, 63, 82). For example, Michaut and colleagues (63) found reduced twitch activation from 2-min to 48-h following 5-sets of 10 eccentric contractions. Although it appears that multiple sets and a low number of repetitions of a LCA optimize a PAP response, the effect is mediated by both strength-level and exercise intensity (78, 92). It is likely that athletes who lack ST experience will develop higher levels of fatigue compared to those who are familiar with LCA-type exercises, however the enhanced fatigue resistance of endurance-trained athletes means they display similar recovery profiles to strength-trained individuals (66). Thus a relatively low volume (≤ 6-sets x 3-5 repetitions or ~10-s) of sub-maximal contractions is most likely to yield a beneficial response (59, 78). Further research is warranted to ratify this suggestion.

A limitation of many PAP inducing techniques is the requirement for heavy and expensive equipment, which cannot be easily accessed in a field-based setting or prior to competition. Having the option to elicit a PAP response without the need for specialist equipment or facilities would be of considerable practical benefit for endurance athletes and their coaches.

Thus, there is appeal in protocols that add additional load to sport-specific movement patterns using portable inexpensive strategies (5, 29). Plyometric-based exercise may also provide an effective means of achieving a PAP outcome, however this is yet to be determined in middle- and long-distance athletes.

Recovery following loaded conditioning activity

The recovery time between a LCA and the outcome activity is crucial to ensuring fatigue has dissipated sufficiently yet a state of potentiation in the neuromuscular system remains (92). This presents a dilemma, which several studies have attempted to resolve by investigating the time course of the decay in PAP and fatigue to identify the optimal window of time where the net gain from potentiation is highest (36, 52, 53). Passive rest intervals of between 5-12 min after heavy resistance activities (38, 78, 92) and 1-6 min following a ballistic exercise (59) have been suggested to enhance a short duration task. However, the temporal profile of a PAP response is also modulated by training status. Although weaker individuals appear to require longer (> 8-min) recovery periods to realise a PAP response, aerobic fitness is related to an ability to recover from high-intensity exercise (84). Benefits to the early part of middle-distance efforts have been shown using a recovery duration of 4-5 min in endurance-trained athletes (21, 29), however overall performance did not benefit from this scenario, perhaps suggesting some residual fatigue caused by the LCA was still present. Depending upon the activity utilized to induce PAP, it is therefore likely that a recovery period of between 5-10 min should be adopted to maximize the likelihood of middle- and long-distance performance being enhanced.

Outcome activity

A PAP response is transient and appears to provide negligible effects on power performance beyond approximately 12-min post-LCA (38, 92), but prevails for longer in endurance-trained athletes compared to power-trained individuals (66, 70). This indicates that if long-distance athletes benefit from a PAP response, it would be likely to affect only the initial part of a performance. It may also be the case that middle-distance performances lasting < 3-min might gain more benefit compared to longer distance efforts. Studies that have used high-intensity sprinting as part of a warm-up lend support to this notion as improvements in swimming, running and kayak performance lasting 1-2 min have been demonstrated (11, 43, 48).

Studies to date have tended to focus upon measuring TT performance (21, 29, 79), which provides a high level of ecological validity. Assessment of movement economy and efficiency, which have been shown to benefit from chronic exposure to ST (6, 9) are also likely to benefit from acute potentiation of the neuromuscular system. Preliminary evidence is contradictory in this regard as Barnes and colleagues (5) observed large improvements in running economy following a series of weighted vest sprints, whereas Silva et al. (79) found no change in $\dot{V}O_2$ during a 20 km cycle TT. The discrepancy is likely due to the intensities used to assess economy in these two papers, therefore future work should use a common relative intensity (below lactate threshold) in participants.

SUMMARY AND FUTURE RESEARCH

Warm-ups are commonplace in the pre-performance routine of middle- and long-distance athletes with the majority of research focussing on the $\dot{V}O_2$ kinetic response to various priming protocols. Over a decade ago, authors speculated that a PAP response evoked by a LCA included within an endurance athlete's warm-up routine would provide a benefit to performance (42, 75). This was based upon the argument that PAP has its greatest effect during activities which require motor units to fire at relatively low force frequencies. However, despite an abundance of literature investigating the acute effects of a LCA on subsequent ballistic performance tasks, only recently have studies emerged that have investigated the PAP phenomenon in middle- and long-distance athletes. Despite the limited number of studies that have been conducted in this area to date, the tentative conclusion is that well-trained middle- and long-distance athletes are likely to obtain some benefit, particularly during the early stages of a performance, by including a LCA in their warm-up routine.

It is recommended that middle- and long-distance athletes experiment with a warm-up protocol (Figure 1) that involves a 5-10 min self-paced warm-up at a low intensity (~60% maximum heart rate or 40-60% peak power output) followed 5-10 min later by a LCA. It is likely that a short bout of high-load resistance exercise (4-6 sets x 5-RM) or series of sprint efforts (4-6 sets x ~10-s), which include the addition of a light-moderate load will elicit a PAP response. A recovery of 5-10 min should be permitted following the LCA to ensure fatigue has dissipated sufficiently to realize a benefit to performance.

Given the dearth of literature in this area, there is scope for a future research to address a number of important questions concerning the efficacy of PAP protocols in middle- and long-distance athletes (Figure 1). There is good evidence for including high-intensity sprints to enhance $\dot{V}O_2$ kinetics, however a PAP-inducing LCA may also benefit the initial stages of performance via different mechanisms. It is unknown whether a combination of these approaches (priming and LCA) would augment performance to an even greater extent, or in fact produce excessive fatigue that attenuates performance. There is also a need to explore the value of different LCA's including heavy resistance exercise, plyometrics and loading of the sport-skill itself. If indeed a LCA provides a benefit to middle- and long-distance performance, the optimal prescription to maximize a PAP response should also be investigated. Based upon current literature, it appears that a LCA may provide a performance advantage during the first few minutes of exercise, however it is currently unknown whether this effect could be longer lasting, or whether other determinants of performance are also affected favourably. At present very few studies have investigated whether a LCA could positively impact sub-populations of middle- and long-distance athletes such as females and different age groups. A young group of high-performing middle-distance athletes represent an intriguing group to investigate, as it is likely they would possess a higher proportion of type II fibres compared to their more experienced senior counterparts (93). Finally, the mechanisms underlying how a LCA may positively affect middle- and long-distance performance remain speculative, thus future work in this area should also attempt to address this gap in knowledge.

REFERENCES

1. Aagaard P, Simonsen EB, Andersen JL, Magnusson P, and Dyhre-Poulsen P. Neural adaptation to resistance training: changes in evoked V-wave and H-reflex responses. J Appl Physiol 92: 2309-2318, 2002.
2. Arampatzis A, De Monte G, Karamanidis K, Morey-Klapsing G, Stafilidis S, and Bruggemann GP. Influence of the muscle-tendon unit's mechanical and morphological properties on running economy. J Exp Biol 209: 3345-3357, 2006.
3. Aspenes ST, and Karlsen T. Exercise-training intervention studies in competitive swimming. Sports Med 42: 527-543, 2012.
4. Bailey SJ, Vanhatalo A, Wilkerson DP, Dimenna FJ, and Jones AM. Optimizing the "priming" effect: influence of prior exercise intensity and recovery duration on O2 uptake kinetics and severe-intensity exercise tolerance. J Appl Physiol 107: 1743-1756, 2009.
5. Barnes KR, Hopkins WG, McGuigan MR, and Kilding AE. Warm-up with a weighted vest improves running performance via leg stiffness and running economy. J Sci Med Sport 18: 103-108, 2015.
6. Beattie K, Kenny IC, Lyons M, and Carson BP. The effect of strength training on performance in endurance athletes. Sports Med 44: 845-865, 2014.
7. Bernardi M, Solomonow M, Nguyen G, Smith A, and Baratta R. Motor unit recruitment strategy changes with skill acquisition. Eur J Appl Physiol Occ Physiol 74: 52-59, 1996.
8. Berryman N, Maurel DB, and Bosquet L. Effect of plyometric vs. dynamic weight training on the energy cost of running. J Strength Cond Res 24: 1818-1825, 2010.
9. Berryman N, Mujika I, Arvisais D, Roubeix M, Binet C, and Bosquet L. Strength training for middle- and long-distance performance: a meta-analysis. Int J Sports Physiol Perf 1-27, 2017. doi: 10.1123/ijspp.2017-0032. [Epub ahead of print].

10. Bishop D. Warm up II: performance changes following active warm up and how to structure the warm up. Sports Med 33: 483-498, 2003.

11. Bishop D, Bonetti D, and Spencer M. The effect of an intermittent, high-intensity warm-up on supramaximal kayak ergometer performance. J Sports Sci 21: 13-20, 2003.

12. Blagrove RC, Brown N, Howatson G, and Hayes PR. Strength and Conditioning Habits of Competitive Distance Runners. J Strength Cond Res, 2017. doi: 10.1519/jsc.0000000000002261 [Epub ahead of print].

13. Boullosa DA, Tuimil JL, Alegre LM, Iglesias E, and Lusquinos F. Concurrent fatigue and potentiation in endurance athletes. Int J Sports Physiol Perf 6: 82-93, 2011.

14. Brandon LJ. Physiological factors associated with middle distance running performance. Sports Med 19: 268-277, 1995.

15. Brughelli M, and Cronin J. Influence of running velocity on vertical, leg and joint stiffness : modelling and recommendations for future research. Sports Med 38: 647-657, 2008.

16. Burnley M, Doust JH, Ball D, and Jones AM. Effects of prior heavy exercise on VO(2) kinetics during heavy exercise are related to changes in muscle activity. J Appl Physiol 93: 167-174, 2002.

17. Burnley M, Doust JH, and Jones AM. Effects of prior heavy exercise, prior sprint exercise and passive warming on oxygen uptake kinetics during heavy exercise in humans. Eur J Appl Physiol 87: 424-432, 2002.

18. Burnley M, Doust JH, and Jones AM. Effects of prior warm-up regime on severe-intensity cycling performance. Med Sci Sports Exerc 37: 838-845, 2005.

19. Burnley M, and Jones AM. Oxygen uptake kinetics as a determinant of sports performance. Eur J Sport Sci 7: 63-79, 2007.

20. Chiu LZ, Fry AC, Weiss LW, Schilling BK, Brown LE, and Smith SL. Postactivation potentiation response in athletic and recreationally trained individuals. J Strength Cond Res 17: 671-677, 2003.

21. Chorley A, and Lamb KL. The effects of a cycling warm-up including high-intensity heavy-resistance conditioning contractions on subsequent 4 km time trial performance. J Strength Cond Res, 2017. doi: 10.1519/jsc.0000000000001908 [Epub ahead of print]

22. Comyns TM, Harrison AJ, Hennessy L, and Jensen RL. Identifying the optimal resistive load for complex training in male rugby players. Sports Biomech 6: 59-70, 2007.

23. Costill DL, Daniels J, Evans W, Fink W, Krahenbuhl G, and Saltin B. Skeletal muscle enzymes and fiber composition in male and female track athletes. J Appl Physiol 40: 149-154, 1976.

24. Costill DL, Fink WJ, and Pollock ML. Muscle fiber composition and enzyme activities of elite distance runners. Med Sci Sports 8: 96-100, 1976.

25. de Luca CJ, Foley PJ, and Erim Z. Motor unit control properties in constant-force isometric contractions. J Neurophysiol 76: 1503-1516, 1996.

26. Doma K, and Deakin GB. The effects of combined strength and endurance training on running performance the following day. Int J Sport Health Sci 11: 1-9, 2013.

27. Doma K, Deakin GB, and Bentley DJ. Implications of impaired endurance performance following single bouts of resistance training: an alternate concurrent training perspective. Sports Med, 2017. doi: 10.1007/s40279-017-0758-3 [Epub ahead of print]

28. Dumke CL, Pfaffenroth CM, McBride JM, and McCauley GO. Relationship between muscle strength, power and stiffness and running economy in trained male runners. Int J Sports Physiol Perf 5: 249-261, 2010.

29. Feros SA, Young WB, Rice AJ, and Talpey SW. The effect of including a series of isometric conditioning contractions to the rowing warm-up on 1,000-m rowing ergometer time trial performance. J Strength Cond Res 26: 3326-3334, 2012.

30. Fitts RH, and Holloszy JO. Contractile properties of rat soleus muscle: effects of training and fatique. Am J Physiol 233: C86-91, 1977.

31. Fletcher JR, Esau SP, and MacIntosh BR. Changes in tendon stiffness and running economy in highly trained distance runners. Eur J Appl Physiol 110: 1037-1046, 2010.

32. Fletcher JR, Groves EM, Pfister TR, and Macintosh BR. Can muscle shortening alone, explain the energy cost of muscle contraction in vivo? Eur J Appl Physiol 113: 2313-2322, 2013.

33. Fletcher JR, and MacIntosh BR. Running Economy from a Muscle Energetics Perspective. Front Physiol 8: 433, 2017.

34. Folland JP, Wakamatsu T, and Fimland MS. The influence of maximal isometric activity on twitch and H-reflex potentiation, and quadriceps femoris performance. Euro J Appl Physiol 104: 739-748, 2008.

35. Gago P, Arndt A, Tarassova O, and Ekblom MM. Post activation potentiation can be induced without impairing tendon stiffness. Euro J Appl Physiol 114: 2299-2308, 2014.

36. Gilbert G, and Lees A. Changes in the force development characteristics of muscle following repeated maximum force and power exercise. Ergon 48: 1576-1584, 2005.

37. Gourgoulis V, Aggeloussis N, Kasimatis P, Mavromatis G, and Garas A. Effect of a submaximal half-squats warm-up program on vertical jumping ability. J Strength Cond Res 17: 342-344, 2003.

38. Gouvêa AL, Fernandes IA, Cesar EP, Silva WA, and Gomes PS. The effects of rest intervals on jumping performance: a meta-analysis on post-activation potentiation studies. J Sports Sci 31: 459-467, 2013.

39. Green H, and Jones S. Does post-tetanic potentiation compensate for low frequency fatigue? Clin Physiol Funct Imaging 9: 499-514, 1989.

40. Güllich A, and Schmidtbleicher D. MVC-induced short-term potentiation of explosive force. New Stud Athlet 11: 67-84, 1996.

41. Gurd BJ, Peters SJ, Heigenhauser GJ, LeBlanc PJ, Doherty TJ, Paterson DH, and Kowalchuk JM. Prior heavy exercise elevates pyruvate dehydrogenase activity and

speeds O2 uptake kinetics during subsequent moderate-intensity exercise in healthy young adults. J Physiol 577: 985-996, 2006.

42. Hamada T, Sale DG, and Macdougall JD. Postactivation potentiation in endurance-trained male athletes. Med Sci Sports Exerc 32: 403-411, 2000.

43. Hancock AP, Sparks KE, and Kullman EL. Postactivation potentiation enhances swim performance in collegiate swimmers. J Strength Cond Res 29: 912-917, 2015.

44. Hayes PR, and Caplan N. Leg stiffness decreases during a run to exhaustion at the speed at VO2max. Eur J Sport Sci 14: 556-562, 2014.

45. Hirst GD, Redman SJ, and Wong K. Post-tetanic potentiation and facilitation of synaptic potentials evoked in cat spinal motoneurones. J Physiol 321: 97-109, 1981.

46. Hoogkamer W, Kipp S, Spiering BA, and Kram R. Altered running economy directly translates to altered distance-running performance. Med Sci Sports Exerc 48: 2175-2180, 2016.

47. Houston ME, Green HJ, and Stull JT. Myosin light chain phosphorylation and isometric twitch potentiation in intact human muscle. Pflugers Arch 403: 348-352, 1985.

48. Ingham SA, Fudge BW, Pringle JS, and Jones AM. Improvement of 800-m running performance with prior high-intensity exercise. Int J Sports Physiol Perf 8: 77-83, 2013.

49. Jones AM, Koppo K, and Burnley M. Effects of prior exercise on metabolic and gas exchange responses to exercise. Sports Med 33: 949-971, 2003.

50. Jones AM, Wilkerson DP, Burnley M, and Koppo K. Prior heavy exercise enhances performance during subsequent perimaximal exercise. Med Sci Sports Exerc 35: 2085-2092, 2003.

51. Kakuda N, and Nagaoka M. Dynamic response of human muscle spindle afferents to stretch during voluntary contraction. J Physiol 513: 621-628, 1998.

52. Kilduff LP, Bevan HR, Kingsley MI, Owen NJ, Bennett MA, Bunce PJ, Hore AM, Maw JR, and Cunningham DJ. Postactivation potentiation in professional rugby players: Optimal recovery. J Strength Cond Res 21: 1134, 2007.

53. Kilduff LP, Owen N, Bevan H, Bennett M, Kingsley MI, and Cunningham D. Influence of recovery time on post-activation potentiation in professional rugby players. J Sports Sci 26: 795-802, 2008.

54. Lai A, Schache AG, Lin Y-C, and Pandy MG. Tendon elastic strain energy in the human ankle plantar-flexors and its role with increased running speed. J Exp Biol 217: 3159-3168, 2014.

55. Lawton TW, Cronin JB, and McGuigan MR. Strength testing and training of rowers: a review. Sports Med 41: 413-432, 2011.

56. Lindinger SJ, Holmberg HC, Muller E, and Rapp W. Changes in upper body muscle activity with increasing double poling velocities in elite cross-country skiing. Eur J Appl Physiol 106: 353-363, 2009.

57. Lüscher H, Ruenzel P, and Henneman E. Composite EPSPs in motoneurons of different sizes before and during PTP: implications for transmission failure and its relief in Ia projections. J Neurophysiol 49: 269-289, 1983.

58. MacIntosh BR, and Rassier DE. What is fatigue? Can J Appl Physiol 27: 42-55, 2002.

59. Maloney SJ, Turner AN, and Fletcher IM. Ballistic exercise as a pre-activation stimulus: a review of the literature and practical applications. Sports Med 44: 1347-1359, 2014.

60. Maturana FM, Peyrard A, Temesi J, Millet GY, and Murias JM. Faster VO2 kinetics after priming exercises of different duration but same fatigue. J Sports Sci: 1-8, 2017. doi: 10.1080/02640414.2017.1356543 [Epub ahead of print].

61. McIntyre JP, and Kilding AE. Effects of high-intensity intermittent priming on physiology and cycling performance. J Sports Sci 33: 561-567, 2015.

62. McLaughlin JE, Howley ET, Bassett DR, Jr., Thompson DL, and Fitzhugh EC. Test of the classic model for predicting endurance running performance. Med Sci Sports Exerc 42: 991-997, 2010.

63. Michaut A, Pousson M, Ballay Y, and Van Hoecke J. Effects of an eccentric exercise session short-term recovery of muscle contractility. J Soc Biolog 194: 171-176, 2000.

64. Millet GP, Jaouen B, Borrani F, and Candau R. Effects of concurrent endurance and strength training on running economy and .VO(2) kinetics. Med Sci Sports Exerc 34: 1351-1359, 2002.

65. Moir GL, Mergy D, Witmer C, and Davis SE. The acute effects of manipulating volume and load of back squats on countermovement vertical jump performance. J Strength Cond Res 25: 1486-1491, 2011.

66. Morana C, and Perrey S. Time course of postactivation potentiation during intermittent submaximal fatiguing contractions in endurance- and power-trained athletes. J Strength Cond Res 23: 1456-1464, 2009.

67. Murias JM, Spencer MD, and Paterson DH. The critical role of O2 provision in the dynamic adjustment of oxidative phosphorylation. Exerc Sport Sci Rev 42: 4-11, 2014.

68. Nilwik R, Snijders T, Leenders M, Groen BB, van Kranenburg J, Verdijk LB, and van Loon LJ. The decline in skeletal muscle mass with aging is mainly attributed to a reduction in type II muscle fiber size. Exp Gerontol 48: 492-498, 2013.

69. Obst SJ, Barrett RS, and Newsham-West R. Immediate effect of exercise on achilles tendon properties: systematic review. Med Sci Sports Exerc 45: 1534-1544, 2013.

70. Pääsuke M, Saapar L, Ereline J, Gapeyeva H, Requena B, and Ööpik V. Postactivation potentiation of knee extensor muscles in power-and endurance-trained, and untrained women. Eur J Appl Physiol 101: 577-585, 2007.

71. Paavolainen L, Hakkinen K, Hamalainen I, Nummela A, and Rusko H. Explosive-strength training improves 5-km running time by improving running economy and muscle power. J Appl Physiol 86: 1527-1533, 1999.

72. Rassier DE. The effects of length on fatigue and twitch potentiation in human skeletal muscle. Clin Physiol 20: 474-482, 2000.

73. Rassier DE, and Macintosh BR. Coexistence of potentiation and fatigue in skeletal muscle. Braz J Med Biol Res 33: 499-508, 2000.

74. Roberts TJ, Marsh RL, Weyand PG, and Taylor CR. Muscular force in running turkeys: the economy of minimizing work. Sci 275: 1113-1115, 1997.

75. Sale DG. Postactivation potentiation: role in performance. Br J Sports Med 38: 386-387, 2004.

76. Sale DG. Influence of exercise and training on motor unit activation. Exerc Sport Sci Rev 15: 95-151, 1987.

77. Schluter JM, and Fitts RH. Shortening velocity and ATPase activity of rat skeletal muscle fibers: effects of endurance exercise training. Am J Physiol 266: C1699-1673, 1994.

78. Seitz LB, and Haff GG. Factors modulating post-activation potentiation of jump, sprint, throw, and upper-body ballistic performances: A systematic review with meta-analysis. Sports Med 46: 231-240, 2016.

79. Silva RA, Silva-Júnior FL, Pinheiro FA, Souza PF, Boullosa DA, and Pires FO. Acute prior heavy strength exercise bouts improve the 20-km cycling time trial performance. J Strength Cond Res 28: 2513-2520, 2014.

80. St Clair Gibson A, Lambert EV, Rauch LH, Tucker R, Baden DA, Foster C, and Noakes TD. The role of information processing between the brain and peripheral physiological systems in pacing and perception of effort. Sports Med 36: 705-722, 2006.

81. Steinacker JM. Physiological aspects of training in rowing. Int J Sports Med 14 Suppl 1: S3-10, 1993.

82. Stock MS, Young JC, Golding LA, Kruskall LJ, Tandy RD, Conway-Klaassen JM, and Beck TW. The effects of adding leucine to pre and postexercise carbohydrate beverages on acute muscle recovery from resistance training. J Strength Cond Res 24: 2211-2219, 2010.

83. Tillin NA and Bishop D. Factors modulating post-activation potentiation and its effect on performance of subsequent explosive activities. Sports Med 39: 147-166, 2009.

84. Tomlin DL and Wenger HA. The relationship between aerobic fitness and recovery from high intensity intermittent exercise. Sports Med 31: 1-11, 2001.

85. Tordi N, Perrey S, Harvey A, and Hughson RL. Oxygen uptake kinetics during two bouts of heavy cycling separated by fatiguing sprint exercise in humans. J Appl Physiol 94: 533-541, 2003.

86. Trimble MH, and Harp SS. Postexercise potentiation of the H-reflex in humans. Med Sci Sports Exerc 30: 933-941, 1998.

87. Vandenboom R, Grange RW, and Houston ME. Threshold for force potentiation associated with skeletal myosin phosphorylation. Am J Physiol 265: C1456-1462, 1993.

88. Vandervoort AA, Quinlan J, and McComas AJ. Twitch potentiation after voluntary contraction. Exp Neurol 81: 141-152, 1983.

89. Watsford M, Ditroilo M, Fernández-Peña E, D'amen G, and Lucertini F. Muscle stiffness and rate of torque development during sprint cycling. Med Sci Sports Exerc 42: 1324-1332, 2010.

90. Wilkerson DP, Koppo K, Barstow TJ, and Jones AM. Effect of prior multiple-sprint exercise on pulmonary O2 uptake kinetics following the onset of perimaximal exercise. J Appl Physiol 97: 1227-1236, 2004.

91. Wilson GJ, Murphy AJ, and Pryor JF. Musculotendinous stiffness: its relationship to eccentric, isometric, and concentric performance. J Appl Physiol 76: 2714-2719, 1994.

92. Wilson JM, Duncan NM, Marin PJ, Brown LE, Loenneke JP, Wilson SM, Jo E, Lowery RP, and Ugrinowitsch C. Meta-analysis of postactivation potentiation and power: effects of conditioning activity, volume, gender, rest periods, and training status. J Strength Cond Res 27: 854-859, 2013.

93. Wilson JM, Loenneke JP, Jo E, Wilson GJ, Zourdos MC, and Kim J-S. The effects of endurance, strength, and power training on muscle fiber type shifting. J Strength Cond Res 26: 1724-1729, 2012.

Authors	Participants	Sport	Training status	Potentiation protocol	Recovery	Performance protocol	Main findings compared to control condition
Barnes et al. (6)	11 male	Distance runners	Well-trained ($\dot{V}O_{2max}$ 62.1 ±5.9 ml.kg^{-1}.min^{-1}, 5 km 16.0 ±1.0 min)	6 x 10 s weighted vest (20% BM) sprints ~1500 m pace	10 min	5 min run @14 km.h^{-1}, incremental test to exhaustion	RE: -6.0% (ES=1.40), peak running speed 2.9% (ES=0.35), %$\dot{V}O_{2max}$ -7.2% (ES=0.68)
Chorley and Lamb (22)	10 male	Cyclists	Highly-trained ($\dot{V}O_{2max}$ 65.3 ±5.6 ml.kg^{-1}.min^{-1}, 8.2 ±6.0 years cycling),	3 x 10 s @70% PP, 60 rpm (30 s recovery)	5 min	4 km Wattbike TT	TT: -0.5% (ES=0.26), mean power (ES=0.24), mean Force (ES=0.21) all NSS. 0-1.5 km $\dot{V}O_2$: 6.8% (p<0.05, ES=0.97) 4 km TT $\dot{V}O_2$: 2.4% (p<0.05, ES=0.28)

Feros et al. (32)	9 male, 1 female	Rowers	Elite ($\dot{V}O_{2max}$ 68.7 ±3.1 $ml.kg^{-1}.min^{-1}$, >5 years RT history)	5 x 5 s (15 s recovery) isometric CC on rowing ergometer	4 min	1 km rowing ergometer TT	0-500 m TT split: -1.9% (*p*=0.009, ES=0.62) 0-500 m TT power: 6.6% (*p*=0.007, ES=0.64). 1 km TT (ES=0.21), mean power (ES=0.26) both NSS
Silva et al. (85)	11 male	Cyclists	Well-trained ($\dot{V}O_{2peak}$ 56.7 ±6.7 $ml.kg^{-1}.min^{-1}$, 2-10 years running)	4 x 5RM leg press	10 min	20 km static cycle TT	TT: -6.1% (*p*=0.02, ES=0.38). 0-2 km mean power: 5.8% (*p*=0.06, ES=0.22) 2-18 km (2.7%) and 18-20 km (0.8%) both NSS. Mean power (ES=0.11), $\dot{V}O_2$ (ES=0.19), BL (ES=0.13) all NSS

Table 1. Summary of studies which have investigated the acute effects of a loaded conditioning activity upon variables related to performance in middle- and long-distance athletes.

BL = blood lactate, BM = body mass, CC = conditioning contractions, ES = effect size, PP = peak power, NSS = no statistical significance ($p<0.05$), RE = running economy, RM = repetition maximum, rpm = revolutions per minute, RT = resistance training, TT = time trial

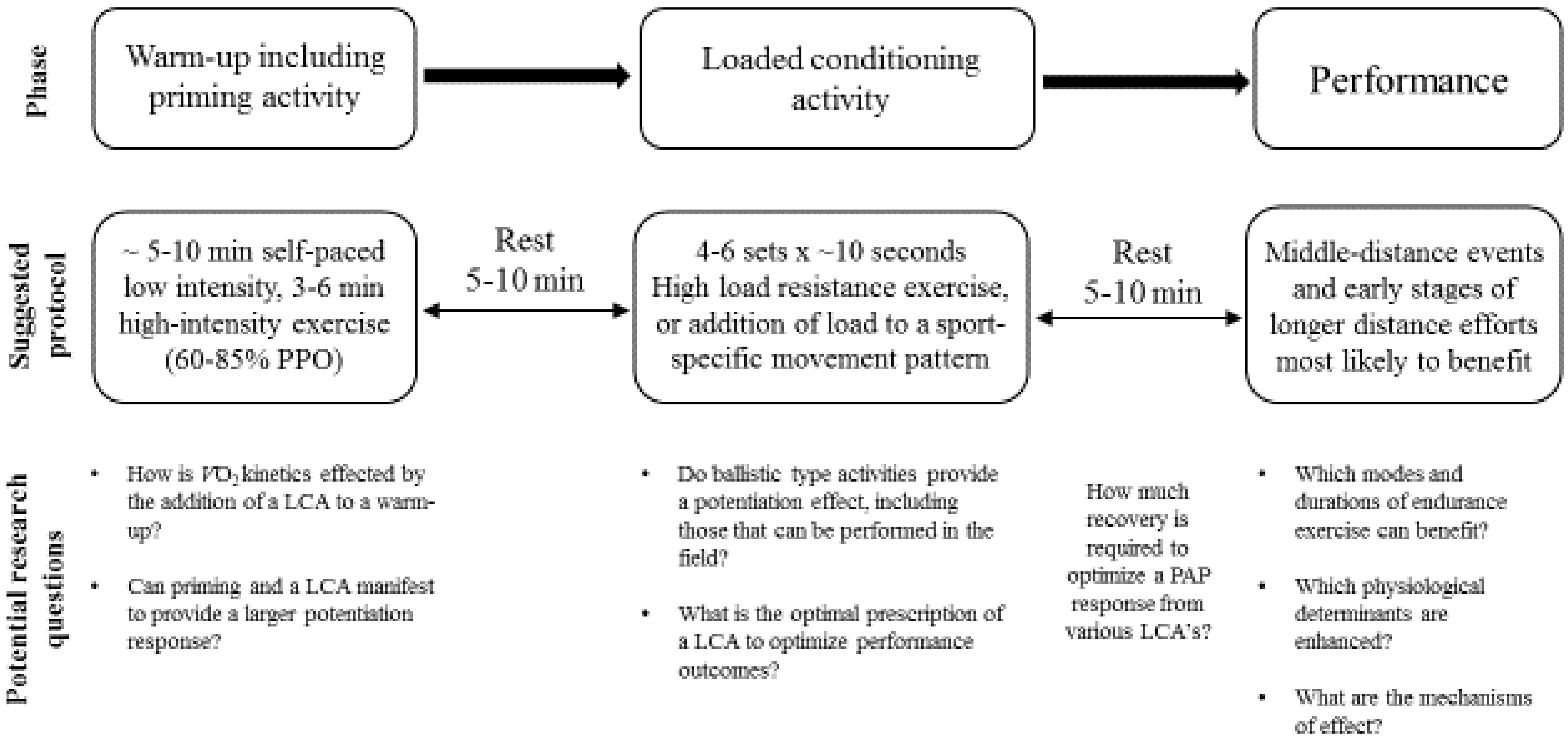

Figure 1. Suggested warm-up protocol for a middle- or long-distance athlete, including use of a conditioning activity to potentiate performance, and potential areas for future research.

LCA = loaded conditioning activity, PAP = post activation potentiation, PPO = peak power output